Published in final edited form as:

Clin Imaging. 2015 ; 39(3): 421–426. doi:10.1016/j.clinimag.2014.11.020.

Heart-Rate Dependent Improvement in Image Quality and Diagnostic Accuracy of Coronary Computed Tomographic Angiography by Novel Intra-cycle Motion Correction Algorithm

Iksung Cho, MD¹, Kimberly Elmore, BSIS¹, Bríain ó Hartaigh, PhD¹, Josh Schulman-Marcus, MD¹, Heidi Granser, MS², Valentina Valenti, MD¹, Guanglei Xiong, PhD¹, Patricia M Carrascosa, MD³, and James K Min, MD¹

¹Department of Radiology, NewYork-Presbyterian Hospital and the Weill Cornell Medical College, New York, NY, USA

²Departments of Imaging and Medicine, Cedars-Sinai Heart Institute, Cedars- Sinai Medical Center, Los Angeles, CA, USA

³CT and Nuclear Medicine Departments, Diagnóstico Maipú, Buenos Aires, Argentina

Abstract

Background—To determine the effect of a novel intra-cycle motion correction algorithm (MCA) on diagnostic accuracy of coronary CT angiography (CCTA)

Methods—Coronary artery phantom models were scanned at static and heart rates (HR) simulation of 60–100 beat/min and reconstructed with a conventional algorithm (CA) and MCA.

Results—Among 144 coronary segments, improvements in image interpretability, quality and diagnostic accuracy by MCA were observed for HRs of 80 and 100 ($P < 0.05$ for all), but not for HR of 60.

Conclusion—Novel intra-cycle motion correction algorithm demonstrates improved heart-rate dependent image interpretability, and quality and accuracy, particularly at higher heart rates.

1. Introduction

Since the introduction of 64-slice multi-detector computed tomography, cardiac computed tomographic angiography (CCTA) has been widely utilized as a non-invasive diagnostic modality for visualizing the coronary arteries to detect coronary artery disease (CAD). Although the diagnostic accuracy of CCTA for detection of obstructive CAD has been validated by numerous retrospective and prospective trials, most of the available study samples consisted of selecting patients whose heart rate (HR) was deemed optimal (i.e., < 60 – 80 beats per minute [bpm]) for CCTA [1–5]. Further still, the diagnostic accuracy of CCTA is known to be diminished by elevations in the HR due to motion artifact, and while efforts have been made to minimize this limitation (i.e., increasing gantry rotational speed

Address for correspondence: James K Min, Professor of Radiology and Medicine, Dalio Institute of Cardiovascular Imaging, NewYork-Presbyterian Hospital and the Weill Cornell Medical College, 413 E. 69th Street, Suite 108, Phone: 646-962-6192, jkm2001@med.cornell.edu.

and use of dual sources scanners), motion artifact still remains a major challenge for the diagnostic interpretability of CCTA [6,7].

More recently, there have been additional attempts to mitigate motion artifact by using a novel intra-cycle motion correction reconstruction algorithm (MCA) [8]. MCA adjusts the motion of coronary arteries and defines the actual vessel location by using the adjacent cardiac phase information [9]. To date, however, few studies have evaluated the beneficial effects of MCA, and how it might augment image quality and diagnostic accuracy beyond current conventional image reconstruction strategies are sparse [10]. Therefore, in this experimental study using a coronary motion phantom model, we systematically investigated the efficacy of a novel MCA for enhancing the image quality and diagnostic performance according to varying levels of HR.

2. Materials and methods

2.1. Ex-vivo motion phantom model and CTA scanning protocol

We utilized a quantitative pulsating coronary phantom (Mocomo, Fuyo Corp, Japan) for the analysis (Figure 1A). The simulated coronary artery tubes were attached to two small and large rings, permitting the tubes to move in a 15-degree rotational angle with z-axis directional movement by 20 mm. The simulated coronary artery tubes were constructed with diameters of 3 mm and 4 mm. Each tube comprised six segments: segments 1 and 6 without stenosis, segments 5, 3, and 4 with 25%, 50%, and 75% non-calcified plaque stenosis, respectively, and segment 2 displaying 50% stenosis with calcified plaque (Figure 1B and 1C). Tubes were filled with iodixanol 270mg/ml (GE Healthcare, Princeton, NJ) diluted with deionized water at a concentration of 20:1, resulting in target attenuation of approximately 350 Hounsfield units (HU). We positioned the phantom on the multi-detector computed tomography table to move into the scan field of view during image acquisition.

