Clinical Imaging 39 (2015) 1000–1005

Contents lists available at ScienceDirect

Clinical Imaging

journal homepage: http://www.clinicalimaging.org

Dual energy imaging and intracycle motion correction for CT coronary angiography in patients with intermediate to high likelihood of coronary artery disease☆

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ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form 7 July 2015
Accepted 16 July 2015

Keywords:
Imaging
Beta blockers
Interpretability
Multidetector
Spectral

ABSTRACT

We explored whether intracycle motion correction algorithms (MCAs) might be applicable to dual energy computed tomography coronary angiography in patients with intermediate to high likelihood of coronary artery disease. MCA reconstructions were associated with higher interpretability rates (96.7% vs. 87.9%, $P<.001$), image quality scores (4.12 ± 0.9 vs. 3.76 ± 1.0; $P<.0001$), and diagnostic performance [area under the curve of 0.95 (95% confidence interval [CI] 0.92–0.97) vs. 0.89 (95% CI 0.86–0.92); $P<.0001$] compared to conventional reconstructions. In conclusion, application of intracycle MCA reconstructions to dual energy computed tomography acquisitions was feasible and resulted in significantly higher image quality scores, interpretability, and diagnostic performance.

1. Introduction

During the past decade, computed tomography coronary angiography (CTCA) has been established as the noninvasive diagnostic tool with the highest sensitivity and negative predictive value (NPV) for the evaluation of patients at intermediate risk of coronary artery disease (CAD) [1–3]. Notwithstanding, the unrestricted extrapolation of these results to the real-world scenario remains limited by technical, patient-related, and/or lesion-specific issues. Most of these limitations are related to the presence of motion artifacts or diffusely calcified plaques, commonly leading to overestimation of coronary stenosis and false-positive findings [4,5]. Calcified lesions usually seem larger on single energy CTCA (SECT) studies, being this mainly attributed to blooming and beam-hardening effects. Dual energy imaging (DECT) has recently emerged as a potential means to mitigate most of the aforementioned limitations, thereby possibly improving the assessment of CAD in selected populations where SECT fails to provide an accurate diagnosis. The basic principle of DECT is the acquisition of two datasets from the same anatomic location with rapid-switching kVp. This enables the generation of synthesized monochromatic image reconstructions that might attenuate technical issues related to the polychromatic nature of x-rays and the energy dependency of x-ray attenuation [6].

In parallel, we have recently demonstrated the ability of intracycle motion correction algorithms (MCAs) to compensate for coronary motion in SECT studies, leading to higher interpretability rates and image quality scores compared to conventional reconstructions [7]. In addition, this vendor-specific MCA has been shown to improve the diagnostic accuracy of CTCA using single energy CT in selected patient populations but has yet to be evaluated using dual energy CTCA [8].

We therefore sought to explore whether MCA might be applicable to DECT studies, by evaluating the interpretability and diagnostic accuracy of CTCA performed in patients suspected of CAD referred to invasive coronary angiography.

2. Methods

2.1. Study population

The present study was a single-center, investigator-driven, prospective investigation that involved patients with suspected CAD referred for invasive coronary angiography between May and August 2014. All patients included were more than 18 years old, in sinus rhythm, able to maintain a breath-hold for 15 s, and without a history of contrast-related allergy, renal failure, or hemodynamic instability. Additional exclusion criteria comprised a history of previous myocardial infarction

Abbreviations: CTCA, computed tomography coronary angiography; CAD, coronary artery disease; DECT, dual energy computed tomography; MCA, motion correction algorithm.

☆ We declare that Drs. Patricia Carrascosa and Jonathon Leipsic are Consultants of GE. There are no competing interests related to the manuscript for any of the other authors.

