Multislice CT angiography in cardiac imaging. Part III: radiation risk and dose reduction

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ABSTRACT

With the introduction of 64- or more-slice computed tomography (CT) technology, multislice CT angiography has been increasingly used as a non-invasive modality for the diagnosis of coronary artery disease. Despite its potential advantages and promising clinical results, multislice CT angiography suffers from high radiation dose which contributes to radiation-induced malignancy in patients undergoing cardiac CT examinations. This has raised serious concerns in clinical practice. A number of strategies have been recommended and implemented to reduce the radiation dose associated with multislice CT angiography in cardiac imaging. The aim of this review is to present an overview of the various approaches used for radiation dose reduction. Future directions of multislice CT angiography with regard to the judicious use of this promising technique and increased awareness of the radiation risk are highlighted.

Keywords: cancer, coronary artery disease, multislice CT, radiation dose, risk

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INTRODUCTION

Radiation dose is becoming a major issue for multislice computed tomography (MSCT) angiography, since 64- or more-slice CT has shown improved and promising results in the diagnosis of coronary artery disease (CAD).[1-4] It is estimated that in daily practice, an effective dose of cardiac MSCT angiography may reach up to 40 mSv in female patients if no dose-saving strategies are applied, and this is associated with radiation exposure to breast tissues.[5] Cardiac patients may also be exposed to other sources of medical radiation, including nuclear medicine and invasive coronary angiography examinations. With repeated examinations and the cumulated radiation dose, radiation exposure has become a definite risk to patients. Given the fact that CT is a high-dose imaging modality, it is essential to minimise the radiation dose associated with cardiac MSCT examinations.

Many clinicians may still be unfamiliar with the magnitude of radiation exposure arising from coronary MSCT in daily practice and with factors that contribute to the radiation dose. Therefore, the benefit of using coronary MSCT angiography in the diagnostic workup and in patient management must be weighed against the potential risks related to radiation exposure. Recently, tremendous progress has been made to lower the radiation dose for coronary MSCT angiography. In this article, we review the strategies that are currently available to address radiation dose reduction. Future directions, including increased awareness of radiation risk among both patients and physicians as well as justification of the use of MSCT in cardiac imaging, are highlighted.

CORONARY MSCT ANGIOGRAPHY-RADIATION DOSE ISSUE

Recent advances and improvements to the spatial and temporal resolution of cardiac CT have increased its ability to diagnose CAD; however, this has resulted in increased radiation dose. The radiation risks associated with cardiac CT have raised serious concerns and have become a hot topic of debate in the literature.[6-8] Two recent studies published in the Archives of Internal Medicine have highlighted the importance of the standardisation of common CT imaging including cardiac CT imaging, as well as the cancer risk associated with radiation.[9,10] Smith-Bindman et al collected the actual data on radiation doses for the most commonly used CT imaging techniques at four institutions and found a surprising variation in radiation dose – a mean 13-fold variation between the highest and lowest dose for each CT type studied (a range of 6- to 22-fold difference across study types). The researchers estimated that one in every 270 women aged 40 years who undergo a CT coronary angiogram will develop cancer from the procedure.[9] In another study, Berrington de González et al estimated that CT imaging done in 2007 could have led to 29,000 excess cancers. These cancers will appear in the next 20–30 years, and by the authors' estimates, at a 50% mortality rate, will cause approximately 15,000 deaths annually.[10]

Radiation-induced malignancy is a problem that

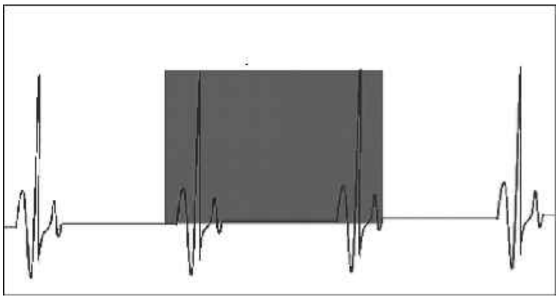

Fig. 1 Normal retrospective electrocardiogram-gating without tube current modulation. The X-ray beam is turned on during the entire cardiac cycle without adjusting the tube current.

