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LEARNING OBJECTIVES

Upon completion of this activity, participants should be able to:

- Identify the radiation dose of cardiac CT studies
- Apply methods to reduce the dose for clinical CCTA studies
- Describe what parameters and techniques have the lowest associated dose
- Assess the risk of CCTA dose

Minimizing radiation dose in coronary CT angiography

By James P. Earls, M.D.

Coronary CT angiography has emerged as a dependable and accurate tool for detecting coronary artery disease.¹⁻⁹ It reliably rules out the presence of a coronary stenosis in patients with a low to intermediate probability of coronary artery disease. CCTA is gaining widespread clinical acceptance, changing how patients with known or suspected coronary artery disease are evaluated.

Awareness is growing among healthcare providers and the general public, however, regarding the potential harmful effects of low-dose radiation. The seventh report on the health effects of exposure to low-dose ionizing radiation released by the National Research Council's Committee on the Biological Effects of Ionizing Radiation, the

BEIR VII report,¹⁰ concluded that radiation exposure from diagnostic procedures is related to the development of cancers in humans.

CCTA and diagnostic conventional coronary angiography are often compared, and radiation dose is a concern in both. While more invasive than CT, CCA has traditionally used lower effective radiation dose levels, ranging from 3.1 to 9.4 mSv per examination.^{11,12} The effective radiation dose in two recent studies using 64-row multislice CT was 13 to 15 mSv in men and 18 to 21.4 mSv in women.^{7,8} Table 1 summarizes recent reports using 64-row MSCT and dual-source CT systems.^{2-8,13-15, 19} Reported effective doses of CCTA with the new DSCT systems are also relatively high, ranging from 8 to 16.1 mSv.^{14,15}

Most CCTA techniques use retrospectively gated helical data acquisition, in which the patient and table move through the gantry at a steady speed. A low pitch of 0.2 to 0.4 is used to ensure that the entire cardiac volume is adequately covered, especially if an ectopic beat is encountered. Because of the low

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COMPARISON OF TUBE CURRENT OVER TIME FOR THREE CCTA TECHNIQUES

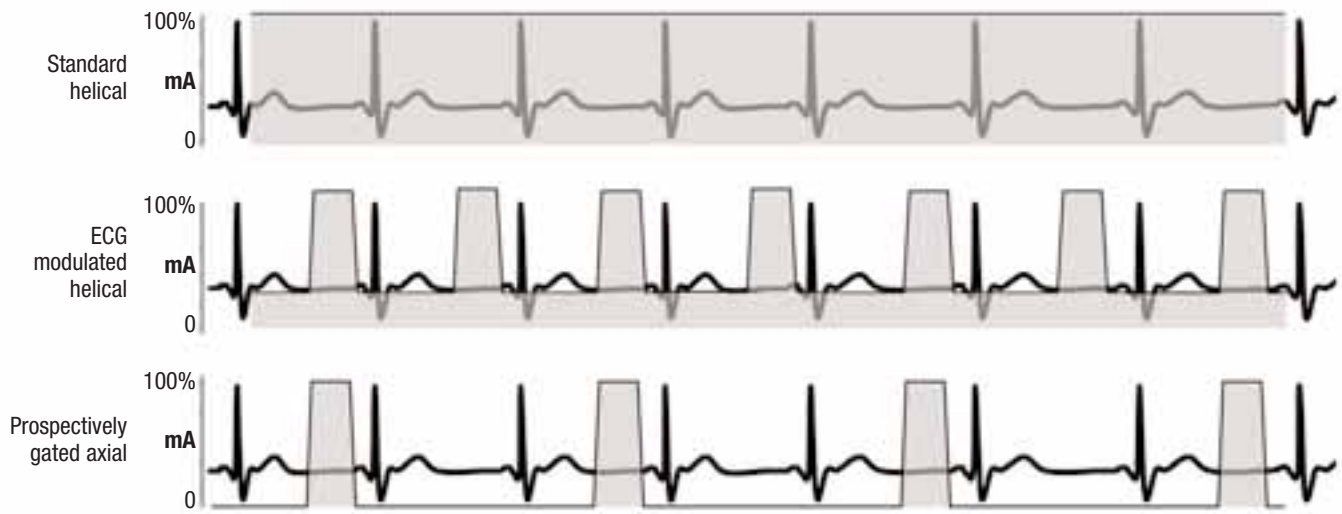


FIGURE 1. In standard helical mode, mA is constant throughout acquisition. In ECG-modulated helical scans, mA peaks in diastole and reduces in other parts of cycle. In prospective gated axial scans, current is off for most of data acquisition period and on for only short period during diastole for three or four cardiac cycles.

pitch, specific anatomy may be exposed to the x-ray beam as many as four or five times during an examination. Net radiation dose to the patient is cumulative for each pass, yielding the relatively high total dose.

