The 'what, when, where, who and how?' of cardiac computed tomography in 2009: Guidelines for the clinician

Primary Panel: Benjamin JW Chow MD FRCPC FACC FASNC (Chair)[1,2], Eric Larose DVM MD FRCPC FAHA[3], Sylvie Bilodeau MD FRCPC[3]; Mary Lou Ellins MD FRCPC[4], Paul Galiwango MD FRCPC[5], Malek Kass MD FRCPC[1], Tej Sheth MD FRCPC[6]

Secondary Panel: Davinder S Jassal MD FRCPC[7,8], Iain DC Kirkpatrick MD FRCPC[8], GB John Mancini MD FRCPC[9], John Mayo MD FRCPC[10], Arun Abraham MBBS FRACP[1], James White MD FRCPC[11]

WHAT IS CARDIAC COMPUTED TOMOGRAPHY?

Diagnostic medical imaging has undergone a dramatic evolution over the past decade, owing to rapid technological advancement and innovative clinical applications. Newer diagnostic imaging technologies, particularly cardiac computed tomography (CT), are rapidly being adopted in Canada for the noninvasive diagnosis of obstructive coronary artery disease (CAD). Marked improvements in both temporal and spatial resolution have allowed recent-generation CT scanners to acquire high-quality, noninvasive angiography of the coronary vasculature. Despite demonstration of high accuracy for the exclusion of obstructive CAD, data supporting its widespread use in clinical practice are limited. In addition, the potential impact on health care resources and economics is unknown (1).

The appropriate use of cardiac CT has the potential to improve cardiovascular care. With this goal in mind, a working group of cardiologists and radiologists with expertise in cardiac imaging and cardiac CT prepared the present document to highlight the current potential utility and appropriate applications for cardiac CT in Canada in 2009. While we recognize that the American Colleges of Cardiology and Radiology recently published joint appropriateness guidelines (2), the present manuscript expands on the current limitations of CT with the goal of improving patient selection and patient preparation to increase the usefulness of this technique in Canada.

WHEN IS CARDIAC CT INDICATED?

The clinical indications for cardiac CT continue to evolve and those outlined in the present document are deemed 'acceptable' based on expert consensus and current literature (Table 1). Although other clinical indications may be acceptable, they should be assessed on a 'case-by-case' basis through dialogue between the referring physician and the cardiovascular imaging specialist.

Symptomatic patients

According to Bayes' theorem, patients with an intermediate pretest probability for a disease or condition are likely to benefit the most from diagnostic investigations (3). The use of cardiac CT and CT coronary angiography (CTA) for the exclusion of obstructive CAD (greater than 50% diameter stenosis) is therefore best applied in symptomatic patients with an intermediate pretest probability for CAD. It would also be appropriate in patients in whom an equivocal stress test result (noninterpretable or nondiagnostic test, or results discrepant from clinical suspicion) has led to uncertainty regarding the patient's diagnosis or cardiovascular risk.

Patients with a high pretest probability for CAD or those with known CAD are more likely to benefit from well-established diagnostic imaging modalities with therapeutic or prognostic value. Such patients should be routinely considered for invasive coronary angiography or for functional imaging. However, CTA may be acceptable in patients reluctant to undergo invasive angiography or functional imaging, especially when CTA results are likely to influence therapeutic decisions.

Additionally, CTA has been shown to accurately assess the patency and location of previous coronary artery bypass grafts (4). However, it is important to recognize the potential limitation of evaluating native coronary vasculature in patients with bypass grafts because they are more likely to have severe coronary calcification and diffuse disease.

Patients with a low pretest probability for CAD may be considered for cardiac CT and CTA evaluation in the setting of a presurgical evaluation for cardiac surgery (eg, valve surgery) or for the exclusion of CAD as a cause for dilated cardiomyopathy of unknown etiology. Given the high negative predictive value for obstructive CAD (2,3), CT may be an appropriate noninvasive alternative to invasive coronary angiography in these clinical settings.