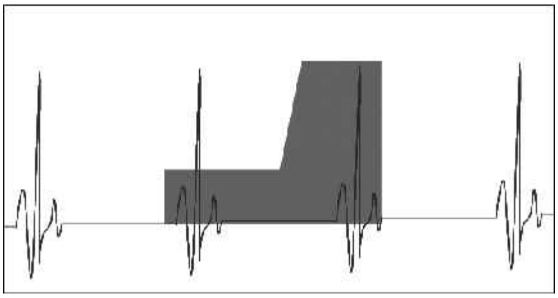

Fig. 2 Retrospective electrocardiogram-gating with tube current modulation. The normal tube current is applied only during the image reconstruction phase (late diastolic phase), while the tube current is reduced during the systolic phase.

has been addressed by the National Research Council of the United States.[11] It is reported that the radiation dose from a CT image has been significantly underestimated by radiologists and physicians.[6,12] Despite increased awareness regarding the radiation risk, many clinicians and researchers do not realise the amount of radiation exposure associated with cardiac CT, or the possibility of tailoring the imaging protocols to reduce radiation dose. An international multicentre study, which included 50 study sites, on the estimated radiation dose during cardiac CT angiography has shown a wide range of the median effective radiation dose, which ranged from 5–30 mSv. The study has also indicated that radiation exposure can be reduced substantially by applying available strategies for dose reduction; however, these strategies are not frequently used in clinical practice.[7] Currently, there are a number of dose-saving algorithms available to lower the radiation dose from cardiac CT imaging. Thus, selection of the appropriate MSCT imaging protocols is necessary to keep the radiation dose as low as reasonably achievable (ALARA).

Strategies to reduce radiation dose

The radiation dose of cardiac MSCT imaging reported in the literature varies greatly, depending on the scan parameter settings.[7] Factors affecting radiation dose include scanner geometry, tube voltage, tube current, scan range, electrocardiogram (ECG) gating (prospective vs. retrospective), slice thickness, pitch and shielding. These factors need to be considered for the reduction or minimisation of the radiation dose during cardiac MSCT imaging.

Strategies to reduce radiation dose: tube current modulation

One effective approach for radiation dose reduction is through the use of ECG-controlled tube current modulation. Most cardiac MSCT scans are performed using the retrospective ECG gating technique, which indicates that the volume data is acquired during the entire cardiac cycle within a single breath-hold helical scan (Fig. 1). However, image reconstruction of the data only takes place in a specific phase of the cardiac cycle (end systole or mid diastole). This implies that the tube current can be adjusted in different cardiac phases so that high-quality diagnostic images of coronary arteries during the reconstruction window, and low-quality higher noise images of the cardiac chamber and cardiac valves during the rest of the cardiac cycle, can be acquired. This algorithm restricts the prescribed tube current to a pre-defined time window during the diastolic phase and decreases the tube current in the systolic phase of the cardiac cycle[13] (Fig. 2), thus achieving significant dose reduction using this method. ECG-controlled tube current modulation has been reported to reduce radiation dose by 30%–50%.[13,14] While ECG-regulated dose modulation can be implemented in the majority of patients, sometimes it cannot be utilised due to scanning conditions requiring additional image reconstructions during different phases of the cardiac cycle (such as irregular heart rhythms and fast heartbeats).[15]

The automatic tube current modulation technique is used to maintain diagnostic images while reducing radiation exposure on the basis of patient geometry (anatomy-adapted tube current modulation). It is regarded as an effective dose-saving algorithm, as the tube current is adjusted according to the patient's size and anatomic shape, or both (e.g. the tube current is increased for obese patients and decreased for small patients to generate a diagnostic image quality at the lowest dose). Adjustment of the tube current can be performed in three-dimensional directions, including the x, y and z-axes (anatomy-based adaptation). However, automatic tube current modulation is expected to play a limited role in dose reduction in cardiac CT angiography because of the relatively smaller angular or z-axis fluctuation of attenuation at the heart level.[16] Advanced tube current modulation schemes with novel