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http://dx.doi.org/10.1016/j.clinimag.2015.07.023
0899-7071/

Table 1
Demographical characteristics ($n=32$)

Age (years±S.D.)	62.6±11.8
Male (%)	23 (72%)
Body mass index (kg/m2±S.D.)	27.9±3.4
Heart rate (bpm±S.D.)	59.8±12.4
Diabetes (%)	5 (16%)
Hypertension (%)	20 (63%)
Hypercholesterolemia (%)	23 (72%)
Previous or current smoking (%)	20 (63%)
Family history of CAD (%)	10 (31%)
Previous myocardial infarction (%)	9 (28%)
Left ventricular ejection fraction (%±S.D.)	57.9±12.1%
Total cholesterol (mg/dl±S.D.)	194.6±50.8
High-density lipoprotein-cholesterol (mg/dl±S.D.)	47.6±15.0
Creatinine (mg/dl±S.D.)	0.95±0.2
Systolic blood pressure (mmHg±S.D.)	145.6±23.1
Diastolic blood pressure (mmHg±S.D.)	88.5±15.8
Baseline medication	
Aspirin (%)	28 (88%)
Statin (%)	23 (72%)
Angiotensin-converting enzyme inhibitor/ angiotensin II receptor antagonist (%)	19 (59%)
Beta-blocker/calcium antagonist (%)	26 (81%)
Anti-diabetic agents (%)	5 (18%)
Clinical presentation	
Anginal chest pain (%)	25 (78%)
Asymptomatic with positive stress test (%)	7 (22%)

within the previous 30 days, previous percutaneous coronary revascularization or coronary bypass graft surgery, or chronic heart failure. Patients under rate-control medications were advised to withhold for the previous 24 h. Coronary risk factors and clinical status were recorded at the time of the CT scan, and clinical variables were defined as indicated by the Framingham risk score assessment. No rate-control medications were administrated prior to the scan.

The aim of our study was to evaluate the interpretability, image quality, and diagnostic performance of the MCA compared to conventional reconstructions (without MCA) using DECT in patients referred to invasive angiography due to suspected CAD.

The institutional review board approved the study protocol, which complied with the Declaration of Helsinki, and written informed consent was obtained from all patients.

2.2. Image acquisition

All studies were acquired using a 64-slice high-definition CT scanner (Discovery HD 750, GE Healthcare, Milwaukee, WI, USA). Sixty to 80 ml of iodinated contrast (iobitridol, Xenetix 350™, Guerbet, France) were injected using a three-phase injection protocol, as follows: Phase 1: 80% of the total iodinated contrast volume being injected undiluted at a rate of 4.5 to 5.0 ml/s; Phase 2: the other 20% of the contrast medium mixed at a 50% saline dilution, injected at a rate of 4.5 to 5.0 ml/s; and Phase 3: a 30- to 40-ml saline chasing bolus at a rate of 4.5 to 5.0 ml/s. A bolus tracking technique was used to synchronize the arrival of contrast at the level of the coronary arteries with the start of the scan. Image acquisition was performed after sublingual administration of 2.5–5 mg of isosorbide dinitrate.

All studies were acquired using prospective electrocardiogram (ECG)-gating applying a 100-ms padding centered at 75% of the cardiac cycle for patients with a heart rate (HR) lower than 60 bpm, a 200-ms padding centered at 60% of the cardiac cycle for patients with a HR between 60 and 74 bpm, and a 100-ms padding centered at 40% of the cardiac cycle for patients with a HR higher than 74 bpm. DECT was performed by rapid switching (0.3–0.5 ms) between low and high tube potentials (80–140 kV) from a single source, thereby allowing the reconstruction of low and high energy projections and generation of monochromatic image reconstructions ranging from 40 to 140 keV. Iterative reconstruction was performed in all cases at 40% adaptive statistical iterative reconstruction. Other scanner-related parameters were a collimation width of 0.625 mm and a slice interval of 0.625 mm. All patients underwent coronary artery calcium (CAC) scoring before the enhanced (dual energy computed tomography coronary angiography [DE-CTCA]) scan.

2.3. Image analyses

CTCA image analyses were performed off-line on a dedicated workstation, using a commercially available dedicated software tool (AW 4.6, GE Healthcare) by consensus of two experienced Level 3-certified coronary CTCA observers (PC, AD), blinded to the clinical data and to the reconstruction mode since images were anonymized and loaded by a third party. The same observers were randomly assigned MCA or conventional reconstructions of each patient, with at least a 2-week window period between paired examinations. In addition, as a post-hoc analysis, after an additional 2-week period, the same observers were assigned to reanalyze MCA reconstructions with energy levels available only up to 69 keV. This ancillary analysis, since it involved the whole dataset, further served as surrogate for reproducibility analysis.