Several methods can be used to minimize the radiation dose in CCTA studies (Table 2). Careful selection of scanning parameters, including mA, kVp, field-of-view, and z-axis coverage, is critical to achieving a dose that adheres to the as low as reasonably achievable (ALARA) principle. Use of ECG-gated modulation reduces the tube current in real-time during portions of the cardiac cycle, allowing for a decrease in overall radiation dose of between 30% and 50% (Figure 1).^{16,17} A new approach for cardiac scanning known as prospectively gated axial (PGA) CCTA, which uses combined step-and-shoot axial data acquisition and an incrementally moving table with adaptive ECG triggering, can reduce mean effective dose to the patient by up to 80% (Figure 2).^{18,19}

MEASURING RADIATION DOSE

Radiation dose is proportional to the tube current, exposure time, and square of tube voltage and is inversely proportional

to the pitch for helical acquisition. CT specific values are precisely defined, allowing direct comparisons of the radiation doses of various protocols and of similar protocols on differing CT systems.

Effective dose reflects the nonuniform radiation absorption within the body and

is determined from information about dose to individual organs and the relative radiation risk assigned to each organ. The dose is determined using mathematical simulations of the absorption and scattering of x-ray photons in various tissues of the human body. A reasonable approxi-

TABLE 1. COMPARISON OF EFFECTIVE DOSE ON CCTA EXAMS USING 16- AND 64-ROW MSCT AND DSCT SYSTEMS

Author	Technique	Dose no ECG modulation	Dose with ECG modulation
16-row MSCT			
Hunhold ²	Helical	10.9 to 13.0 mSv	
Morin ⁵	Helical	9.3 to 11.3 mSv	
Flohr ³	Helical	5.7 to 10.5 mSv	2.9 to 7.4 mSv
Trabold ⁴	Helical	8.1 to 10.9 mSv	4.3 to 5.6 mSv
64-row MSCT			
Earls ¹⁹	Prospective axial	2.8 mSv	
Raff ⁶	Helical		13 to 18 mSv
Leber ⁶	Helical		10 to 14 mSv
Mollet ⁷	Helical		15.2 to 21.4 mSv
Gaspar ¹³	Helical		13 to 15 mSv
DSCT			
Weustink ¹⁴	Helical		11.1 to 16.1 mSv
Ropers ¹⁵	Helical		8 to 12 mSv

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mation of the effective dose for a patient can be obtained by multiplying dose length product (DLP) by a conversion factor k (in $\text{mSv} \times \text{mGy}^{-1} \times \text{cm}^{-1}$) that varies depending on the body region that is imaged.²⁰

- **Increased dose with 64-row CT.** Sixty-four-row multislice CT has increased spatial and temporal resolution as compared with prior MSCT systems using 16 or fewer detector rows.¹⁻⁹ The increased detector z-coverage of the 64-row MSCT significantly shortens the total acquisition time, leading to improved heart rate stability and image quality. While 64-row MSCT has improved overall accuracy for CCTA, the mean effective dose for CCTA studies has increased as compared with studies performed with 16-row MSCT (Table 1).^{2-8,13-15,19}

The improved temporal resolution of 64-row systems is due primarily to improved gantry rotation speeds or, in the case of dual-source CT, the addition of a second x-ray source. The rotation time for MSCT systems has decreased from 500 msec to approximately 330 msec. For DSCT, the effective temporal

resolution is even shorter. Tube current must be increased, however, to maintain image quality over the new shorter acquisition windows. The newer systems have greater tube capacity, increasing from below 400 mA to up to 800 mA, depending on vendor and specific CT system. Such an increase in tube capacity provides x-ray flux well over the required amount for rotation speed compensation.

Improved spatial resolution, due mostly to a decrease in detector aperture, must also be accompanied by an increase in tube current to maintain image quality. While postprocessing filtering partially compensates for the increase in noise, tube current must again be increased. Increasing tube current increases radiation exposure and the effective dose to the patient.

DECREASING RADIATION DOSE

Various methods have been introduced to decrease radiation dose.

