

Guidelines

SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT

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Abstract. Over the last few years, computed tomography (CT) has developed into a standard clinical test for a variety of cardiovascular conditions. The emergence of cardiovascular CT during a period of dramatic increase in radiation exposure to the population from medical procedures and heightened concern about the subsequent potential cancer risk has led to intense scrutiny of the radiation burden of this new technique. This has hastened the development and implementation of dose reduction tools and prompted closer monitoring of patient dose. In an effort to aid the cardiovascular CT community in incorporating patient-centered radiation dose optimization and monitoring strategies into standard practice, the Society of Cardiovascular Computed Tomography has produced a guideline document to review available data and provide recommendations regarding interpretation of radiation dose indices and predictors of risk, appropriate use of scanner acquisition modes and settings, development of algorithms for dose optimization, and establishment of procedures for dose monitoring.

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Preamble

Noninvasive imaging with cardiovascular computed tomography (CT) has rapidly evolved over the past several years, and radiation dose reduction has been an important area of development. The Society of Cardiovascular

Computed Tomography has formed a Radiation Committee to provide guidance for CT imagers about critical topics in the areas of radiation dosimetry, projected cancer risk, and optimization of scan techniques in terms of radiation dose and its monitoring in adult patients referred for cardiovascular CT. Development of guiding principles includes

Conflict of interest: The authors report their conflicts of interest in Appendix 1.

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consideration of not only radiation dose but also the clinical benefit of information obtained through imaging, which may lead to superior patient outcomes.

A guideline document has been developed to review available data and to provide recommendations about interpretation of radiation dose indices and predictors of risk, scanner acquisition modes and settings, algorithms for dose optimization, and dose monitoring. A Writing Group of the Radiation Committee conducted several telephone conferences, email exchanges, and in-person meetings to determine necessary topics and content for the guideline document. Recommendations were proposed for each main topic area on the basis of published literature and consensus about best practices. Final recommendations were unanimously approved by the Radiation Committee. Recommendations appear individually near relevant text within the document and are summarized in a single table (Table 1).

The Society of Cardiovascular Computed Tomography Guidelines Committee makes every effort to avoid any actual or potential conflicts of interest that might arise as a result of an outside relationship or a personal interest of a member of the Guidelines Committee (Appendix 1) or its Writing Group (Appendix 2) or External Peer Review Group (Appendix 3). Specifically, all members of the Guidelines Committee and of the Writing Group and External Peer Review Group were asked to provide disclosure statements of all such relationships that might be perceived as real or potential conflicts of interest relevant to the document topic. This information about relationships with industry for Committee, Writing Group, and External Peer Review Group members is published in the appendices of the document. These disclosures are reviewed by the Guidelines Committee and updated as changes occur.

Introduction

As recently documented, case fatality rates for cardiovascular morbidity and mortality in the United States and other developed countries have been significantly reduced over the past 40 years.¹ From 1997 to 2007, death from cardiovascular disease has declined by 27.8%.² These successes coincide with decreases in risk factor prevalence, advances in treatment strategies, and innovations in noninvasive cardiovascular imaging. In particular, cardiovascular computed tomography (CT) imaging with or without the administration of iodinated contrast has recently developed into a robust, readily available modality that expedites the accurate diagnostic triage of patients at risk of cardiovascular disease. In addition, cardiovascular CT has already replaced some diagnostic procedures that carry a higher risk or are of inferior accuracy.

Several distinct cardiovascular CT procedures are used routinely in clinical practice. These include coronary calcium scanning; coronary CT angiography; noncoronary

cardiovascular CT imaging for myocardial disease, pericardial disease, valvular heart disease, cardiac masses, congenital heart disease, aortic disease, and venous disease; and combined systemic and pulmonary arterial phase CT angiography, which is commonly referred to as triple rule-out CT. Research is ongoing for some additional applications, including stress/rest myocardial CT perfusion imaging.

Noncontrast coronary calcium scanning allows clinicians to quantify calcified atherosclerotic plaque and allows for lower radiation doses (1–3 millisieverts [mSv]) because of less-demanding requirements for spatial resolution and image noise.³ Coronary CT angiography, however, requires high spatial and temporal resolution and low noise, which results in a wider range of radiation doses across patients and imaging facilities (1–20 mSv).^{4,5}

Noncoronary cardiovascular CT indications have various imaging requirements, which should be tailored to provide only the information necessary for diagnosis. It is important to note that a tailored examination for noncoronary cardiovascular CT frequently does not meet the requirements for adequate evaluation of the coronary arteries. Despite lower radiation exposure per rotation for some noncoronary cardiovascular CT scans, higher patient doses than are used in coronary artery imaging are sometimes required because greater z-coverage is needed (eg, for evaluation of the pulmonary arteries and aorta).

Different radiation exposure requirements exist for stress/rest myocardial CT perfusion. This technique typically requires several repeated CT acquisitions of the same imaging volume (rest, stress, possibly noncontrast, and delayed enhancement).

CT use has more than doubled over the past 10 years; an estimated 62 million CT scans were performed in 2006 in the United States.⁶ A recent report estimated that approximately 2.3 million chest CT angiograms and 0.6 million coronary calcium scans were performed in 2007.⁷ Not surprisingly, then, radiation exposure from CT, including cardiovascular CT, and the associated biologic risk have been the focus of considerable discussion and controversy.^{8,9}

The use of cardiovascular CT, similar to any diagnostic procedure involving ionizing radiation, requires consideration of the benefit–risk ratio and whether an alternative nonradiation procedure might be sufficient for diagnosis in a particular patient. However, when applied in clinically appropriate patients, CT has a potential benefit to the person that far outweighs the projected small stochastic risk of development of radiation-induced malignancy.

Even though no evidence exists to link radiation received from medical imaging with malignancies, radiation protection philosophy espouses the theory that some risk is associated with even small doses of ionizing radiation. Hence, the ALARA principle, which states that the radiation dose to a patient should be As Low As Reasonably Achievable, is generally accepted. However, a radiation dose level exists below which certain scans may become

Table 1 Summary of recommendations listed by section heading or subheading containing relevant text within the document**Radiation dose standards and measurements**

The volume CT dose index (CTDI_{vol}) [expressed in units of mGy] should be used for optimizing cardiovascular CT protocols.

