Reviews

Recent Improvement in Coronary Computed Tomography Angiography Diagnostic Accuracy

Address for correspondence:
Matthew J. Budoff, MD, Department of Cardiology, Harbor-UCLA Medical Center, Los Angeles, CA 90502, mbudoff@labiomed.org

Anas Alani, MD; Rine Nakanishi, MD, PhD; Matthew J. Budoff, MD
Department of Cardiology, Harbor-UCLA Medical Center, Los Angeles, California

ABSTRACT

Although invasive coronary angiography has been the gold standard for evaluating coronary artery disease (CAD), it should not be routinely performed as an initial test to assess CAD in subjects with suspected CAD by the recent guidelines, due to cost, invasiveness, and measurable risk. Coronary computed tomography angiography (CCTA) is a rapidly growing, noninvasive imaging modality that developed quickly over the last decade, and its role for evaluation of CAD becomes of great promise with high diagnostic accuracy. Although artifact issues have created some challenges for CCTA, recent advances — including the introduction of more detectors, leading to broader coverage, and faster and higher-definition scanners — allow improved precision and fewer uninterpretable studies. This review article summarizes the current key literature regarding the diagnostic accuracy of CCTA in native coronary arteries, stents, coronary artery bypass grafts, lesions with high calcification, and the functional assessment of CAD.

Introduction

The rapid development of coronary computed tomography angiography (CCTA) over the past decade improves the ability to noninvasively visualize and assess cardiac anatomy, especially coronary arteries. The advances in the temporal and spatial resolution of CCTA allow valuable information to be available to physicians that was not previously available by noninvasive methods. The new generations of cardiac computed tomography (CT) have made very rapid improvements in both image quality and diagnostic accuracy. Some improvements include increased number of detectors, more volumetric coverage, the introduction of dual-source and dual-energy scanners, high-definition detectors, and advanced workstations. Since the earlier introduction of CCTA, it has been compared with other, more established modalities such as invasive coronary angiography (ICA), and many studies proved the high diagnostic accuracy of CCTA.[1–3] According to the recent European Society of Cardiology guidelines and American College of Cardiology Foundation/American Heart Association appropriate-use criteria, CCTA is a level IIa recommendation as an alternative to the stress test for ruling out stable coronary artery disease (CAD) in patients with low to intermediate pretest probability.[4,5] This review article summarizes the current key literature regarding the diagnostic accuracy of CCTA in native coronary arteries, stents, coronary artery bypass grafts (CABG), lesions with high calcification, and the functional assessment of CAD.

The authors have no funding, financial relationships, or conflicts of interest to disclose.

Diagnostic Accuracy of Coronary Computed Tomography Angiography

Assessment of Native Coronary Arteries

The diagnostic accuracy of CCTA for native coronary arteries had been established by numerous previous studies, including 3 multicenter studies, with very high sensitivity ranging between 85% and 99% and negative predictive value (NPV) ranging between 83% and 99%.[1–3] Given the recent technology, CCTA provides greater spatial and temporal resolutions, as well as broad coverage, which allows fewer artifacts and better image quality. The largest temporal resolution improvement was achieved with the introduction of dual-source CT,[6] which has made cardiac scans less affected by the heart rate, eliminating the need for postprocessing dual-segment reconstruction algorithms and resulting in better image quality in patients with higher heart rates or arrhythmias.[7] Ropers et al. observed that there was no difference in diagnostic accuracy between patients with heart rates of ≥65 beats per minute (bpm) and <65 bpm.[8] The development of broad detector (256-slice and 320-slice) systems allows volumetric scanning. The 64-slice CCTA can scan 40 mm of *z*-axis coverage per rotation; thus, 3 rotations are needed to cover the entire heart, which may cause gaps and artifacts, especially in patients with heart-rate variability. On the other hand, the new 256-slice and 320-slice systems have a wider coverage, with 80 mm to 160 mm per rotation with 1 to 2 heartbeats, which allows for fewer misregistration

Clin. Cardiol. 37, 7, 428–433 (2014)
Published online in Wiley Online Library (wileyonlinelibrary.com)
DOI:10.1002/clc.22286 © 2014 Wiley Periodicals, Inc.

