Post-hoc motion correction for coronary computed tomography angiography without additional radiation dose - Improved image quality and interpretability for “free”

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ABSTRACT
Objective: To evaluate the impact of a motion-correction (MC) algorithm, applicable post-hoc and not dependent on extended padding, on the image quality and interpretability of coronary computed tomography angiography (CCTA).

Methods: Ninety consecutive patients undergoing CCTA on a latest-generation 256-slice CT device were prospectively included. CCTA was performed with prospective electrocardiogram-triggering and the shortest possible acquisition window (without padding) at 75% of the R-R-interval. All datasets were reconstructed without and with MC of the coronaries. The latter exploits the minimal padding inherent in cardiac CT scans with this device due to data acquisition also during the short time interval needed for the tube to reach target currents and voltage (“free” multiphase). Two blinded readers independently assessed image quality on a 4-point Likert scale for all segments.

Results: A total of 1,030 coronary segments were evaluated. Application of MC both with automatic and manual coronary centerline tracking resulted in a significant improvement in image quality as compared to the standard reconstruction without MC (mean Likert score 3.67 [3.50;3.81] vs 3.58 [3.40;3.73], \( P = 0.005 \), and 3.7 [3.55;3.82] vs 3.58 [3.40;3.73], \( P < 0.001 \), respectively). Furthermore, MC significantly reduced the proportion of non-evaluable segments and patients with at least one non-evaluable coronary segment from 2% to as low as 0.3%, and from 14% to as low as 3%. Reduction of motion artifacts was predominantly observed in the right coronary artery.

Conclusions: A post-hoc device-specific MC algorithm improves image quality and interpretability of prospectively electrocardiogram-triggered CCTA and reduces the proportion of non-evaluable scans without any additional radiation dose exposure.

KEYWORDS
coronary artery disease, coronary CT angiography, motion artifact, motion correction

Introduction
Coronary computed tomography angiography (CCTA) is a well-established diagnostic modality for the evaluation of suspected coronary artery disease (CAD) in low-to intermediate-risk patients [1]. Due to the high negative predictive value, it reliably serves as a gatekeeper for invasive coronary angiography [2]. However, its diagnostic accuracy is highly dependent on the image quality, which, in turn, is affected by patient, cardiac or respiratory motion.
Despite the recent technological advancements of CT scanners, motion artifacts can still impair image quality, rendering scans or parts thereof non-evaluable and necessitating repeated CT acquisitions. Low heart rate (HR) and low heart rate variability are the prerequisites for diagnostic image quality, especially if prospective electrocardiogram (ECG) triggering is applied [3]. Therefore, routine administration of beta-blockers prior to CCTA is a crucial part of adequate patient preparation in most cases [4, 5]. However, despite the use of beta-blockers, not all patients reach the target HR, potentially resulting in motion artifacts particularly affecting the right coronary artery [6]. Motion-correction algorithms have been developed for patients in whom the target HR or low variability cannot be achieved with rate-control medication. The algorithms rely on integrating information on coronary motion from different cardiac phases within a single cardiac cycle, resulting in a new motion-corrected dataset [7, 8]. However, such algorithms require an extension of the temporal acquisition window and, consequently, imply an increase in a radiation dose. Furthermore, the specific acquisition protocols must be planned a priori and cannot be applied to any existing CT dataset. By contrast, a vendor- and device-specific algorithm used in the current study allows for motion correction without the need for padding and is applicable post-hoc. It allows for correcting for motion-induced image quality degradation, but for “free”, that is, without the need for any widening of the standard acquisition window of the CT scan which is associated with increased radiation dose.

This study aimed to evaluate the impact of this free motion-correction (FMC) algorithm on the image quality and interpretability of CT scans compared to the standard reconstruction technique without FMC in a real-world clinical routine population.

Materials and methods

Study population

Consecutive patients referred for clinically indicated contrast-enhanced CCTA were prospectively included. Exclusion criteria were known CAD with a history of revascularization, renal insufficiency with a glomerular filtration rate <60 ml/min/1.73 m², pregnancy or breastfeeding, allergy to iodinated contrast, and contraindications to nitroglycerin. Patients with severe arrhythmia in whom CT image acquisition parameters were altered prior to the scan to assure diagnostic image quality were also excluded from the study. The study was approved by the local ethics committee (KEK-ZH-Nr. 214-0632) and all patients provided written informed consent.

