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Intra-Cycle Motion Correction in Coronary CT Angiography

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Abstract Coronary computed tomography angiography (CCTA) has demonstrated high diagnostic performance for coronary lesions detection. However, coronary artery motion blurring, related to high or variable heart rate (HR) is a common drawback. Recently, a novel intracycle motion-correction (MC) algorithm has been developed. Aim of the present review is to evaluate the published literature regarding the impact of MC algorithm compared with standard reconstruction on diagnostic performance of CCTA and to integrate the published data with our local experience. The 2 single-center published studies showed a significant improvement of image quality and coronary interpretability in per-segment and per-artery analysis with MC reconstruction. In the study of Fuchs, these data were obtained using low radiation dose. The study of Leipsic also showed an improvement of diagnostic accuracy. Our experience is consistent with the literature data, demonstrating better coronary evaluability in high HR patients. The multicenter trial ViCTORY will determine if MC algorithm will allow a routine improvement of CCTA diagnostic performance.

Keywords Motion correction algorithm · Coronary computed tomography angiography · Motion artifact · Heart rate · Heart rate variability

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Introduction

Coronary computed tomography angiography (CCTA) is becoming an increasingly widespread tool for the noninvasive evaluation of coronary arteries, stents, and bypass grafts [1]. Although an overall good image quality and diagnostic accuracy for coronary artery evaluation has been demonstrated, beam-hardening artifacts resulting from large calcified plaques and motion artifacts because of high heart rate (HR) and heart rate variability (HRv) during the scan may impair image quality and significantly reduce CCTA evaluability and diagnostic accuracy [1, 2]. Many studies demonstrated that high HR and HRv are the primary cause of unevaluability of coronary arteries and that up to 12 % of coronary artery segments are deemed unevaluable because of motion artifacts alone [2–6]. This prompted the Society of Cardiovascular Computed Tomography [7] to adopt guidelines on CCTA, encouraging the use of HR-control medications including oral and intravenous beta-blockers and, more recently, oral ivabradin before the scan [8]. Nevertheless, in a sizable number of patients it is impossible to obtain HR values that are ideal for CCTA because patients are nonresponders to therapy or have contraindications to medications (eg, for beta-blockers, heart failure, or chronic obstructive pulmonary disease). For this reason, in the last years different technologies have been introduced in clinical practice for reducing motion artifacts and improving CCTA diagnostic performance in patients with high HR, including dual-source computed tomography, high-pitch computed tomography and 320-detector row computed tomography [9–12]. More recently, a new vendor-specific intra-cycle motion-correction (MC) algorithm (GE Healthcare, Waukasha, WI) has been developed and introduced in the clinical field with the aim of characterizing and compensating coronary motion blurring. The purpose of the present review is to evaluate the available literature concerning the impact of the intra-cycle MC algorithm as compared to standard (STD) reconstruction on motion artifacts, image quality and coronary evaluability of CCTA and to integrate the published data with our local experience in the clinical settings in which MC algorithm appears to be more advantageous.

Review of the Published Literature

Our prespecified inclusion criteria were: (1) English language literature; (2) Prospective or retrospective studies; (3) Human studies. Using our predetermined criteria, we searched MEDLINE combining the search terms coronary computed tomography angiography, motion correction algorithm, motion artifact, heart rate, heart rate variability, and included the studies published until December 2013.