The dose-length-product (DLP) [expressed in units of mGy-cm] should be used for comparing radiation doses and characterizing radiation dose from a cardiovascular CT study.

Radiation risk

Estimations of stochastic risk from radiation delivered during medical imaging examinations should be interpreted cautiously, considering the uncertain relationship between dose and risk at low levels of radiation dose.

Potential risk of future stochastic events must be balanced with the potential benefits of the examination and potential risks of forgoing the examination or obtaining a nondiagnostic examination because of excessive dose reduction.

General methods for radiation dose reduction**Appropriate use criteria**

Cardiovascular CT should only be performed if indicated by best available evidence and published guidelines, appropriate use criteria, or certain clinical scenarios or patient-specific clinical factors/comorbidities that support testing for a given patient.

The cardiovascular CT imaging protocol should be tailored to the clinical question and patient characteristics.

Scan modes

Retrospective ECG-gated helical techniques may be used in patients who do not qualify for prospective ECG-triggered scanning because of irregular heart rhythm or high heart rates or both (specific value depends on specific scanner characteristics and cardiovascular indication).

Prospective ECG-triggered axial techniques should be used in patients who have stable sinus rhythm and low heart rates (typically <60–65 beats/min, but specific values depend on specific scanner characteristics and cardiovascular indication).

For prospective ECG-triggered axial techniques, the width of the data acquisition window should be kept at a minimum.

Tube potential

A tube potential of 100 kV could be considered for patients weighing ≤ 90 kg or with a BMI ≤ 30 kg/m²; a tube potential of 120 kV is usually indicated for patients weighing >90 kg and with a BMI > 30 kg/m². Higher tube potential may be indicated for severely obese patients.

Tube current

If retrospective ECG-gated helical data acquisition is indicated, ECG-based tube current modulation should be used except in patients with highly irregular heart rhythm.

The scanner default tube current values should be adjusted, based on each individual patient's size and clinical indication, to the lowest setting that achieves acceptable image noise.

Scan length

The scan length should be set at the minimum length clinically necessary.

Reconstruction slice thickness

Images should be reconstructed with the greatest possible slice thickness for the given cardiovascular CT indication, and the tube current should be adjusted with the understanding that a lower tube current can be used with the reconstruction of thicker slices.

Predictors of radiation dose with cardiac CT

Use of breast shields is not recommended for cardiovascular CT.

Imaging centers (especially those initiating coronary CT angiography and those with lower case volumes) may participate in collaborative quality improvement programs.

Applying algorithms for dose optimization in clinical practice

Individual sites should consider developing site-specific algorithms for radiation dose optimization, which should be reviewed and revised if needed at least annually.

Considerations for coronary calcium scoring

Coronary calcium scans should be performed with prospective ECG-triggered axial or prospective ECG-triggered helical techniques, a 120-kV tube potential, a patient size-adjusted tube current, and the widest beam collimation that allows for reconstruction of 3-mm slices.

Considerations for coronary CT angiography

If coronary calcium scans can only be performed with retrospective ECG-gated helical scanning, ECG-based tube current modulation should be used along with a 120-kV tube potential, a patient size-adjusted nominal tube current, and the widest beam collimation that allows for reconstruction of 3-mm slices.

If possible, the patient's heart rate during scanning should be <65 beats/min and ideally <60 beats/min for coronary CT angiography (specific values depend on specific scanner characteristics and cardiovascular indication) to provide the best image quality and allow use of lower-dose acquisition modes.

Considerations for noncoronary cardiovascular CT

For some noncoronary cardiovascular CT studies, lower-dose settings can be used and thicker slices reconstructed to achieve acceptable image noise.

Pulmonary vein anatomic mapping CT studies may be best performed with non-ECG-referenced or single heartbeat techniques for patients with atrial fibrillation.

Dose monitoring

CTDI_{vol} [expressed in mGy] and DLP [expressed in mGy-cm] should be recorded for each patient.

Review of sites' radiation levels and adherence to institutional algorithms for radiation dose optimization should be performed at least twice per year.

uninterpretable, which would remove the potential benefit from the test and significantly alter the benefit–risk ratio for patients. A nondiagnostic study may lead to additional imaging and thereby to substantially higher net radiation, or to inappropriate invasive testing, delayed or lack of targeted treatment, or nontreatment. For example, too little radiation exposure for a given patient during coronary CT angiography can result in excessive image noise and unevaluable coronary segments. It is therefore critically important to appropriately balance the desire to achieve low radiation doses with the likelihood of obtaining a useful diagnostic image.

Radiation dose standards and measurements

CTDI, CTDI_w, and CTDI_{vol}

The fundamental dose parameter in CT is the CT dose index (CTDI). The CTDI represents the average absorbed dose along the longitudinal axis from a single exposure that would produce 1 tomographic image. This value is obtained from measurement during an axial CT scan and is calculated by dividing the absorbed dose at the axis by the total x-ray beam width. The CTDI is commonly measured with a 100-mm length ionization chamber (CTDI₁₀₀) placed in a standard polymethyl methacrylate (Plexiglas) phantom of 16- or 32-cm diameter.¹⁰

The variation in dose distribution from periphery to center within the imaging (x-y) plane is accounted for by averaging CTDI values to obtain a weighted sum. The CTDI_w is the sum of one-third the CTDI value measured at the center and two-thirds the CTDI value measured at the periphery. To determine the dose for a specific CT protocol, which almost always involves a series of scans, gaps or overlaps between the radiation-dose profiles from consecutive rotations of the x-ray tube must be taken into account. This is accomplished by use of a dose descriptor known as the volume CTDI (CTDI_{vol}). CTDI_{vol} is the ratio of the CTDI_w to the level of overlap between rotations. For helical CT, the level of overlap is indicated by pitch (Section 4.5). Therefore, CTDI_{vol} is the ratio of CTDI_w to pitch (CTDI_w/pitch). For axial CT, the level of overlap depends on the number of rotations (N), the total nominal beam width in mm (T), and the increment between rotations in mm (I), such that $CTDI_{vol} = CTDI_w \times ((N \times T)/I)$.