- **ECG modulation.** With retrospective ECG gating, scan data are acquired and available throughout the cardiac cycle, but data used for diagnosis come

TABLE 2. METHODS FOR REDUCING RADIATION DOSE FOR CCTA

Optimized scan parameters
Adjust mA to patient weight
Reduce kVp to 100 in low BMI patients
Limit z-axis coverage
Reduce field-of-view (25 cm)
ECG dose modulation
30% to 40% dose reduction
Prospective axial gating
Up to 80% dose reduction

TABLE 2. Effective dose of coronary CTA studies can be lowered by appropriate adjustment of various parameters as well as use of newer techniques such as ECG modulation and prospective gating.

most commonly from the diastolic phase. Thus, a high tube current may be required only during the diastolic phase, while a low tube current is acceptable during the remaining cardiac phase.

Modulating the tube current online with prospective ECG control (dose

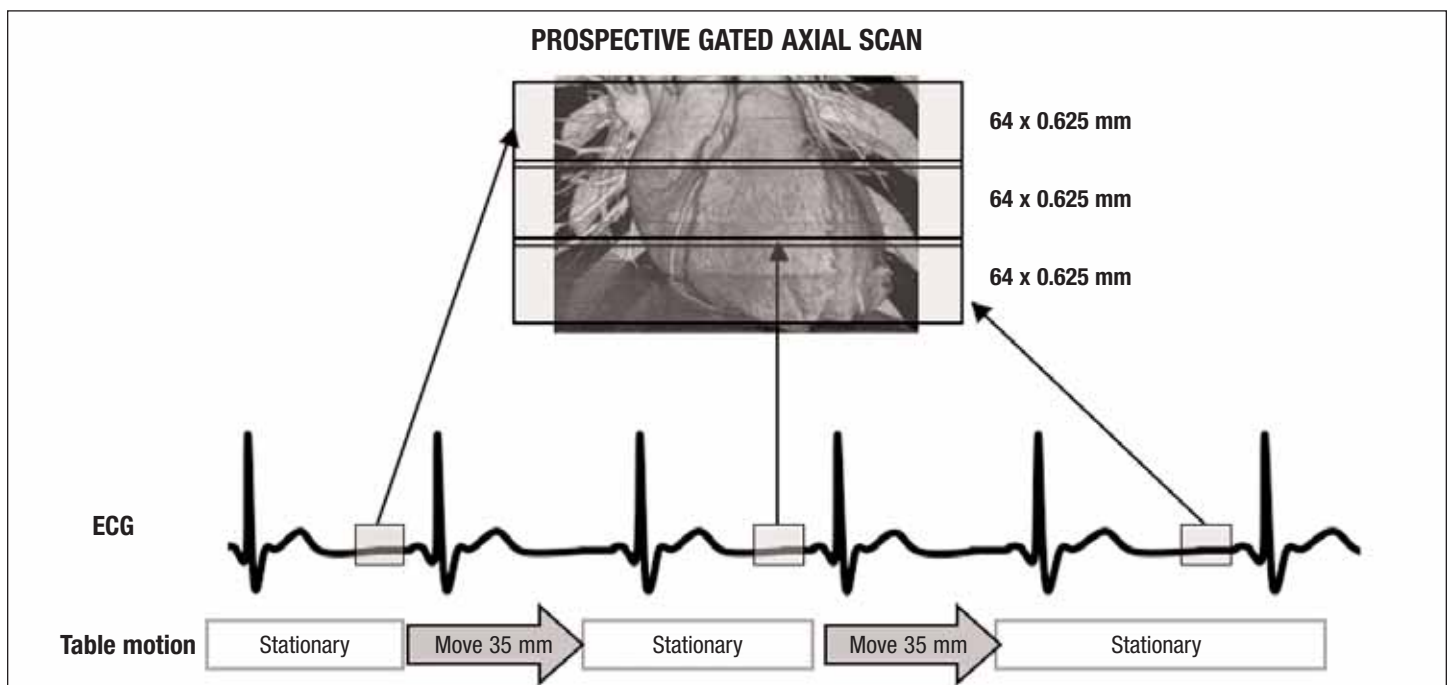


FIGURE 2. Technique relies on combined approach using axial data acquisition and incrementally moving table with adaptive ECG triggering. Table is stationary during acquisition of 40-mm (64×0.625 mm) group of axial images, then translates 35 mm, allowing 5-mm overlap of image groups, to next location for another scan initiated by subsequent normal cardiac cycle. Result is very little overlap between scans, up to 80% reduction in effective radiation dose, and more robust and adaptive ECG gating.