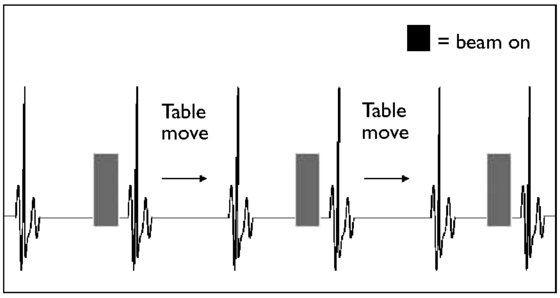

Fig. 3 Prospective electrocardiogram-triggering with X-ray beam turned on during a portion of the cardiac cycle, while in the remaining cardiac phase, the X-ray beam is turned off.

reconstruction algorithms are being developed to reduce the radiation dose to superficial radiation-sensitive tissues such as the breast.[16]

Strategies to reduce radiation dose: adjustment of kVp and mAs

Another effective method that is currently being undertaken in clinical practice to reduce radiation dosage is to lower the tube voltage, since the radiation dose varies with the square of the kV. Modern CT scanners include tube voltages of 120 kV or 140 kV, reflecting the settings that most often result in adequate image quality. However, cardiac CT acquisition with a voltage of 100 kV, or even lower, is possible and has been suggested as an effective means to reduce the radiation dose in cardiac CT imaging.[17-19] It has been shown that decreasing the radiography tube voltage from 120 kV to 80 kV resulted in a 70% reduction in radiation exposure for a constant tube current.[20] Previous studies have also shown reductions in radiation dose by up to 53% with the use of 100 kV for 16- and 64-slice CT, with increased image noise and an unchanged contrast-to-noise ratio.[17,18,21] Studies utilising dual-source CT have compared a 100 kV protocol to the routine 120 kV for cardiac CT, and demonstrated a 25%–54% reduction in radiation dose, depending on the tube current time product.[22,23]

Reduction of the tube current is a practical method of reducing the CT dose, as there is a linear relationship between adjustment of the tube current and subsequent radiation dose change. It has been reported that individually weight-adapted protocols, achieved by adjusting the mAs to the patient's weight, have been successfully applied in coronary CT angiography, with a dose reduction of 17.9% for men and 26.3% for women, keeping noise constant.[24] The reduction of mAs results in a lower radiation dose, but leads to higher image noise, thereby negatively affecting the image quality. Therefore, the mAs should be tailored to the patient's body mass index (BMI) and the desired image noise. It should be emphasised that the tube current should be increased only to the level that is necessary for acquiring images of adequate quality for diagnostic purposes. In the daily practice of coronary MSCT angiography, lowering the tube current mainly occurs by means of ECG-controlled tube current modulation instead of individual adjustment of the tube current. Fei et al have shown that scanning protocols using lower mAs are less accurate for the evaluation of coronary artery stenoses.[25]

Strategies to reduce radiation dose: adjustment of pitch value with dual-source CT

For cardiac MSCT angiography, a low pitch (0.2–0.4) is used to produce volume coverage without gaps in each phase of the cardiac cycle with multiple overlapping regions of high radiation exposure. Very low pitch values are typically required for coronary data acquisition to ensure continuous z-axis coverage between image stacks reconstructed from consecutive cardiac cycles. This is usually performed in the retrospective ECG-gating technique, as the same position has to be exposed by the detector during consecutive cardiac cycles so that the data from several cardiac cycles will be used for image reconstruction. A dual-source CT scanner has greater temporal resolution, so the pitch may vary automatically with the heart rate.[26] With dual-source scanners, the pitch can be increased at higher heart rates, resulting in a faster table speed and a corresponding reduction in radiation exposure.