CTDI_{vol} is the most accessible dose indicator because it is automatically displayed on CT scanners. Because the method to derive CTDI_{vol} is uniform among manufacturers, this value can be used to directly compare the radiation dose from different scanner protocols. However, CTDI_{vol} is only an index of the patient radiation dose from a particular scanner for a particular protocol and derived from a cylindrical Plexiglas phantom examination

and should not be misinterpreted as a direct patient dose measurement.

Recommendation

The volume CT dose index (CTDI_{vol}) [expressed in units of mGy] should be used for optimizing cardiovascular CT protocols.

Dose-length-product

CTDI_{vol} is the same across CT scans that extend short or long distances in the longitudinal or z-direction; however, the total amount of radiation delivered to the patient varies. This is reflected by the dose-length-product (DLP) measure, which is the product of CTDI_{vol} and the scan length. On most CT scanners, DLP is displayed after completion of the scan along with CTDI_{vol} and can be used for estimating radiation dose and risk from a specific CT scan.

Recommendation

The dose-length-product (DLP) [expressed in units of mGy-cm] should be used for comparing radiation doses and characterizing radiation dose from a cardiovascular CT study.

Absorbed dose, organ dose, and effective dose

Absorbed dose, which is indirectly measured in CT, is the amount of energy absorbed by various tissues in the body. The absorbed dose for various organs is expressed as organ dose. Absorbed doses are greatest in those organs in the path of the primary x-ray beam. Organs adjacent to the primary beam receive only internal scatter. For example, in cardiovascular CT, the main organs in the path of the primary x-ray beam are the heart, part of the lungs and mediastinum, part of the muscle, breasts, and skin.

The radiation risk from cardiovascular CT imaging is typically estimated and expressed by the concept of effective dose. The effective dose is a dose parameter that describes a nonuniform exposure to radiation in terms of its risk compared with that resulting from a uniform whole-body exposure.¹¹ This measure takes into account all of the organs exposed during a CT scan and their corresponding sensitivities to radiation-induced mutagenic changes.

Given specific knowledge about individual scanner characteristics, the effective dose, expressed in mSv, can be estimated from sophisticated Monte Carlo simulations in which absorbed doses to various organs are adjusted by a weighting factor that accounts for organ sensitivity, patient age, and patient sex. In clinical practice, a reasonable estimate of effective dose can be obtained by multiplying the DLP provided by the scanner with a weighting factor (k), in which k depends only on the exposed body regions (not

patient age, sex, or size). A k value of 0.014 mSv per mGy-cm for the chest^{12,13} is currently used for estimating effective dose from cardiovascular imaging procedures for adult patients (a size-corrected factor is used for pediatric patients). This factor has been subject to change in the past and will most likely be revised in the future with the emergence of new data from epidemiologic studies and models relating cancer risk and hereditary disease to radiation dose.¹⁴

The use of this single conversion factor for all adult patients is thought to underestimate dose for cardiovascular CT because the value is independent of the specific CT scanner and scan mode,¹⁵ as well as patient size and sex.¹⁶ In addition, the use of a chest conversion factor that assumes imaging of the entire chest, rather than just the heart, is thought to underestimate dose for cardiac CT scanning.¹⁷

Despite these limitations, effective dose values estimated from the scanner DLP aid in determining radiation risk for different CT scans and comparing radiation risk among various x-ray imaging procedures.^{5,18} Effective dose estimates also permit comparison of risk from different sources of ionizing radiation, including other medical sources (eg, nuclear medicine scans) and environmental sources (eg, background radiation from radon, cosmic radiation, terrestrial radiation).⁶

The effective dose is the dose quantity most commonly used to relate exposures from low doses of ionizing radiation to the probability of detrimental health effects. However, it must be recognized that effective dose is associated with a level of uncertainty on the order of $\pm 40\%$ when it is used to quantify dose for medical exposures.¹⁴ The concept of effective dose has been developed for use in occupational radiation protection; it is not intended to express absolute patient-specific risk (ie, risk to specific individuals of known age, sex, and size) but rather risk to the general population. However, the concept of effective dose might be helpful in comparing the biological risk of different medical procedures that use ionizing radiation.

Radiation risk

Health effects

Two primary detrimental health effects are associated with ionizing radiation: stochastic effects and deterministic effects. A stochastic effect of radiation is one in which the probability of the effect, rather than its severity, increases with radiation dose. Radiation-induced cancer and genetic effects are stochastic in nature. For example, the probability of radiation-induced leukemia is substantially greater after an exposure to 1 Gy than to 1 mGy, but there will be no difference in the severity of the disease if it occurs.

There are other effects in which the probability of causing biological harm is zero at small radiation doses, but, above a threshold dose, the probability increases rapidly as the dose increases. The severity of the effect

also increases with increased dose beyond the threshold. Such effects are called deterministic or nonstochastic effects and include cataracts, skin burns, erythema, epilation, and even death. Possible stochastic effects from radiation at dose levels required for CT are associated with a latency period of 10–30 years,¹⁹ whereas most deterministic effects are usually observed almost immediately.

Stochastic effects are regarded as the principal health risk from medical radiation and thus from exposures during cardiovascular CT procedures. Deterministic effects from x-ray-based modalities are typically limited to procedures in which the x-ray tube remains in the same position for repeated imaging of the same anatomic location, such as x-ray fluoroscopy, and are therefore not usually a concern with CT. The exception is CT perfusion studies, in which there is a risk of deterministic effects when these tests are performed in addition to other x-ray-based diagnostic imaging studies²⁰ or when they are performed improperly.

Risk models

Radiation effects on biological systems are well documented at high energy levels such as those required for radiation therapy. However, radiation levels commonly seen in diagnostic imaging, including x-ray, CT, and fluoroscopy, are comparatively low, and there is no strong evidence to indicate an occurrence of biological effects similar to those observed with high dose levels. Radiation doses for most cardiovascular CT scans fall within the range of low doses (0.5–30 mSv).