Image acquisition

Prior to the examination, all patients received 0.4 mg of isosorbide dinitrate (Isoket, Schwarz Pharma, Monheim, Germany) sublingual. Additionally, up to 30 mg of beta-blocker (Beloc Zok, Astra Zeneca, London, UK) was injected intravenously to reach a target heart rate <65 beats per minute (bpm). All patients underwent a contrast-enhanced CCTA scan on a 256-slice CT scanner (Revolution CT, GE Healthcare, Waukesha, WI, USA) with acquisition during inspiration breath-hold and prospectively ECG-triggered single-beat acquisition at 75% of the R-R-interval. No padding was applied. Iodixanol (Visipaque 320, 320 mg/mL, GE Healthcare, Buckinghamshire, UK) was injected into an antecubital vein followed by a 50 mL saline solution based on a body-mass adapted volume and flow rate [5]. Collimation of 256 × 0.625 mm with a z-coverage of 12–16 cm was used with a display field of view of 25 cm. All scans were acquired in high-resolution mode with an in-plane spatial resolution of 0.23 × 0.23 mm. Gantry rotation time was 280 ms.

Image reconstruction

All scans were reconstructed using a high-definition kernel and adaptive statistical iterative reconstruction-veo (ASIR-V) at a level of 70%. In addition, all datasets were reconstructed with the FMC algorithm (SnapShot Freeze, GE Healthcare). The latter exploits the minimal padding inherent to a CT scan due to this scanner type always acquiring at least a fullscan worth of data and due to the short time-interval needed for the tube to reach target currents and voltage. Depending on the HR, “free” multiphase acquisition comprises an additional 3–7% of the RR-interval. Three reconstructions are created from the acquired dataset and are then used to estimate coronary artery motion trajectories and, subsequently, for correction (Central illustration). The FMC algorithm relies on coronary artery centerline tracking, which is performed automatically. However, in case of failed, incomplete, or errant coronary artery vessel centerline tracking, manual adjustments of the centerline is possible where necessary. For the present study, in addition to the completely automated approach (FMCauto), we also manually optimized the centerlines in every dataset (FMCmanual). Thus, three different reconstructions were obtained for each patient: 1) a standard reconstruction without motion correction as per clinical routine (NMC), 2) FMCauto, and 3) FMCmanual.

Image analysis

All reconstructions were independently reviewed by two readers with at least 2 years of experience, blinded to the reconstruction method and patient history. All datasets were viewed on a dedicated workstation (AW 4.6, GE Healthcare, Milwaukee, WI, USA) in a random order to minimize observer bias. Image quality assessment was performed per coronary artery segment, using a 15-segment model, according to the American Heart Association classification [9]. All segments with a diameter of 1.5 mm at their origin were included in the analysis, and the following 4-point Likert-scale was applied: 1 – non-evaluable due to excessive coronary motion or other artifacts, resulting in poor vessel wall delineation, 2 – reduced image quality but evaluable, 3 – good image quality with only minimal motion artifacts,
4 - perfect image quality with no motion artifacts and excellent interpretability (Fig. 1). The average of the results of two reads was subsequently used as a segment score. The mean score was then calculated per patient and per vessel (left anterior descending artery [LAD]; segments 5–10; left circumflex artery [LCX]; segments 11–15; right coronary

Central illustration. Schematic representation of the “free” motion correction algorithm. This algorithm exploits the short time interval (blue) needed for the tube current to reach target levels and uses this system-inherent padding to create a multi-phase reconstruction which then serves as the basis for motion correction. Illustrated is the tube current profile for single-phase acquisition for a patient with a heart rate of 80 beats per min.

Fig. 1. Representative examples of subjective image quality assessment. An example is given for each score from 1 (non-evaluable) to 4 (perfect) (A–D, respectively)
artery [RCA]: segments 1–4). Image quality derived from NMC was used as the standard of reference.