[1]*Department of Medicine (Cardiology), University of Ottawa Heart Institute;* [2]*Department of Radiology, Ottawa Hospital, University of Ottawa, Ottawa, Ontario;* [3]*Multidisciplinary Department of Cardiology and Department of Medical Imaging, Québec Heart and Lung Institute, Laval Hospital, Laval University Medical School, Sainte-Foy, Québec;* [4]*Department of Radiology, Hamilton Health Sciences, McMaster University, Hamilton;* [5]*Department of Internal Medicine (Cardiology), Rouge Valley Health Centre, Toronto;* [6]*Department of Medicine (Cardiology), Hamilton Health Sciences, McMaster University, Hamilton, Ontario;* [7]*Department of Internal Medicine (Cardiology);* [8]*Department of Radiology, St Boniface General Hospital, University of Manitoba, Winnipeg, Manitoba;* [9]*Department of Medicine, Vancouver Hospital and Health Sciences Centre, University of British Columbia;* [10]*Department of Radiology, Vancouver General Hospital, University of British Columbia, Vancouver, British Columbia;* [11]*Department of Medicine (Cardiology), London Health Sciences Centre, University of Western Ontario, London, Ontario*

Correspondence: Dr Benjamin JW Chow, University of Ottawa Heart Institute, 40 Ruskin Street, Ottawa, Ontario K1Y 4W7. Telephone 613-761-4044, fax 613-761-4929, e-mail bchow@ottawaheart.ca

Received for publication January 15, 2009. Accepted January 18, 2009

TABLE 1
Cardiac computed tomography: Indications

Recommendations
Diagnosis of obstructive CAD in symptomatic patients with an intermediate pretest likelihood of CAD, or symptomatic patients with equivocal or inconclusive stress test results
Assessment of patency or course of coronary bypass grafts
Exclusion of obstructive CAD in low-risk patients who require invasive coronary angiography
Identification or definition of the course of anomalous coronary arteries
Assessment of left or right ventricular size, volume and function when alternative imaging modalities are unavailable or inconclusive
Assessment of pulmonary venous anatomy before and after pulmonary vein isolation for atrial fibrillation
Assessment of coronary venous anatomy before cardiac resynchronization therapy
Assessment of cardiac and extracardiac structures (eg, aorta, pericardium and cardiac masses)

CAD Coronary artery disease

TABLE 2
Cardiac computed tomography: Contraindications

Recommendations
Uncontrolled rapid heart rate or frequent atrial or ventricular ectopy, or irregular heart rate*
Inability to perform breathhold or remain motionless for 15 s to 20 s
Routine screening in asymptomatic patients
Patients with a high pretest probability of coronary artery disease or high-risk acute coronary syndrome patients
Presence of coronary stents (especially those less than 3.5 mm in diameter)
Contraindications to radiation exposure (eg, pregnancy)
Contraindications to contrast media (eg, renal disease, dye allergy)

**Based on currently acceptable technology. This may change with future advancements*

Congenital coronary anomalies

Although cardiac magnetic resonance imaging (MRI) can offer sufficient image quality for the evaluation of most congenital coronary abnormalities, CTA is more widely available, and can accurately serve to characterize and delineate the course of coronary artery anomalies and fistulae (5,6). Its use for the evaluation of known or suspected congenital abnormalities of the coronary tree is therefore considered appropriate.

Ventricular function

Experience with the imaging of noncoronary structures with cardiac CT continues to expand as the technology becomes embraced and new applications are explored. Preliminary studies have demonstrated that left and right ventricular volumes measured by CT correlate well with other established modalities (7). However, at the present time, given the limited temporal resolution of cardiac CT and the associated radiation exposure, cardiac CT cannot be recommended as a preferred method for measuring ventricular volumes and ejection fraction if alternative modalities are readily available.

Electrophysiology applications

The imaging of pulmonary and coronary venous anatomy is now important for the preprocedural planning of newer specialized cardiac interventions such as pulmonary vein isolation for atrial fibrillation and cardiac resynchronization therapy for medically refractory heart failure. Cardiac CT has the ability to characterize the architecture and spatial orientation of the pulmonary veins for the performance of image-assisted radiofrequency ablation. The assessment of the coronary venous tree also has the potential to assist in the planning of pacemaker lead delivery for the performance of cardiac resynchronization; however, the impact of this evaluation on clinical care and outcomes has yet to be explored (8-10).

Other applications

Cardiac CT may be used to evaluate a wide range of other noncoronary cardiovascular diseases, inclusive of acquired and congenital valve disease, complex congenital heart disease, cardiac masses, pericardial disease and diseases of the thoracic aorta. These applications have not been systematically evaluated in large clinical series but remain potentially appropriate indications when conventional modalities are unavailable, nondiagnostic or contraindicated.

