Reduced Axial Scan Length Coronary Calcium Scoring Reduces Radiation Dose and Provides Adequate Clinical Decision-Making Before Coronary CT Angiography

Colin R. Young[1,2,3], David A. Reynolds[1,2,4], Neil Gambill[1], Daniel I. Brooks[1], and Todd C. Villines[1,2,5]

[1]Walter Reed National Military Medical Center, Bethesda, MD; [2]Uniformed Services University of the Health Sciences, Bethesda, MD; [3]Department of Radiology, Yale New Haven Hospital, New Haven, CT; [4]Brooke Army Medical Center, Fort Sam Houston, TX; and [5]University of Virginia Health Center, Charlottesville, VA

Corresponding Author
Colin R. Young, MD
Department of Radiology, Yale New Haven Hospital, 20 York Street, New Haven, CT, 06510;
E-mail: c.young@yale.edu

Key Words: Radiation dose, coronary calcium score, cardiac CT, coronary CT angiography
Abbreviations: computed tomography (CT), coronary computed tomography angiography (CCTA), full scan length (FSL), reduced scan length (RSL), dose length product (DLP), computed tomography dose index (CTDI), milliampere (mA), kilovolts-peak (kVp), Walter Reed National Military Medical Center, Bethesda (WRNMMC-B), coronary artery calcium (CAC), computed tomography angiography (CTA)

ABSTRACT

Extensive coronary artery calcium (CAC) diminishes the accuracy of coronary computed tomography angiography (CCTA). Many imagers adjust CCTA acquisition parameters depending on a preCCTA Agatston CAC score to optimize diagnostic accuracy. Typical preCCTA CAC imaging adds considerably to radiation exposure, partially attributable to imaging beyond the area known for highest CAC, the proximal coronary arteries. We aimed to determine whether a *z*-axis reduced scan length (RSL) would identify the majority of CAC and provide adequate information to computed tomography angiography providers relative to a standard full-scan length (FSL) preCCTA noncontrast CT. We retrospectively examined 200 subjects. The mean CAC scores detected in RSL and FSL were 77.4 (95% CI 50.6 to 104.3) and 93.9 (95% CI 57.3 to 130.5), respectively. RSL detected 81% of the FSL CAC. Among false negatives, with no CAC detected in RSL, FSL CAC severity was minimal (mean score 2.8). There was high concordance, averaging 88%, between CCTA imaging parameter adjustment decisions made by 2 experienced imagers based on either RSL or FSL. CAC detected and decision concordance decreased with increasing CAC burden. CAC detected was lower, and false negatives were more common in the right coronary artery owing to its anatomic course, placing larger segments outside RSL. Axial scan length and effective dose decreased 59% from FSL (~14.5 cm/~1.1 mSv) to RSL (~5.9 cm/~0.45 mSv). This retrospective study suggests that RSL identifies most CAC, results in similar CCTA acquisition parameter modifications, and reduces radiation exposure. Our colleagues corroborated these results in a recently published prospective study.

INTRODUCTION

Coronary computed tomography angiography (CCTA) is a well-established noninvasive method to evaluate coronary pathology; however, the accuracy of CCTA varies depending on the amount and location of calcified plaques in the coronary arteries (1). A high coronary artery calcium (CAC) score is often associated with a nondiagnostic CCTA (2, 3). Beam hardening in densely calcified coronary arteries causes decreased sensitivity and specificity of CCTA in patients with high CAC. To counteract this, in many CCTA examinations, imagers perform a preCCTA-gated noncontrast computed tomography (CT) for identification and scoring of CAC, and then they use this information to adjust CCTA parameters to optimize acquisition parameters (eg, dose, gating) (4–6). One meta-analysis suggests that careful pre-CCTA planning is crucial in patients with CAC score ≥400 to ensure diagnostic accuracy (7).

Radiation doses of a standard pre-CCTA CAC scoring, covering the entire heart, are typically 1–3 mSv (8, 9), whereas the radiation dose of CCTA is typically 2–8 mSv (10). Therefore, performing a standard pre-CCTA CAC scoring exposes patients who are undergoing CCTA to considerable radiation. One approach to minimize patient radiation exposure in cardiac CT is to limit the scan length in the *z*-axis (ie, the craniocaudal dimension) (5). A typical scan length for CAC scoring is from the carina through the diaphragm (8). However, the majority of coronary artery calcifications occurs in the proximal to mid portions of the coronary

ISSN 2379-1381 https://doi.org/10.18383/j.tom.2020.00041

arteries (11, 12), so CT exposure above and below the proximal to mid-coronary arteries often yields little diagnostic information but adds to the radiation dose (6).