Received: February 25, 2014
Accepted: March 13, 2014

artifacts.[9] Several studies demonstrated that 320-slice CCTA resulted in very high sensitivity of 93% to 100%, NPV of 94% to 100%, and high diagnostic accuracy compared with ICA.[10–14] When compared with patients undergoing 64-slice CCTA, however, previous studies showed significant difference in image quality among those undergoing broad detectors with 256-slice or 320-slice CCTA,[15,16] while not improving diagnostic accuracy.[11,17]

Assessment of In-stent Restenosis

The evaluation of stents by CCTA is still more challenging than that of native coronary arteries.[18] According to the recent meta-analysis studies, the diagnostic accuracy of stents is ~90%, with sensitivity of 89.7% to 90%, specificity of 91% to 92.2%, positive predictive value (PPV) of 72.5%, and NPV of 97.4%.[19,20] Potential reasons for the lower accuracy compared with that of native coronary arteries are 3 types of artifacts: motion, beam hardening caused by metallic stents, and partial volume from highly attenuated stent struts.[18] Indeed, when investigated nonassessable segments are included, the sensitivity significantly drops to 79% and specificity drops to 81%.[20] Heart-rate control is important for not only feasibility of native coronary arteries but also coronary stents and result in higher feasibility. Andreni et al demonstrated heart rate >60 bpm provided 3% reduction of diagnostic accuracy of in-stent restenosis (ISR) compared with <60 bpm.[21] The stent size or thickness also plays an important role. Visualization of smaller stents is more challenging and these can be nonevaluable; stent evaluability increases if stent diameter is ≥3 mm.[21–24] In the study by Andreni et al, the sensitivity, specificity, PPV, NPV, and accuracy were 67%, 78%, 57%, 85%, and 75%, respectively, for stents <3.0 mm in diameter; whereas for stents ≥3.0 mm in diameter, the sensitivity, specificity, PPV, NPV, and accuracy were 89%, 100%, 100%, 97%, and 98%, respectively.[21] In this regard, the current appropriate-use criteria suggest that CCTA should be done only for patients who have stents ≥3 mm in diameter or a stent in the left main coronary artery.[25] In addition, thinner stents have a higher diagnostic accuracy (98%) compared with thicker stents (93%).[21] Although the diagnostic accuracy of stents was investigated by visual assessment in the most previous CCTA studies, our group previously demonstrated the unique technique for quantitative assessment of stents using the different contrast densities in coronary arteries. Abdelkarim et al found that a significant density drop (in Hounsfield units [HU]) >19% inside the lumen stent compared with a reference vessel was associated with ISR, with high sensitivity and specificity for stent diameter ≥2.5 mm.[26] This technique may have a potential role in assessing coronary stents by the different approach and solving the major issue of blooming artifacts with stents.

The introduction of the high-definition CT scanner (HDCT) provides higher resolution with superior spatial resolution of 0.23 mm[27] and the ability to reconstruct images with an adaptive statistical iterative reconstruction (ASIR) algorithm.[28] This provides superior results for stent visualization, allowing even smaller-diameter stents or stents with heavy calcification to be more accurately evaluated and ISR better detected.[29–33] In a study investigating 180 patients undergoing both ICA and intravascular ultrasound (IVUS) for detection of ISR, beam-hardening artifact was lower with HDCT with a diagnostic accuracy of 96%, compared with 91% with standard definition CT (SDCT). The correlation was higher between HDCT and ICA.[32] A recent in vivo study by Fuchs et al compared HDCT vs SDCT, finding that imaging quality was superior with HDCT with decreases in partial volume artifacts, lower luminal attenuation, and larger mean measured in-stent luminal diameter (1.2 ± 0.4 mm vs 0.8 ± 0.4 mm, $P < 0.05$) compared with SDCT.[33] Having small-diameter stents with heavy calcification is not uncommon; HDCT can be a good choice for detection of ISR for stents with smaller diameter (<3 mm) where using SDCT is more challenging and leads to more nonevaluable stents. New techniques using CT myocardial perfusion imaging in stent patients may further enhance CT capabilities to accurately discern ISR and decrease uninterpretable studies.

Assessment of Coronary Artery Bypass Grafting

Coronary computed tomography angiography can be used to assess the patency of CABG cases with high diagnostic accuracy compared with ICA and even with a better performance than assessment of native coronaries. This superior diagnostic accuracy may be due to the following reasons: fewer motion artifacts (grafts have less motion through the cardiac cycle than native coronary vessels do), larger vessel diameter of grafts, and lower propensity to develop calcified plaques compared with native coronaries.[34,35] In a meta-analysis by Hamon et al,[36] the diagnostic accuracy of assessing grafts by CCTA was exceptionally high (sensitivity, 97.6%; specificity, 96.7%; and NPV, 98.9%). Coronary computed tomography angiography also can allow visualizing of these closures by the "stump" on the aortic wall or actual closed graft lumen.[37] Two studies investigated CCTA accuracy in graft visualization. One demonstrated 2 cases out of 147 in which grafts were patent by CCTA after being deemed closed by ICA, and the second found 3 grafts out of 96 with patency only detected by CCTA.[38,39] Coronary computed tomography angiography can be a useful noninvasive method for diagnosis of coronary artery stenosis in CABG patients with a higher diagnostic accuracy, exceeding that of native coronary arteries, and the advantage of visualizing grafts that cannot be detected or accessed by ICA.