Numerous models exist for describing the relationship between exposure to low doses of radiation and the risk of stochastic effects. These include hormesis, linear-no-threshold, and supralinear models. Hormesis, at one extreme, is the hypothesis that chronic exposure to low doses of ionizing radiation is beneficial,^{21–23} stimulating otherwise dormant repair mechanisms that protect against disease. At the other extreme, supralinearity describes a dose-response relationship, with a steeper slope at lower radiation dose levels compared with higher radiation dose levels (ie, risk increases more rapidly at low levels of exposure). The prevailing theory for radiation protection is based on the conservative linear-no-threshold hypothesis that falls between these two extremes. This hypothesis presumes that risk is directly proportional to dose at all dose levels, such that some risk is associated with even the smallest doses of radiation.

The linear-no-threshold model was primarily developed for the protection of workers exposed to radiation but has also been applied to patients undergoing medical imaging. This has led to some controversy, because there are insufficient data to support this model; in addition, for patients undergoing medical imaging procedures, the benefits from such procedures can outweigh the potential associated risks.^{24–26} Generally, the linear-no-threshold phenomenon is well supported for high radiation dose levels (Sv) but not for low radiation dose levels (mSv).

Lifetime attributable risks

The leap from radiation exposure to the risk of stochastic effects such as cancer is controversial, particularly for individual patients, because of known uncertainties in dose estimates and risk models.

Lifetime attributable risks are described in statements such as the Biological Effects of Ionizing Radiation (BEIR VII) report.²⁷ Risk estimations are based on studies that were performed in atomic bomb survivors in Hiroshima and Nagasaki after World War II and indicate risk from any type of radiation. The lifetime attributable risk increases dramatically at high dose levels (>500 mSv). At lower levels, risk estimations have a wide margin of error.

Assuming that cardiovascular CT doses normally fall in the range of 0.5 to 30 mSv, the lifetime attributable risk from a single cardiovascular CT procedure is very small, particularly in the context of other exposures and other life risks; notably, the risk of cardiovascular disease.⁹ The risk of fatal malignancy or death posed by exposure to ionizing radiation from coronary CT angiography is 2 to 6 times lower than the risk from exposure to the average amount of arsenic in drinking water and the average amount of radon in a home in the United States.⁹ The risk is also much lower (2–24 times lower) than the lifetime odds of dying from drowning, a pedestrian accident, passive smoking, or a motor vehicle accident.⁹

Recommendations

Estimations of stochastic risk from radiation delivered during medical imaging examinations should be interpreted cautiously, considering the uncertain relationship between dose and risk at low radiation dose levels.

Potential risk of future stochastic events must be balanced with the potential benefits of the examination and potential risks of forgoing the examination or obtaining a nondiagnostic examination because of excessive dose reduction.

High-risk groups

Determinants of radiation risk include not only radiation dose levels but also patient size, age, and sex. Smaller patients are at greater risk than larger patients from the same amount of radiation exposure because smaller patients absorb much higher amounts of the radiation in the more radiosensitive organs. For larger patients, exit radiation is much less intense than entrance radiation because of x-ray attenuation by the patient's body; for smaller patients, exit and entrance radiation levels are of similar intensity. Smaller patients therefore show a smaller radiation dose gradient from the center to the periphery and higher absolute values of absorbed doses.²⁸ It is important to

note, then, that although higher x-ray parameter settings are required for imaging of heavier patients, the increased x-ray exposure does not necessarily increase radiation risk in these patients.²⁹

Younger patients are at greater risk than older patients from the same radiation dose because of their longer life expectancy and the latency period associated with stochastic health effects from ionizing radiation. In addition, pediatric patients are at greater risk than adult patients because the cells of pediatric patients are dividing more rapidly. Sex also contributes to differences in risk because organs vary in radiosensitivity, and the organs of interest for imaging of the chest are different for men and women. Because of breast tissue, women are at greater risk than men from the same radiation exposure during a cardiovascular CT examination.

General methods for radiation dose reduction

Several scanner features are designed to reduce radiation exposure by preventing x-rays not contributing to the final formation of the image from reaching the patient; these features are applied by default with the selection of the scan mode. These include prepatient z-collimators³⁰ and cardiac-specific x-ray filters.³¹

Numerous data acquisition parameters can be modified to reduce radiation dose. These can be broadly grouped as primary and secondary factors. Primary factors include scan acquisition modes, x-ray tube potential, x-ray tube current, and pitch (for helical scanning).¹¹ Secondary factors include scan length and scan field of view (on some systems). Both primary and secondary factors can be modified automatically or manually to directly reduce radiation dose.

Selection of some image reconstruction parameters provides an indirect means of reducing dose by altering image quality and by prompting the scanner operator to change data acquisition parameters that directly influence dose. Examples include the use of noise-reducing reconstruction algorithms and the reconstruction of thicker slices; advanced planning of these reconstruction options allows for selection of lower tube settings before data acquisition, thus reducing radiation exposure.

In this section, methods for adjusting user-modifiable parameters to optimize radiation dose are discussed. The various methods presented can and should be used in combination; some dose-reduction strategies are additive, and the combined use of these strategies can result in very low doses with diagnostic image quality in appropriate patients. The information presented here highlights the need for intelligent systems implemented at the scanner console that provide recommendations for the optimal combination of patient-specific dose-related parameters to the technologist/physician.

Appropriate use criteria

The most powerful strategy for reducing radiation exposure is to avoid unnecessary studies through the application of appropriate use criteria. The usefulness of cardiovascular CT is generally accepted for several indications but is considered inappropriate for other indications.³² Therefore, the potential risks of cardiovascular CT imaging have to be weighed against the benefit to the patient according to currently available appropriate use criteria.

Different scan protocols and techniques for radiation dose optimization can be applied for different indications. Some cardiovascular indications (assessment of coronary arteries, cardiac valves) require high spatial and temporal resolution, associated with a higher radiation dose, whereas other indications (assessment of pulmonary vein, myocardium) may permit imaging with lower spatial and temporal resolutions and, subsequently, lower radiation doses. In addition, clinical needs can determine tolerable noise levels. For example, if anomalous origin and course of coronary arteries is to be determined in young patients, then a higher noise level may be tolerable, and aggressive radiation dose-reduction techniques may be considered.

Recommendations

Cardiovascular CT should only be performed if indicated by best available evidence and published guidelines, appropriate use criteria, or certain clinical scenarios or patient-specific clinical factors/comorbidities that support testing for a given patient.