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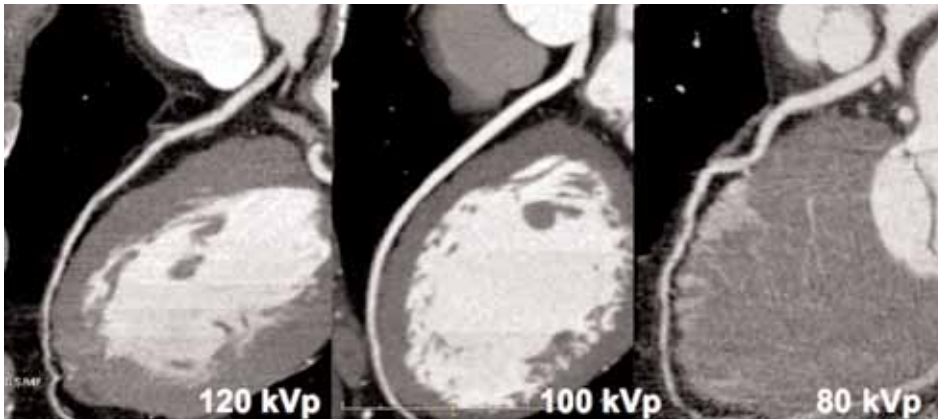


FIGURE 3. Lowering kVp from 120 to 100 is possible in CCTA and will significantly reduce effective radiation dose without adversely diminishing image quality. Further reduction to 80 kVp may adversely affect edge and plaque discrimination in some patients.

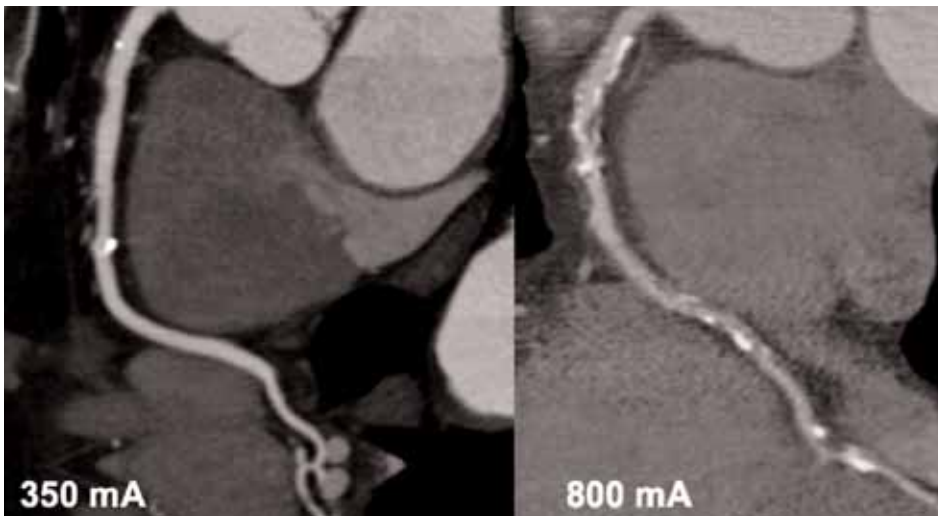


FIGURE 4. Use of weight- or BMI-adjusted mA helps optimize image quality while using minimum necessary dose required for diagnostic image quality. Helical study on left, performed on 56-year-old man with a BMI of 21 using mA of 350, resulted in an effective dose of 6.7 mSv. On right is 48-year-old man with a BMI of 42; using an mA of 800 yielded an effective dose of 21.1 mSv.

modulation) reduces radiation exposure substantially without decreasing diagnostic image quality (Figure 1). Aggressive ECG modulation, depending on heart rate, can reduce overall effective radiation dose by 20% to 40%.^{16,17,21} The effects of dose reduction are more pronounced for lower heart rates. ECG modulation is now available from all CT vendors and is commonly employed. In most cases, reconstructed data from diastole are acquired during peak tube current, and no compromise in image quality is noted.

There are some limitations to the benefits of ECG modulation. At higher heart rates, there is less time to rapidly change

the tube current, and a less substantial reduction in effective dose will be realized. In patients with irregular heart rates, ECG modulation may inadvertently reduce tube current during the optimal imaging phase, yielding reduced image quality and diagnostic utility.²¹

• **Lowering tube voltage.** Lowering the tube voltage also allows for a reduction in effective dose. Radiation dose varies with the square of the kilovoltage. Therefore, relatively small reductions in voltage will result in disproportionately larger reductions in overall effective dose.^{17,21} Decreased voltage has the added benefit of increased opacification

of vessels due to an increase in the photoelectric effect and a decrease in Compton scattering.

