tion exposure to the population. Depending on machine-specific factors and the user-specified acquisition protocol, cardiac CT examinations may deliver radiation doses that exceed 20 mSv, substantially higher than other CT examinations of the chest (3–9 mSv). Note that the overall patient dose may be reduced if the cardiac CT examination replaces multiple other examinations that deliver a higher cumulative dose (e.g., meta-iodobenzylguanidine scanning and cardiac catheterization).

Because image quality on CT is dominated by quantum noise (mottle), the radiation dose is closely linked to diagnostic accuracy and confidence. Too low a radiation dose leads to high-noise-level images that are clearly nondiagnostic. However, at intermediate noise levels, subtle image degradation occurs that may lead to diagnostic errors or low diagnostic confidence, effects that are difficult to detect and measure. Image noise also affects the accuracy of CT attenuation measurements that can cause errors in assessing disease activity and progression on longitudinal follow-up scans. Validated standardized acquisition protocols can help reduce these potential errors.

In the absence of evidence-based standardized acquisition protocols, radiologists often obtain CT images using high radiation exposure levels to minimize image noise and maximize image quality. This ad hoc approach leads to wide variation in the radiation dose for the same examination [1, 2] with no detectable difference in outcome. Radiologists, referring clinicians, and patients...
may be unaware of the high level of radiation exposure associated with specific CT examinations [3]. As with other CT examinations, there is currently no research investigating the relationship between image quality and diagnostic accuracy in cardiac-gated chest CT. Unlike CT of other body parts, no guidelines exist regarding dose-length product for cardiac CT. This knowledge gap should be addressed because of the increasing use of this technique.

The purpose of this article is to review, first, evidence indicating the detrimental effect of radiation dose at the level administered in cardiac CT; second, the radiation dose measurement; and third, techniques to reduce radiation dose while preserving cardiac CT diagnostic image quality.

Radiation Bioeffects
Considerable debate has taken place within the medical community regarding the risk of low-level radiation exposure from CT. The reason for this debate arises from an incomplete knowledge of the complex link between ionizing radiation and future negative outcomes in humans. In broad overview, the negative outcomes of ionizing radiation in humans can be divided into two major categories based on time and exposure: deterministic effects seen immediately after large exposures, and stochastic effects seen after a long period of latency (6–25 years) after low exposures.

Deterministic effects—skin erythema, skin necrosis, and hair loss—occur only above a threshold dose that is well above those delivered during standard examinations in cardiac CT. These effects will not be discussed further in this article.

By comparison, stochastic effects are believed to have no radiation dose threshold and therefore are associated with the low radiation doses delivered during chest CT. Mechanistically, stochastic effects are believed to be mediated by chemical damage to the DNA molecule; they clinically manifest as an increased risk of cancer and genetic defects. Stochastic effects occur randomly, and the risk of their occurrence depends on the type of ionizing radiation administered, the tissue receiving the irradiation, and the age of the subject. It is believed that dose fractionation, a substantial modifier of detrimental effects for deterministic radiation doses, does not substantially modify the stochastic risk [4]. Stochastic risks are believed to be cumulative, with an increasing risk occurring in successive exposures.

Subjects exposed to the atomic bomb explosions in 1945 have been extensively studied in the past 60 years. This group is unique because it is large, it covers all ages, and it was not selected on the basis of underlying disease. A substantial portion of the 25,000 survivors received less than 50 mSv, a low level of exposure that approximates the dose range delivered by multiple chest CT examinations. The major negative effect in this group is an increase in the number of cancers over that found in a nonexposed population. An earlier presentation of cancers has not been observed. However, the dose from a cardiac CT scan (3–20 mSv) requires extrapolation to even lower doses when studying this population, and the nature of this extrapolation has been highly controversial.