Briefly, the MCA multiphase reconstruction (Snapshot Freeze, GE Healthcare, Milwaukee, WI, USA) algorithm, after automated coronary vessel tracking, utilizes information from two adjacent cardiac phases within a single cardiac cycle to characterize vessel motion (vessel path and velocity) in order to determine the actual vessel position at the prespecified target phase and adaptively compensate for any residual motion at that phase. Contrary to multisector reconstructions techniques, MCA aims at coronary-specific motion and is less vulnerable to

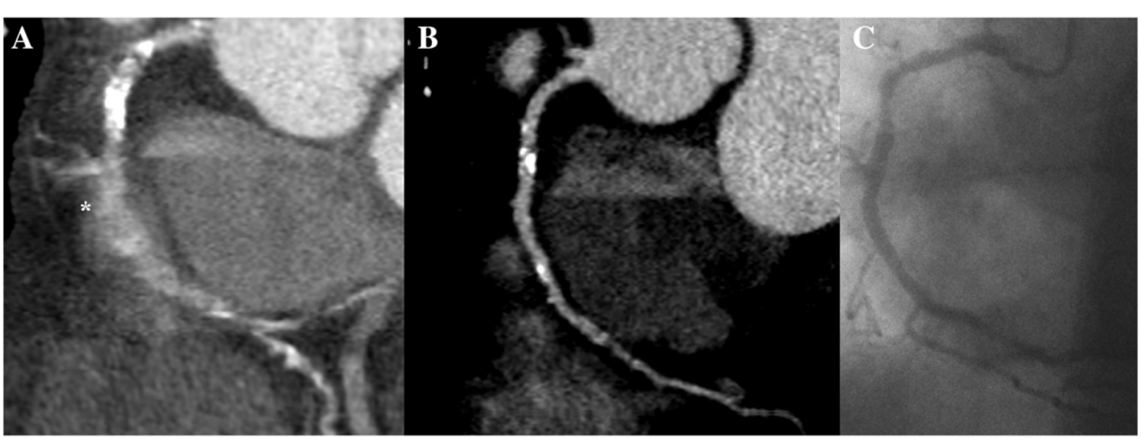

Fig. 1. Dual energy CTCA (curved multiplanar reconstructions) acquired at a HR of 69 bpm in a 70-year-old with multiple coronary risk factors, previous myocardial infarction, and shortness of breath. Using conventional (without MCA) reconstructions, severe motion artifacts are observed at the right coronary artery (Panel A, *) that preclude the assessment. After application of MCA (Panel B), the vessel is clearly depicted, and a significant lesion is identified and further confirmed at invasive angiography (Panel C).

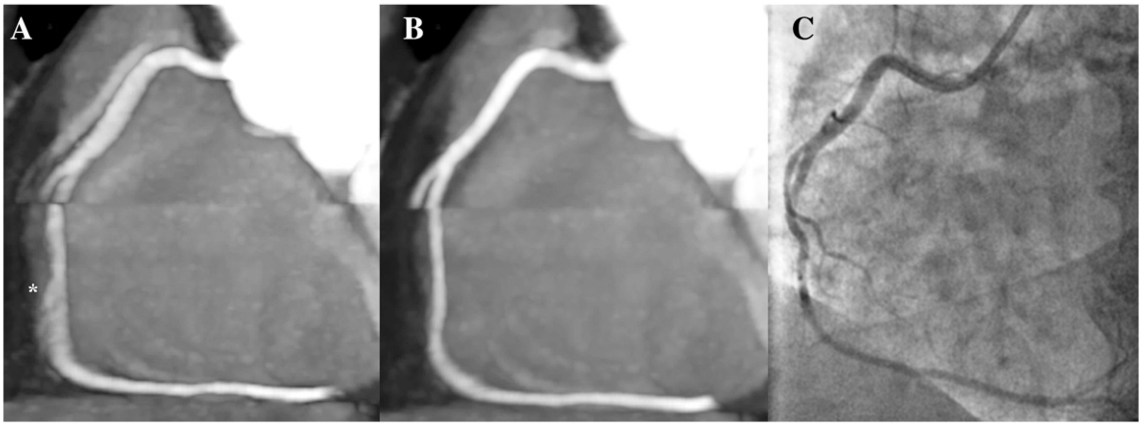

Fig. 2. Mild motion artifacts (*, Panel A) observed at the mid/distal right coronary artery (HR 66 bpm) of a 62-year-old female with shortness of breath and a positive stress test. Conventional reconstruction (without application of MCA) is shown in Panel A. After application of MCA image quality is enhanced (Panel B). Invasive angiography confirms the absence of significant stenosis (Panel C).

beat-to-beat variability [9]. The time required for MCA reconstruction to be completed is 27 s, whereas conventional reconstructions entail 9 s.