Coronary artery calcification

Controlling for age, sex, ethnicity and cardiac risk factors, coronary artery calcification (CAC) is an independent predictor of all-cause mortality (11). Recognizing that coronary calcium scoring has prognostic value for the determination of cardiovascular risk, it may be of value in asymptomatic individuals at intermediate cardiovascular risk (11,12). Patients with Agatson scores greater than 400 and greater than 1000 have a mortality rate higher than 6% and higher than 12%, respectively, at 10 years (11). However, in the absence of data demonstrating that further risk stratification with CAC is cost effective or can improve patient morbidity or mortality, CAC is recommended only for patients in whom the results are likely to influence clinical decision-making. CAC scoring is unlikely to be incrementally beneficial in patients at low and high risk for future cardiovascular events.

Acute chest pain syndromes

Cardiac CT may have a role in triaging patients with acute chest pain syndromes. Cardiac CT may result in modestly lower costs and a shorter length of stay for some 'low-risk' patients presenting to the emergency room with chest pain (13,14), and CT may yield an alternate noncardiac diagnosis. However, several potential limitations exist that may reduce its general applicability. Although CTA may identify obstructive CAD, it cannot readily differentiate between acute coronary syndrome (ACS) and chronic stable CAD. Similarly, indiscriminate use of the 'triple rule-out' protocol (protocol used to rule out pulmonary embolism, CAD and aortic dissection) in lieu of clinical acumen exposes the patient to a potentially high radiation dose and increased contrast volume, and may compromise optimal contrast enhancement. Also, its impact on local workflow and resource allocation may limit its routine use.

WHEN IS CARDIAC CT CONTRAINDICATED?

Several modifiable factors limit study interpretation and, thus, should be optimized before a cardiac CT study is performed. Patients should be screened for factors that might limit the diagnostic accuracy or safety of a cardiac CT, thereby prompting consideration of an alternate test (Table 2).

Uncontrolled heart rate

Although the temporal resolution of CT has dramatically improved in recent years, CT scanners using a single x-ray source (temporal resolution: 165 ms to 220 ms) fall short relative to echocardiography, MRI and fluoroscopy (15). To compensate for this limitation, heart rate (HR) control is crucial for optimal acquisition of cardiac CT images. Resting HRs of more than 65 beats/min can often result in suboptimal image quality. Although different reconstruction algorithms may be used to compensate for faster HRs, slower HRs (fewer than 60 beats/min) typically yield better images. Patients who have uncontrolled rapid HRs should not be routinely imaged by single-source cardiac CT.

Irregular cardiac rhythm

Multiple image sets taken over several heartbeats are required to obtain a full data set with 64-slice CT scanners. Consequently, optimal image quality is dependent on a regular slow heart rhythm. Irregular heart rhythms (atrial fibrillation, frequent atrial or ventricular ectopy) are likely to cause significant misregistration (stair-step) artifacts. Newer scanners with a larger coverage and/or improved temporal resolution may help ameliorate these problems. Patients with frequent atrial or ventricular ectopy, or irregular HRs (atrial fibrillation) should not routinely undergo CTA with existing 64-slice CT scanners.

Severe coronary calcification

Severe coronary calcification can result in significant beam-hardening artifacts, thus limiting diagnostic accuracy. Decisions regarding the performance of CTA in these patients should be made after careful review of the amount and distribution of coronary calcium on the images acquired for coronary calcium scoring. Patients with known severe coronary calcification should not undergo cardiac CT to exclude CAD if an alternative imaging modality is available.

Asymptomatic patients

Cardiac CTA should not be used as a routine screening modality to detect calcific and noncalcific atherosclerosis in individuals lacking signs or symptoms suggestive of obstructive CAD. Assessment of coronary atherosclerosis has prognostic value but there is limited evidence supporting the treatment of asymptomatic, nonocclusive CAD. Because the screening of asymptomatic patients with CTA may be costly and may expose a large number of individuals to unwarranted ionizing radiation, it cannot be recommended (16).