Disagreement regarding the low-dose extrapolation of nuclear explosion data is based on three nonresolvable issues: uncertainty as to the actual radiation exposure received because on-site radiation dose measurements were not obtained, differences in the natural cancer risk of the Japanese population compared with other populations, and the different quality of the irradiation imparted by atomic bombs as opposed to x-ray-based medical imaging. As a result of differences in interpretation, expert groups have come to varying conclusions about the risk attributable to radiation exposure at the levels found in chest CT. The International Commission on Radiologic Protection (ICRP) used a linear no-threshold extrapolation of nuclear explosion data and estimated 50 additional fatal cancers induced per 1,000,000 people exposed to 1 mSv of medical radiation [5]. In contrast, the French Academy of Science concluded there was not sufficient evidence to support an increased cancer risk associated with radiation exposures less than 20 mSv [6], a level similar to that delivered in cardiac CT examinations. Further conflicting evidence on the impact of low-level radiation exposure is found in tissue culture experiments that have shown induction of free radical detoxification mechanisms with low-level radiation exposure [7]. This has led some to suggest that low-level radiation exposure may be beneficial, an effect known as radiation hormesis. Finally, a large-cohort, long-term outcome study of British radiologists showed lower cancer mortality than predicted by the atomic bomb data [8]. Possible explanations for the better outcome of this cohort have been proposed, including healthy worker effect, beneficial effects of dose fractionation, and physician overestimation of the dose received by the atomic bomb survivors.

In 2007, additional important data were added to this debate [9] when a 15-country study reported the cancer induction effect of low-level radiation exposure studied in 407,000 radiation workers who were followed up for as long as 20 years (i.e., 5.2 million person-years of follow-up). That study is unusual because it reported on the largest cohort to date, had accurate dosimetry, and investigated multiethnic workers. Ninety percent of the subjects received a dose of less than 50 mSv; on average, each worker received a dose of 19 mSv. Therefore, that study is focused on low-level doses similar to that received during a cardiac CT examination. The authors reported an excess relative risk for all-cause mortality of 0.42/Sv (0.00042/mSv), with a statistically significant increasing excess relative risk with increasing radiation dose (p < 0.02), indicating a dose response effect. The increased risk in all-cause mortality was mainly due to an increase in mortality from all cancers.

A subanalysis stratified by dose categories (<400, 200, 150, and 100 mSv) showed that cancers in the highest dose categories did not drive the risk estimates [9]. Therefore, that study supports the concept that there is a small cancer risk from low-dose radiation delivered in cardiac CT examinations and supports the use of the ALARA (as low as reasonably achievable) principle for these examinations.

However, there are limitations to these new data [9]. Ninety percent of the participants were men who received more than 98% of the cumulative dose, leading to minimal information on radiation exposure effects in women. The largest excess mortality from all contributing countries is found in the data from Canada, and statistical significance is lost if this cohort is not included. Finally, the largest discrepancy between this study and the atomic bomb cohort arises in the lung cancer mortality rate, suggesting that the confounding effects of smoking may have been inadequately allowed.

The influence of sex and age at exposure has been studied in the nuclear explosion cohort, showing that radiation risk is substantially modified by these factors [10, 11]. Decreasing age clearly increases radiation sensitivity, making radiation exposure a larger issue in cardiac CT examinations in children and young adults. At all ages, women have approximately twice the risk compared to men in this cohort.

Radiation Dose in Cardiac CT

The influence of sex and age at exposure has been studied in the nuclear explosion cohort, showing that radiation risk is substantially modified by these factors [10, 11]. Decreasing age clearly increases radiation sensitivity, making radiation exposure a larger issue in cardiac CT examinations in children and young adults. At all ages, women have approximately twice the risk compared to men in this cohort.

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with men for the same level of exposure. Increased risk in young females is heightened in cardiac CT by the presence of radiosensitive breast tissue in the irradiated field. Radiation dose to breast tissue in chest CT examinations has been calculated [12] and directly measured [13, 14], with reports showing wide variation in average values of 10–70 mGy. The variation in values is related to CT parameter settings, differences in size and configuration of breast tissue, and methods to calculate or directly measure radiation dose. There is no debate that all CT-associated breast radiation dose values are substantially greater than the average glandular dose of 3 mGy for standard two-view screening mammography. Note that there is a strong age-at-exposure effect for breast tissue, with lower risk for subjects [15] older than 40 years. These factors must be taken into account in setting cardiac radiation dose parameters in women. Breast shields, thyroid shields [16, 17], and x-ray tube current modulation techniques have been used to decrease radiation dose to these radiosensitive tissues in the chest. These techniques have been shown to decrease breast and thyroid radiation exposure delivered in chest CT scans. However, these dose-modifying techniques must be used with consideration of their impact on image quality.