Therefore, we sought to assess whether CAC as assessed from scans with reduced scan length (RSL), shortened in the z-axis to include only the proximal and mid-coronary arteries, would aid in the identification of the majority of coronary artery calcification and provide adequate information to computed tomography angiography imagers of patients referred for CCTA compared with CAC assessed using standard full scan length (FSL).

METHODS

Overview

We retrospectively simulated RSL in 200 patients by conducting a postprocessing truncation of a set of standard FSL images. Clinicians viewed both RSL and FSL scans and determined a CAC score for each. We calculated the percentage of FSL CAC detected in RSL. To help recoup decreased detection of CAC in RSL, linear regression equations were derived to attempt to predict FSL CAC scores from RSL CAC scores. We also replicated the decision-making process of adjusting CCTA parameters to identify whether RSL would result in similar decisions when compared with standard FSL. Finally, we estimated the radiation dose savings that could be expected by implementing RSL CAC scoring protocol in routine clinical practice.

Patient Selection

Data in this study were collected from 200 subjects, ≥50 years, who had had a CCTA performed at our institution between July 1, 2013 and December 31, 2014. Patients were included if they underwent a clinically indicated noncontrast CAC scan and subsequent CCTA. Patients of at least 50 years of age were selected based on experience that this cohort is more likely to have substantial CAC, which might influence CCTA scan parameters and is a cohort where many providers most commonly perform pre-CCTA calcium scans.

CT Examination Protocol

All imaging was conducted on a General Electric Discovery LightSpeed™ CT750 HD 64 Slice scanner (GE Medical Systems, Waukesha, WI). Patients underwent CT imaging consisting of a noncontrast CAC scoring and subsequent contrast-enhanced CCTA in accordance with SCCT guidelines.

FSL CAC Score Acquisition

Following standard institutional protocol, FSL images were acquired from each research subject from the carina through the diaphragm and were stored in a picture archiving and communication software (PACS) system (AGFA version 6.4.0.5510, Mortsel, Belgium). CAC scoring was performed in accordance with the Agatston method (13) on a GE Advantage Workstation (GE Healthcare, Chicago, IL) for diagnostic imaging post processing. In total, 3 groupings of coronary arteries were analyzed for calcium, specifically the left coronary arteries, the right coronary artery, and the right and left coronary arteries combined. Although left CAC in more precise anatomic locations was originally scored, all CAC scores from the left main, left anterior descending, and left circumflex coronary arteries were merged into an inclusive group for the purpose of this analysis. This decision was based on the assumption of large interobserver variability in accurate classification of CAC near the bifurcation of the left coronary artery system into one of its tributaries (ie, the distal left main or the proximal left anterior descending or proximal left circumflex).

RSL CAC Score Calculations

FSL images were postprocessed to generate RSL images. FSL image volume was truncated in the z-axis, from 1 cm below the carina to the greatest convexity of the right atrium, to produce RSL image volume. For each RSL image, Agatston CAC scores were generated. The same 3 groupings of coronary vessels were analyzed for calcium. See Figure 1 for a representative visual comparison between FSL and RSL. The proportion of the Agatston CAC score on FSL captured in RSL was assessed.

Clinical Decision-Making

FSL images from each research subject were interpreted in consensus by both a radiologist and a cardiologist, both board-certified with >10 years of clinical experience in the performance of cardiac CT. On a separate occasion, RSL images were randomly presented to the same 2 physicians for interpretation. The RSL and FSL images were presented to these interpreting physicians

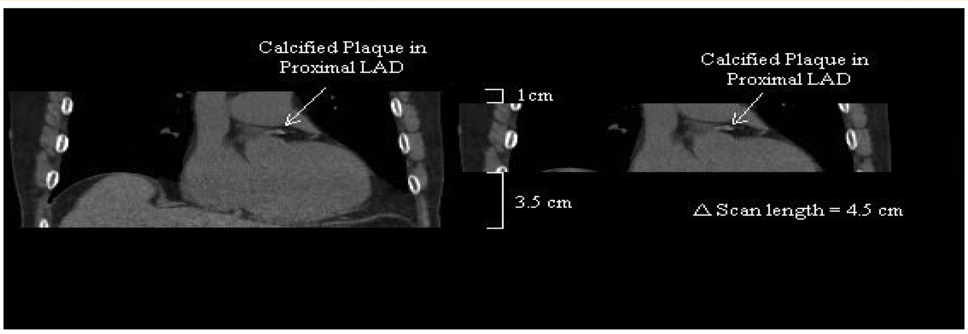

Figure 1. Representative coronal image showing differences between full scan length (FSL) and reduced scan length (RSL).