The use of weight-adapted low-kilovoltage settings has been shown to be effective for both chest imaging and evaluation of the myocardium following infarction.^{22,23} Abada et al recently reduced the kV in CCTA from the traditional 120 to 80 kV in low body mass index patients undergoing CCTA, and found that dose reduction of up to 88% could be obtained.¹⁷

Care must be taken in lowering the kV in CCTA exams (Figure 3). While the image signal improves with lower tube voltage, image noise also increases. Abada et al reported relatively high image noise and noted blurring at the edge of the coronary artery wall that made assessment of coronary plaque more difficult.¹⁷ They stated that coronary stent visualization could be substantially less satisfactory using the 80-kVp protocol. For this reason, in our clinical practice, we may lower the voltage to 100 kVp for low-BMI patients, but we routinely use 120 kVp for most other patients.

• **Lowering tube current.** The new 64-slice CT systems are usually equipped with higher capacity tubes, often with the ability to produce up to 800 mA. Clinically, studies performed using higher mA have less noise and higher signal-to-noise and image contrast-to-noise ratios. This often makes them more visually appealing and somewhat easier to read than studies performed at lower mA, and they can be very useful in heavily calcified vessels or those with intracoronary stents. This capability can also make what would have been a nondiagnostic case diagnostic in patients with a high BMI.

It is tempting to overuse the higher available tube capacity. We were unpleasantly surprised to find that our average mA using 64-row MSCT for helical acquisitions was over 18 mSv.¹⁹ A review of 82 patients showed that we often relied on 600 to 700 mA independent of BMI.

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The mA should be individually tailored to each study based on the patient's BMI, chest circumference, and estimated muscle and breast mass (Figure 4). We have developed more rigorous guidelines for mA selection and have been able to reduce our effective dose in helical studies by about 20%.

- *Minimizing dose on all scan series.* A CCTA exam often consists of several scans, in addition to data acquisition during the coronary angiogram. These include calcium scoring scans (or "low-dose" scouts), timing scans, and other series such as a "completeness" scan of the lung apices and aortic arch. Together, these can add another 3 to 5 mSv or more, depending on the technique chosen. Each of these series should be optimized with an eye to reduction of effective dose. We have successfully implemented a significant reduction in both tube current and voltage for each of the additional scans commonly performed with CCTA. This has helped to reduce the cumulative dose.

- *Prospective axial gating.* Hsieh et al developed and published a new approach for CCTA, which we refer to as prospective gated axial (PGA) (Figure 2).¹⁸ This technique uses a combined step-and-shoot axial data acquisition and an incrementally moving table with prospective adaptive ECG triggering. It takes advantage of the large 40-mm volume coverage available with the 64-row MSCT scanner, which enables complete coverage of the heart in two to three steps. Using this technique, the table is stationary during image acquisition then moves to the next position for another scan initiated by the subsequent cardiac cycle. The result is very little overlap between scans, significant 50% to 80% reduction in radiation dose, and more robust and adaptive ECG gating.

PGA CCTA software (Snapshot Pulse, GE Healthcare, Milwaukee) has received FDA 510(k) clearance for CT scanning of the body, and we use a version that will be in wide clinical release during 2007. The prescribed phase for data acquisition