Radiation Dose Measurement

Many methods are currently in use for quantifying ionizing radiation [18]; however, the most widely used in cardiac CT is effective dose. Effective dose estimates the whole-body dose that would be required to produce the same stochastic risk as the partial-body dose that was actually delivered in the cardiac CT scan. It is useful because it allows comparison of CT dose to that delivered in other medical examinations. Effective dose is calculated by summing the absorbed doses to individual organs (e.g., breast, lungs) weighted for their radiation sensitivity [5]. The measurement unit is the sievert (Sv) or millisievert (mSv). Because effective dose requires determination of absorbed dose to each body organ multiplied by the organ radiation sensitivity, the distribution of radiation doses in the body must be determined. Cardiac CT has a markedly asymmetric dose distribution, with a higher dose found on the skin surface and a lower dose centrally due to the shielding effects of body tissue. This makes it difficult to calculate the exact effective dose for each patient. Instead, a simpler calculation is performed (Fig. 1). Scanner manufacturers use dose data derived from measurements made in head and body phantoms to determine a weighted CT dose index (CTDI) for each CT scanner model at all available selections for tube voltage (kVp), tube current (mA), and rotation time. The selected pitch value is then incorporated to produce a CT dose index called the CTDIvol. Once the scan length is determined from the topogram, the appropriate CTDIvol is combined with the actual length scanned in the patient to calculate the dose–length product (DLP). Because the administered radiation dose is linearly related to the length scanned in the patient, only the clinically appropriate volume should be imaged to avoid excessive radiation dose.

The DLP is a measure of the radiation dose delivered to the patient during the scan. An estimated effective dose for the specified CT scan can be calculated by multiplying the DLP value by the normalized effective dose coefficients (Table 1) for the scanned body part. This normalized effective dose coefficient accounts for the radiation sensitivity of the body region scanned based on exposed organ radiosensitivities. The DLP value is displayed on the scanner console once the topogram has been obtained and the scan prescribed. In cardiac CT, multiplying the DLP by 0.017 allows the radiologist or technologist to calculate the estimated effective dose of the examination before scan acquisition (Fig. 2). The DLP value can be archived in the PACS by storing the protocol page. Newer DICOM standards for CT enable the storage of dose data in the DICOM header of each examination.

Note that effective dose, although easy to calculate and convenient, is an imperfect dose descriptor [19]. The committee-determined tissue-weighting factors represent a subjective balance between cancer incidence, cancer mortality, life shortening, and hereditary risk. In the past, weighting factors have been modified, and there is no assurance that they will not be modified in the future as further knowledge is gained. Because the weighting factors are averaged over sex and age, effective dose risk assessment is appropriate to a 30-year-old hermaphrodite. As a result, the estimated risk of cancer may be a factor of 3 higher or lower when applied to a reference patient and will be more variable when applied to an individual [20]. An alternative approach has been described [19] that uses measured or calculated organ radiation doses, applies them to age- and sex-specific organ risk estimates from the BEIR (biological effects of ionizing radiation) VII report [21], and calculates an effective risk from the examination. Effective risk would attempt to estimate the risk of developing cancer from the partial-body irradiation of the examination. It would not consider hereditary effects that are currently embodied in the calculation of effective dose. Although this is a new approach requiring further evaluation, it has the potential to improve communication to patients and physicians of the risk from CT radiation exposure.

Cardiac CT Technique Overview

Visualization of the coronary arteries is technically challenging because these vessels are small (<5 mm in diameter proximally) and are subject to rapid cyclic motion [22]. Eliminating physiologic motion to allow