The stepwise process for the image acquisition, reconstruction, and interpretation were summarized in Figure 2. The phantom model was scanned by a multidetector row CT scanner (Revolution CT, GE Healthcare). Scanner parameters included 256×0.625 collimation, detector coverage was 160 mm, with a reconstruction slice thickness of 0.6 mm. All acquisitions happened within one heart cycle and the padding required was 80 milliseconds. Gantry rotation time was 0.28 second per rotation and the maximum tube current was 455 mA with a tube voltage of 120 kVp. The initial scan was conducted without motion for reference, followed by motion that simulated heart rate values of 60 bpm, 80 bpm, and 100 bpm.

2.2. Image Reconstruction and Analysis

All images were reconstructed using conventional algorithm (CA) and motion correction algorithm (MCA) techniques (SnapShot Freeze, GE Healthcare) using both 45% and 75% of the R-R intervals (Figure 3). Two experienced independent readers, who were masked to the tube size, stenosis, and reconstruction methods, evaluated image quality and measured the diameter and area of the inner lumen. Image qualities were evaluated using a 4-point Likert scale on a per-segment level: 1=non-interpretable; 2=suboptimal but interpretable; 3=good but mild motion; and 4=excellent. Motion artifacts were scored using a 5-point Likert scale

on a per-segment level as follows: 1=completely unreadable because of motion artifacts; 2=significant motion; 3=apparent motion; 4=minor motion; 5=no residual motion in the segment being evaluated. Readers also evaluated calcium blooming artifact for calcified segments using a 3-point Likert scale: 1=blooming, no lumen visible; 2=blooming, but lumen clearly visualized; 3: no or minimal calcium blooming. Image noise was measured by placing a circular region of interest (100 mm²) within the contrast-enhanced lumen of the tube for determining the standard deviation of CT attenuation. The contrast-to-noise ratio (CNR) was calculated by dividing the contrast between tube lumen and surrounding water by the image noise.

Minimal luminal diameter (MLD) was measured with an electronic caliper and minimal luminal area (MLA) was measured using a manual ROI function. MLD and MLA of each segment were compared with those corresponding to the motion free segment (reference) and the percentage (%) of measurement error was calculated. For consistency, all images were evaluated at the same clinically appropriate window width and level: 730/260 for non-calcified plaque and 1500/500 for calcified plaque.

2.3. Statistical Analysis

Continuous variables are expressed as mean $\pm$ standard deviation (SD) or 95% confidence interval (CI) and categorical variables are presented as frequencies. Variables were compared by use of the non-parametric Wilcoxon rank-sum test for continuous variables when non-normally distributed, and the chi-square test was employed for categorical variables. Interobserver agreement was calculated with κ statistics for image quality and motion score [11], and by the intraclass correlation coefficient for MLD and MLA (2-way random, single measure) [12]. Image quality and motion artifact were further examined by Wilcoxon rank-sum test comparing the mean Likert scores according to MCA and CA, as well as separately stratifying by categories of HR. Within group variation in the measurement error of the luminal diameter and area according to HR groups was also examined by ANOVA, separately for both MCA and CA methods. A 2-tailed P value less than 0.05 was considered statistically significant. Statistical analyses were performed using STATA software (version 11, StataCorp, College Station, Texas, USA).

3. Results

3.1 Overall image quality improvement by MCA

Interobserver agreements for image quality and motion score were excellent ($\kappa = 0.76$ and 0.75 , respectively). The intraclass correlation coefficient for MLD and MLA were 0.944 and 0.870 . Of 72 segments that were evaluated, the overall interpretability was significantly improved by MCA (72 segments, 100%) as compared with CA (60 segments, 83.3%) ($p < 0.001$ for difference) (Table 1). Among interpretable images, MCA significantly improved the image quality as well: 79% of the reconstructed images by MCA were classified as good or excellent, whereas only 40% of the images were defined as good or excellent by conventional algorithm (p for trend < 0.001). Moreover, the motion artifact relative to the MCA method was lower compared with CA thereby demonstrating improved image quality. That is, cases deemed completely unreadable due to motion artifact were 12.5% according to

CA, while all cases were suitable for reading on the background of using MCA. The proportion of images presenting with significant or apparent motion (e.g., Likert scale 2 or 3) were 66.6% for CA, though notably, decreased to 23.6% for MCA ($p<0.001$).