Axial planes, curved multiplanar reconstructions, and maximum intensity projections at 1–5-mm slice thickness were used according to the 18-segment Society of Cardiovascular Computed Tomography Classification [10]. Images were evaluated on a per-segment basis and per-patient basis. Segments with a reference diameter lower than 1.5 mm were not included in the analysis. Each segment was graded as follows: normal; nonsignificant stenosis (<50%); significant stenosis (≥50%); or uninterpretable. Uninterpretable segments due to motion artifacts or severe concentric calcification were assumed as positive for the diagnostic performance analysis.

Image quality was assessed using a 5-point Likert scale, as follows: 1) unacceptable: nondiagnostic, impaired image quality due to motion artifacts or severe calcification that precluded appropriate assessment; 2) below average: suboptimal and nondiagnostic, reduced image quality due to motion artifacts, image noise, or low contrast attenuation; 3) average: acceptable image quality, presence of mild to moderate motion artifacts, image noise, coronary calcifications, or low contrast but preserved ability to evaluate the presence of stenosis as well as to identify the presence of mild atherosclerosis; 4) above average: good image quality, presence of mild motion artifacts, image noise, coronary calcifications, or low contrast but preserved ability to evaluate the presence of stenosis as well as to identify the presence mild atherosclerosis; 5) excellent image quality: absence of motion artifacts, high intraluminal attenuation, and clear delineation of vessel walls, with the ability to evaluate both the presence of obstructive disease and mild atherosclerosis. For image quality assessment, all energy levels were available to the observers.

CAC scores were calculated by an independent observer (MDZ) blinded to the clinical data and DE-CTCA findings using dedicated software (SmartScore; GE Healthcare), which automatically defined the presence of calcified lesions as those with >130 HU. Median total CAC score and median CAC score per vessel were calculated using the Agatston method as previously established, and subgroup analysis was performed according to individual vessel CAC scores [11]. Each coronary segment was assigned a vessel territory and further stratified into tertiles according to the individual vessel CAC score.

CT effective radiation dose was derived by multiplying the dose-length product with the weighting (k) value of 0.014 mSv/mGy/cm for chest examinations, as suggested by the Society of Cardiovascular Computed Tomography [12].

2.4. Invasive angiography acquisition and analyses

All procedures were performed in accordance to standard techniques. Coronary angiograms were obtained in multiple projections after administration of intracoronary nitrates. Quantitative coronary angiography analysis was performed by an independent observer blinded to the CTCA data (AG). The catheter tip was cleared of contrast for accurate calibration. Lesion measurements were performed using the "worst" view of an end-diastolic frame.

2.5. Statistical analysis

Discrete variables are presented as counts and percentages. Continuous variables are presented as means±S.D. Comparisons among groups were performed using paired sample t tests and one-way analysis of variance, with Bonferroni tests being performed for multiple comparisons.

To determine the accuracy of MCA versus conventional (without MCA) reconstructions for the detection of stenoses ≥50% by invasive angiography, we calculated the sensitivity, specificity, negative predictive value (NPV), positive predictive value (PPV), and likelihood ratios, accounting for potential nonuniform distribution [95% confidence intervals (CIs)]. Receiver-operating characteristic (ROC) curve analyses

Table 2
Dual energy CTCA

Reconstruction mode	MCA	Conventional	P value
Per segment (n=480)	4.12±0.9	3.76±1.0	<.0001
Per territory			
Right coronary artery (n=160)	4.03±0.9	3.63±1.1	<.0001
Left main coronary artery (n=32)	4.69±0.5	4.31±0.8	.03
Left anterior descending (n=158)	4.18±0.8	3.89±0.9	<.0001
Left circumflex (n=130)	4.03±0.9	3.62±1.1	<.0001

Analysis of variance (ANOVA) for differences between territories among the same group was significant for MCA reconstructions (P<.001) and for conventional reconstructions (P=.001). Image quality scores with MCA and conventional (without MCA) reconstructions according to coronary territories.