The amount of radiation reduction is dependent on the patient's heart rate. Ketelsen et al, in their study based on an Alderson-Rando-Phantom (Alderson Research Laboratories Inc, Stanford, CT, USA) showed a significant reduction in the radiation dose with increased heart rate due to the effect of increased pitch values resulting in less overlapping and a reduced radiation dose. They concluded that a dose reduction of 31.9% for cardiac CT angiography and 29.6% for calcium scoring with dual-source CT images was achieved at a heart rate of 100 bpm (pitch 0.5) when compared to the scans performed at a heart rate of 40 bpm (pitch 0.2).[27] An increased heart rate tends to degrade image quality in cardiac CT imaging with a single-source CT, and thus, an aggressive approach, such as the administration of beta-blockers prior to CT imaging, is commonly used to lower the patient's heart rate.[28] The improved temporal resolution of dual-source CT results in a robust image quality within a wide range of heart rates, and thus provides the opportunity to image patients with higher heart rates without requiring pre-examination beta-blockage.[26-29]

Studies using dual-source CT in the cardiac imaging of patients with CAD show the feasibility of high-pitch spiral acquisition with prospective ECG-triggering.[30,31] Diagnostic image quality with a very low radiation dose (0.78–2.1 mSv) was achieved in the majority of patients by prospectively ECG-triggering high-pitch spiral coronary CT angiography (pitch 3.2–3.4). An effective radiation dose can even be lowered to less than 1 mSv with the prospective ECG-triggering technique,[30] and this contrasts significantly with the higher radiation dose associated with retrospectively gated cardiac MSCT angiography (up to 21 mSv).[32,33]

Strategies to reduce radiation dose: prospective ECG-triggering

Although a high diagnostic accuracy is achieved with retrospective ECG-gating, the disadvantage of this method is the increased radiation dose, as the radiograph tube is turned on continuously throughout the entire cardiac cycle. In contrast, the prospective ECG-triggered cardiac CT uses the partial scan technique to the motion of the heart, so that the scan is triggered by the ECG signal instead of spiral CT acquisition. This technique allows data to be acquired during a certain phase of the cardiac cycle, preferably in the diastolic phase when cardiac motion is minimal (Fig. 3).

Prospective ECG-triggered scans use the same technique as that used in electron-beam CT, which is defined as the step-and-shoot method.[34] The technique was initially used for the quantification of the calcium burden, but recently, it has been increasingly used for CT coronary angiography examinations. Unlike retrospective ECG-gating, prospective ECG-triggering allows for the acquisition of data by selectively turning on the radiograph tube only in the selected phase, triggered by the ECG signal, and turning it off during the rest of the R-R cycle (Fig. 2). The effective pitch of prospective ECG-triggering is 1.0. Unlike retrospective ECG-gating, in prospective ECG-triggering, exposure only occurs at the pre-defined cardiac phase rather than during the entire cardiac cycle. Prospective ECG-triggering has been confirmed to be one of the most efficient techniques for radiation dose reduction in cardiac CT angiography.[35]

The use of prospective ECG-triggering with 64-slice or dual-source CT has been reported to reduce the effective radiation dose by up to 90% when compared to the retrospective ECG-gating technique, with diagnostic image quality being achieved in more than 90% of cases.[36-42] Earls et al reported their experience with prospective ECG-triggering in the largest clinical group, which included more than 2,000 cases. With adequate preparation and patient selection, the authors concluded that most patients would benefit from prospective gating with acceptable diagnostic images and a significant reduction in the effective radiation dose when compared to retrospective gating.[39]

The disadvantages of prospective gating lie in the following two areas: it is restricted to patients with a heart rate lower than 75 bpm due to the short z-axis coverage (4 cm for 64-slice CT), and cardiac images are acquired only during a small portion of the R-R interval; thus, functional information about cardiac valve motion or wall motion is not available.[39] With the recent emergence of 256- and 320-slice CT, extended z-axis coverage (12.8–16 cm) can be acquired with a single gantry rotation without table movement, thus eliminating the above limitations. Studies using 320-slice CT have demonstrated the improvements to prospective gating with the new generation of CT scanners.[7,41,43] The majority of patients can be imaged in a single heartbeat, with excellent image quality showing simultaneous evaluation of coronary atherosclerosis and its physiological significance. The reduction in radiation dose achieved with 320-slice CT is due to the fact that it does not require overscanning and overranging; thus, the effective dose can be reduced significantly.[4] In patients with an irregular or high heart rate, two or three beats are used for image acquisition to allow adequate multisegment reconstruction for improved temporal resolution.