3.2 Image quality improvement by MCA according to varying heart rate

The image quality and degree of motion artifact according to HR are reported in Figure 4. Overall, the interpretability of the Likert score was significantly higher for images reconstructed by MCA (3.00, 95% CI 2.85–3.15) than those by CA (2.33, 95% CI 2.11–2.55) ($p<0.001$). When stratifying by HR, no significant differences were found in the interpretability Likert score between CA (3.13; 95% CI, 2.77–3.48) and MCA (3.38; 95% CI, 3.07–3.68) when considering a HR of 60 bpm (p for difference = 0.317). Conversely, the image quality improvement by MCA was present at higher HR, with differences evident when HR increased to 80 bpm (2.04 for CA vs. 2.88 for MCA) (p for difference <0.001) and 100 bpm (1.83 for CA vs. 2.75 for MCA) (p for difference <0.001) as compared with CA. In Figure 4B images reconstructed by MCA demonstrated improved motion artifact, with a significant reduction found to be present mainly on the background of a high HR.

3.3 Diagnostic accuracy improvement by MCA according to heart rate

As depicted in Figure 5, compared with the reference static images, MCA significantly reduced measurement error in the luminal diameter and area compared with CA (6.04% vs. 12.11% and 7.9% vs. 17.8%, respectively, $p<0.001$ for all). When using CA, the within measurement error increased with increasing HR categories ($p=0.012$ and $p=0.002$ for MLD and MLA, respectively), but not when considering MCA ($p=NS$ for both). Subsequently, there was no difference in measurement error of the lumen diameter or area between MCA and CA given a HR 60 bpm. On the other hand, the measurement errors for MCA were substantially lower than those found for CA when HR was reported to be 80 bpm and 100 bpm, respectively.

3.4 Calcium blooming artifact and image noise

The contrast to noise ratio of images did not differ appreciably when comparing MCA (16.2 ± 3.8) with CA (15.9 ± 4.6) ($p=0.683$). Additionally, the calcification blooming artifacts of images by MCA (1.83; 95% CI, 1.59–2.08) were similar to those found by CA (1.50; 95% CI, 1.17–1.83) ($p=0.090$).

4. Discussion

4.1. Main Findings

In the current experimental study using a coronary motion phantom model, we demonstrated that the use of a novel intra-cycle motion correction algorithm improved image interpretability, quality, and accuracy in the setting of a rapid heart rate.

4.2. Motion artifact and coronary CT angiography

The motion artifact from continuous and rapid cardiac motion during CCTA imaging acquisition remains a major challenge of diagnostic accuracy of CCTA [13]. Considering the temporal resolution of currently used CCTA scanners, HR reduction below 60–65 bpm is

generally required [13,14]. To achieve a suitable HR for CCTA, typically beta-blockers have been prescribed prior to CCTA. Nevertheless, such medications are often contraindicated or ineffective for a sizable number of patients [14]. Further still, numerous efforts to minimize motion artifact have been introduced including multi-segmental reconstruction, increasing gantry rotation speed, wider-detector scanners, along with dual source scanners [15,16]. In spite of these efforts, previous studies have demonstrated that motion artifact persists, thereby diminishing the image quality of CCTA.

4.3. Motion correction algorithm

MCA corrects motion artifact by utilizing both coronary artery path and velocity from adjacent cardiac phases in a single cardiac cycle. Hence, MCA is considered less susceptible to HR variability and requires lower radiation doses than multiphase reconstruction. Moreover, an important aspect of MCA is that it can be applied to prospective electrocardiography (ECG)-triggered image acquisition as well as retrospective ECG-triggered image acquisition [10]. In light of this, the current study clearly demonstrates that the MCA method could successfully improve image interpretability and quality by reducing the motion artifact associated with CCTA. Importantly, there was no benefit in image quality for the images with a low HR (i.e., 60 bpm). In spite of this, the current findings indicated that MCA significantly improved image quality and diagnostic accuracy of CCTA in the presence of a rapid HR (i.e., 80–100 bpm). Thus, MCA is perhaps most beneficial in patients with insufficient HR control who are contraindicated or ineffective to beta blockade.

Indeed, few previous clinical studies reported that MCA improved image interpretability per segment and per artery in patients with a mean HR of approximately 70 bpm [8,10]. The current study findings support as well as extend these observations whereby motion artifact remained stable with increasing HR, notably as far as 100 bpm. The latter observation suggests MCA may afford a novel method that improves image interpretability, and is likely applicable to patients with high HR values beyond those previously observed in the extant literature.

Previously, given the lack of availability of standard static imaging, prior studies found it challenging to determine the diagnostic accuracy of MCA. A novel aspect of the current study, however, was the ability to evaluate the diagnostic accuracy of MCA in comparison to a static image as a reference. In doing so, we demonstrated that measurement errors in in MLD or MLA did not increase among MCA-reconstructed images, though clearly additional studies are needed to confirm these findings.