separated by adequate time and at random intervals, such that they were blinded to the identity of the research subjects. After viewing each image, the faculty radiologist and cardiologist made a rapid global assessment of the overall CAC burden. This approach was meant to replicate the process used at the scanner when performing CCTA. Using both their assessments of CAC burden and patient demographics (age, sex, body mass index, heart rate), the investigators selected subsequent CCTA parameters including mA, kVp, padding (the additional CT scan acquisition time beyond the minimum time required to acquire an image of the heart at a single point in mid-diastole), gating (the choice between retrospective versus prospective image processing), and whether high-definition scanning (a unique feature of the Discovery CT750 HD scanner) (14) should be used. For each research subject, the parameter adjustments for the follow-on CCTA were examined to determine whether a significant difference existed between the decisions made based on RSL and FSL scans.

Radiation Dose

Dose length product (DLP) (mGy) and computed tomography dose index (CTDI) (mGy-cm) were obtained from General Electric Discovery LightSpeed CT750 HD 64 Slice scanner (GE Medical Systems) for FSL images. FSL DLP and CTDI were multiplied by the RSL/FSL ratio to obtain the corresponding DLP and CTDI values for RSL. Effective dose was calculated by multiplying the CTDI by a k-value of 0.014 mSv/(mGy-cm) (15).

Research Endpoints and Statistical Analyses

To assess the ability of RSL to detect FSL CAC, the RSL CAC score of each coronary vessel grouping was summed across all research subjects and divided by the FSL CAC score of each coronary vessel summed across all research subjects to give a percentage detected. In cases where RSL failed to detect CAC, which was detected in FSL, the magnitude of the undetected CAC was evaluated to understand the potential consequences of these false-negative RSL examinations. We stratified our analyses to determine whether RSL underdetection of CAC or false negatives increased with larger FSL CAC burden. The McNemar chi-square test was used to evaluate concordance in CCTA imaging parameter decision-making based on FSL and RSL images. Statistical analyses were conducted using R Version 3.2.2 (R Core Team, Vienna, Austria). Continuous variables were reported as means with 95% confidence interval, and categorical variables were reported as a percentage.

Institutional Review and Research Setting

This retrospective study was approved with a waiver of informed consent by Walter Reed National Military Medical Center Bethesda (WRNMMC-B) Institutional Review Board (protocol #394857) in compliance with all applicable federal regulations governing the protection of human subjects. This assessment was conducted at WRNMMC-B, a moderate-sized tertiary care facility providing for Military Health System beneficiaries residing in the National Capital Region near Washington, D.C. No external funding was used in support of this research.

RESULTS

Research Subject Baseline Parameters

Images and clinical data from a total of 200 subjects (104 men and 96 women) were included in this study. The mean age, body mass index, and heart rate were 60 years, 29.3 kg/m2, and 56 beats/min, respectively.

Ability of RSL to Detect FSL CAC

Table 1 describes the RSL and FSL CAC data sets. Among all research subjects where the FSL total CAC was >0, RSL detected 81.34% of FSL CAC. A stratified analysis showed that RSL detected 98.4% of FSL CAC in the left coronary artery. A stratified analysis of RSL's ability to detect FSL CAC in the right coronary artery yielded different results than those seen in the left and total CAC analyses. Among the subjects where the FSL right CAC was >0, RSL detected 28.46% of CAC. As the FSL CAC burden increased, RSL detected progressively less of this CAC. Table 2 presents these results in more detail.

False Negatives with Detection of CAC in FSL and No Detection in RSL

In 3.5% of research subjects (n = 7), FSL showed total CAC, which was not detected with RSL. Among these 7 examinations, the average total CAC in FSL was 2.9 and the maximum was 9. In 2.5% of subjects (n = 5), FSL showed left CAC, which was not detected with RSL. Among the 5 examinations where RSL did

Table 1. Standard Descriptive Statistics of the Full Scan Length and Reduced Scan Length Data Sets

	Reduced Scan Length CAC Scores	Full Scan Length CAC Scores
Average (mean)	77.43	93.91
Standard deviation	193.73	263.98
Standard error of the mean	13.70	18.67
95% confidence interval	50.57–104.28	57.32 to 130.49
Range	0–1969	0–2137
Median	4.0	4.5
Interquartile range	0–71.25	0–68.5

Abbreviation: CAC, coronary artery calcium.