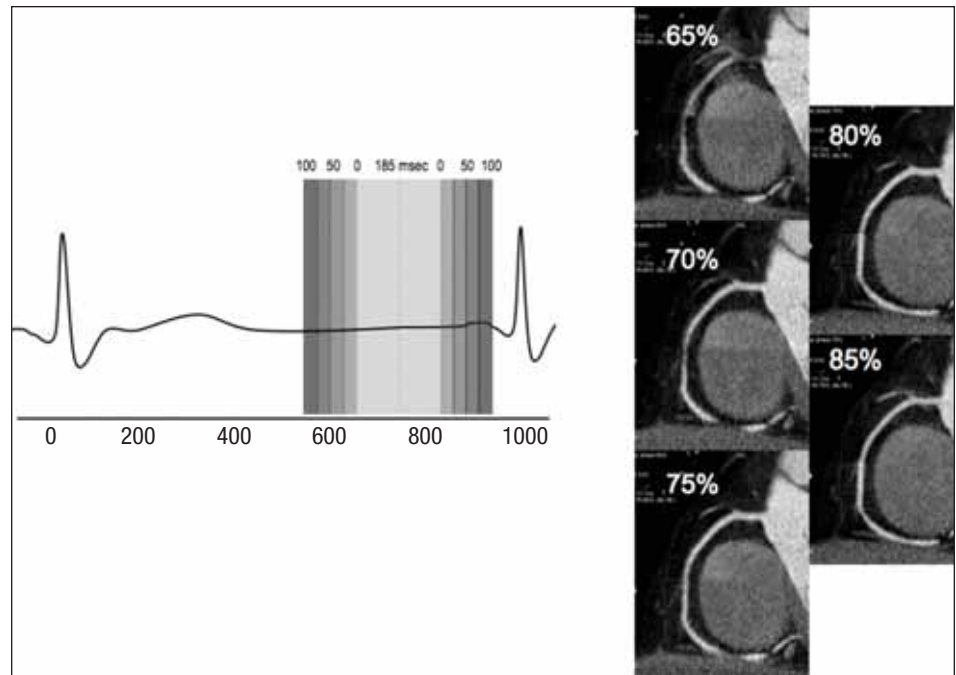


FIGURE 5. In PGA studies, padding is use of extra tube on-time to acquire image data during additional cardiac phases. Padding is needed in case heart rate varies during exam. For example, if the heart rate fluctuates by 10% beat to beat (drops from 60 to 54 bpm or increases from 60 to 66 bpm), then +/-10% of phase (100 msec) padding is needed to ensure that prescribed phase location is acquired for all table locations. In this example, prescribed phase was 75%. 100 msec of padding allowed phases 65% to 85% to be captured and reconstructed.

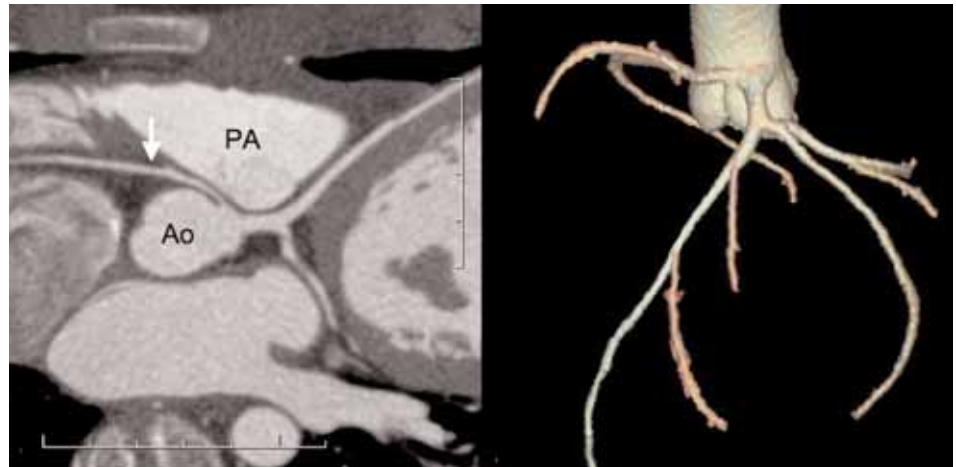


FIGURE 6. PGA CCTA exam in an 11-year-old with intermittent chest pain. Anomalous RCA (arrow) is seen to arise from left sinus of Valsalva and run between aorta (Ao) and pulmonary artery (PA). Effective radiation dose was 0.66 mSv.

is usually 75% (mid-diastole) for all subjects. Minimum scan time at each axial location is 230 msec (180° plus a fan angle), which translates to an effective temporal resolution of 175 msec with the half-scan weighting. Additional "padding" of tube on time can be used, depending on perceived heart rate instability (Figure 5). The padding technique

allows the reconstruction to adapt to minor heart rate variations and produce consistent image quality, since the reconstruction window can be modified retrospectively to ensure identical cardiac phases from scan to scan. To minimize effective dose, we usually employ relatively narrow amounts of padding: 0 to 100 msec for most studies.

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We compared the PGA technique with studies performed with the conventional helical technique.¹⁹ Effective dose for the PGA group (mean 2.84 mSv) was significantly lower than for the helical group (mean 18.4 mSv, $p < .001$). This represents a mean 83.2% reduction. We found PGA to be reliable, as 119 (98.3%) of 121 clinical studies were clinically diagnostic as compared with 81 (98.7%) of 83 helical studies. The number of assessable coronary segments was also not statistically different between the two groups.