**Radiation dose estimation**

Effective radiation dose from CCTA in Millisieverts (mSv) was calculated as the product of dose-length product times a conversion coefficient for the chest \( k = 0.014 \text{ mSv} \times \text{[mGy cm]}^{-1} \) [3]).

**Statistical analysis**

Statistical analysis was performed using the statistical software package SPSS 20.0 (IBM, Armonk, NY, USA). Normally distributed continuous variables were expressed as mean ± SD, not-normally distributed continuous variables as median and interquartile range, while categorical variables were represented as percentages. Friedman Test with a Bonferroni post-hoc correction (adjusted \( P < 0.017 \)) for a per-patient basis comparison and \( P < 0.005 \) for a per-vessel basis comparison) was used to compare the average Likert score between the reconstructions. Cochran’s Q test with a post hoc multiple McNemar’s test with a subsequent manual Bonferroni correction (adjusted \( P < 0.017 \)) was used to compare the number of evaluable segments and patients with evaluable scans between the reconstructions. Interobserver variability for the assessment of image quality was determined using Cohen’s kappa (\( k \)) coefficient. A \( P \)-value of less than 0.05 was considered statistically significant, if not mentioned otherwise.

**Results**

**Patient characteristics**

Ninety consecutive patients were included. The detailed patient characteristics are summarized in Table 1. Three-hundred-and-twenty (31%) segments were either non-existent or excluded from the analysis due to the small diameter (i.e. <1.5 mm at their origin). Hence, a total of 1,030 coronary segments were analyzed. The mean effective radiation dose from CCTA was 1.16 [1.01;1.33] mSv.

**Image quality analysis**

There was a good inter-observer agreement for the image quality of coronary segments in the group of NMC as well as in the group of FMCauto and FMCmanual (\( k = 0.75, 0.77, \) and 0.71, respectively).

**Discussion**

The main finding of our study is a significant improvement of image quality and a higher yield of CCTA exams with diagnostic quality enabled by a motion correction algorithm which is not depending on additional padding but instead exploits the “free” multiphase acquisition inherent to every cardiac scan with this type of device. Of note, the motion correction algorithm can be applied post-hoc and does not result in additional radiation dose exposure. Although statistically significant, the increase in subjective quality conferred by FMC may be considered small and, arguably, clinically negligible. Of note, however, a considerable proportion of segments and patients initially presenting with non-diagnostic image quality were evaluable after the
Fig. 2. Comparison of the image quality between the different reconstructions per patient (Fig. A) and per vessel (Fig. B) basis.

Fig. 3. The number of non-evaluable coronary segments (A) and the number of patients with at least one evaluable coronary segment (B) for each reconstruction algorithm.

Fig. 4. Coronary computed tomography angiography of a 55 year-old patient reconstructed without (A) and with (B) motion correction. Note that how, despite a heart rate of only 66 bpm, the right coronary artery shows distinct motion artifacts, hampering its evaluability. By contrast, application of the fully automated motion correction results in good image quality.
application of FMC. In fact, the use of FMC\textsubscript{auto} and FMC\textsubscript{manual} led to a reduction of non-evaluable patients by 47% and 77%, respectively, as compared to the standard of reference NMC.

Interestingly, among the patients with at least one non-evaluable segment, only a minority did not reach the target HR during image acquisition. Furthermore, the effect of FMC was predominantly conferred by corrections of motion artifacts in the RCA, while the effect on segments of the LAD or LCX was negligible and non-significant, a finding that is generally in line with previous studies [8, 10]. This can be explained by the fact that among all coronary segments, the ones attributable to the RCA feature the highest velocities in three-dimensional space across the R-R interval and, more importantly, exhibit an early and steep incline of velocity in the late diastolic/early systolic phase, rendering the RCA segments particularly prone to motion artifacts even in patients in whom rate control can be achieved through the application of beta-blockers [6]. As these patients cannot be easily identified a priori, the clinical value of a motion correction algorithm that can be applied post-hoc becomes strikingly evident.