4.4. Limitations

There are several limitations that need to be emphasized in this study. First, the current study—while enabling systematic evaluation of static as well as defined increasing heart rates—was performed in a simulated quantitative pulsating coronary phantom model. Future clinical studies should consider evaluating whether MCA improves the diagnosis of obstructive CAD in patients with a rapid HR. Further, given that the *in vitro* phantom model is less susceptible to other confounding factors, it enabled us to fully evaluate the effect of MCA for various HR, degree of stenosis, and plaque characteristics. Second, we only

evaluated MCA using a single-source CCTA scanner. Considering dual-source detectors have demonstrated the benefit in temporal resolution, our approach utilizing dual-source detectors should be evaluated in future studies. We evaluated the image quality improvement by MCA in a regular heart beat simulation setting. The effect of the MCA in a high beat-to-beat variability situation remains to be established. Last, we used the simulated coronary artery tubes with diameters of 3 mm and 4 mm, which represented most of the coronary artery segments that are clinically important and candidate for coronary intervention [17]. The effect of MCA in the coronary arteries with smaller luminal diameter should be address in future study.

5. Conclusion

The current study findings demonstrate that the use of a novel intra-cycle motion correction algorithm improves HR-dependent image interpretability, quality, and accuracy. Prospective clinical trials should aim at establishing and validating this novel approach in the clinical population setting.

Acknowledgments

Research reported in this manuscript was supported by the National Heart, Lung, and Blood Institute of the National Institutes of Health (Bethesda, MD) under Award R01 HL111141, R01 HL118019, and R01HL115150 and by a generous gift from the Dalio Foundation and the Michael Wolk Foundation (New York, NY).

References

1. Meijboom WB, Meijs MF, Schuijf JD, Cramer MJ, Mollet NR, van Mieghem CA, Nieman K, van Werkhoven JM, Pundziute G, Weustink AC, de Vos AM, Pugliese F, Rensing B, Jukema JW, Bax JJ, Prokop M, Doevendans PA, Hunink MG, Krestin GP, de Feyter PJ. Diagnostic accuracy of 64-slice computed tomography coronary angiography: a prospective, multicenter, multivendor study. *J Am Coll Cardiol.* 2008; 52:2135–44. [PubMed: 19095130]
2. Miller JM, Rochitte CE, Dewey M, Arbab-Zadeh A, Niinuma H, Gottlieb I, Paul N, Clouse ME, Shapiro EP, Hoe J, Lardo AC, Bush DE, de Roos A, Cox C, Brinker J, Lima JA. Diagnostic performance of coronary angiography by 64-row CT. *N Engl J Med.* 2008; 359:2324–36. [PubMed: 19038879]
3. Budoff MJ, Dowe D, Jollis JG, Gitter M, Sutherland J, Halamert E, Scherer M, Bellinger R, Martin A, Benton R, Delago A, Min JK. Diagnostic performance of 64-multidetector row coronary computed tomographic angiography for evaluation of coronary artery stenosis in individuals without known coronary artery disease: results from the prospective multicenter ACCURACY (Assessment by Coronary Computed Tomographic Angiography of Individuals Undergoing Invasive Coronary Angiography) trial. *J Am Coll Cardiol.* 2008; 52:1724–32. [PubMed: 19007693]
4. Abdulla J, Abildstrom SZ, Gotzsche O, Christensen E, Kober L, Torp-Pedersen C. 64-multislice detector computed tomography coronary angiography as potential alternative to conventional coronary angiography: a systematic review and meta-analysis. *European Heart Journal.* 2007; 28:3042–50. [PubMed: 17981829]
5. Min JK, Shaw LJ, Berman DS. The present state of coronary computed tomography angiography a process in evolution. *J Am Coll Cardiol.* 2010; 55:957–65. [PubMed: 20202511]
6. Lesser JR, Flygenring BJ, Knickelbine T, Longe T, Schwartz RS. Practical approaches to overcoming artifacts in coronary CT angiography. *J Cardiovasc Comput Tomogr.* 2009; 3:4–15. [PubMed: 19201371]
7. Hassan A, Nazir SA, Alkadhi H. Technical challenges of coronary CT angiography: today and tomorrow. *Eur J Radiol.* 2011; 79:161–71. [PubMed: 20227210]