The recently published Clinical Outcomes Utilizing Revascularization and Aggressive Drug Evaluation (COURAGE) trial (17) demonstrated that in the absence of high-risk anatomy, optimal medical therapy and percutaneous coronary intervention appear to be equivalent. Conversely, patients with high-risk coronary anatomy are more likely to benefit from coronary revascularization (18). There are very limited data supporting the use of cardiac CT to guide revascularization strategies (19). Patients who have test results consistent with high-risk CAD or uncontrolled symptoms are more likely to benefit from invasive coronary angiography. CTA may be considered in situations when optimal medical therapy is preferred.

Anatomical versus functional imaging

With further advancements and experience, cardiac CT may be used to characterize the severity of noncalcified coronary anatomy in symptomatic patients. However, its high negative predictive value suggests that it may currently be best used only as a 'rule-out' test (1,20,21). It is also widely acknowledged that there are limitations to anatomical imaging and that there is often a large disparity between an anatomical stenosis and the functional significance, particularly in lesions with 40% to 80% diameter stenosis. Although it is accepted that lesions with 70% or greater diameter stenosis are more likely to be hemodynamically significant, moderate lesions may require further functional assessment, including myocardial perfusion imaging, echocardiography, cardiac MRI and/or fractional flow reserve.

ACS

The 'early invasive' strategy has been adopted by many centres with immediate access to invasive coronary angiography. Although cardiac CT may provide coronary anatomy, there are limited data supporting its use for risk-stratifying patients presenting with high-risk ACS (abnormal biomarkers or dynamic electrocardiogram [ECG] changes).

Coronary stents

Noncalcific high-density structures may result in significant artifacts, rendering image interpretation difficult. Stents are subject to these artifacts and the detection of stent patency can be difficult, particularly with stents that are less than 3.0 mm in diameter. Studies have shown that a significant proportion (up to 42%) of stents are nonevaluable and the assessment for instent restenosis remains poor (22). Larger stents (greater than 3.5 mm in diameter), including left main stents, can be assessed more accurately (23-25).

Other contraindications

Patients with contraindications to contrast media (ie, significant renal impairment, dye allergy) or radiation exposure (eg, pregnancy) should have the risks and benefits of the test weighed. If an equally weighted alternative imaging test is available, and is of potentially equal diagnostic value, cardiac CT should not be performed.

Radiation risk

Cardiac CT can be performed with retrospective or prospective ECG gating. With retrospective gating, the estimated radiation dose for CTA examination is 10 mSv to 15 mSv (26). With prospective gating, the estimated radiation dose for calcium scoring is 0.5 mSv to 1.8 mSv (27). The radiation exposure with retrospective gating is greater than many other forms of medical imaging but similar to that of single positron emission tomography imaging (9.2 mSv to 14.8 mSv [technetium-99m] and 15.7 mSv to 18.9 mSv [thallium-201]) (28). Retrospectively ECG-gated CTA can reduce radiation dose through the use of ECG-gated 'tube modulation'. This feature reduces the x-ray tube output during portions of the cardiac cycle that are less commonly used to assess the coronary arteries. Using ECG-gated tube modulation can result in a dose reduction of approximately 35% to 45% (28,29).

Prospectively ECG-gated CTA is a relatively new technique that is now available on all major CT vendor platforms. With this technique, radiation is only used during a specific phase of the cardiac cycle. The duration of this window can be adjusted, thereby reducing radiation dose on a case-by-case basis (30). In general, the radiation dose for prospectively gated CTA is dramatically reduced to a mean dose of 2.4 mSv to 4.2 mSv (31-35). Radiation doses in this range are lower than invasive angiography, with doses quoted in the literature widely varied (between 2.3 mSv and 22.7 mSv) (27); the United Nations Scientific Committee on Effects of Atomic Radiation cites a value of approximately 7 mSv (36,37).

Initial comparisons of prospectively gated CTA with retrospectively gated cardiac CTA suggest that diagnostic accuracy is maintained. Because prospectively gated CTA does not acquire images throughout the cardiac cycle, information about ventricular function is sacrificed. However, adoption of this approach will substantially reduce concerns regarding the radiation dose used for cardiac CT. Because this technique is currently restricted to certain patient characteristics (controlled HRs, regular rhythms, no ectopic beats), it may not be applicable to all patients. Avoiding unnecessary radiation exposure and minimizing each patient's cumulative radiation exposure is of utmost importance. Annual radiation exposure (from background radiation) is approximately 3.0 mSv (38). Estimates of cancer risk from retrospectively gated CTA have been developed through statistical modelling approaches based primarily on the radiation-related health risks of atomic bomb survivors. These analyses suggest that a single retrospectively gated CTA scan, like any other study using ionizing radiation, affects the subsequent risk of thoracic malignancy (lung and breast cancer). This effect varies significantly by age and sex. For example, the lifetime attributable risk of breast cancer after a CTA study without dose modulation was estimated to be 0.70% in 20-year-old women compared with 0.075% in 80-year-old women (39). Retrospectively gated CTA should therefore be used selectively, taking into account dose considerations, patient age and sex (40). The high radiation dose should limit the use of retrospectively gated CTA for repeat assessments and for the evaluation of asymptomatic individuals (41).