The first study evaluating the impact of the MC algorithm on CCTA image quality, interpretability, and diagnostic accuracy in a population of patients referred for transcatheter aortic valve replacement (TAVR) was published in 2012 by Leipsic et al. [13••]. The authors enrolled 36 consecutive patients undergoing both cardiovascular CT (including CCTA) and invasive coronary angiography (ICA) as part of a routine clinical evaluation before TAVR. They did not use beta-blockers for HR reduction because evaluation of coronary arteries was not clinically required and for concerns regarding severe aortic stenosis. For this reason and for the usually high HR in patients with severe aortic stenosis, the study evaluated a subset of patients with HR characteristics that are typically associated with CCTA motion artifacts. Indeed, mean HR, HRv, and mean maximum HR during scan were 72±13 bpm, 17±8 bpm, and 87±14 bpm, respectively. Moreover, 14 patients had atrial fibrillation. All CCTA were performed with a 64-slice Discovery HD 750 High Definition scanner (GE Healthcare) and retrospective ECG gating. Regarding image processing, STD reconstructions were generated for 75 % and 45 % of the R-R interval as typically done in standard CCTA studies. To generate MC reconstructions, raw cardiac CT data were processed off-line with an advanced coronary MC technique. Briefly, after cardiac multi-phase reconstruction and automated coronary vessel tracking, the MC algorithm (Snapshot Freeze; GE Healthcare) uses information from adjacent cardiac phases within a single cardiac cycle to characterize vessel motion (both path and velocity), to determine the actual vessel position at the prescribed target phase and adaptively compensate for any residual motion at that phase, effectively compressing the reconstruction temporal window. This approach works on a per-vessel and per-segment basis to correct for differing degrees of motion for each voxel of the coronary vessel. Unlike multi-sector reconstruction techniques, the algorithm directly targets coronary-specific motion by adaptively compressing the temporal window within the localized regions where it is most needed. Because this approach characterizes motion within a single heart cycle, it is less susceptible to beat-to-beat inconsistencies, heart period, or gantry period resonance points, which can limit multi-sector (ie, multiple heart cycle) reconstruction. Also MC images were reconstructed at 45 % and 75 % of the R-R interval. The results of the of Leipsic et al. study are striking in terms of image quality, coronary interpretability, and diagnostic accuracy when the MC algorithm was used instead of STD. Particularly, they found a significant improvement of the image quality grade (Likert score) from 2.4 with STD to 2.9 with MC, a significant improvement of coronary interpretability in both per-segment (from 88 % with STD to 97 % with MC) and per-artery (from 84 % with STD to 96 % with MC) analysis and a significant improvement of CCTA diagnostic accuracy (using ICA as the gold standard imaging technique) in both per-segment (from 78 % with STD to 91 % with MC) and per-artery (from 72 % with STD to 86 % with MC) analysis. The mean radiation dose was 13±2 mSv, using the conversion coefficient for the chest=0.014 mSv/mGy/cm as previously described [14]. On the basis of Leipsic et al. results (significant improvement of CCTA diagnostic performance with MC, yet with the drawback of high radiation exposure), in a very recent study Fuchs et al. [15••] evaluated the impact of the MC algorithm on image quality with low-dose CCTA performed with prospective ECG triggering and ASIR, 2 technical approaches that already demonstrated to be

Table 1 Comparison between baseline characteristics and CCTA findings of Leipsic et al. and Fuchs et al. studies

	Leipsic et al.	Fuchs et al.
Age (mean±SD), yr	83±6	60±12
Male (%)	47	70
HR during scan (mean±SD), bpm	72±13	69±9
HRv during scan (mean±SD), bpm	17±9	3±5
Mean maximum HR (mean±SD), bpm	87±14	73±11
Image quality score, STD evaluation	2.4	3.0
Image quality score, MC evaluation	2.9	3.4
Per-segment interpretability , STD evaluation	88 %	86 %
Per-segment interpretability, MC evaluation	97 %	93 %
Per-artery interpretability, STD evaluation	84 %	78 %
Per-artery interpretability , MC evaluation	96 %	88 %
Per-segment accuracy, STD evaluation	78 %	-
Per-segment accuracy, MC evaluation	91 %	-
Per-segment accuracy, STD evaluation	72 %	-
Per-segment accuracy, MC evaluation	86 %	-
Effective dose (mean±SD), mSv	13.3±1.8	2.3±0.8