The cardiovascular CT imaging protocol should be tailored to the clinical question and patient characteristics.

Scan modes

CT data are acquired with either helical (also known as spiral) or axial scans. In the helical scan mode, data are acquired during continuous rotation of the gantry and simultaneous translation of the patient table. In the axial scan mode, data are typically acquired during a full (360-degree) or partial (180-degree + fan-angle of the detector) rotation of the x-ray tube and detector system around the patient while the patient table is stationary; the patient table moves along the z-axis between periods of data acquisition.

For cardiovascular CT scans that do not require electrocardiogram (ECG)-synchronization (eg, imaging of the descending aorta for stent planning), helical scanning is typically performed because it offers the advantage of shorter scan times compared with non-ECG-referenced axial scanning on most systems. Most cardiovascular CT indications, however, require correlation of data acquisition or reconstruction to the cardiac cycle to obtain images during a desired cardiac phase. This is accomplished with

the use of the patient's ECG signal to either prospectively trigger data acquisition or retrospectively gated data reconstruction.

With low-pitch helical scanning, data are typically retrospectively gated to a simultaneously recorded ECG signal; data are acquired continuously until the entire scan length is covered and then retrospectively referenced to the ECG signal during image reconstruction. Synchronization of axial scanning with the cardiac cycle is accomplished using the ECG signal to prospectively trigger data acquisition during only the desired cardiac phase. Some scanners capable of achieving very high pitch values permit the acquisition of prospective ECG-triggered helical data; helical data acquisition is initiated by the patient's ECG signal and continues until the entire scan length is covered.³³

Retrospective ECG-gated helical scan

Retrospective ECG-gated helical scanning, which is very robust and less prone to motion artifacts, has been considered the conventional scan technique for cardiovascular CT for many years. In retrospective ECG-gated helical scanning, x-ray data are acquired throughout the entire cardiac cycle with a continuous rotation of the gantry and simultaneous table movement. CT data are retrospectively gated to a simultaneously recorded ECG signal, allowing for retrospective ECG-gated image reconstruction at defined time points within the cardiac cycle. If the tube current is maintained at the nominal output (100%) throughout the cardiac cycle, images can be reconstructed at identical image noise levels at any time point of the cardiac cycle (eg, from 0% to 99% of the R-R interval).

For cardiovascular CT, the associated radiation dose for retrospective ECG-gated helical scanning is highest when the tube current is at a maximum throughout the cardiac cycle. However, for most cardiovascular indications, including coronary CT angiography, only CT data from the cardiac phase with the least motion (eg, the mid-diastolic or end-systolic phase) are usually used for image reconstruction so that cardiac motion artifacts are minimized. A large amount of CT data outside of these cardiac phases, then, is not needed. Accordingly, algorithms have been developed that modulate the tube current according to the patient's ECG signal, with the full tube current applied during the relevant phases of the cardiac cycle and the tube current down-regulated to lower levels during the remaining phases (see "ECG-based tube current modulation in helical data acquisition"). With the use of these algorithms, the radiation burden with retrospective ECG-gated helical scanning drops significantly. When applied to evaluation of the coronary arteries, a 40% reduction in radiation dose values has been reported for ECG-dependent tube current modulation in clinical practice.³⁴

For coronary artery evaluation, retrospective ECG-gated helical scanning is preferred for patients with high heart rates or irregular heart rhythms. Retrospectively ECG-gated

techniques are, theoretically, less sensitive to arrhythmia; most scanner software allows for the deletion of extra systolic beats, the insertion of nondetected R-peak markers, and the shifting of R-peak markers to adjust for arrhythmia.³⁵ Other advantages of the retrospectively ECG-gated helical technique for some cardiovascular applications (eg, valvular assessment) include the ability to reconstruct data from multiple cardiac phases throughout the cardiac cycle. For evaluation of long scan lengths (eg, for aortic dissection), retrospective ECG-gated helical scanning offers the advantage of shorter scan times compared to axial scanning on some systems.

Recommendation

Retrospective ECG-gated helical techniques may be used in patients who do not qualify for prospective ECG-triggered scanning because of irregular heart rhythm or high heart rates (specific value depends on specific scanner characteristics and cardiovascular indication) or both.

Prospective ECG-triggered axial scan

Prospective ECG-triggered axial scanning has emerged more recently as a lower-dose alternative to retrospective ECG-gated helical scanning. Axial data acquisition is initiated after the detection of an R peak and is limited to only a predefined phase of the R-R interval (eg, phase with greatest likelihood of minimal cardiac motion). X-ray emission is then suspended while the patient table is moved to the next z-axis position, and the process is repeated until the entire scan length is covered. The total number of required axial data acquisitions (steps) decreases with an increase in total nominal beam width (product of the number of active detector rows and the individual detector row width), occasionally referred to as z-coverage, and can be as little as one (ie, no table movement) with the use of wide z-coverage scanners (eg, 320-row CT). Images can be reconstructed only during the prespecified phase of data acquisition, which limits functional analysis. Some scanners do permit axial data acquisition during two phases (eg, diastole and end systole) of the cardiac cycle, thus expanding the possibilities for functional analysis but increasing x-ray exposure.

Researchers have reported substantially lower radiation dose estimates and in many cases improved image quality for prospective ECG-triggered axial scanning compared with retrospective ECG-gated helical scanning for coronary CT angiography.^{36–41} Available experience with prospective ECG-triggered axial coronary CT angiography suggests that diagnostic studies can be obtained at doses of 1–6 mSv.^{36–39,41–46} The comparability of retrospective ECG-gated helical and prospective ECG-triggered axial scans in terms of image quality was established in a large randomized, multicenter, noninferiority trial.⁴⁰ In this trial,

which included 400 selected patients with mean heart rate of 55 ± 6 beats/min, the image quality score was comparable between the scan modes, whereas radiation exposure was significantly lower (69%) with axial scans (3.5 ± 2.1 mSv) compared with helical scans (11.2 ± 5.9 mSv). Because prospective ECG-triggered axial scanning is an effective approach for lowering radiation dose in cardiovascular CT, the use of this scan mode should be strongly considered when it is available on the scanner. However, patients need to be carefully selected for this scan technique; compared with retrospective ECG-gated helical scanning, prospective ECG-triggered axial scanning is more susceptible to cardiac motion artifacts, particularly in patients with high or irregular heart rates, because appropriate timing of data acquisition within a given R-R interval relies on accurate estimates of the duration of the upcoming R-R interval. A low and stable heart rate, then, is considered a prerequisite for achieving diagnostic image quality with prospective ECG-triggered axial scanning, particularly for evaluation of the coronary arteries^{40,44,47} in a high percentage of patients. On the basis of available data, a heart rate of <65 beats/min is generally suggested as a cutoff for axial scanning of the coronary arteries. Scanners with faster rotation times or an increased number of x-ray source/detector systems or both and, subsequently, higher temporal resolution may permit higher heart rate cutoffs.⁴⁸