WHO SHOULD REQUEST A CARDIAC CT?

Patient referral

As with other imaging modalities, cardiac CT has important limitations and should not be used indiscriminately. The impact of providing knowledge of a patient's coronary anatomy to clinicians inexperienced with evaluating its clinical relevance is an important consideration. Therefore, cardiac CT should be available to clinicians who understand the risks and benefits of cardiac CT, can recognize risks and benefits of alternative imaging modalities and are able to use the results to positively direct patient management.

WHERE SHOULD WE REFER OUR PATIENTS?

Cardiac CT centres

As this technology spreads across Canada, numerous institutions will be able to perform cardiac CT. Similarly, an increasing number of referring physicians will have access to this new imaging modality. Cardiac CT is likely best performed at centres with adequate experience, expertise and cardiac CT volumes. There is concern that inappropriate use will adversely affect patient care or unnecessarily increase the cost of health care. Reflecting this, until further data are available, cardiac CT has not been uniformly accepted by all provincial governments in Canada.

HOW SHOULD WE PREPARE OUR PATIENTS?

There are many unmodifiable factors that may affect image quality and diagnostic accuracy in patients undergoing cardiac CT. Given the current temporal resolution of single-source CT scanners, bradycardia is paramount. Although several reconstruction algorithms are available, single-segment reconstruction is preferred and is best performed in patients with an HR of less than 60 beats/min. In the absence of contraindications, referring physicians should initiate the administration of HR-lowering agents (beta-blockers) for a target HR of less than 65 beats/min. Contraindications to beta-blockers should be clearly stated on the requisition form.

Although the spatial resolution of CT is excellent, diagnostic accuracy is reduced when assessing very small structures (less than 0.4 mm to 0.5 mm in diameter). To facilitate visualization of the entire coronary anatomy, sublingual nitroglycerin is often administered. All erectile dysfunction medications should be withheld 24 h to 72 h before the CT. Contraindications to sublingual nitroglycerin should be clearly stated on the requisition form (eg, severe aortic stenosis, hypertrophic obstructive cardiomyopathy).

Irregular heart rhythms (atrial fibrillation, frequent extrasystoles) may adversely affect image quality. For patients with irregular rhythms, an ECG should be performed and reviewed.

Intravenous contrast is required to opacify the cardiac and vascular structures; therefore, contraindications to contrast agents should be identified. Contrast allergies and contrast-induced nephropathy may be of concern. A serum creatinine test should be performed to identify patients with decreased glomerular filtration rates. Patients with impaired renal function should understand the risks and benefits of the procedure before being referred for contrast-enhanced CT. In cases where the potential benefits of cardiac CT outweigh its potential risks, standard preparation protocols to minimize renal impairment or allergic reactions to contrast material are warranted.

To eliminate respiratory motion artifact, image acquisition is performed during a breathhold of 15 s. During a breathhold, severely dyspneic patients may experience a rise in HR. Patients should be able to hold their breath for more than 15 s to 20 s without a significant rise in HR. Patients unable to perform an adequate breathhold should not have a cardiac CT. Simple breathhold training before scanning may be useful.

CONCLUSION

Advances in diagnostic imaging technology and an eagerness to embrace noninvasive imaging strategies for coronary angiography continue to drive interest and expansion in cardiac CT within Canada. Further advancements will improve accuracy and reduce the risks associated with cardiac CT, thus widening its clinical acceptance. We anticipate that, with careful attention to appropriate patient selection and further validation of its clinical usefulness in discrete patient populations, this modality will become an important component of the cardiovascular standard of care during the coming years.