Assessment of Coronary Arteries With High Calcium Score

A heavily calcified coronary artery is a notable problem that can reduce diagnostic accuracy of CCTA. The potential mechanism underlying the reduced accuracy in calcified lesions may be explained by the extent, density, or volume of calcification as well as the size of the coronary artery. A recent publication by Kruk et al[40] extensively examined the impact of specific calcified plaque characteristics on diagnostic accuracy of CCTA when compared with stenosis severity quantitatively assessed by IVUS.[40] In this study examining 60 patients, lumen underestimation by CCTA was observed in 16.3% of calcified lesions, due to the extensive calcified plaque with calcium arc ≥47 degrees and a smaller lumen diameter with ≤2.8 mm. By contrast,

Published online in Wiley Online Library (wileyonlinelibrary.com)
DOI:10.1002/clc.22286 © 2014 Wiley Periodicals, Inc.

the excessive lumen overestimation by CCTA was less likely to be observed in only 8.3% of calcified plaques. This underestimation is caused by 2 features including maximum calcium density <869 HU, calcium length <2.4 mm, or total calcium volume <6.4 mm^3. This may be explained by a limited spatial resolution of CCTA compared with IVUS.[40] Coronary artery calcium score (CACS) scanning is an emerging tool to identify the presence and extent of coronary artery calcium, as well as to stratify risk of future cardiovascular events.[41,42] Also, CACS may be used as a gatekeeper to avoid unnecessary CCTA among patients with higher CACS.[43] Current appropriate-use criteria of CCTA noted the diagnostic yield among patients with CACS ≥400 is still uncertain.[44] In several multicenter studies and current meta-analyses,[1,45,46] a higher CACS (≥400 or ≥600) provided 35% to 48% reduction of specificity, while not reducing sensitivity. Thus, the recent guideline does not recommend performing CCTA for patients with very high CACS, and these patients ought to be sent for functional examination or directly undergo ICA based on their pretest probability of CAD.[4]

Dual-energy imaging allows for subtraction algorithms to remove calcium and improve the evaluation of coronary artery segments with heavy calcification.[9,47,48] This fast-switching dual-kVp algorithm removes calcification. The first studies were done using ex vivo human heart specimens.[49] The technique is to use the 2 tube voltages, between 80 kVp and 140 kVp, in 1 gantry rotation, which gives different attenuation measurements based on 2 projections of data, allowing for removal of calcification from the coronary artery. The potential issue is that additional radiation is required; however, this method may be clinically useful to improve evaluation of older patients with high levels of coronary calcification. Clinical studies examining the utility of this technique to assess CAD are currently underway.

Physiological Assessment of Coronary Artery Disease (Perfusion, Fractional Flow Reserve Computed Tomography, and Transluminal Contrast Attenuation Gradient)

Several recent studies have demonstrated that CCTA can measure anatomical as well as hemodynamic significance of CAD. Because the severity of stenosis in CAD does not always equate to physiological significance, hemodynamic assessment by CCTA could be considered across a broad spectrum of clinical settings as additional information for symptomatic patients who have possible coronary stenosis.[50,51] There are 3 methods to evaluate physiological ischemia of CAD by CCTA to date: CT perfusion (CTP), transluminal contrast attenuation gradient (TAG), and fractional flow reserve CT (FFRCT).