HR heart rate, *HRv* heart rate variability, *MC* motion correction, *SD* standard deviation, *STD* standard very effective in reducing radiation exposure without image quality impairment [16–20]. In fact, the MC approach should be considered advantageous also from a radiation dose perspective. Indeed, the algorithm can be applied to both retrospective-gated and prospective-triggered CCTA. Moreover, as opposed to the multisector technique that requires multiple exposures at a given image location across successive heart cycles, the new approach simply needs a relatively small window of data within 1 heart cycle to support multi-phase reconstruction for subsequent MC processing [13••]. Fuchs et al. studied 40 patients who were referred for the assessment with CCTA of known or suspected CAD and in whom the target <63 bpm HR before scan was not reached despite intravenous metoprolol. All CCTA were performed with a 64-slice Discovery HD 750 High Definition scanner (GE Healthcare), using prospective ECG triggering and the smallest X-ray window (only 75 % of the R-R cycle) plus an enlargement of the window of additional±80 msec (padding=80). This 80-msec window corresponds to the lowest value employable for the MC algorithm, allowing the reconstruction of 2 adjacent cardiac phases (ie, 70 % to 80 % of R-R cycle), the minimum needed for MC reconstruction. All scans were reconstructed using the high-definition kernel and ASIR 30 %. Both STD and MC images were reconstructed at 75 % of the R-R interval. The mean HR, HRv, and mean maximum HR during scan were 69±9 bpm, 3±5 bpm, and 73 ±11 bpm, respectively. The results in terms of coronary image quality and interpretability improvement after MC reconstruction were in agreement with those of Leipsic et al. Particularly, Fuchs et al. found a significant improvement of the image quality grade (Likert score) from 3.0 with STD to 3.4 with MC and a significant improvement of coronary interpretability in both per-segment (from 86 % with STD to 93 % with MC) and per-artery (from 78 % with STD to 88 % with MC) analysis. Notably, the radiation exposure was lower, as previously demonstrated for prospective ECG-triggering scans with small padding, with a mean effective dose of 2.3±0.8 mSv (using the conversion coefficient for the chest=0.014 mSv/mGy/cm). Table 1 compares the most important baseline characteristics and CCTA findings of Leipsic et al. and Fuchs et al. studies. The most relevant difference is the radiation exposure and is well explained by the use of prospective ECG triggering with small padding in the Fuchs et al. study, associated with an impressive reduction of the effective dose. Another remarkable finding of the Fuchs et al. study is the higher grade of image quality score of MC evaluations compared with STD, which is in agreement with the lower HR and HRv during scan allowing the use of prospective ECG triggering with the smallest padding (80 msec) in all patients. Further studies will be needed for evaluating the impact of MC on image quality of prospective ECG-triggering CCTA performed with large padding (200 msec) in patients with HR and HR variability values similar to those reported by Leipsic et al. Indeed, a large padding is more effective in a high HR setting, allowing the reconstruction of 4 distinct diastolic phases (ie, 45 % to 75 % of R-R cycle). The latest study we found in the literature reports the rationale and design of ViCTORY (Validation of an Intracycle CT Motion CORrection Algorithm for Diagnostic AccuracY), an international, prospective, multicenter trial that has the aim of determining