Table 2. Percentage of Full Scan Length Coronary Artery Calcium Detected in Using Reduced Scan Length[a]

	Percentage of FSL CAC Detected by RSL at Varying Burdens of FSL CAC in Respective Coronary Vessel			
Both left and right coronary artery systems	FSL CAC > 0	FSL CAC > 100	FSL CAC > 200	FSL CAC > 1000
	81.34%	78.87%	70.95%	65.42%
Left coronary arteries	98.44%	98.32%	90.41%	89.60%
Right coronary artery	28.46%	15.57%	13.24%	10.56%

[a] Separate analyses were conducted to independently analyze the left coronary artery system, the right coronary artery, and the right and left coronary arteries combined.

not detect left CAC, the average FSL left CAC in FSL was 2.2 and the maximum was 4. In 10% of subjects (n = 20), FSL showed total CAC, which was not detected with RSL. In these 20 examinations, the average FSL right CAC was 64.6 and the maximum was 653.

Subsequent CCTA Parameter Decision-Making Comparison

There was overall high concordance between the CCTA parameter manipulation decisions based on RSL and FSL interpretation (Table 3). The highest discordance occurs for individuals with higher CAC scores. Figure 2 shows that with CAC scores >0, concordance rapidly falls to near 50% and kVp concordance decreases to ~75% in the upper quartiles of CAC.

Radiation Reduction

See Table 4 for differences in scan length and radiation dose between FSL and RSL.

DISCUSSION

In this study, we retrospectively examined the clinical feasibility of using a pre-CCTA CAC score with RSL in the *z*-axis with the intention of reducing patient radiation exposure. Our study shows multiple important findings including:

1. RSL detects most CAC seen in FSL;
2. RSL results in a small percentage of false-negative CAC examinations and is highly predictive of FSL CAC scores;
3. RSL CAC scans result in similar decision-making regarding parameter adjustment for subsequent CCTA; and
4. RSL CAC scans may significantly reduce patient radiation exposure if used clinically.

Among all research subjects where FSL total CAC was >0, RSL detected >80% of FSL CAC. As the burden of CAC increased to >1000, the percent detection dropped to ~65%. Similar results were seen in the left coronary arteries, where RSL detected >98% of FSL CAC with a similar decreased detection efficiency of ~90% as the CAC burden increased >1000. Very different results were seen in the right coronary artery with RSL detecting <30% of FSL CAC, with detection efficiency decreasing to ~10% as the CAC burden increased >1000.

False negatives (ie, detection of CAC on FSL without detection on RSL) were infrequent, particularly in the total and left coronary artery analyses. In these false negatives, the magnitude of the undetected CAC score never exceeded an Agatston score of 9, a generally very small quantity. False negatives were the most frequent in the right coronary artery, where they occurred in 10% of research subjects. In these false negatives, a larger magnitude of undetected CAC was observed, on average an Agatston score of ~65 and in the most extreme case was 653.

As described in the previous paragraphs, when compared with RSL of the total and left CAC, the RSL right CAC score shows a markedly greater percentage of underdetection of CAC, and a higher percentage of false negatives with larger burdens of CAC was not observed. The right coronary artery has a more inferior (ie, caudal) origin along the aortic root than the left main

Table 3. Percentage Concordance between Decisions for Coronary Computed Tomography Angiography (CCTA) Parameter Adjustments Based on Full Scan Length (FSL and Reduced Scan Length (RSL)[a]

	Concordance (%)	**Average Change Based on FSL**	**Average Change Based on RSL**	**Major Discrepancies**
mA	71% (*P* = .7277)	97.18	82.09	0
kVp	87.5% (*P* = .8383)	20	18.97	1
Padding	96% (*P* = .1306)	50	61.1	1
Gating	99% (*P* < .001)	N/A	N/A	N/A
High definition	89% (*P* = .0190)	N/A	N/A	N/A

[a] *P*-values were calculated using the McNemar chi-square with 1 degree of freedom. Average CCTA parameter changes are based on both FSL and RSL. The number of major CCTA imaging parameter decision-making discrepancies are presented, defined as differences of >100 for mA, 20 for kVp, and 50 milliseconds for padding.