<table>
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<tr>
<th>Study</th>
<th>E / DLP (mSv / mGy × cm)</th>
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<tr>
<td>Head</td>
<td>0.0023</td>
</tr>
<tr>
<td>Chest</td>
<td>0.017</td>
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<td>Abdomen</td>
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<td>Abdomen and pelvis</td>
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motion-free CT images entails two approaches: minimizing image acquisition time by optimizing image reconstruction and gantry rotation, and gating image acquisition to the most motion-free portion of the cardiac cycle. Using current CT acquisition algorithms, a minimum of 180° of raw scan data are required for image reconstruction. One hundred eighty-degree reconstruction algorithms are universally used in cardiac CT as compared with the 360° reconstruction algorithms used in other body regions. Although these algorithms minimize image acquisition time, there are associated compromises in signal-to-noise ratio and spatial resolution. The entire 180° of data may be acquired in one heartbeat or can be built up over a number of heartbeats in a segmented reconstruction. Segmented reconstructions can suffer from blurring due to beat-to-beat variability in the position of the coronary arteries. At the gantry level, raw scan data are acquired as quickly as possible using the fastest available x-ray tube rotation time, typically less than 350 milliseconds. The combination of reconstruction and gantry time optimization allows acquisition of 180° of scan data in approximately 165 milliseconds for a single-tube system and 85 milliseconds for a dual-tube system. The cardiac-gating scheme targets this rapid scan data acquisition to the most motion-free phase of the cardiac cycle, diastole, defined as the end of rapid ventricular filling but before atrial contraction. Diastole typically occurs at 60–80% of the R-R interval. Diastole is longer at lower heart rates, accounting for the decrease in image quality observed at higher heart rates and the drive to image patients with heart rates less than 70 beats per minute. Heart rate variations or premature contractions can dramatically alter the location and duration of diastole relative to the ECG and lead to sections having poor image quality. The second most motion-free portion of the cardiac cycle occurs in end-systole (25–45% of the R-R interval). This time segment can also be targeted for cardiac CT.

**Radiation Dose in Cardiac CT**

The greatest flexibility for the reconstruction of motion-free images is provided by retrospectively gated helical acquisitions. These scans use a low helical pitch (0.2–0.5, depending on the heart rate and single vs dual tube) to obtain CT attenuation measurements (raw scan data) at all spatial locations in the heart in all phases of the cardiac cycle. The raw scan data set and a digital recording of the patient’s ECG signal are stored on the scanner database. Selective reconstruction of these data allows viewing of the coronary arteries at any time point in the R-R interval. Using images reconstructed at 5% or 10% increments, cine images of the beating heart can be created that show the chamber wall and valve motion. For the coronary arteries, the most motion-free reconstruction interval can be found by viewing images at a specified location at 5% increments through the cardiac cycle. The entire cardiac volume can then be reconstructed at the most motion-free interval. Alternatively, algorithms have been developed to detect minimum motion in the raw scan data and automatically target image reconstruction to this time point (“best diastole reconstructions”). Finally, if the heart rate and pitch factor are low enough, there may be sufficient redundancy in the raw scan data set to allow an entire heartbeat to be dropped without missing a spatial location in the heart. In this situation, the data set is doubly redundant. Using this facility, the ECG can be manually edited to remove premature ventricular contractions or individual heartbeats with an anomalous rate, improving image quality in specific coronary segments. Depending on the heart rate and pitch factor used, a large amount of the raw scan data obtained in helical retrospective acquisitions may never be viewed.

The large reconstruction flexibility of helical retrospective acquisitions comes with a cost: high radiation exposure. As with all helical scans, radiation exposure scales according to the pitch factor. Compared with a helical chest CT scan using a pitch factor of 1, helical retrospective acquisitions using identical kVp, mA, and gantry rotation time but a modified pitch factor of 0.2 deliver 5 times the radiation dose. For this reason, reported effective radiation dose in recent studies using 64-MDCT have ranged from 9 to 32 mSv [23, 24]. Given these high dose values, a number of dose reduction strategies have been developed.

**ECG-Correlated Tube Current Modulation**

ECG-correlated tube current modulation is added to retrospectively gated helical acquisitions to reduce tube current and radiation exposure during the high-motion portions of the cardiac cycle, when cardiac motion precludes successful reconstruction of the coronary arteries. Using ECG modulation, the tube current is at its maximum during mid-diastole (60–80% of the R-R interval) and is reduced by approximately 46–80% for the remainder of the cardiac cycle. This allows the production of high-quality thin slices of the coronary arteries during diastole and lower-quality, higher-noise images of the cardiac chambers and valves for the remainder of the cardiac cycle (Fig. 3). This has been shown to reduce radiation exposure by 37% on 64-MDCT cardiac scanners in patients with a stable sinus rhythm while maintaining diagnostic quality [25]. More recent technical advances allow more extensive manual selection of the minimum tube current, changes in the duration of the full tube current, and improved detection and handling of arrhythmias, with potentially greater radiation dose reduction. We recommend that all retrospectively gated helical coronary