DISCLOSURES: Benjamin Chow is supported by the Canadian Institutes of Health Research New Investigator Award #MSH-83718. He receives research and fellowship support from GE Healthcare, and education support from TeraRecon, Inc. Arun Abraham is supported by the Heather and Whit Tucker Research Fellowship in Cardiology. The remaining authors have no conflicts of interest to disclose.

REFERENCES

1. Stein PD, Yaekoub AY, Matta F, Sostman HD. 64-slice CT for diagnosis of coronary artery disease: A systematic review. Am J Med 2008;121:715-25.
2. Hendel RC, Patel MR, Kramer CM, et al. ACCF/ACR/SCCT/SCMR/ASNC/NASCI/SCAI/SIR 2006 appropriateness criteria for cardiac computed tomography and cardiac magnetic resonance imaging: A report of the American College of Cardiology Foundation Quality Strategic Directions Committee Appropriateness Criteria Working Group, American College of Radiology, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, American Society of Nuclear Cardiology, North American Society for Cardiac Imaging, Society for Cardiovascular Angiography and Interventions, and Society of Interventional Radiology. J Am Coll Cardiol 2006;48:1475-97.
3. Meijboom WB, Van Mieghem CA, Mollet NR, et al. 64-slice computed tomography coronary angiography in patients with high, intermediate, or low pretest probability of significant coronary artery disease. J Am Coll Cardiol 2007;50:1469-75.
4. Anders K, Baum U, Schmid M, et al. Coronary artery bypass graft (CABG) patency: Assessment with high-resolution submillimeter 16-slice multidetector-row computed tomography (MDCT) versus coronary angiography. Eur J Radiol 2006;57:336-44.
5. Shi H, Aschoff AJ, Brambs HJ, Hoffmann MH. Multislice CT imaging of anomalous coronary arteries. Eur Radiol 2004;14:2172-81.
6. Schmitt R, Froehner S, Brunn J, Wagner M. Congenital anomalies of the coronary arteries: Imaging with contrast-enhanced, multidetector computed tomography. Eur Radiol 2005;15:1110-21.
7. Cury RC, Nieman K, Shapiro MD, et al. Comprehensive assessment of myocardial perfusion defects, regional wall motion, and left ventricular function by using 64-section multidetector CT. Radiology 2008;248:466-75.
8. Matsuo S, Matsumoto T, Nakae I, Ito M, Horie M. Anomaly of the left atrium in patients with atrial fibrillation detected by ECG-gated multi-slice computed tomography. Int J Card Imaging 2005;21:455-8.
9. Burke SJ, Aggarwala G, Stanford W, Mullan B, Thompson B, van Beek EJ. Preablation assessment for the left atrium: Comparison of ECG-gated cardiac CT with echocardiography. Academic Radiology 2008;15:835-43.
10. Jongbloed MR, Bax JJ, Lamb HJ, et al. Multislice computed tomography versus intracardiac echocardiography to evaluate the pulmonary veins before radiofrequency catheter ablation of atrial fibrillation: A head-to-head comparison. J Am Coll Cardiol 2008;45:343-50.
11. Budoff MJ, Shaw LJ, Liu ST, et al. Long-term prognosis associated with coronary calcification. J Am Coll Cardiol 2007;49:1860-70.
12. Detrano R, Guerci AD, Carr JJ, et al. Coronary calcium as a predictor of coronary events in four racial or ethnic groups. N Engl J Med 2008;358:1336-45.
13. Goldstein JA, Gallagher MJ, O'Neill WW, Ross MA, O'Neil BJ, Raff GL. A randomized controlled trial of multi-slice coronary computed tomography for evaluation of acute chest pain. J Am Coll Cardiol 2007;49:863-71.
14. Ladapo JA, Hoffmann U, Bamberg F, et al. Cost-effectiveness of coronary MDCT in the triage of patients with acute chest pain. AJR Am J Roentgenol 2008;191:455-63.
15. de Feyter PJ, Nieman K. New coronary imaging techniques: What to expect? Heart 2002;87:195-7.
16. Kramer CM. All high-risk patients should not be screened with computed tomographic angiography. Circulation 2008;117:1333-9.
17. Boden WE, O'Rourke RA, Teo KK, et al. Optimal medical therapy with or without PCI for stable coronary disease. N Engl J Med 2007;356:1503-16.