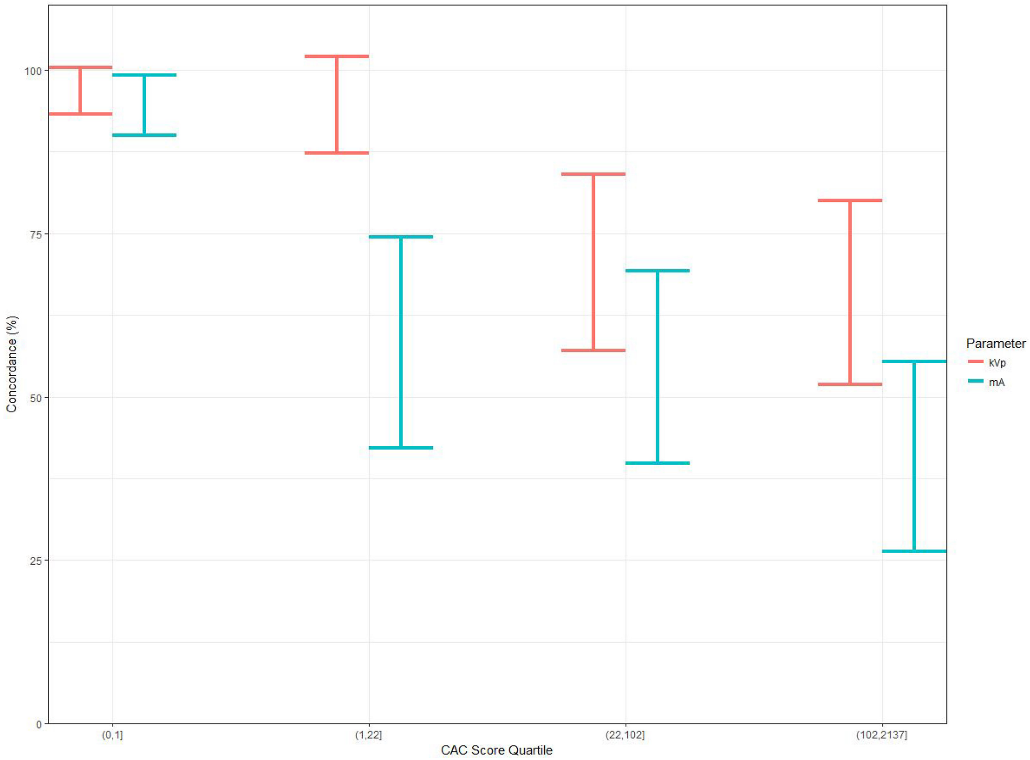

Figure 2. Concordance of multiple parameters (mA, kVp, gating, padding, and high definition) as a function of coronary artery calcium (CAC) score quartiles. Error bars are 95% confidence intervals.

coronary artery and it travels in a more inferiorly oriented course along the pericardium than the other major coronary artery branches. We postulate that the more inferior origin and course of the right coronary artery subsequently position its proximal and mid portions closest to being off of the inferior margin of RSL, and thus results in greater underdetection of CAC in the right coronary artery than in the other major coronary vessels. Furthermore, previous studies suggest that unlike in the left coronary arteries where CAC is concentrated in the proximal portions of the arteries, the right coronary artery has a more uniform distribution or even distally concentrated distribution (16).

There was overall high concordance in decision-making regarding imaging parameter adjustment based on FSL and RSL CAC scores for the subsequent CCTA. In total, 4 of the 5 parameters (ie, kVp, padding, choice of prospective/retrospective gating, and use of high definition) evaluated showed >87% concordance, with the remaining parameter (ie, mA) showing 70% concordance. Concordance dropped as FSL CAC score increased. For the imaging parameters which were continuous variables (ie, mA, kVp, and padding), the average magnitude of the differences in the changes was minimal. In addition, the number of large discrepancies (ie, ΔkVp > 20, ΔmA > 100, Δpadding > 50 milliseconds) was minimal.

Our results show a reduction in axial scan length and a directly proportional reduction in radiation dose of ~60% from FSL (~14.5 cm and ~1.1 mSv) to RSL (~5.9 cm and ~0.45 mSv). Given that the mean effective radiation dose of CCTA is typically between 2 and 8 mSv (10), this result represents a noteworthy decrease in dose to the combined imaging sequence of a CAC score followed by CCTA.