Thus, the FMC algorithm may be of particular clinical value in patients where impaired image quality cannot be expected prior to the scan and, hence, no adjustments are made regarding the acquisition technique (e.g. padding). Theoretically, the application of the FMC algorithm can be considered in all patients in clinical routine to improve the overall image quality. However, this leads to increased image reconstruction time, which should be considered in centers with very high patient throughput. Furthermore, with the advent of modern CT scanners with very fast rotation time and/or dual-source technology, CCTA may be less prone to coronary motion artifacts as compared to slower scanners. However, motion artefacts particularly of the RCA occur nevertheless, as evidenced by the present study, where a state-of-the-art CT scanner with a fast rotation time of 280 ms was used.

Several studies have previously reported on the value of motion-correction algorithms for CCTA [7, 8, 10–14]. Among them, Fuchs et al. have reported on the merits of a motion correction algorithm by the same vendor and have demonstrated an increase in overall image quality in 40 patients who did not reach the target HR despite administration of beta-blockers (mean maximum HR during acquisition: 73 bpm) [8]. Hence, the need for motion correction was evident a priori. Furthermore, and contrary to the present study, the motion correction algorithm evaluated by Fuchs et al. and others remains dependent on padding (i.e. a scan time that is 80 ms longer than the minimal acquisition window), resulting in an increased average radiation dose exposure of 2.3 mSv [8]. Similar to Fuchs et al., Fan et al. have provided results for the same motion correction algorithm in 30 patients, demonstrating a substantial increase of interpretability from 78% without versus 93% with motion correction [10]. Finally, Andreini et al. have convincingly demonstrated the beneficial impact on image quality and diagnostic performance in a large multicenter study comprising 230 patients undergoing both CCTA with retrospective gating or prospective ECG-triggering (but with a widened acquisition window) and invasive coronary angiography [14]. Similar to the present study, Andreini et al. have shown a substantial decrease in the proportion of non-evaluable segments, particularly of the RCA, and an overall improvement in diagnostic accuracy of CCTA as compared to the standard of reference.

To the best of our knowledge, the present study is the first to evaluate the impact of a “free” and post-hoc motion correction algorithm. Despite the principles of image quality restoration being similar to previously published motion correction algorithms, the one evaluated in the present study is not dependent on padding, does not lead to increased radiation dose exposure, and, most importantly, can be quickly applied post-hoc whenever deemed necessary in everyday clinical routine, potentially further increasing the rate of scans with diagnostic image quality necessary to fully exploit the potential of CCTA to optimize patient management and reduce downstream resource utilization.

Study limitations

It may be perceived as a limitation that we did not use a standard of reference such as invasive coronary angiography. It was beyond the scope of the present study, however, to revalidate the diagnostic accuracy of the motion correction algorithm per se as data on its validity are already available from Andreini et al. and others. By contrast, the aim of the study was rather to provide qualitative data on its merits if applied post-hoc in a real-world setting by demonstrating a substantial reduction in non-evaluable segments. Obtaining diagnostic image quality in all coronary segments inarguably constitutes the prerequisite for the clinical value of this imaging modality which is conferred through its high sensitivity and negative predictive value in the setting of suspected CAD.

Conclusion

A post-hoc vendor-specific motion-correction algorithm improves image quality and interpretability of prospectively electrocardiogram-triggered CCTA and reduces the proportion of non-evaluable scans without any additional radiation dose exposure.

Authors’ contribution: The authors have made substantial contributions to the conception (GD, FM, JV, CG, LSK, RB, DC, CG, APP, PAK, RRB), design of the work (APP, PAK, RRB), the acquisition and analysis (GD, FM, JV, CG, LSK, RB, DC, CG), interpretation of data (GD, FM, LSK, RB, DC, CG), have drafted the work or substantively revised it (GD, FM, JV, CG, LSK, RB, DC, CG, APP, PAK, RRB), have approved the submitted version (GD, FM, JV, CG, LSK, RB, DC, CG, APP, PAK, RRB). All authors agreed to submit it to IMAGING for publication.

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**Abbreviations list**

| Bpm | Beats per minute |
| CAD | Coronary artery disease |
| CCTA | Coronary computed tomography angiography |
| FMC | Free motion-correction |
| HR | Heart rate |
| MC | Motion-correction |
| NMC | Standard reconstruction without motion-correction |
| LAD | Left anterior descending artery |
| LCX | Left circumflex artery |
| RCA | Right coronary artery |

**REFERENCES**