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**Fig. 2—**60-year-old man with 30-pack-year history of smoking. **A** and **B**, Transverse 1-mm-collimation unenhanced chest CT scans viewed at lung parenchymal settings (window, 1,500 HU; level, –700 HU). Stage IA 7 × 5 mm pathologically proven adenocarcinoma (arrow) in apical segment of right upper lobe is seen equivalently on low-dose screening examination (40 mAs; dose-length product [DLP], 107 mGy × cm; effective dose, 1.8 mSv) (**A**) and high-dose CT scan for fuzzy wire-guided excision biopsy (130 mAs; DLP, 368 mGy × cm; 6.3 mSv) (**B**).
CT angiograms use ECG tube current modulation unless optimal image quality is required throughout the entire cardiac cycle (e.g., valve or cardiac mass assessment).

**Prospective Axial Gating**

Although retrospectively gated helical scanning was the primary acquisition technology at the introduction of cardiac CT, a new, more radiation-efficient strategy, the prospectively gated transverse acquisition, has been developed [26] (Fig. 4). This acquisition technique acquires 40-mm-thick sections through the heart at 60–80% of the R-R interval with the table stationary. The table is then advanced incrementally by 35 mm during the next heartbeat and another 40-mm-wide section is obtained, triggered by the following heartbeat. In this fashion, the entire cardiac volume is acquired over five to seven heartbeats. This acquisition results in an effective pitch of 0.875. The reduction from a pitch of 1.0 arises from the 5-mm overlap between adjacent acquisitions. This overlap reduces the potential to miss a segment of the coronary arteries if the heart comes to a slightly different position between beats. In addition, the tube current is turned on only during diastole, another form of ECG tube current modulation. The combination of the elevated pitch factor and ECG tube current modulation results in a radiation dose reduction of 77% over retrospectively gated helical acquisitions [27]. Because the prospectively gated transverse technique does not scan in systole, there is no potential to produce cine images of the chamber walls or valves. Increasing the duration of the acquisition at each location allows a multisegment reconstruction that provides limited evaluation of heart motion. Because there is no redundant data acquisition, this technique is less tolerant of arrhythmias. In the current iteration of this protocol, heart rates are limited to less than 70 beats per minute, which in the reported trial was achieved in 92% of the patients [28] (Figs. 5 and 6).

**Tube Voltage Reduction**

Typically, adult CT protocols use 120 kVp as the standard tube voltage. Recent research has shown diagnostic image quality using 100 or 80 kVp in small adult and pediatric subjects, respectively [25, 29]. Reduced tube voltage increases subject contrast, especially when imaging contrast-enhanced vessels, due to the K-edge of iodine. The limitation of decreased kVp scanning is increased noise levels and higher tube heating due to increased tube current. In small or average-sized patients, this is not problematic, but increased noise makes this technique unacceptable in larger patients.

**Scan Length**

A further dose reduction strategy is the accurate specification of the scan volume. Using retrospectively gated helical acquisitions, a scan length reduction of 1 cm results in an approximate dose savings of 1 mSv. Prescribing the scanned volume from the topogram obtained at the same level of inspiration as the cardiac CT scan can optimize the scanned volume. This can reduce radiation dose compared with using a standard scan volume extending from the carina to the mid liver.

**Attenuation-Dependent Tube Current Modulation**

In the past, the tube current of CT scanners was uniform at all angles around the patient and for the full longitudinal (cranio-caudal) extent of the scan. However, the chest is an elliptical object that has higher attenuation from left to right than from anterior to posterior. Attenuation also varies as a result of the chest being scanned in the cranio-caudal direction because of the shoulders. CT image quality is disproportionately degraded.
Radiation Dose in Cardiac CT

by views with few photons (photon starvation) compared with the image quality improvement associated with views with high photon counts. To address this issue, manufacturers have introduced programs that adjust the tube current depending on the attenuation of the object in both the transverse (x, y) and the longitudinal (z) directions to minimize either photon-starved or photon-rich projections, maximizing image quality while minimizing radiation dose. This tube current modulation technique has been shown to produce a substantial reduction in radiation dose [30–32] with minimal degradation of image quality in non–cardiac-gated studies. Routine use of dose modulation systems is recommended because they compensate for asymmetry in the size and density of the body section being scanned, resulting in a signal-to-noise ratio that is adequate for diagnosis but not excessive [33]. Advanced tube current modulation schemes with novel reconstruction algorithms are being developed to reduce radiation dose to superficial radiation-sensitive tissues such as the breast and thyroid. Further experience with these new radiation dose modulation systems is required before they can be widely used.