Our study has several important limitations. First, this study involved patients undergoing only CAC scoring before CCTA and

Table 4. Differences in Scan Length and Radiation Dose between FSL and RSL

	Axial (z) Scan Length (cm)	Computed Tomography Dose Index (mGy)	Dose Length Product (mGy-cm)	Effective Dose (mSv) [Calculated Using k = 0.014 mSv/(mGy-cm)]
FSL	14.54 ± 0.24	5.42 ± 0.09	79.96 ± 1.92	1.12 ± 0.03
RSL	5.85 ± 0.17	2.18 ± 0.06	32.08 ± 1.03	0.45 ± 0.01
Change	−8.69 ± 0.22	−3.24 ± 0.09	−47.88 ± 1.55	−0.67 ± 0.02

All values are reported using ±95% confidence intervals.

thus our results should not be extrapolated to CAC scoring for coronary artery disease screening. Second, our examination was restricted to a single medical center, a single scanner platform, and age >50 years, and thus, these results may not be broadly generalizable to other patient populations, CT scanners, or age groups. Although our study incorporated a large sample size of 200 subjects, many of these subjects showed very low CAC scores, with 81 subjects showing CAC scores of 0 and additional 78 subjects showing CAC scores of <100. As defined in the goals of our research, the objectives were to determine the percentage of CAC detected and whether similar CCTA parameter adjustment decision-making occurred based on the amount of CAC detected. It is outside the scope of our examination to determine whether the RSL CAC score as a stand-alone value is predictive of acute coronary syndrome events. Finally, this study was a retrospective examination aimed primarily at hypothesis generation; however, our results were prospectively corroborated in a recently published prospective clinical trial—the Focused field of view calcium scoring prior to coronary CT angiography (FOCUS-CCTA; ClinicalTrials.gov Identifier: NCT02972242) (17).

CONCLUSION

RSL noncontrast CT scan identifies the majority of CAC and is associated with similar post-CAC decision-making regarding parameter adjustment for subsequent CCTA. These results are hypothesis generating and should be assessed, along with other CAC dose reduction methods, in prospective comparative studies.

DISCLOSURE

Conflicts of Interest/Funding: We deny any financial or other relationships that may pose a relevant conflict of interest. No funding was used in support of this research.

Disclaimer: (1) The views expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of the Departments of the Navy or Army, Department of defense or the US Government. Nothing in this paper implies any Federal/DoD/DA/DON endorsement. (2) We certify that all individuals who qualify have been listed; that each has participated in the conception and design of this work, the analysis of data, the writing of the document, and the approval submission of this version; that the document represents valid work; and that each takes public responsibility for it.