8. Leipsic J, Labounty TM, Hague CJ, Mancini GB, O'Brien JM, Wood DA, Taylor CM, Cury RC, Earls JP, Heilbron BG, Ajlan AM, Feuchtner G, Min JK. Effect of a novel vendor-specific motion-correction algorithm on image quality and diagnostic accuracy in persons undergoing coronary CT angiography without rate-control medications. *J Cardiovasc Comput Tomogr*. 2012; 6:164–71. [PubMed: 22551593]
9. Min JK, Arsanjani R, Kurabayashi S, Andreini D, Pontone G, Choi BW, Chang HJ, Lu B, Narula J, Karimi A, Roobottom C, Gomez M, Berman DS, Cury RC, Villines T, Kang J, Leipsic J. Rationale and design of the ViCTORY (Validation of an Intracycle CT Motion CORrection Algorithm for Diagnostic AccuracY) trial. *J Cardiovasc Comput Tomogr*. 2013; 7:200–6. [PubMed: 23849493]
10. Fuchs TA, Stehli J, Dougoud S, Fiechter M, Sah BR, Buechel RR, Bull S, Gaemperli O, Kaufmann PA. Impact of a new motion-correction algorithm on image quality of low-dose coronary CT angiography in patients with insufficient heart rate control. *Acad Radiol*. 2014; 21:312–7. [PubMed: 24332603]
11. Fleiss, JL. Statistical methods for rates and proportions. 2. New York: Wiley; 1981.
12. McGraw KO, Wong SP. Forming inferences about some intraclass correlation coefficients. *Psychological Methods*. 1996; 1:30–46.
13. Herzog C, Arning-Erb M, Zangos S, Eichler K, Hammerstingl R, Dogan S, Ackermann H, Vogl TJ. Multi-detector row CT coronary angiography: influence of reconstruction technique and heart rate on image quality. *Radiology*. 2006; 238:75–86. [PubMed: 16373760]
14. Abbara S, Arbab-Zadeh A, Callister TQ, Desai MY, Mamuya W, Thomson L, Weigold WG. SCCT guidelines for performance of coronary computed tomographic angiography: a report of the Society of Cardiovascular Computed Tomography Guidelines Committee. *J Cardiovasc Comput Tomogr*. 2009; 3:190–204. [PubMed: 19409872]
15. Oncel D, Oncel G, Tastan A. Effectiveness of dual-source CT coronary angiography for the evaluation of coronary artery disease in patients with atrial fibrillation: initial experience. *Radiology*. 2007; 245:703–11. [PubMed: 18024451]
16. Scheffel H, Alkadhi H, Plass A, Vachenauer R, Desbiolles L, Gaemperli O, Schepis T, Frauenfelder T, Schertler T, Husmann L, Grunenfelder J, Genoni M, Kaufmann PA, Marincek B, Leschka S. Accuracy of dual-source CT coronary angiography: First experience in a high pre-test probability population without heart rate control. *Eur Radiol*. 2006; 16:2739–47. [PubMed: 17031451]
17. Dodge JT Jr, Brown BG, Bolson EL, Dodge HT. Lumen diameter of normal human coronary arteries. Influence of age, sex, anatomic variation, and left ventricular hypertrophy or dilation. *Circulation*. 1992; 86:232–46. [PubMed: 1535570]

Figure 1. Schematic figure (A) and maximum intensity projection image (B) with an example image of segment information (C) of a coronary motion phantom.

Figure 2. Summary of image acquisition, reconstruction, and interpretation process.

Figure 3. Representative cross-sectional images with conventional and motion correction algorithm (MCA) at heart rate simulation of static, 60, 80, and 100 beat per minutes (bpm).

Figure 4. Interpretability (A) and degree of motion artifacts (B) according to heart rate of images reconstructed by conventional (CA) and motion correction algorithm (MCA)

Figure 5.
Measurement errors in minimal luminal diameter (A) and area (B) of images reconstructed by conventional and motion correction algorithm according to heart rate compared with the reference static images

Table 1

Image quality according to reconstruction algorithms

	Motion correction algorithm	Conventional algorithm	<i>p</i> -value
Overall interpretability	72 (100%)	60 (83.3%)	<0.001
Interpretability Likert Scale			<0.001 *
1. Non-interpretable	0 (0 %)	12 (16.7 %)	
2. Sub-optimal	15 (20.8 %)	35 (48.6 %)	
3. Good, but mild motion	42 (58.3 %)	14 (25.0 %)	
4. Excellent	15 (20.8 %)	11 (15.3%)	
Motion Likert scale			<0.001 *
1. Completely unreadable	0 (0%)	9 (12.5%)	
2. Significant motion	8 (11.1%)	14 (19.4%)	
3. Apparent motion	9 (12.5%)	25 (34.7%)	
4. Minor motion	53 (73.6%)	22 (30.6%)	
5. No motion	2 (2.8%)	2 (2.8%)	

*
p-value for trend