Dose modulation systems may interact with the patient position and x-ray beam filters, producing an increased radiation dose in patients who are incorrectly centered in the CT gantry. Algorithms to automatically center patients are being developed [34]. In longitudinal research studies, careful attention to scanning parameters and patient positioning is an important component of both radiation dose reduction and interscan reproducibility. Finally, repeated scanning of the same region increases the radiation dose in a linear fashion. Therefore, the timing of follow-up examinations involves a trade-off between additional information and the radiation dose detriment of the associated dose buildup effect.

Appropriateness Criteria for Cardiac CT Studies

A critical element in cardiac CT dose reduction lies in screening requests to ensure that all studies are appropriate. Well-established clinical guidelines for performing coronary CT angiography [35] have largely limited indications to symptomatic patients at intermediate risk who have equivocal stress-test results. Because no dose reduction strategy can lower dose to a greater extent than not performing the examination, patient selection is key. Triaging patients for the examination should go beyond ensuring appropriate clinical indications and extend to evaluation of the coronary calcium scoring scanning performed before the cardiac CT angiographic study. Because patients with a high coronary calcium burden and associated elevated Agatston scores prove problematic for accurate stenosis evaluation at cardiac CT angiography [36], proceeding with this high dose in the setting of a high calcium score is of questionable value. In this situation, alternative tests such as nuclear perfusion imaging may better serve the patient.

Cardiac CT Image Quality

Reduction in CT radiation exposure results in increased image noise and decreased image quality. Studies assessing the subjective evaluation of chest CT scans have shown that radiologists consistently gave higher image quality scores to images obtained with a higher radiation dose [37, 38]. The choice of reconstruction algorithm affects image noise, with higher noise associated more with high-spatial-frequency reconstruction algorithms (e.g., bone or lung algorithms) than with lower-spatial-frequency algorithms (e.g., standard soft-tissue algorithm). In cardiac CT, high-spatial-frequency reconstruction algorithms are most commonly used to assess stents. The increased noise associated with these algorithms is usually not a diagnostic problem because the level of contrast en-

Fig. 5—54-year-old man with atypical chest pain.
A, Orthogonal projection type of image of aortic valve at end-diastole (75% of R-R interval) with valve leaflets coapted.
B, Orthogonal gray scale inversion CT image at same level as A during systole (35% of R-R interval) with ECG dose modulation displays normal valve opening. Note diagnostic image quality was achieved with dose reduction of approximately 75%.

Fig. 6—54-year-old man with atypical chest pain.
A, Curved multiplanar reformatted image using low-dose prospective axial scanning technique displays extensive noncalcified plaque in left anterior descending artery with short-segment occlusion.
B, Axial image displays similar features without sacrificing image quality.
hancement is high. New adaptive reconstruction algorithms are being developed that can decrease image noise, providing improved image quality at a lower radiation dose. These advanced algorithms should further facilitate radiation dose reduction.

Conclusion

The development of cardiac-gated CT has introduced a powerful new diagnostic tool for cardiac disease, with the negative issue of increased radiation exposure. Currently, the radiation dose from cardiac CT is high, although a number of dose reduction strategies have been introduced that preserve image quality. The detrimental effect of radiation dose in the range provided by cardiac CT has been confirmed by a 15-country study [9]. Further research is required to produce reference dose values to guide the practice of cardiac CT. Radiologists need to monitor the radiation dose delivered in cardiac CT examinations at their institutions and to investigate further dose reduction strategies in their own practices. Further research into the complex relationship between radiation exposure, image noise, and diagnostic accuracy should be encouraged to scientifically establish the minimum radiation doses that provide adequate diagnostic information for standard clinical questions in cardiac CT.

As dispensers of a known carcinogen, radiologists must take the lead in promoting all of these measures for patient protection. Because children, young adults, and women, especially pregnant women, have been shown to have increased radiation sensitivity, the most strident dose reduction efforts should be focused on these groups. Finally, the complexity of CT requires close collaboration between radiologists and medical physicists to successfully reduce radiation dose while maintaining diagnostic accuracy.

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