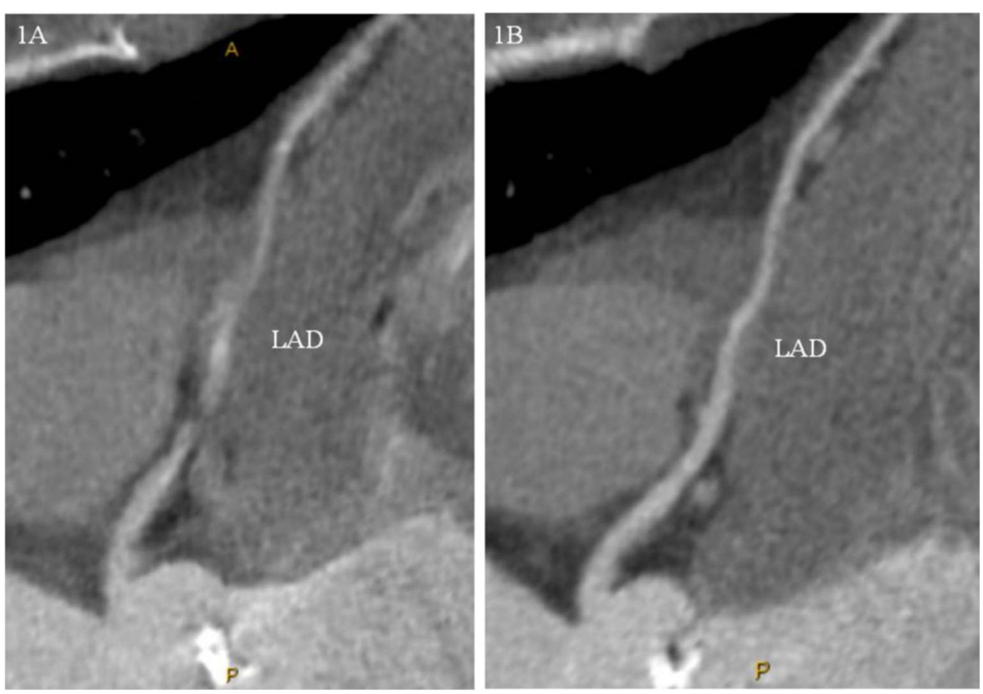

Fig. 1 Left anterior descending coronary artery imaged by retrospective ECG-triggering CCTA performed with standard reconstruction (panel **a**) and motion-correction algorithm (panel **b**) in a patient with HR of 91 bpm during the scan. Note the marked correction of the multiple motion artifacts achieved with the new algorithm. *LAD* left anterior descending artery

whether the MC algorithm improves the diagnosis of obstructive CAD in patients undergoing CCTA who are not receiving HR-lowering medications [21••]. The target ViCTORY population includes patients with suspected CAD who are referred for clinically indicated nonemergent ICA. The ViCTORY trial will be performed in up to 10 investigative sites in the United States, Italy, Japan, South Korea, and the United Kingdom with approximately 218 patients to be enrolled. Any center will be allowed to enroll no more than 25 % of the total number of patients. The primary end point of the trial is to determine the diagnostic accuracy of CCTA in identifying anatomically obstructive CAD at the patient level when reconstructed by MC vs STD reconstruction using binary outcomes compared with ICA as the reference standard. The secondary end points of trial are (1) per-subject, per-vessel, and per-segment measures of diagnostic performance of the MCA, including accuracy, sensitivity, specificity, PPV, and NPV of CCTA with the use of binary outcomes compared with ICA as the reference standard; (2) compare the CCTA diagnostic image quality and interpretability of the MCA vs STD; (3) determine the additive value of the MCA vs STD. The primary and secondary end points of the VICTORY trial were chosen to have a wide range of HR to adequately test the efficacy of MC vs traditional reconstruction. Inclusion criteria include patients who provide written informed consent, are scheduled to undergo clinically indicated nonemergent ICA and are undergoing investigational≥64-multidetector row CCTA within 60 days before ICA. Exclusion criteria include prior coronary artery bypass graft surgery or percutaneous coronary intervention, suspected acute coronary syndrome (acute myocardial infarction or unstable angina), myocardial infarction within 40 days of ICA, known complex congenital heart disease, prior implantation of pacemaker or ICD, prosthetic heart valve, significant arrhythmia or tachycardia, chronic renal failure (serum creatinine >1.5 mg/dL), known allergy to iodinated contrast, pregnancy or unknown pregnancy status, use of a beta-blocker with a direct contraindication to temporarily withdraw it, need of an emergent procedure, evidence of ongoing, or active clinical instability, any active, serious, life-threatening disease with a life expectancy of <2 months, and inability to comply with study procedures. All CCTA scans will be performed with a Discovery CT750 HD scanner (GE Healthcare). Laboratories will follow local CCTA scanning protocols for ViCTORY-enrolled patients