Table 3
Dual energy CTCA

	Tertile 1 (<54 bpm) (n=170)	Tertile 2 (54–63 bpm) (n=170)	Tertile 3 (>63 bpm) (n=187)	P (ANOVA)
MCA	4.36±0.76	4.36±0.79	3.65±0.83	<.0001
Conventional	4.06±0.89	4.15±0.89	3.04±0.96	<.0001
P value	<.0001	<.0001	<.0001	

The following post-hoc comparisons (Bonferroni) among the MCA group were significant: Tertile 1 vs. Tertile 3, P<.001; Tertile 2 vs. Tertile 3, P<.001. Image quality scores with MCA and conventional (without MCA) reconstructions according to HR tertiles.
The following post-hoc comparisons among the conventional reconstruction group were significant: Tertile 1 vs. Tertile 3, P<.001; Tertile 2 vs. Tertile 3, P<.001.

Table 4
Dual energy CTCA

Reconstruction	MCA		Conventional
	<70 keV	All energy levels	
Sensitivity	95.1 (88.0–98.7)	93.9 (86.3–98.0)	92.7 (84.8–97.3)
Specificity	90.8 (87.5–93.5)	95.4 (92.8–97.2)	85.9 (82.0–89.2)
PPV	68.4 (59.1–76.8)	81.1 (71.7–88.4)	58.0 (49.1–66.7)
NPV	98.9 (97.1–99.7)	98.7 (96.9–99.6)	98.2 (96.2–99.4)
Positive likelihood ratio (LR+)	10.3 (7.5–14.2)	20.4 (12.9–32.1)	6.6 (5.1–8.5)
Negative likelihood ratio (LR−)	0.05 (0.02–0.14)	0.06 (0.03–0.15)	0.09 (0.04–0.18)
Area under the curve (ROC)	0.93 (0.90–0.95)	0.95 (0.92–0.97)[*†]	0.89 (0.86–0.92)

Data expressed with 95% CIs. Per-segment diagnostic accuracy of MCA and conventional (without MCA) reconstructions for detection of stenosis ≥50% based on invasive angiography.

[*] z statistic all energy levels vs. conventional 3.98, $P<.0001$.

[†] z statistic<70 keV vs. all energy levels 2.04, $P=.04$.

Table 5
Dual energy CTCA

Reconstruction	MCA		Conventional
	<70 keV	All energy levels	
Sensitivity	100 (85.2–100)	95.7 (78.1–99.9)	95.7 (78.1–99.9)
Specificity	66.7 (29.9–92.5)	66.7 (29.9–92.5)	66.7 (29.9–92.5)
PPV	88.5 (69.9–97.6)	88.0 (68.8–97.5)	88.0 (68.8–97.5)
NPV	100 (54.1–100)	85.7 (42.1–99.6)	85.7 (42.1–99.6)
LR+	3.0 (1.19–7.56)	2.9 (1.13–7.26)	2.9 (1.13–7.26)
LR−	0.00 (NA)	0.07 (0.01–0.47)	0.07 (0.01–0.47)
Area under the curve (ROC)	0.83 (0.66–0.94)	0.81 (0.64–0.93)	0.81 (0.64–0.93)

Data expressed with 95% CI. Per-patient diagnostic accuracy of MCA and conventional (without MCA) reconstructions for detection of stenosis ≥50% based on invasive angiography. No differences are observed between conventional reconstruction and analysis including all energy levels.

were also performed to evaluate the diagnostic performance of the two reconstruction approaches using specific software for ROC analysis (MedCalc Software, Ostend, Belgium). The difference between the two areas under the curve was tested with the z test. Differences in the Parameters A and B of two ROC curves are tested using the bivariate chi-square test, as previously described [13,14]. All other statistical analyses were performed using SPSS software, Version 22 (Chicago, IL, USA). A two-sided P value of less than .05 indicated statistical significance.