Despite its promising results with significant radiation dose reduction, there is a lack of sufficient evidence to confirm the diagnostic value of prospective ECG-triggering in the detection of CAD. Only a few studies have reported that the high diagnostic value of MSCT angiography for the detection of CAD was acquired with prospective ECG-triggering, and this is comparable to that acquired with retrospective ECG-gating.[43-45]

HOW LOW CAN THE RADIATION DOSE BE?

The increased spatial and temporal resolution of MSCT, from the early generations of 4- and 16-slice to the recent scanners of 64-slice or dual-source CT, comes at the cost of an increased radiation dose. Initial studies using 4-slice CT delivered approximately 8–10 mSv compared with a conventional diagnostic coronary angiography of 3–9 mSv.[3] A substantial increase to 13–21 mSv has been reported using 16-slice and 64-slice CT.[32,33,46] It is expected that the radiation dose will be even higher with 64- or more-slice scanners; however, prospective ECG-triggering is increasingly being used in most of the studies, and thus, the effective dose is reported to be lower than 7–8 mSv with 64-, dual-source or the latest CT scanners.[35-42,47] Using many of the technologies and strategies discussed above, it is possible to lower the dose to less than 5 mSv, and doses less than 1 mSv have also been reported in the literature.[30] Dose consistency less than 1mSv for MSCT coronory angiography can be achieved with prospective gating in patients with a BMI of less than 30 kg/m^2 and a heart rate of less than 70 bpm. For comparison, the average yearly background radiation dose is around 3 mSv. Depending on the technique used and the dose-saving algorithms taken, MSCT angiography may have a higher or lower effective dose than invasive coronary angiography.

HOW HIGH CAN THE ESTIMATED RISK OF CANCER ASSOCIATED WITH MSCT BE?

The general view about radiation dose is that a cancer risk is associated with coronary CT angiography. The National Academies' Biological Effects of Ionizing Radiation 7th Report (BEIR VII Phase 2) provides a framework for estimating the cancer risk that is associated with radiation exposure from coronary MSCT angiography.[11] BEIR VII developed the risk estimates for cancer from exposure to low-level ionising radiation using the most current data and epidemiological models available on the health effects of radiation. According to this report, it is estimated that 1 in 1,000 patients will develop cancer due to an exposure of 10 mSv. Brenner and Hall estimated that approximately 1.5%–2% of all cancers in the United States may be attributed to radiation exposure from CT examinations.[6]

Einstein et al determined the life attributable risk (LAR) of radiation-induced cancer from 64-slice CT angiography using the Monte Carlo simulation methods. The authors observed a marked variation by age, gender and scan protocol for cancer risk associated with radiation exposure from coronary CT angiography using the approach described in the BEIR VII report. The LAR ranged from less than 0.02% to nearly 1%, depending on the patient's age and scanning protocol. The authors noticed that an estimated reduction in cancer risk by about 35% was achieved if the tube current was reduced by 35%. Their estimates suggest that the cancer risk increases with combined cardiac and aortic scanning, and it is significantly greater for women and young patients. The authors concluded that the use of 64-slice CT angiography in cardiac imaging is associated with a non-negligible LAR of cancer, so patient selection and protocol optimisation are equally important to minimise the cancer risk.[48]