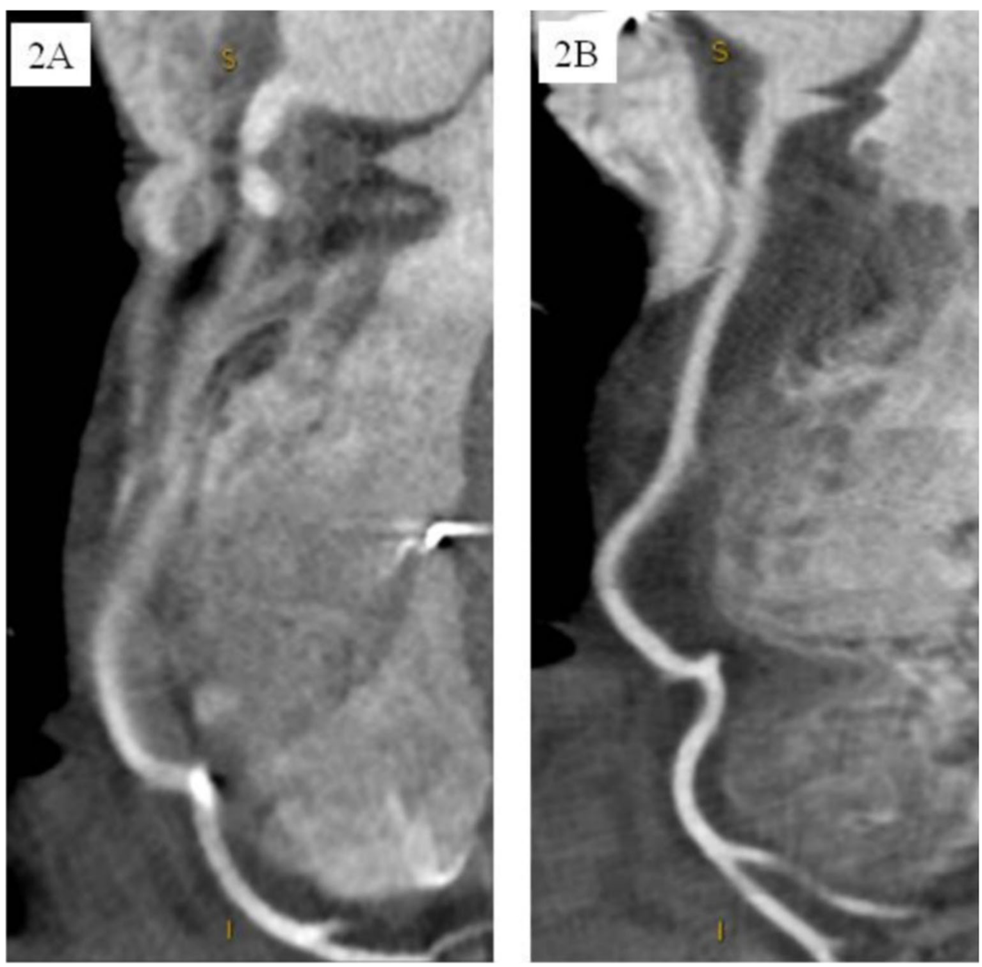

Fig. 2 Head-to-head comparison between standard (panel **a**) and MC (panel **b**) reconstructions of a right coronary artery imaged by CCTA performed with prospective ECG triggering and padding 200 in a patient with a prescanning HR of 71 bpm and a HRv of 16 bpm (from 71 to 87 bpm) during the scan. The correction of multiple motion artifacts along the vessel obtained with the new algorithm is evident. *MC* motion correction, *RCA* right coronary artery