3. Results

Thirty-two patients were prospectively included in the study protocol. The mean age was 62.6±11.8 years. Twenty-three (72%) patients were male. Demographical characteristics are depicted in Table 1. The mean HR was 59.8±12.4 bpm (minimum 36 bpm, maximum 95 bpm). The mean effective radiation dose related to CTCA was 5.3±1.2 mSv, and the median CAC scoring was 648.5 (interquartile range, 44–1132).

3.1. Image quality and interpretability

A total of 480 coronary segments were evaluated using conventional and MCA reconstructions. MCA reconstruction improved image quality compared to conventional reconstruction in 128/480 segments (26.7%). In four (0.8%) segments, image quality was deemed inferior with MCA compared to conventional reconstructions. Overall, MCA reconstructions were associated to higher interpretability rates (464/480; 96.7% vs. 422/480; 87.9%, $P<.001$) and image quality scores (4.12±0.9 vs. 3.76±1.0; $P<.0001$) compared to conventional reconstructions (Figs. 1 and 2). As shown in Table 2, image quality scores were significantly higher in MCA reconstructions among all coronary territories. Categorization according to HR tertiles demonstrated a significant beneficial effect of MCA over conventional reconstructions in image quality at post-hoc comparisons only at the highest tertile (HR higher than 63 bpm). Furthermore, image quality scores of MCA were significantly higher than conventional reconstructions among all HR tertiles. These results are shown in Table 3.

3.2. Diagnostic performance

Twenty-three (72%) patients had evidence of obstructive CAD (≥50% stenosis) at invasive angiography, and 18 (56%) patients had evidence of stenosis ≥70%.

MCA reconstructions were associated with a significantly higher diagnostic performance compared to conventional reconstructions, with an area under the curve of 0.95 (95% CI 0.92–0.97) versus 0.89 (95% CI 0.86–0.92), respectively ($P<.0001$). No significant differences were identified on a per-patient basis in this regard [area under the curve of 0.81 (95% CI 0.64–0.93) vs. 0.81 (95% CI 0.64–0.93), respectively, for MCA and conventional reconstructions ($P=1.0$)]. All other diagnostic measures are depicted in Tables 4 and 5.

Based on post-hoc analysis on a per-segment basis, evaluation of all energy levels appeared to provide a mild improvement in diagnostic performance compared to evaluation restricted to energy levels lower than 70 keV, with an area under the curve of 0.95 (95% CI 0.92–0.97) versus 0.93 (95% CI 0.90–0.95), respectively ($P=.04$).

Categorized analyses according to HR tertiles demonstrated a significant effect in diagnostic performance only at mid [area under the curve 0.92 (95% CI 0.86–0.96) vs. 0.89 (95% CI 0.83–0.94); $P=.018$] and higher [area under the curve 0.94 (95% CI 0.89–0.97) vs. 0.84 (95% CI 0.77–0.89); $P=.0004$] HRs (Table 6).

Finally, after discrimination into CAC tertiles on a per-vessel basis (right coronary artery, Tertile 1 CAC below 38, Tertile 2 CAC 38–345, Tertile 3 CAC above 345; left main coronary artery, Tertile 1 CAC 0, Tertile 2 CAC 1–16, Tertile 3 CAC above 16; left anterior descending artery, Tertile 1 CAC below 85, Tertile 2 CAC 85–416, Tertile 3 CAC above 416; left circumflex, Tertile 1 CAC 0, Tertile 2 CAC 1–136, Tertile 3 CAC above 136), the largest differences between reconstruction modes were observed among segments with more diffuse underlying calcification (Table 7). Ancillary analyses regarding the diagnostic accuracy of MCA reconstructions for the detection of severe stenosis (≥70%) compared to conventional reconstructions are provided in Tables 8 and 9.

4. Discussion

Our findings indicate that compared to conventional reconstructions, application of intracycle MCA reconstructions to DECT acquisitions is feasible and results in significantly higher image quality scores, interpretability, and diagnostic performance.

Since dual source CT scanners are not widely available, there is an enduring call for technical developments that enable a mitigation of motion-related artifacts associated to CTCA acquisitions aimed at achieving HR-independent motion-free coronary artery imaging. It could be alleged that motion artifacts can be attenuated by lowering HR to reach a temporal window of at least the temporal resolution of the technique. Nonetheless, this cannot be achieved in a number of clinical situations, such as tachycardia in the context of the triage of patients with acute chest pain, contraindications for beta-blockers or calcium-channel antagonists, or heart failure.