DEGREE OF AWARENESS REGARDING RADIATION RISK AMONG PATIENTS AND PHYSICIANS

There is a growing trend in medical practice where patients are becoming more involved in medical decision-making.[49-51] Degner et al found that 44% of patients with breast cancer wanted to make treatment decisions in collaboration with their physician, while 34% peferred to leave the decision to their physician.[50] Similarly, in a recent study, Caoili et al reported that 83% of their patients had discussed the reasons for undergoing a CT examination with their physician, and the decision to undergo CT imaging was shared by both the physician and the patient in 44% of the cohort.[51] However, patients' knowledge about ionising radiation associated with CT examination is limited. Caoili et al's survey showed that most of the patients were not aware of the risks associated with medical imaging, with only 6% of respondents having the knowledge that radiation exposure from CT increases the lifetime risk of cancer.[51]

Similarly, physicians and radiologists lack awareness regarding the potential risks associated with common radiological examinations including CT.[12,52] Lee et al found that only 47% of radiologists and 9% of emergency department physicians believed that there was an increased risk of cancer associated with CT imaging.[12] Thus, there is an urgent need for physicians to educate themselves and increase their awareness about ionising radiation from CT and its associated risks. This is similar to the situation when radiographic imaging goes digital; physicians will need to familiarise themselves with viewing images on a display screen,[53] and be aware of the potential risk of radiation exposure associated with CT imaging when MSCT becomes the routine imaging modality in clinical practice.

MSCT ANGIOGRAPHY IN CAD: JUSTIFICATION OF ITS USE

There is no doubt that with increasing technological improvements, MSCT will continue to play an important role in the detection and diagnosis of CAD. Judicious use of MSCT in cardiac imaging by clinicians is essential to maximise its clinical applications while minimising the associated potential risk of radiation exposure. This is particularly important for young individuals, especially women, for whom alternative diagnostic modalities that do not involve the use of ionising radiation should be considered, such as stress electrocardiography, echocardiography or magnetic resonance imaging.[47] The benefit-to-risk ratio for imaging patients suspected of CAD must be driven by the benefit and appropriateness of the cardiac MSCT examination requested by the cardiologists. The main purpose of utilising MSCT imaging is to address specific medical questions without allowing concerns about radiation exposure to dissuade cardiologists or their patients from obtaining or undergoing the required MSCT examination.

SUMMARY AND CONCLUSION

Radiation exposure associated with cardiac multislice

CT angiography has increased substantially over the past two decades and is a major concern that needs to draw the attention of both clinicians and manufacturers. Radiation exposure is especially important for young and female patients who present with atypical symptoms, but do not have high pre-test likelihood for actually having haemodynamically significant coronary stenosis. Cardiac CT angiography should be performed with dose-saving strategies whenever possible so as to reduce the radiation dose to patients. MSCT imaging protocols in cardiac imaging should be standardised across institutions with the aim of reducing dose variation across patients and facilities. Physicians need to follow guidelines for reducing dosages, such as national dose reference levels for radiation dose, and they are recommended to participate in the radiation dose registry to obtain feedback on radiation dose levels compared to other institutions. Utilisation of cardiac MSCT angiography must be defined as whether it leads to the greatest benefit and whether the radiation risk may be greater than the benefit expected from the CT examinations.