We performed blinded reads to determine differences in image quality between the PGA and helical techniques. This step revealed that the PGA technique was preferred, with very strong statistical significance ($p < .001$). The improvement ranged from 0.209 (on the 1 to 5 image quality scale) in the right coronary artery to 0.325 in the left anterior descending artery. Considering that most image quality scores were in the highest categories, this is a fairly large increase in average score. Of interest, there were seven subjects, each with a low BMI (mean 21.4) in the PGA group who had a radiation dose of ≤ 1 mSv (Figure 6). We believe that these are the lowest reported effective doses for a CCTA. The technique was equally robust in patients of higher BMI, and we appropriately adjusted the mA for these patients and found excellent image quality (Figure 7).

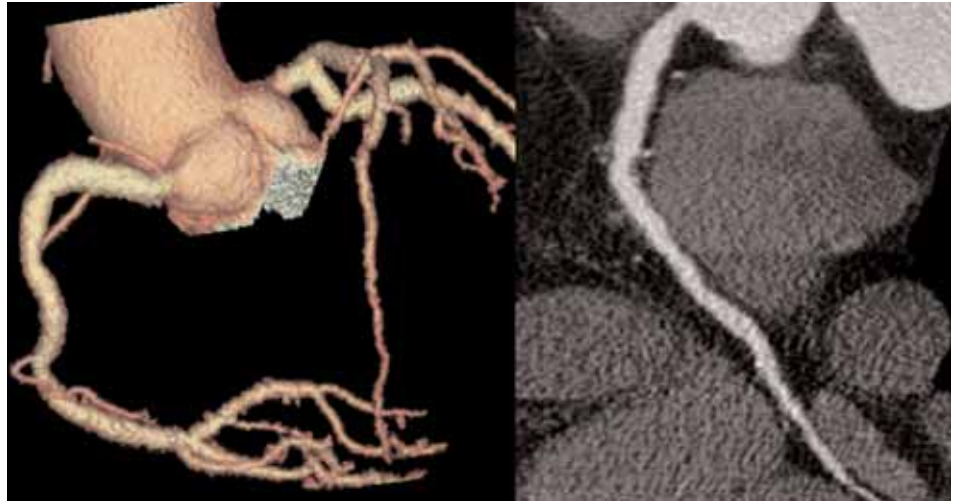


FIGURE 7. PGA CCTA in an obese 65-year-old woman (BMI 38) with chest pain. Study revealed ectasia of RCA and mild diffuse nonobstructive atherosclerosis. Despite her high BMI and use of 750 mA, total effective dose to patient was only 2.33 mSv.

RADIATION AND CANCER RISKS

Physicians performing CCTA in general adhere to the ALARA principle and set CT scanner settings so that a minimal amount of x-ray tube current is used, based on a patient's specific condition, to produce a diagnostic quality image. Even with strict adherence to this guideline, however, the radiation dose remains relatively high, and long-term risk to the patient of developing a radiation-induced cancer is small but real over large populations.

The BEIR VII report concluded that there is a linear no-threshold dose response relationship between exposure to ionizing radiation and the development of cancer.¹⁰ The BEIR committee

calculates that a dose of 10 mSv would cause one in 1000 lifetime cancers based on a normal distribution of the U.S. population, but the report acknowledges that this calculation could be off by a factor of two or three, and the conclusion is controversial.¹² The International Commission on Radiological Protection (ICRP) had previously estimated that a dose of 10 mSv would cause one in 2000 lifetime cancers.²⁴

Based on the above estimates, a helical coronary CT angiogram with an effective dose of 15 mSv has a one in 677 (BEIR VII) to 1333 (ICRP) risk of inducing a fatal cancer. A CCTA performed with PGA technique and an estimated dose of 2.8 mSv would yield a theoretical risk of one in 3571 (BEIR VII) to 7143 (ICRP) (Table 3 and Figure 8).

OTHER CARDIAC STUDIES

It may be useful to put the CCTA effective doses in context with other cardiac diagnostic tests. We have previously noted that conventional coronary angiography has an approximate dose of 5.6 mSv.¹¹ Nuclear cardiac imaging procedures generally have higher doses, depending on the radiopharmaceutical used. A rest-stress myocardial SPECT scan using technetium-99m has an effective dose of 8 to 17.5 mSv.^{12,25,26} A thalli-

TABLE 3. ESTIMATED FATAL LIFETIME CANCER RISK FROM A SINGLE CORONARY CTA EXAM

Scan type	Technique	ECG modulation	Effective dose (ref)	BEIR risk ¹⁰	ICRP risk ²⁴
16-row	Helical	no	10.3 mSv ⁶	1/971	1/1941
16-row	Helical	yes	5.15 mSv ⁴	1/1941	1/3883
64-row	Helical	yes	12 mSv ⁹	1/833	1/1667
64-row	Prospective axial	n/a	2.8 mSv ¹⁹	1/3571	1/7142
DSCT	Helical	yes	12.1 mSv ^{22,23}	1/826	1/1652