On the other hand, although the diagnostic performance of CTCA is high among a wide spectrum of patients suspected of CAD, it does not provide a significant incremental diagnostic value in patients with high likelihood of CAD and in patients with diffusely calcified coronary arteries [3,15–17].

The impending role of CTCA using DECT imaging for the assessment of CAD seems to be related to the potential incorporation of a wider population within the scope of the technique. This hypothesis is

Table 6
Dual energy CTCA

Reconstruction	Tertile 1		Tertile 2		Tertile 3	
	MCA	Conventional	MCA	Conventional	MCA	Conventional
Sensitivity	96.6 (82.2–99.9)	93.1 (77.2–99.2)	87.5 (61.7–98.5)	87.5 (61.7–98.5)	93.9 (79.8–99.3)	93.9 (79.8–99.3)
Specificity	95.8 (90.5–98.6)	93.3 (87.2–97.1)	96.2 (91.4–98.8)	91.0 (84.8–95.3)	94.5 (89.0–97.8)	74.0 (65.4–81.4)
PPV	84.9 (68.1–94.9)	77.1 (59.9–89.6)	73.7 (48.8–90.9)	53.9 (33.4–73.4)	81.6 (65.7–92.3)	48.4 (35.8–61.3)
NPV	99.1 (95.3–100)	98.2 (93.8–99.8)	98.5 (94.6–99.8)	98.4 (94.3–99.8)	98.4 (94.2–99.8)	97.9 (92.7–99.8)
LR+	23.0 (9.7–54.3)	13.9 (7.0–27.2)	23.3 (9.7–56.1)	9.7 (5.5–17.2)	17.0 (8.3–35.2)	3.6 (2.7–4.9)
LR−	0.04 (0.01–0.25)	0.07 (0.02–0.28)	0.13 (0.04–0.48)	0.14 (0.04–0.50)	0.06 (0.02–0.25)	0.08 (0.02–0.31)
AUC (ROC)	0.96 (0.92–0.99)	0.93 (0.88–0.97)*	0.92 (0.86–0.96)	0.89 (0.83–0.94)†	0.94 (0.89–0.97)	0.84 (0.77–0.89)‡

AUC refers to area under the ROC curve. Data expressed with 95% CIs. Diagnostic accuracy of MCA and conventional reconstructions for detection of lesions ≥50% according to HR tertiles (Tertile 1<54 bpm; Tertile 2 54–63 bpm; Tertile 3>63 bpm).
* z statistic 1.46, P=.15.
† z statistic 2.37, P=.018.
‡ z statistic 3.56, P=.0004.

supported by the ability of DECT to attenuate the adverse effect of beam-hardening artifacts (BHAs).

We have recently demonstrated in a different cohort of patients that MCA reconstructions performed in patients with suspected CAD using conventional single energy CT lead to higher interpretability rates and image quality scores compared to conventional reconstructions [18]. Until now, MCA were not applicable to DECT imaging. The present investigation is to the best of our knowledge the first to explore the effect of MCA using DECT imaging in patients suspected of CAD referred to invasive angiography. The relevance of our findings rely mainly in the fact that we tested a combined approach of two different techniques that show promise to attenuate some of the aforementioned technical limitations commonly observed during CTCA studies.

Overall, MCA reconstructions were associated to higher interpretability rates, image quality scores, and diagnostic performance compared to conventional reconstructions. Improvements in image quality and diagnostic performance seemed to be evident only among patients at the highest HR tertile. It should be noted that such benefit was obtained despite the median HR of the study sample was relatively low, being this possibly attributed to the inclusion of a high-risk population, with over 80% patients receiving baseline rate-control medications. Our results might partially be explained by the fact that BHA and blooming artifacts are commonly aggravated by motion; therefore, the combination of techniques that moderate BHA (DECT imaging) and motion artifacts (MCA reconstruction) might be useful in selected populations. Indeed, post-hoc analysis revealed that the largest differences between reconstruction modes were observed among segments with more diffuse underlying calcification.

Noticeably, MCA were associated to higher image quality scores among all coronary arteries, whereas in a previous study involving single energy CT MCA reconstructions, this was more evident within the analysis of the right coronary artery that has been established as the epicardial artery with the fastest motion velocity [18,19]. Moreover, image quality scores remained above average among patients at the highest HR tertile.