Computed Tomography Perfusion: For a few decades, numerous studies demonstrated the accuracy of physiological assessment by myocardial perfusion single-photon emission computed tomography (SPECT) imaging (MPI) for subjects with suspected CAD,[52] which has been widely used in a clinical setting. By the same principle, CCTA recently allows the assessment of myocardial perfusion to identify the hemodynamic significance of coronary artery stenosis. Computed tomography perfusion was validated, with good results, in multiple studies comparing it with other diagnostic modalities including SPECT, ICA, or invasive FFR. A meta-analysis by Tashakkor et al included 5 studies with 132 patients comparing CTP to MPI with good sensitivity (87%) and NPV (83%) but not high specificity (69%) or PPV (72%), which leads to high false-positive rates with CTP.[53] Similarly, in the same meta-analysis with the 3 studies including 94 subjects compared with ICA, high sensitivity and NPV were demonstrated, but high specificity and PPV were not, a finding that is possibly explained by motion or beam-hardening artifacts.[53] Based on this meta-analysis, CTP alone does not have sufficiently high accuracy to identify physiological significance of CAD when compared with other modalities. The incremental value of combined CTP + CCTA to improve accuracy of anatomic and hemodynamic significance of CAD was investigated in multiple studies.[53] The recent Coronary Artery Evaluation Using 320-Row Multidetector CT Angiography (CORE320) study[54] was the first prospective multicenter study to investigate the incremental diagnostic value of CTP over CCTA compared with the combination of ICA and MPI, which are the gold standards to date for identifying anatomical and hemodynamic significance of CAD. This study enrolled 381 patients age 45 to 85 years, including 34% of subjects with a history of CAD. The authors demonstrated that the combination of CTP and CCTA provides the good diagnostic accuracy to predict hemodynamic significance of CAD among the whole cohort (area under the curve [AUC]: 0.87), patients without myocardial infarction (AUC: 0.90), and those without prior CAD (AUC: 0.93) when compared with diagnostic accuracy of ICA and MPI.[54] Computed tomography perfusion may also add the incremental diagnostic value of CCTA among patients with stents. Rief et al investigated 91 subjects who underwent PCI and stents in the CORE320 study.[55] They observed that CTP improved the diagnostic performance for detection of ISR and CAD (CCTA + CTP vs CCTA alone; 87% vs 71%, $P < 0.001$). The hemodynamic assessment could be a potential to improve diagnostic accuracy in particular among subjects with stents or heavily calcified coronary arteries. As a single noninvasive test, CCTA + CTP can be used for assessment of CAD stenosis and a guide for patient selection to undergo revascularization procedures. However, CTP requires both resting and stress scans, with additional radiation and contrast. In CORE320, there was an approximate 3× increase in the radiation dose of CCTA when combined with CTP (CCTA vs CTP vs CTP + CCTA; 3.16 vs 5.31 vs 9.32 mSv).[54]

Fractional Flow Reserve by Computed Tomography: Measurement of FFR by ICA is the gold-standard method for evaluating the hemodynamic significance of coronary artery stenosis that could cause ischemia. This can be done by measuring the blood flow proximal and distal to the stenosis during maximal hyperemia.[56] Recent advances in CT allow this noninvasive modality to measure FFR (FFRCT); FFRCT was calculated using computational fluid dynamics applied to CCTA images during rest and maximal hyperemic state.[57] In the Diagnosis of Ischemia-Causing Stenoses Obtained Via Noninvasive Fractional Flow Reserve (DISCOVER-FLOW) study, which was the first study to investigate novel computational fluid dynamics to noninvasively assess the physiological effect of coronary artery

Published online in Wiley Online Library (wileyonlinelibrary.com)
DOI:10.1002/clc.22286 © 2014 Wiley Periodicals, Inc.

lesions, FFR by ICA and FFRCT measurements were well correlated ($r = 0.717$, $P < 0.001$) with a slight underestimation by FFRCT.[57] In 103 patients, the accuracy by FFRCT was 84.3% to detect ischemia with FFR ≤0.80 and for CCTA alone was 58.5% to detect stenosis ≥50%. In per-vessel analysis, FFRCT improved 15% of accuracy to detect functionally significant CAD compared with anatomical stenosis severity with ≥50% (AUC for FFRCT vs CCTA: 0.90 vs 0.75, $P = 0.001$).[57] Subsequent to this study, in the larger, multicenter, prospective Determination of Fractional Flow Reserve by Anatomic Computed Tomographic Angiography (DeFACTO) study, with 252 patients with suspected or known CAD, FFRCT similarly improved diagnostic accuracy over CCTA, using invasive FFR ≤0.80 as a gold standard (CTA alone vs FFRCT: 0.68 vs 0.81, $P < 0.001$).[58] The FFRCT technique is still evolving, and each image requires a computationally complex 3 to 4 hours of time on an off-site supercomputer to solve equations describing fluid dynamics; yet the high sensitivity and NPV for this novel method that can combine anatomical and physiological assessment in 1 test, without additional medication, scans, radiation, or contrast, are quite promising. It allows identification of ischemic lesions with unprecedented accuracy as compared with other noninvasive modalities.