REFERENCES

1. Raff GL, Gallagher MJ, O'Neill WW, et al. Diagnostic accuracy of non-invasive coronary angiography using 64-slice spiral computed tomography. J Am Coll Cardiol 2005; 46:552-7.
2. 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. In press.
3. Rybicki FJ, Otero HJ, Steigner ML, et al. Initial evaluation of coronary images from 320-detector row computed tomography. Int J Cardiovasc Imaging 2008; 24:535-46.
4. Dewey ME, Zimmermann E, Deissenrieder ZF, 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; 120:867-75.
5. Paul JF, Abada HT. Strategies for reduction of radiation dose in cardiac multislice CT. Eur Radiol 2007; 17:2028-37.
6. Brenner DJ, Hall EJ. Computed tomography – an increasing source of radiation exposure. N Engl J Med 2007; 357:2277-84.
7. Hausleiter J, Meyer T, Hermann F et al. Estimated radiation dose associated with cardiac CT angiography. JAMA 2009; 301:500-7.
8. Raff GL, Chinnaiyan KM, Share DA, et al. Radiation dose from cardiac computed tomography before and after implementation of radiation dose-reduction techniques. JAMA 2009; 301:2340-8.
9. Smith-Bindman R, Lipson J, Marcus R, et al. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. Arch Intern Med 2009; 169:2078-86.
10. Berrington de González A, Mahesh M, Kim KP, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. Arch Intern Med 2009; 169:2071-7.
11. Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation; Nuclear and Radiation Studies Board, Division on Earth and Life Studies, National Research Council of the National Academies. Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2. Washington: The National Academies Press, 2006.
12. Lee CI, Haims AH, Monico EP et al. Diagnostic CT scans: assessment of patient, physician, and radiologist awareness of radiation dose and possible risks. Radiology 2004; 231:393-8.
13. Abada HT, Larchez C, Daoud B, et al. MDCT of the coronary arteries: feasibility of low-dose CT with ECG-pulsed tube current modulation to reduce radiation dose. AJR Am J Roentgenol 2006; 186(6 Suppl 2):S387-90.
14. Jakobs TF, Becker CR, Ohnesorge B, et al. Multislice helical CT of the heart with retrospective EKG gating: reduction of radiation exposure by ECG-controlled tube current modulation. Eur Radiol 2002; 12:1081-6.
15. Gopal A, Mao S, Karlsberg D, et al. Radiation reduction with prospective ECG-triggering acquisition using 64-multidetector Computed Tomographic angiography. Int J Cardiovasc Imaging 2009; 25:405-16.
16. Xu L, Zhang Z. Coronary CT angiography with low radiation dose. Int J Cardiovasc Imaging 2010; 26:17-25.
17. 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. Circulation 2006; 113:1305-10.
18. Park EA, Lee W, Kang JH, et al. The image quality and radiation dose of 100-kVp versus 120-kVp ECG-gated 16-slice CT coronary angiography. Korean J Radiol 2009; 10:235-43.
19. Bae KT, Seeck BA, Hildebolt CF, et al. Contrast enhancement in cardiovascular MDCT: effect of body weight, height, body surface area, body mass index, and obesity. AJR Am J Roentgenol 2008; 190:777-84.
20. Feuchtner GM, Jodocy D, Klauser A, et al. Radiation dose reduction by using 100-kV tube voltage in cardiac 64-slice computed tomography: A comparative study. Eur J Radiol 2009. In press.
21. Luaces M, Akers S, Litt H. Lower kVp imaging for dose reduction in dual-source cardiac CT. Int J Cardiovasc Imaging 2009. In press.
22. Pflederer T, Rudofsky L, Ropers D, et al. Image quality in a low radiation exposure protocol for retrospectively ECG-gated coronary CT angiography. Am J Roentgenol 2009; 192:1045-50.
23. Leschka S, Stolzmann P, Schmid F, et al. Low kilovoltage cardiac dual-source CT: attenuation, noise and radiation dose. Eur Radiol 2008; 18:1809-17.
24. Jung B, Mahnken AH, Stargardt A, et al. Individually weight-adapted examination protocol in retrospectively ECG-gated MSCT of the heart. Eur Radiol 2003; 13:2560-6.
25. Fei X, Du X, Li P, et al. Effect of dose-reduced scan protocols on cardiac coronary image quality with 64-row MDCT: a cardiac phantom study. Eur J Radiol 2008; 67: 85-91.
26. Johnson TR, Nikolaou K, Wintersperger BJ, et al. Dual-source CT cardiac imaging: initial experience. Eur Radiol 2006; 16:1409-15.
27. Ketelsen D, Thomas C, Werner M, et al. Dual-source computed tomography: estimation of radiation exposure of ECG-gated and ECG-triggered coronary angiography. Eur J Radiol 2010; 73:274-9.
28. Brodoefel H, Burgstahler C, Tsiflikas I, et al. Dual-source CT: effect of heart rate, heart rate variability, and calcification on image quality and diagnostic accuracy. Radiology 2008; 247:346-55.
29. Donnino R, Jacobs JE, Doshi JV, et al. Dual-source versus single-source cardiac CT angiography: comparison of diagnostic image quality. AJR Am J Roentgenol 2009; 192:1051-6.
30. Achenbach S, Marwan M, Ropers D, et al. Coronary computed tomography angiography with a consistent dose below 1 mSv using prospectively electrocardiogram-triggered high-pitch spiral acquisition. Eur Heart J 2010; 31:340-6.