Some additional data beyond the minimum required for image reconstruction can be acquired to permit minor retrospective adjustments of the reconstruction window, potentially reducing cardiac motion artifacts, but these adjustments come at the expense of increased radiation exposure. As a consequence, the data acquisition window should be kept as narrow as possible. So far, there are minimal scientific data showing a diagnostic benefit of widening the data acquisition window in patients with a low and stable sinus rhythm; however, standard use of a wider window is associated with a considerable increase in radiation exposure for coronary imaging.⁴⁹ Many manufacturers have also introduced automated arrhythmia rejection methods that postpone axial data acquisition until the heart rate stabilizes if an irregularity is detected. However, the utility of such algorithms has not been systematically evaluated.

Other potential limitations of axial imaging on some CT systems are misalignment artifacts and long scan times as a result of having to move the patient table between data acquisitions. Artifacts can arise from axial data acquisition when slight differences in the position of the heart or phase of the cardiac cycle occur between acquisitions. Misalignment of images that cover critical structures (eg, coronary arteries) can also compromise image analysis. The probability of a misalignment artifact appearing in the reconstructed image set decreases with the number of steps needed to cover the anatomy of interest when the heart rate is low and regular.

It is important to note that prospective ECG-triggered axial scanning can also be combined with other measures such as a reduced tube potential in selected patients, which will result in further reduction of radiation exposure.

Recommendations

Prospective ECG-triggered axial techniques should be used in patients who have stable sinus rhythm and low heart rates (typically <60–65 beats/min, but specific values depend on specific scanner characteristics and cardiovascular indication).

For prospective ECG-triggered axial techniques, the width of the data acquisition window should be kept at a minimum.

Prospective ECG-triggered axial scan with wide detector arrays

Wide detector arrays with ≤ 320 detector rows allow acquisition of a maximum of 16 cm along the z-axis per gantry rotation. Such wide coverage enables acquisition of data from the entire heart during two heartbeats with only one table movement^{50,51} or even at a single time point within one cardiac cycle without table movement.^{52,53} Single heartbeat acquisition with 320-row CT, introduced in 2008, eliminates misalignment artifacts and provides temporal uniformity, because there is no time delay for imaging from the base to the apex of the heart. The temporal acquisition window of not only each slice but also of the entire cardiac volume with the use of a 320-row CT is approximately 175 milliseconds when single heartbeat imaging is used.

However, because of the slower gantry rotation time (350 milliseconds) required with the current 320-detector row scanner configuration, a low and stable heart rate (cutoff of approximately 65 beats/min) is required for single heartbeat imaging. Patients with higher heart rates can still be imaged on these systems by obtaining multiple prospective ECG-triggered axial data acquisitions at the same table position (covering the entire heart) during consecutive heart cycles and combining data with multicycle reconstruction algorithms to improve effective temporal resolution. However, this improved temporal resolution is achieved at the cost of significantly increased radiation exposure.^{52–54}

Prospective ECG-triggered high-pitch helical scan

With the advent of dual-source CT configuration, the prospective ECG-triggered high-pitch helical scan mode was introduced in 2009.^{55,56} With conventional ECG-gated helical data acquisition, pitch values are typically considerably <1 (eg, 0.22), which indicates that the table is advanced by much less than one detector row width during one rotation of the scanner. Thus, the same region within the heart is exposed during several consecutive rotations, which increases radiation dose. With single-source CT systems, pitch is limited to a maximum value of 1.5 for gapless

data acquisition in the z-direction. At higher pitch values, data gaps occur, which may result in image artifacts and errors in image reconstruction. However, with second-generation dual-source CT, the second tube/detector system is used to fill the data gaps; accordingly, the pitch can be increased to values >3.⁵⁷ This results in very short CT data acquisition times.

The acquisition time for a typical coronary CT angiogram is approximately 300 milliseconds, allowing for data acquisition during a single diastolic phase. Early studies have shown the feasibility of prospective ECG-triggered high-pitch helical scanning for coronary CT angiography in patients with a low and stable heart rate (<60 beats/min) with doses consistently <1 mSv when combined with tube potentials of 100 kV.^{4,58,59} The utility of this technique for imaging of the aorta has also been shown, although longer scan lengths and subsequently longer scan times spanning multiple cardiac cycles are required.^{60,61}

Tube potential

The tube potential is the electrical potential applied across an x-ray tube to accelerate electrons toward a target material, expressed in units of kilovolts (kV). Tube potential determines the energy of the x-ray beam. Tube potentials ranging from 80 to 140 kV are available for diagnostic imaging on commercial CT scanners, with 120 kV being the tube potential most commonly used.

Radiation exposure with CT is approximately proportional to the square of the tube potential, such that a reduction in tube potential from 120 to 100 kV results in a 31% reduction in dose (assuming no other changes to dose-related parameters are made).⁶² Reducing the tube potential lowers the energy of x-rays, which reduces their penetration capability and increases noise. Image noise is proportional to 1/tube potential, such that a reduction in tube potential from 120 to 100 kV results in a 20% increase in image noise.

As with x-ray tube current, x-ray tube potential can be adjusted according to patient size to avoid unnecessary exposure in slimmer patients. Higher tube potentials of 120 to 140 kV are used for scanning obese patients; lower tube potentials of 80 to 100 kV are reserved for scanning thin patients and children.⁶³ In practice, selection of a lower tube potential may require an increase in tube current in some patients to minimize the negative effect on image noise while maintaining a net decrease in x-ray exposure.