Transluminal Contrast Attenuation Gradient: Transluminal contrast attenuation gradient is another method that can be used for functional assessment of stenosis by determining the change in the contrast opacification (by measuring the reduction in HU) along coronary arteries; this reduction can occur faster in stenosed coronaries. Transluminal contrast attenuation gradient is defined as a linear-regression coefficient between luminal attenuation and axial distance from the coronary ostium.[59] Steigner et al first assessed TAG using 320-slice CCTA and found that gradients were linear and reproducible across 36 patients with normal coronary arteries.[59] Transluminal contrast attenuation gradient was not significantly different between 3 major coronary arteries used for calculation, but they noted that cardiac phases, heart rates, body mass index, and different readers might affect results. Using the same method, they also assessed 22 patients with ≥50% stenosis in the left anterior descending artery and found a significant difference in the gradient between normal and diseased coronaries.[59] Choi et al investigated TAG using 64-slice CCTA and found incremental value when added to CCTA in classification of CAD stenosis severity by ICA.[60] A few recent studies have demonstrated the correlation between TAG and invasive FFR to evaluate functional severity of CAD.[61,62] Wong et al was the first to investigate 320-slice CCTA in TAG measurements, observing good correlation between TAG-calculated and invasive FFR among 54 patients with stable chest pain.[61] In this study, a −15.1 HU/10 mm cutoff was found to predict FFR ≤0.8, with a bootstrapped sensitivity of 77% and specificity of 74%, PPV of 67%, and NPV of 86%. There was an incremental value to detect functionally significant coronary artery stenosis with improved AUC from 0.81 for TAG alone or 0.79 for CCTA alone to 0.89 for combined CCTA and TAG to predict significant FFR ≤0.8.[61] By contrast, Yoon et al investigated the relation of TAG to other functional assessment by invasive FFR and FFRCT among 65 patients who underwent 64-slice CCTA.[62] In this study, TAG did not provide incremental diagnostic value of CCTA to predict functional stenosis severity by invasive FFR (AUC for FFRCT: 0.94, compared with TAG: 0.63, $P < 0.001$, and CCTA stenosis: 0.73, $P < 0.001$).[62] Similar to FFRCT, this method does not require any additional scans, contrast, or radiation. In contrast to FFRCT, only simple measurements of HU are required for TAG in coronary arteries, without an off-site computation.

Conclusion

Coronary computed tomography angiography has been a reliable noninvasive imaging test that can substantially contribute to the assessment of CAD with high diagnostic accuracy, guiding clinical decisions in patients with low to intermediate pretest likelihood of CAD. Coronary computed tomography angiography has excellent results in assessment of native coronary arteries and CABG. The recent development in CT techniques allows it to evaluate challenging cases, such as coronary artery stents of smaller diameter, with improved diagnostic accuracy. New methods have been developing and require further investigation to assess coronary arteries with heavily calcifications. Finally, the ability to combine anatomical and physiological cardiac evaluation in a single examination is a promising new technique that can provide further optimization for the assessment of patients with suspected or known CAD.

References

1. Budoff MJ, Dowe D, Jollis JG, et al. 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;52:1724–1732.
2. Miller JM, Rochitte CE, Dewey M, et al. Diagnostic performance of coronary angiography by 64-row CT. *N Engl J Med*. 2008;359: 2324–2336.
3. Meijboom WB, Meijs MF, Schuijf JD, et al. Diagnostic accuracy of 64-slice computed tomography coronary angiography: a prospective, multicenter, multivendor study. *J Am Coll Cardiol*. 2008;52:2135–2144.
4. Montalescot G, Sechtem U, Achenbach S, et al. 2013 ESC guidelines on the management of stable coronary artery disease: the Task Force on the Management of Stable Coronary Artery Disease of the European Society of Cardiology. *Eur Heart J*. 2013;34:2949–3003.
5. Wolk MJ, Bailey SR, Doherty JU, et al. ACCF/AHA/ASE/ASNC/HFSA/HRS/SCAI/SCCT/SCMR/STS 2013 Multimodality Appropriate Use Criteria for the Detection and Risk Assessment of Stable Ischemic Heart Disease: a Report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, American Heart Association, American Society of Echocardiography, American Society of Nuclear Cardiology, Heart Failure Society of America, Heart Rhythm Society, Society for Cardiovascular Angiography and Interventions, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, and Society of Thoracic Surgeons. *J Am Coll Cardiol*. 2014;63:380–406.
6. Flohr TG, McCollough CH, Bruder H, et al. First performance evaluation of a dual-source CT (DSCT) system [published correction appears in *Eur Radiol*. 2006;16:1405]. *Eur Radiol*. 2006;16:256–268.
7. Guo SL, Guo YM, Zhai YN, et al. Diagnostic accuracy of first-generation dual-source computed tomography in the assessment of coronary artery disease: a meta-analysis from 24 studies. *Int J Cardiovasc Imaging*. 2011;27:755–771.

Published online in Wiley Online Library (wileyonlinelibrary.com)
DOI:10.1002/clc.22286

© 2014 Wiley Periodicals, Inc.