TABLE 3. Based on estimates from BEIR VII report (1/1000 for a 10 mSv dose)¹⁰ and ICRP (1/2000 for a 10 mSv dose).²⁴

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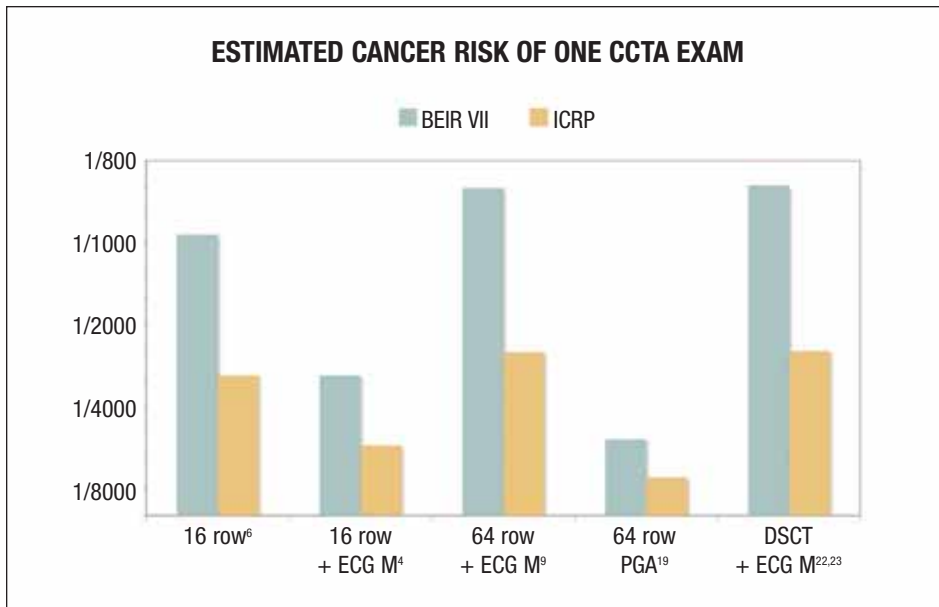


FIGURE 8. Estimated lifetime risk of having a fatal cancer induced by ionizing radiation of one CCTA exam. BEIR committee calculates that a dose of 10 mSv would cause one in 1000 lifetime cancers, while the International Commission on Radiological Protection estimates that a dose of 10 mSv would cause one in 2000 lifetime cancers.^{10,24} Dose estimates are mean reported for referenced studies. + ECG M = ECG modulation used, PGA = prospective gated axial technique.

um-201 stress and reinjection study has a dose of 18 to 25.1 mSv, and a dual-isotope study using Th-201 and Tc-99m has an effective dose of 27.3 mSv.^{12,25}

WHO BENEFITS?

While all patients will benefit from lowering the effective dose of CCTA exams, this approach is especially promising for those at potentially higher risk for radiation-induced malignancies. This group

would include premenopausal women (because of the direct breast exposure) and younger patients as a whole because of the lag time for a cancer to develop. Patients who might in the future have repeat CCTA studies, such as those with coronary stents, bypass grafts, complex congenital anomalies, or known coronary stenoses, may also benefit because of the lower cumulative dose.

No groups of patients now routinely

undergo serial or follow-up CCTA exams. CCTA has been used as a one-time problem-solving tool for symptomatic patients with a low to intermediate risk of having significant coronary artery disease. Most other noninvasive cardiac tests are performed numerous times during the course of a patient's illness or lifetime, however, and it is not unreasonable to assume that CCTA will also be performed in a similar manner in patients with CAD. Assuming additional studies show potential clinical benefit of serial or periodic reevaluation with CCTA, the PGA technique will clearly help minimize these patients' long-term dose and, therefore, their long-term risk of cancer development.

SUMMARY

Radiation dose is a concern for those ordering and performing coronary CTA because of the inherent high doses associated with these exams. Use of ECG modulation as well as careful reduction of tube current and voltage can help reduce the mean effective dose. The prospective gated axial technique shows great promise to substantially reduce dose while improving image quality. Because of the growing use of CCTA, physicians should continue to adhere to the ALARA principles, including the use of the minimal amount of x-ray tube current that will still produce diagnostic quality images. ■

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