Small studies have reported promising results for image quality and radiation dose with the use of an 80-kV tube potential for coronary CT angiography in adult patients with a body weight ≤ 60 kg⁶⁴ or BMI <22.5 kg/m².⁶⁵ However, because of the increase in image noise with 80-kV imaging, diagnostic noninferiority, and the ability to assess small vessel pathologies such as noncalcified coronary plaques need to be investigated in further studies

before 80-kV scan protocols can be recommended for coronary CT angiography in clinical practice.

A tube potential of 100 kV was applied very infrequently during cardiovascular CT in the past,^{62,66} but several small studies and a large randomized, multicenter trial have robustly shown the noninferiority of image quality of 100-kV versus 120-kV imaging of coronary arteries in nonobese adult patients.^{34,45,47,66–71} Although size cutoff thresholds may depend on the specific scanner used, on the whole these studies support 100-kV imaging for patients weighing ≤ 90 kg or with a BMI ≤ 30 kg/m².^{68,72} In markedly obese patients, higher tube potentials such as 135 or 140 kV

might be considered for obtaining diagnostic image quality with acceptable image noise⁷³; however, there is a paucity of data to support recommendations for size cutoffs for cardiovascular imaging. Further, appropriate size cutoffs for the highest tube potentials may be too dependent on CT scanner performance, namely maximum tube output, to permit a general recommendation.

Note that reducing tube potential also results in increased attenuation of the vessel lumen and cardiac chambers when iodinated contrast media are used. This may necessitate changes in the contrast injection protocol to achieve acceptable contrast-to-noise ratios.⁷⁴ In addition, an adjustment of the attenuation threshold level (eg, to slightly higher values for 100 compared to 120 kV imaging) might be needed when an automatic bolus tracking method is used. Lower tube potentials within the diagnostic imaging range are also associated with improved image contrast. Therefore, 80-kV scan protocols might be appropriate or even necessary in some cardiovascular applications, specifically myocardial CT perfusion imaging because of the better delineation of differences in myocardial contrast attenuation.

Recommendation

A tube potential of 100 kV could be considered for patients weighing ≤ 90 kg or with a BMI ≤ 30 kg/m²; a tube potential of 120 kV is usually indicated for patients weighing >90 kg and with a BMI > 30 kg/m². Higher tube potential may be indicated for severely obese patients.

Tube current

The tube current, expressed in milliamperes (mA), is the number of electrons accelerated across an x-ray tube per unit of time and is one of the primary factors that can be modified to reduce radiation exposure. The product of tube current and scan time is the tube current-time product, expressed in milliamperere-seconds (mAs). Both tube current and tube current-time product affect CT dose in a direct and linear manner; these factors also affect image noise.¹¹ If the tube current is lowered while all other technical factors are

kept constant, the radiation dose will be lowered but the CT image may become grainy (noisy) because fewer x-rays are used in its formation.¹¹ A 20% reduction in tube current, for instance, results in a 20% reduction in radiation exposure. However, this dose reduction is achieved at the expense of increased image noise; image noise is proportional to $1/\sqrt{\text{tube current (mA)}}$, such that a 20% reduction in tube current results in a 12% increase in image noise.

Certain CT manufacturers use the concept of effective tube current-time product, defined as the ratio of the tube current-time product to pitch (pitch is defined below). In such CT scanners, to compensate for the increase in image noise when pitch is increased, the tube current is also increased to maintain constant image noise.⁷⁵

Numerous opportunities exist, however, for decreasing x-ray tube current and, subsequently, radiation exposure while still achieving acceptable image noise. For cardiovascular imaging, these include ECG-based and anatomic-based approaches.

ECG-based tube current modulation in helical data acquisition

Although retrospective ECG-gated helical scanning occurs throughout the cardiac cycle, images are reconstructed only during a specified cardiac phase. A large amount of CT data from outside this phase is not used; this prompted the development of algorithms that modulate the tube current according to the patient's ECG signal, with the tube current fully applied during the most relevant phases of the cardiac cycle and reduced or even shut off⁷⁶ during the remaining phases, which are less likely to be motion free (eg, early systole). When a reduced (but nonzero) tube current is applied during certain phases, data are still available throughout the entire cardiac cycle, but image quality is limited during periods of low current. In this case, although retrospective reconstruction of thin slices (<1 mm) of helical data (eg, for coronary evaluation) is restricted to the maximum tube current windows, reconstruction of image series during multiple phases (eg, for functional evaluation such as measurement of left ventricular volumes) may still be possible.⁷⁷ Reconstruction of thicker slices will decrease excessive noise in down-regulated phases and may permit functional assessment. X-ray exposure during retrospective ECG-gated helical CT can be reduced $\geq 50\%$ depending on patient heart rate,⁷⁸ the minimum tube current value,^{76,79} and the duration of the maximum tube current phase.^{80,81}

ECG-based tube current modulation, however, imposes limitations on helical imaging of patients with irregular heart rates. Because ECG-based tube current modulation is prescribed on the basis of averaging previous R-R interval lengths, changes in heart rate could result in unintended lowering of the tube current during a desired phase of reconstruction for a given cardiac cycle. Several manufacturers have developed strategies for increasing the robustness of ECG-based modulation for patients with irregular

heart rates. Widening the maximum tube current duration increases the utility of ECG-based tube current modulation for patients with irregular heart rates but at the expense of increased radiation exposure. For patients with severe arrhythmia, some systems temporarily suspend or permanently switch off ECG-based tube current modulation if beat-to-beat variation exceeds a threshold value during data acquisition. The risk of improperly timed downward modulation of the tube current is virtually eliminated with this safeguard but, again, at the cost of increased radiation exposure. Although radiation exposure with respect to traditional approaches to ECG-based tube current modulation is increased with both strategies, exposure is still less than if ECG-based tube current modulation is not used.⁸²

Anatomy-based tube current adaptation

The x-ray tube current can be reduced for slimmer patients imaged with axial or helical techniques, thus significantly lowering radiation exposure. Attenuation of the incident x-ray beam decreases with the thickness of the tissue between the x-ray source and the detector, such that less radiation exposure is required to penetrate thinner tissues and achieve the desired image noise. Patients can be assigned to size categories on the basis of visual inspection, weight,⁸³ BMI, cross-sectional body measurements from scout images,^{84,85} or noise measurements from a cross-sectional prescan⁸⁶; the tube current can then be adjusted manually to a predefined value.