provided that they satisfy quality standards accepted by the imaging community, as defined and updated by the Society of Cardiovascular Computed Tomography and Inter-societal Commission for the Accreditation of Computed Tomography Laboratories. Coronary images may be acquired by either prospective or retrospective electrocardiogram gating. If the former is used, sufficiently wide acquisition window (at least 80 milliseconds) should be employed to account for at least 2 phases of the cardiac cycle. Coronary images will be transmitted to independent readers at the CCTA core laboratory, who will evaluate them with dedicated 3-dimensional workstations using an 18-segment model of the coronary tree developed by the Society of Cardiovascular Computed Tomography. The severity of luminal diameter stenosis will be graded as none (0 % stenosis), very mild (1 %–24 % stenosis), mild (25 %–49 % stenosis), moderate (50 %–69 % stenosis), obstructive (>70 %–99 % stenosis), totally occluded (100 % stenosis), or nonevaluable. For CCTA analysis, 2 level-III certified readers will assess coronary images on a per-patient, per-vessel, and per-segment basis. In case of disagreement between the 2 core laboratory readers, a third level-III reader will be asked to adjudicate discordance. All readers will be blinded to clinical data and to each other. Motion artifacts will be graded using a motion-specific Likert scale. STD reconstructions will be generated for short intervals at approximately 75 % of the R-R interval exclusively when prospective triggering is used and at 45 % and 75 % of the R-R interval when retrospective gating is used. To generate MC reconstructions, raw cardiac CT data will be processed off-line in a blinded fashion using an advanced coronary MCA technique (Snap Shot Freeze; GE Healthcare). Patients will undergo diagnostic ICA by board-certified interventional cardiologists or country-equivalent specialists in accordance with usual clinical indications and by imaging standards set forth by the American College of Cardiology/Society for Cardiac Angiography and Interventions [22]. A blinded and experienced core laboratory will evaluate all invasive studies by quantitative coronary angiography. In conclusion, the ViCTORY trial end points and methods are aimed at determining the MCA impact on diagnostic accuracy and image quality of routinely acquired CCTA exams in patients who do not receive rate-control medications. The inclusion and exclusion criteria for are conceived to identify a cohort of patients with suspected CAD undergoing nonemergent ICA in a real-world practice scenario. The multicenter prospective nature of this trial limits selection and referral bias, while international recruitment will allow to maximally generalizing study results. Finally, the trial results will answer the question whether the MC algorithm may allow to consistently improving image quality and

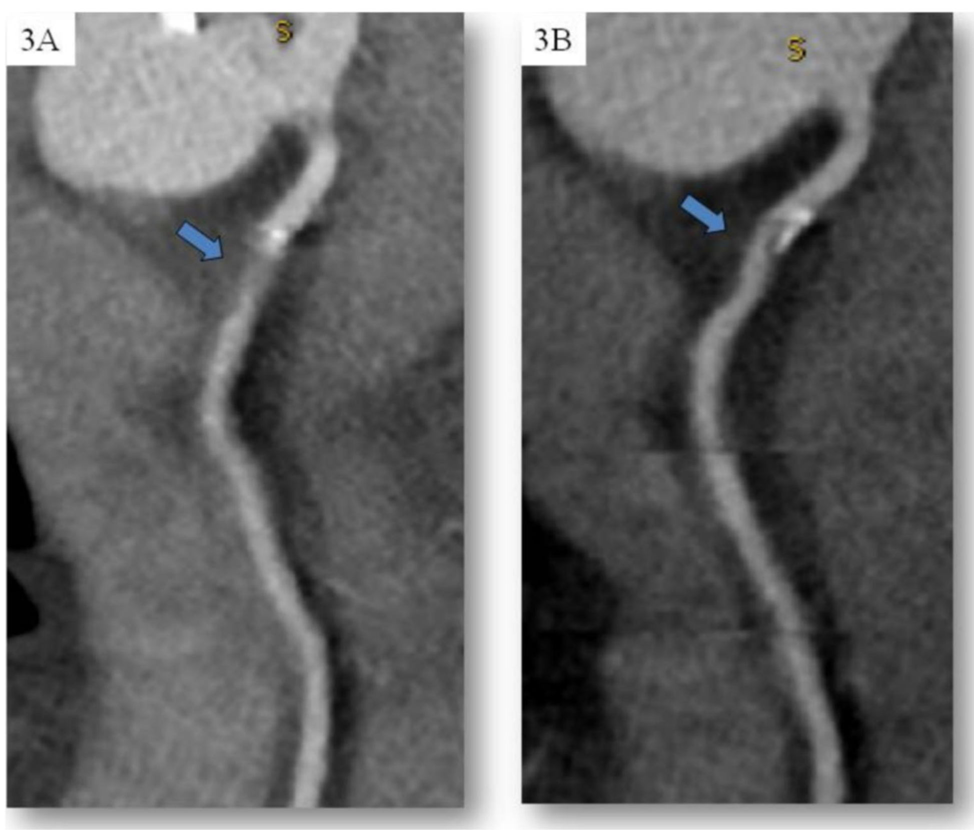

Fig. 3 Multiplanar reconstruction CCTA of a right coronary artery with a severe motion artifact at the site of a mixed plaque (arrow) making the lesion not evaluable with standard reconstruction (panel **a**). The artifact is caused by high HRv (7 bpm) during the scan despite low prescanning HR (58 bpm). The MC algorithm allowed adequate artifact correction making a >50 % stenosis visible (arrow, panel **b**). *HRv* heart rate variability, *MC* motion correction, *RCA* right coronary artery