18. Yusuf S, Zucker D, Passamani E, et al. Effect of coronary artery bypass graft surgery on survival: Overview of 10-year results from randomised trials by the Coronary Artery Bypass Graft Surgery Trialists Collaboration. Lancet 1994;344:563-70.
19. Miller JM, Rochitte CE, Dewey M, et al. Diagnostic performance of coronary angiography by 64-row CT. N Engl J Med 2008;359:2324-36.
20. Hamon M, Biondi-Zoccai GGL, Malagutti P, et al. Diagnostic performance of multislice spiral computed tomography of coronary arteries as compared with conventional invasive coronary angiography: A meta-analysis. J Am Coll Cardiol 2006;48:1896-910.
21. 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;52:1724-32.
22. 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;27:2567-72.
23. Gilard M, Cornily JC, Rioufol G, et al. Noninvasive assessment of left main coronary stent patency with 16-slice computed tomography. Am J Cardiol 2005;95:110-2.
24. Van Mieghem CAG, Cademartiri F, Mollet NR, et al. Multislice spiral computed tomography for the evaluation of stent patency after left main coronary artery stenting: A comparison with conventional coronary angiography and intravascular ultrasound. Circ 2006;114:645-53.
25. Gilard M, Cornily JC, Pennec PY, et al. Assessment of coronary artery stents by 16 slice computed tomography. Heart 2006;92:58-61.
26. Mettler FA Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: A catalog. Radiology 2008;248:254-63.
27. Einstein AJ, Moser KW, Thompson RC, Cerqueira MD, Henzlova MJ. Radiation dose to patients from cardiac diagnostic imaging. Circulation 2007;116:1290-305.
28. Jakobs TF, Becker CR, Ohnesorge B, et al. Multislice helical CT of the heart with retrospective ECG gating: Reduction of radiation exposure by ECG-controlled tube current modulation. Eur Radiol 2002;12:1081-6.
29. Hausleiter J, Meyer T, Hadamitzky M, et al. Radiation dose estimates from cardiac multislice computed tomography in daily practice: Impact of different scanning protocols on effective dose estimates. Circ 2006;113:1305-10.
30. Steigner ML, Otero HJ, Cai T, et al. Narrowing the phase window width in prospectively ECG-gated single heart beat 320-detector row coronary CT angiography. Int J Card Imaging 2009;25:85-90.
31. Earls JP, Berman EL, Urban BA, et al. Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: Improved image quality and reduced radiation dose. Radiology 2008;246:742-53.
32. Hirai N, Horiguchi J, Fujioka C, et al. Prospective versus retrospective ECG-gated 64-detector coronary CT angiography: Assessment of image quality, stenosis, and radiation dose. Radiology 2008;248:431-7.
33. Shuman WP, Branch KR, May JM, et al. Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: Comparison of image quality and patient radiation dose. Radiology 2008;248:431-7.
34. Scheffel H, Alkadhi H, Leschka S, et al. Low-dose CT coronary angiography in the step-and-shoot mode: Diagnostic performance. Heart 2008;94:1132-7.
35. Maruyama T, Takada M, Hasuike T, Yoshikawa A, Namimatsu E, Yoshizumi T. Radiation dose reduction and coronary assessability of prospective electrocardiogram-gated computed tomography coronary angiography: Comparison with retrospective electrocardiogram-gated helical scan. J Am Coll Cardiol 2008;52:1450-5.
36. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000 Report to the General Assembly, with scientific annexes. Vol I and II. New York: United Nations, 2000.
37. Katritsis D, Efstathopoulos E, Betsou S, et al. Radiation exposure of patients and coronary arteries in the stent era: A prospective study. Catheter Cardiovasc Interv 2000;51:259-64.
38. Beanlands RSB, Chow BJW, Dick A, et al. CCS/CAR/CANM/CNCS/CanSCMR joint position statement on advanced noninvasive cardiac imaging using positron emission tomography, magnetic resonance imaging and multidetector computed tomographic angiography in the diagnosis and evaluation of ischemic heart disease – executive summary. Can J Cardiol 2007;23:107-19.
39. Einstein AJ, Henzlova MJ, Rajagopalan S. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. JAMA 2007;298:317-23.
40. Gerber TC, Kuzo RS, Morin RL. Techniques and parameters for estimating radiation exposure and dose in cardiac computed tomography. Int J Card Imaging 2005;21:165-76.
41. Paul JF, Abada HT. Strategies for reduction of radiation dose in cardiac multislice CT. Eur Radiol 2007;17:2028-37.