A limited number of studies have explored the potential of DECT imaging for the assessment of CAD, although early results are promising. Among others, a recent study has shown a significant reduction of high-attenuation artifacts by using higher monoenergetic energy levels [20]. In line with these findings, the diagnostic performance of MCA reconstructions in our study was higher when all energy levels were available to the observer compared to the analysis restricted to lower energy levels, possibly reflecting the reduction of high-attenuation artifacts attained at higher energy levels (>70 keV).

Overall, although preliminary and hypothesis generating, our findings add to the increasing evidence toward less constrained inclusion criteria of CTCA, potentially including patients with intermediate to high probability of CAD that are usually excluded from most studies using single energy imaging. Our findings imply that the combination of DECT imaging and postprocessing techniques such as MCA might lead to a decrease in the number of nonassessable or inconclusive studies since we showed excellent results even in patients with high likelihood of CAD, with a significant increase in PPV compared to conventional reconstructions. Furthermore, the impending goal of combined coronary and stress myocardial perfusion assessment with dual energy CT is promising but requires the ability to image the coronaries at higher HRs. Utilizing an MCA for dual energy CT might potentially aid the clinical application of this combined exam.

A number of limitations should be recognized. The relatively small sample size might lead to selection bias. Accordingly, analyses on a per-patient basis should be judged cautiously. Given the relatively low median HR of the population included despite HR-lowering medications were withheld for 24 h, extrapolation of our findings to patients with higher (>75 bpm) HRs should be avoided, warranting further studies including populations with higher HRs. Finally, we did not include patients with atrial fibrillation; thus, our results should not be extrapolated to such population either.

In conclusion, in this pilot investigation, compared to conventional reconstructions, application of intracycle MCA reconstructions to dual

Table 7
Dual energy CTCA

Reconstruction	CAC Tertile 1		CAC Tertile 2		CAC Tertile 3	
	MCA	Conventional	MCA	Conventional	MCA	Conventional
Sensitivity	100 (75.3–100)	100 (75.3–100)	92.3 (74.9–99.1)	88.5 (69.9–97.6)	93.0 (80.9–98.5)	93.0 (80.9–98.5)
Specificity	97.3 (93.1–99.3)	91.8 (86.1–95.7)	93.8 (88.5–97.2)	84.1 (77.2–89.7)	95.0 (88.6–98.3)	79.8 (70.5–87.2)
PPV	36.5 (13.9–96.0)	52.0 (31.3–72.2)	72.7 (54.5–86.7)	50.0 (34.9–65.1)	88.9 (76.0–96.3)	66.7 (53.3–78.3)
NPV	100 (97.4–100)	100 (97.3–100)	98.6 (94.9–99.8)	97.6 (93.2–99.5)	96.9 (91.2–99.4)	96.3 (89.7–99.2)
LR+	36.5 (13.9–96.0)	12.2 (7.1–20.9)	14.9 (7.8–28.3)	5.6 (3.7–8.3)	18.4 (7.8–43.4)	4.6 (3.1–6.9)
LR−	0	0	0.08 (0.02–0.31)	0.14 (0.05–0.40)	0.07 (0.02–0.22)	0.09 (0.03–0.26)
AUC (ROC)	0.99 (0.95–1.0)	0.96 (0.92–0.98)*	0.93 (0.88–0.96)	0.86 (0.80–0.91)†	0.94 (0.89–0.97)	0.86 (0.80–0.92)‡

Data expressed with 95% CIs. Diagnostic accuracy of MCA and conventional reconstructions for detection of lesions ≥50% according to individual vessel CAC score tertiles. For this purpose, each coronary segment was assigned a vessel territory and categorized into tertiles according to the individual vessel CAC score.
* z statistic 2.04, P=.04.
† z statistic 1.50, P=.13.
‡ z statistic 2.10, P=.03.

energy CT acquisitions was feasible and resulted in significantly higher image quality scores, interpretability, and diagnostic performance.

Declaration of conflicting interests

We declare that Drs. Carrascosa and Leipsic provided consultant work for GE Healthcare in the past 12 months.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinimag.2015.07.023.

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