REFERENCES

1. Palumbo AA, Maffei E, Martini C, Tarantini G, Di Tanna GL, Berti E, Grilli R, Casolo G, Brambilla V, Cerrato M, Rotondo A, Weustink AC, Mollet NR, Cademartiri F. Coronary calcium score as gatekeeper for 64-slice computed tomography coronary angiography in patients with chest pain: per-segment and per-patient analysis. Eur Radiol. 2009;19:2127–2135.
2. Stolzmann P, Scheffel H, Leschka S, Plass A, Baumüller S, Marincek B, Alkadhi H. Influence of calcifications on diagnostic accuracy of coronary CT angiography using prospective ECG triggering. AJR Am J Roentgenol. 2008;191:1684–1689.
3. Vavere AL, Arbab-Zadeh A, Rochitte CE, Dewey M, Niinuma H, Gottlieb I, Clouse ME, Bush DE, Hoe JW, de Roos A, Cox C, Lima JA, Miller JM. Coronary artery stenoses: accuracy of 64-detector row CT angiography in segments with mild, moderate, or severe calcification–a subanalysis of the CORE-64 trial. Radiology. 2011;261:100–108.
4. Halliburton SS, Abbara S, Chen MY, Gentry R, Mahesh M, Raff GL, Shaw LJ, Hausleiter J. Society of Cardiovascular Computed Tomography. SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT. J Cardiovasc Comput Tomogr. 2011;5:198–224.
5. Murphy DJ, Keraliya A, Himes N, Aghayev A, Blankstein R, Steigner ML. Quantification of radiation dose reduction by reducing z-axis coverage in 320-detector coronary CT angiography. Br J Radiol. 2017;90:20170252.
6. Villines TC, Hulten EA, Shaw LJ, Goyal M, Dunning A, Achenbach S, Al-Mallah M, Berman DS, Budoff MJ, Cademartiri F, Callister TQ, Chang HJ, Cheng VY, Chinnaiyan K, Chow BJ, Delago A, Hadamitzky M, Hausleiter J, Kaufmann P, Lin FY, Maffei E, Raff GL, Min JK, Confirm R. Prevalence and severity of coronary artery disease and adverse events among symptomatic patients with coronary artery calcification scores of zero undergoing coronary computed tomography angiography: results from the CONFIRM (Coronary CT angiography evaluation for clinical outcomes: an international multicenter) registry. J Am Coll Cardiol. 2011;58:2533–2540.
7. Abdulla J, Pedersen KS, Budoff M, Kofoed KF. Influence of coronary calcification on the diagnostic accuracy of 64-slice computed tomography coronary angiography: a systematic review and meta-analysis. Int J Cardiovasc Imaging. 2012;28:943–953.
8. Kim KP, Einstein AJ, Berrington de González A. Coronary artery calcification screening: estimated radiation dose and cancer risk. Arch Intern Med. 2009;169:1188–1194.
9. Voros S, Rivera JJ, Berman DS, Blankstein R, Budoff MJ, Cury RC, Desai MY, Dey D, Halliburton SS, Hecht HS, Nasir K, Santos RD, Shapiro MD, Taylor AJ, Valeti US, Young PM, Weissman G. Guideline for minimizing radiation exposure during acquisition of coronary artery calcium scans with the use of multidetector computed tomography: a report by the Society for Atherosclerosis Imaging and Prevention Tomographic Imaging and Prevention Councils in collaboration with the Society of Cardiovascular Computed Tomography. J Cardiovasc Comput Tomogr. 2011;5:75–83.
10. Einstein AJ, Elliston CD, Arai AE, Chen MY, Mather R, Pearson GD, Delapaz RL, Nickoloff E, Dutta A, Brenner DJ. Radiation dose from single-heartbeat coronary CT angiography performed with a 320-detector row volume scanner. Radiology. 2010;254:698–706.
11. Ehara S, Matsumoto K, Hasegawa T, Otsuka K, Sakaguchi M, Shimada K, Yoshikawa J, Yoshiyama M. Characteristic patterns of the longitudinal and circumferential distribution of calcium deposits by parent coronary arteries observed from computed tomography angiography. Heart Vessels. 2016;31:508–518.
12. Golinvaux N, Maehara A, Mintz GS, Lansky AJ, McPherson J, Farhat N, Marso S, de Bruyne B, Serruys PW, Templin B, Cheong WF, Aaskar R, Fahy M, Mehran R, Leon M, Stone GW. An intravascular ultrasound appraisal of atherosclerotic plaque distribution in diseased coronary arteries. Am Heart J. 2012;163: 624–631.
13. Agatston AS, Janowitz WR, Hildner FJ, Zusmer NR, Viamonte M Jr, Detrano R. Quantification of coronary artery calcium using ultrafast computed tomography. J Am Coll Cardiol. 1990;15:827–832.
14. Machida H, Tanaka I, Fukui R, Shen Y, Ishikawa T, Tate E, Ueno E. Current and novel imaging techniques in coronary CT. Radiographics. 2015 Jul;35:991–1010.
15. Messenger B, Li D, Nasir K, Carr JJ, Blankstein R, Budoff MJ. Coronary calcium scans and radiation exposure in the multi-ethnic study of atherosclerosis. Int J Cardiovasc Imaging. 2016;32:525–529.
16. Xu Y, Mintz GS, Tam A, McPherson JA, Iñiguez A, Fajadet J, Fahy M, Weisz G, De Bruyne B, Serruys PW, Stone GW, Maehara A. Prevalence, distribution, predictors, and outcomes of patients with calcified nodules in native coronary arteries: a 3-vessel intravascular ultrasound analysis from providing regional observations to study predictors of events in the coronary tree (PROSPECT). Circulation. 2012;126:537–545.
17. Crimm HA, Fergestrom NM, Dye C, Philip C, Nguyen BT, Villines TC. Focused, low tube potential, coronary calcium assessment prior to coronary CT angiography: a prospective, randomized clinical trial. J Cardiovasc Comput Tomogr. 2020;S1934-5925:30432–30439.