8. Ropers U, Ropers D, Pflederer T, et al. Influence of heart rate on the diagnostic accuracy of dual-source computed tomography coronary angiography. *J Am Coll Cardiol*. 2007;50:2393–2398.
9. Hsiao EM, Rybicki FJ, Steigner M. CT coronary angiography: 256-slice and 320-detector row scanners. *Curr Cardiol Rep*. 2010;12:68–75.
10. Pelliccia F, Pasceri V, Evangelista A, et al. Diagnostic accuracy of 320-row computed tomography as compared with invasive coronary angiography in unselected, consecutive patients with suspected coronary artery disease. *Int J Cardiovasc Imaging*. 2013;29:443–452.
11. de Graaf FR, Schuijf JD, van Velzen JE, et al. Diagnostic accuracy of 320-row multidetector computed tomography coronary angiography in the non-invasive evaluation of significant coronary artery disease. *Eur Heart J*. 2010;31:1908–1915.
12. Dewey M, Zimmermann E, Deissenrieder F, et al. Noninvasive coronary angiography by 320-row computed tomography with lower radiation exposure and maintained diagnostic accuracy: comparison of results with cardiac catheterization in a head-to-head pilot investigation. *Circulation*. 2009;120:867–875.
13. Nasis A, Leung MC, Antonis PR, et al. Diagnostic accuracy of noninvasive coronary angiography with 320-detector row computed tomography. *Am J Cardiol*. 2010;106:1429–1435.
14. van Velzen JE, de Graaf FR, Kroft LJ, et al. Performance and efficacy of 320-row computed tomography coronary angiography in patients presenting with acute chest pain: results from a clinical registry. *Int J Cardiovasc Imaging*. 2012;28:865–876.
15. Klass O, Walker M, Siebach A, et al. Prospectively gated axial CT coronary angiography: comparison of image quality and effective radiation dose between 64- and 256-slice CT. *Eur Radiol*. 2010;20:1124–1131.
16. Khan A, Khosa F, Nasir K, et al. Comparison of radiation dose and image quality: 320-MDCT versus 64-MDCT coronary angiography. *AJR Am J Roentgenol*. 2011;197:163–168.
17. Chao SP, Law WY, Kuo CJ, et al. The diagnostic accuracy of 256-row computed tomographic angiography compared with invasive coronary angiography in patients with suspected coronary artery disease. *Eur Heart J*. 2010;31:1916–1923.
18. Mark DB, Berman DS, Budoff MJ, et al; American College of Cardiology Foundation Task Force on Expert Consensus Documents. ACCF/ACR/AHA/NASCI/SAIP/SCAI/SCCT 2010 expert consensus document on coronary computed tomographic angiography: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. *Circulation*. 2010;121:2509–2543.
19. Andreini D, Pontone G, Mushtaq S, et al. Multidetector computed tomography coronary angiography for the assessment of coronary in-stent restenosis. *Am J Cardiol*. 2010;105:645–655.
20. Sun Z, Almutairi AM. Diagnostic accuracy of 64 multislice CT angiography in the assessment of coronary in-stent restenosis: a meta-analysis. *Eur J Radiol*. 2010;73:266–273.
21. Andreini D, Pontone G, Bartorelli AL, et al. Comparison of feasibility and diagnostic accuracy of 64-slice multidetector computed tomographic coronary angiography versus invasive coronary angiography versus intravascular ultrasound for evaluation of in-stent restenosis. *Am J Cardiol*. 2009;103:1349–1358.
22. Kefer JM, Coche E, Vanoverschelde JL, et al. Diagnostic accuracy of 16-slice multidetector-row CT for detection of in-stent restenosis vs detection of stenosis in nonstented coronary arteries. *Eur Radiol*. 2007;17:87–96.
23. Rixe J, Achenbach S, Ropers D, et al. Assessment of coronary artery stent restenosis by 64-slice multi-detector computed tomography. *Eur Heart J*. 2006;27:2567–2572.
24. Carbone I, Francone M, Algeri E, et al. Non-invasive evaluation of coronary artery stent patency with retrospectively ECG-gated 64-slice CT angiography. *Eur Radiol*. 2008;18:234–243.
25. Taylor AJ, Cerqueira M, Hodgson JM, et al. ACCF/SCCT/ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR 2010 Appropriate Use Criteria for Cardiac Computed Tomography: a Report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, the Society of Cardiovascular Computed Tomography, the American College of Radiology, the American Heart Association, the American Society of Echocardiography, the American Society of Nuclear Cardiology, the North American Society for Cardiovascular Imaging, the Society for Cardiovascular Angiography and Interventions, and the Society for Cardiovascular Magnetic Resonance. *J Cardiovasc Comput Tomogr*. 2010;4:407.e1–407.e33.