diagnostic accuracy of CCTA in patients who do not receive rate-control drugs.

Personal Experience

The MC algorithm is available and used in our Institute since 2012. Our experience consists in more than 1000 cases that were performed with the MC algorithm. Our general impression is consistent with the results of the published studies, in terms of significant improvement of image quality and coronary evaluability obtained with the MC in patients with high HR, HRv, or both these conditions. The clinical settings in which we found the new approach to be more effective are the followings: (1) patients with HR >75 bpm before scanning despite intravenous metoprolol administration (up to 30 mg) or in those with contraindications to beta-blockers; (2) patients with intermediate (between 60 and 75 bpm) prescanning HR and high HRv during the prescan breath-holding test; (3) patients with low (<60 bpm) prescanning HR but high HRv during the prescan breath-holding test; (4) patients with HRv >10 bpm during the scan, irrespective of prescanning HR value. In the first clinical scenario (HR >75 bpm), the MC algorithm demonstrated the most relevant impact on our clinical work. Indeed, we previously did not perform CCTA in this subset of patients, aside from few cases (ie, patients with left ventricular dysfunction leading to better image quality despite high HR), in order to avoid exams with poor and nondiagnostic image quality. On the contrary, in most cases with these HR characteristics using the MC algorithm in conjunction with retrospective ECG triggering we were able to achieve coronary images of at least diagnostic quality. Figure 1 depicts an example of multiple motion artifacts impairing image assessment of a left anterior descending coronary artery in a patient with very high HR during scanning and the marked improvement obtained with the MC algorithm. In the second clinical setting (intermediate prescanning HR and high HRv during the prescan breath-holding test that is a strong predictor of high HRv during the scan), our experience indicates the value of the MC algorithm for 2 reasons: (1) a very effective reduction of coronary motion blurring; and (2) the opportunity to use, in this range of HR, prospective ECG triggering with a large padding (200 msec) instead of retrospective gating, with the advantage of radiation exposure reduction as previously demonstrated [17]. Figure 2 shows a CCTA multiplanar reconstruction of a right coronary artery with severe motion artifacts of the entire vessel leading to nondiagnostic image quality and a marked improvement of vessel evaluability with MC reconstruction. In the third clinical setting (low prescan HR and high HRv during the prescan test), we used prospective ECG triggering with padding of 80 msec in order to apply the MC algorithm in case of motion artifact occurrence with STD reconstruction due to HRv during scanning. Figure 3 shows a representative case of this clinical subset: a patient with prescan HR of 58 bpm in whom the HRv (from 58 to 65 bpm) during the scan caused a motion artifact at the site of a mixed plaque, which was not evaluable with STD reconstruction but well assessable after MC.

Conclusions

Few single-center studies suggest that the intra-cycle MC algorithm is an effective tool to improve CCTA image quality in patients with high HR or HRv. Our large personal experience is consistent with the available data from the literature, showing an important improvement in the coronary evaluability of patients with high or variable HR. The international multicenter ViCTORY trial will allow understanding whether the MC algorithm may achieve clinically relevant enhancement of image quality and diagnostic performance of CCTA in patients who cannot receive rate-control drugs or in whom ideal HR values are not achievable despite these medications.

Compliance with Ethics Guidelines

Conflict of Interest Daniele Andreini received personal fees from GE HealthCare.

Gianluca Pontone received personal fees from GE HealthCare. Saima Mushtaq, Erika Bertella, Antonio L. Bartorelli, and Mauro Pepi declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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