31. Lell MM, Marvan M, Schepis T, et al. Prospectively ECG-triggered high-pitch spiral acquisition for coronary CT angiography using dual source CT: technique and initial experience. Eur Radiol 2009; 19:2576-83.
32. Ropers D, Rixe J, Anders K, et al. Usefulness of multidetector row spiral computed tomography with 64- × 0.6-mm collimation and 330-ms rotation for the noninvasive detection of significant coronary artery stenoses. Am J Cardiol 2006; 97:343-8.
33. Mollet NR, Cademartiri F, van Mieghem CA, et al. High-resolution spiral computed tomography coronary angiography in patients referred for diagnostic conventional coronary angiography. Circulation 2005; 112:2318-23.
34. Hsieh J, Londt J, Vass M, et al. Step-and-shoot data acquisition and reconstruction for cardiac x-ray computed tomography. Med Phys 2006; 33:4236-48.
35. Schoenhagen P. Back to the future: coronary CT angiography using prospective ECG triggering. Eur Heart J 2008; 29:153-4.
36. Husmann L, Valenta I, Gaemperli O, et al. Feasibility of low-dose coronary CT angiography: first experience with prospective ECG-gating. Eur Heart J 2008; 29:191-7.
37. 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.
38. 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; 248:424-30.
39. 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.
40. 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.
41. Kitagawa K, Lardo AC, Lima JAC, George RT. Prospective ECG-gated 320 row detector computed tomography: implications for CT angiography and perfusion imaging. Int J Cardiovasc Imaging 2009; 25:201-8.
42. 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 Cardiovasc Imaging 2009; 25:85-90.
43. Pontone G, Andreini D, Bartorelli AL, et al. Diagnostic accuracy of coronary computed tomography angiography: a comparison between prospective and retrospective electrocardiogram triggering. J Am Coll Cardiol 2009; 54:346-55.
44. Stolzmann P, Goetti R, Baumueller S, et al. Prospective and retrospective ECG-gating for CT coronary angiography perform similarly accurate at low heart rates. Eur J Radiol 2010. In press.
45. Stolzmann P, Scheffel H, Leschka S, et al. Influence of calcifications on diagnostic accuracy of coronary CT angiography using prospective ECG triggering. AJR Am J Roentgenol 2008; 191:1684-9.
46. Mollet NR, Cademartiri F, Krestin GP, et al. Improved diagnostic accuracy with 16-row multi-slice computed tomography coronary angiography. J Am Coll Cardiol 2005; 45:128-32.
47. Sun Z. Multislice CT angiography in cardiac imaging: prospective ECG-gating or retrospective ECG-gating? Biomed Imaging Interv J 2010; 6:e4.
48. Einstein AJ, Henzlova MJ, Rajagopalan SJ. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. JAMA 2007; 298:317-23.
49. van den Brink-Muinen A, van Dulmen SM, de Haes HC, et al. Has patients' involvement in the decision-making process changed over time? Health Expect 2006; 9:333-42.
50. Degner LF, Kristjanson LJ, Bowman D, et al. Information needs and decisional preferences in women with breast cancer. JAMA 1997; 277:1485-92.
51. Caoili EM, Cohan RH, Ellis JH, et al. Medical decision making regarding computed tomographic radiation dose and associated risk: the patient's perspective. Arch Intern Med 2009; 169:1069-71.
52. Shiralkar S, Rennie A, Snow M, et al. Doctors' knowledge of radiation exposure: questionnaire study. BMJ 2003; 327:371-2.
53. Ng KH, Rehani MM. X ray imaging goes digital. BMJ 2006; 333:765-6.