26. Abdelkarim MJ, Ahmadi N, Gopal A, et al. Noninvasive quantitative evaluation of coronary artery stent patency using 64-row multidetector computed tomography. *J Cardiovasc Comput Tomogr*. 2010;4:29–37.
27. Kazakauskaite E, Husmann L, Stehli J, et al. Image quality in low-dose coronary computed tomography angiography with a new high-definition CT scanner. *Int J Cardiovasc Imaging*. 2013;29:471–477.
28. Gebhard C, Fiechter M, Fuchs TA, et al. Coronary artery stents: influence of adaptive statistical iterative reconstruction on image quality using 64-HDCT. *Eur Heart J Cardiovasc Imaging*. 2013;14:969–977.
29. Tanami Y, Jinzaki M, Yamada M, et al. Improvement of in-stent lumen measurement accuracy with new high-definition CT in a phantom model: comparison with conventional 64-detector row CT. *Int J Cardiovasc Imaging*. 2012;28:337–342.
30. Yang WJ, Zhang H, Xiao H, et al. High-definition computed tomography for coronary artery stents imaging compared with standard-definition 64-row multidectector computed tomography: an initial in vivo study. *J Comput Assist Tomogr*. 2012;36:295–300.
31. Min JK, Swaminathan RV, Vass M, et al. High-definition multidetector computed tomography for evaluation of coronary artery stents: comparison to standard-definition 64-detector row computed tomography. *J Cardiovasc Comput Tomogr*. 2009;3:246–251.
32. Andreini D, Pontone G, Mushtaq S, et al. Coronary in-stent restenosis: assessment with CT coronary angiography. *Radiology*. 2012;265:410–417.
33. Fuchs TA, Stehli J, Fiechter M, et al. First in vivo head-to-head comparison of high-definition versus standard-definition stent imaging with 64-slice computed tomography. *Int J Cardiovasc Imaging*. 2013;29:1409–1416.
34. Chiurlia E, Menozzi M, Ratti C, et al. Follow-up of coronary artery bypass graft patency by multislice computed tomography. *Am J Cardiol*. 2005;95:1094–1097.
35. Schlosser T, Konorza T, Hunold P, et al. Noninvasive visualization of coronary artery bypass grafts using 16-detector row computed tomography. *J Am Coll Cardiol.* 2004;44:1224–1229.
36. Hamon M, Lepage O, Malagutti P, et al. Diagnostic performance of 16- and 64-section spiral CT for coronary artery bypass graft assessment: meta-analysis. *Radiology*. 2008;247:679–686.
37. Bourassa MG, Fisher LD, Campeau L, et al. Long-term fate of bypass grafts: the Coronary Artery Surgery Study (CASS) and Montreal Heart Institute experiences. *Circulation*. 1985;72:V71–V78.
38. Jabara R, Chronos N, Klein L, et al. Comparison of multidetector 64-slice computed tomographic angiography to coronary angiography to assess the patency of coronary artery bypass grafts. *Am J Cardiol*. 2007;99:1529–1534.
39. Pache G, Saueressig U, Frydrychowicz A, et al. Initial experience with 64-slice cardiac CT: non-invasive visualization of coronary artery bypass grafts. *Eur Heart J*. 2006;27:976–980.
40. Kruk M, Noll D, Achenbach S, et al. Impact of coronary artery calcium characteristics on accuracy of CT angiography. *JACC Cardiovasc Imaging*. 2014;7:49–58.
41. Budoff MJ, Shaw LJ, Liu ST, et al. Long-term prognosis associated with coronary calcification: observations from a registry of 25 253 patients. *J Am Coll Cardiol*. 2007;49:1860–1870.
42. Budoff MJ, Nasir K, McClelland RL, et al. Coronary calcium predicts events better with absolute calcium scores than age-sex-race/ethnicity percentiles: MESA (Multi-Ethnic Study of Atherosclerosis). *J Am Coll Cardiol*. 2009;53:345–352.
43. Palumbo AA, Maffei E, Martini C, et al. 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.
44. Taylor AJ, Cerqueira M, Hodgson JM, et al. ACCF/SCCT/ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR 2010 Appropriate Use Criteria for Cardiac Computed Tomography: a Report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, the Society of Cardiovascular Computed

Published online in Wiley Online Library (wileyonlinelibrary.com)
DOI:10.1002/clc.22286 © 2014 Wiley Periodicals, Inc.

Tomography, the American College of Radiology, the American Heart Association, the American Society of Echocardiography, the American Society of Nuclear Cardiology, the North American Society for Cardiovascular Imaging, the Society for Cardiovascular Angiography and Interventions, and the Society for Cardiovascular Magnetic Resonance. *Circulation*. 2010;122:e525–e555.
45. Arbab-Zadeh A, Miller JM, Rochitte CE, et al. Diagnostic accuracy of computed tomography coronary angiography according to pre-test probability of coronary artery disease and severity of coronary arterial calcification: the CORE-64 (Coronary Artery Evaluation Using 64-Row Multidetector Computed Tomography Angiography) International Multicenter Study. *J Am Coll Cardiol*. 2012;59:379–387.
46. Abdulla J, Pedersen KS, Budoff M, et al. 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.
47. Yoshioka K, Tanaka R, Muranaka K. Subtraction coronary CT angiography for calcified lesions. *Cardiol Clin*. 2012;30:93–102.
48. Tanaka R, Yoshioka K, Muranaka K, et al. Improved evaluation of calcified segments on coronary CT angiography: a feasibility study of coronary calcium subtraction. *Int J Cardiovasc Imaging*. 2013;(29 suppl 2):75–81.
49. Yamada M, Jinzaki M, Imai Y, et al. Evaluation of severely calcified coronary artery using fast-switching dual-kVp 64-slice computed tomography. *Circ J*. 2011;75:472–473.
50. Meijboom WB, Van Mieghem CA, van Pelt N, et al. Comprehensive assessment of coronary artery stenoses: computed tomography coronary angiography versus conventional coronary angiography and correlation with fractional flow reserve in patients with stable angina. *J Am Coll Cardiol*. 2008;52:636–643.
51. Tamarappoo BK, Gutstein A, Cheng VY, et al. Assessment of the relationship between stenosis severity and distribution of coronary artery stenoses on multislice computed tomographic angiography and myocardial ischemia detected by single photon emission computed tomography. *J Nucl Cardiol*. 2010;17:791–802.
52. Beller GA, Zaret BL. Contributions of nuclear cardiology to diagnosis and prognosis of patients with coronary artery disease. *Circulation*. 2000;101:1465–1478.
53. Tashakkor AY, Nicolaou S, Leipsic J, et al. The emerging role of cardiac computed tomography for the assessment of coronary perfusion: a systematic review and meta-analysis. *Can J Cardiol*. 2012;28:413–422.
54. Rochitte CE, George RT, Chen MY, et al. Computed tomography angiography and perfusion to assess coronary artery stenosis causing perfusion defects by single photon emission computed tomography: the CORE320 study. *Eur Heart J*. 2013; doi:10.1093/eurheartj/eht488.
55. Rief M, Zimmermann E, Stenzel F, et al. Computed tomography angiography and myocardial computed tomography perfusion in patients with coronary stents: prospective intraindividual comparison with conventional coronary angiography. *J Am Coll Cardiol*. 2013;62:1476–1485.
56. Kern MJ, Samady H. Current concepts of integrated coronary physiology in the catheterization laboratory. *J Am Coll Cardiol*. 2010;55:173–185.
57. Koo BK, Erglis A, Doh JH, et al. Diagnosis of ischemia-causing coronary stenoses by noninvasive fractional flow reserve computed from coronary computed tomographic angiograms: results from the prospective multicenter DISCOVER-FLOW (Diagnosis of Ischemia-Causing Stenoses Obtained Via Noninvasive Fractional Flow Reserve) study. *J Am Coll Cardiol*. 2011;58:1989–1997.
58. Min JK, Leipsic J, Pencina MJ, et al. Diagnostic accuracy of fractional flow reserve from anatomic CT angiography. *JAMA*. 2012;308:1237–1245.
59. Steigner ML, Mitsouras D, Whitmore AG, et al. Iodinated contrast opacification gradients in normal coronary arteries imaged with prospectively ECG-gated single heart beat 320-detector row computed tomography. *Circ Cardiovasc Imaging*. 2010;3:179–186.
60. Choi JH, Min JK, Labounty TM, et al. Intracoronary transluminal attenuation gradient in coronary CT angiography for determining coronary artery stenosis [published correction appears in *JACC Cardiovasc Imaging*. 2012;5:129]. *JACC Cardiovasc Imaging*. 2011;4:1149–1157.
61. Wong DT, Ko BS, Cameron JD, et al. Transluminal attenuation gradient in coronary computed tomography angiography is a novel noninvasive approach to the identification of functionally significant coronary artery stenosis: a comparison with fractional flow reserve. *J Am Coll Cardiol*. 2013;61:1271–1279.
62. Yoon YE, Choi JH, Kim JH, et al. Noninvasive diagnosis of ischemia-causing coronary stenosis using CT angiography: diagnostic value of transluminal attenuation gradient and fractional flow reserve computed from coronary CT angiography compared to invasively measured fractional flow reserve. *JACC Cardiovasc Imaging*. 2012;5:1088–1096.