Online adaptation of tube current to patient size can also be used to reduce the dose. The x-ray tube current can be modulated automatically along the x-y plane and the z-dimension during scanning on the basis of local tissue thickness (determined from a chest radiograph [also known as topogram, scout, surview, etc]) without affecting image noise.⁸⁷ Tube current is reduced at projection angles and table positions in which patient anatomy requires less x-ray penetration. Online anatomy-based tube current adaptation has been shown to reduce radiation exposure to the thorax by 20% compared with a fixed tube current without affecting image noise.⁸⁷ However, anatomy-based tube current modulation during ECG-referenced imaging is not commonly used and may not even be available on some scanners. Even on systems that provide anatomy-based adaptation for ECG-referenced imaging, ECG-based tube current modulation is given priority during helical imaging; anatomy-based modulation is used only to determine the nominal tube current necessary to achieve the desired noise level on the basis of patient attenuation in the scout image. Hence, a nominal tube current value is automatically selected before scanning on the basis of patient size, and online tube current modulation is performed during the scan on the basis of only the ECG signal.

In summary, adjustment of tube current on the basis of patient size before imaging is a useful dose-reduction

strategy for all cardiovascular CT scans, whereas online adaptation of the tube current is restricted to non-ECG-referenced cardiovascular CT scans.

Recommendations

If retrospective ECG-gated helical data acquisition is indicated, ECG-based tube current modulation should be used except in patients with highly irregular heart rhythm. The scanner default tube current values should be adjusted, based on each individual patient's size and clinical indication, to the lowest setting that achieves acceptable image noise.

Pitch

The concept of pitch is applicable only to helical scanning. Pitch is defined as the ratio of table travel (mm) per gantry rotation to total nominal beam width.⁷⁵ The spatial distribution of individual scans during helical imaging is described by the pitch; an increase in the pitch results in less overlap between successive data acquisitions, whereas a decrease results in more overlap.⁸⁸ Radiation dose is inversely proportional to pitch, such that a 2-fold increase in pitch results in a 50% reduction in dose (assuming all other parameters are held constant). For cardiac multidetector-row CT, pitch is independent of noise.⁸⁸ The relationship between pitch and spatial resolution in the z-direction depends on the type of interpolation algorithms selected during image reconstruction.

Cardiac imaging with the use of a helical scan with a fast gantry rotation time (eg, 330 milliseconds) typically requires a low pitch (eg, 0.2) to avoid gaps in the imaged volume; a pitch too high for the patient's heart rate results in the table moving too far between consecutive cardiac cycles for the data to be adequately sampled.⁸⁸ This is of particular concern when multicycle reconstruction algorithms that use data from ≥ 2 consecutive cardiac cycles (rather than a single cardiac cycle) are used to reconstruct each image.⁸⁹ In contrast, the latest generation of dual-source CT technology permits ECG-triggered helical scanning at very high pitch values (see also "Prospective ECG-triggered high-pitch helical scan"). By interleaving data measured from 2 detector systems separated by approximately 90 degrees, pitch can be increased up to 3.4.³³ Helical scanning with such high pitch values reduces the amount of redundant data collected, thus substantially decreasing radiation exposure.

Scan length

For cardiovascular imaging, the scan length is typically defined with the use of anatomic landmarks on an anterior-posterior projection image similar to a chest radiograph. The scan length determines the extent of the irradiated

portion of the body in the z-direction and is therefore directly proportional to patient radiation exposure. The scan length should be set at the lowest value possible that will still allow for the clinical question to be answered. The scan length can vary considerably for cardiovascular indications; a scan length of 100 mm may be sufficient for evaluation of the coronary arteries in some patients, whereas 650-mm coverage might be required for evaluation of the thoraco-abdominal aorta.

For coronary imaging in the absence of coronary anomalies, bypass grafts, etc, the scan should typically be started at the mid to lower level of the main pulmonary artery, although a location just below the tracheal carina is frequently used, because this is a more readily apparent anatomic landmark. The coronary scan is usually extended through the apex of the heart. Other areas, such as the aortic arch, should be excluded unless otherwise indicated. If noncontrast or coronary calcium scans are acquired for clinically indicated reasons, these can be used to verify the appropriate selection of the starting and ending z-positions before CT angiography acquisition.⁹⁰ Margins of 10 mm superior and inferior to the most cranial and caudal slices of the noncontrast coronary images that include all portions of the native coronary vessels and the lower portions of the heart have been proposed as appropriate starting and ending z-positions.⁹⁰ These margins account for any variations that might occur as a result of breath-hold inconsistencies.

The scan end should be prespecified, but the scan should be manually stopped (if allowed by the scanner) if the desired anatomy is covered before the programmed value for the ending z-position is reached. To allow for optimal scan length planning, patients should be advised before the cardiovascular CT study to perform each breath-hold at a similar inspiration depth to minimize differences in the position of the diaphragm and heart between scans.

Recommendation

The scan length should be set at the minimum length clinically necessary.

Acquisition FOV

Even though the CT gantry has a physical opening of ≥ 70 cm, the actual acquisition field of view (FOV) is smaller (approximately 50 cm); therefore, the anatomy of interest (cardiac region) has to be within the scan FOV for image reconstruction. Information from outside the acquisition FOV is not available for image reconstruction, so care must be taken to insure that the entire region of interest is included within the acquisition FOV. In addition, filters (flat and beam-shaping [bow-tie] filters)¹¹ placed closer to the x-ray tube absorb unhelpful low-energy x-ray photons. Typically, the beam-shaping filters are of standard

size (small, medium, and large) to accommodate all patient sizes. In certain CT systems, special filters are available for cardiac imaging with the intent to further reduce dose. The radiation dose difference between filter sizes can be as high as 25% when all other parameters are held constant. Careful selection of correct filters for the right patient size is key, because incorrect acquisition FOV can affect both radiation dose and image quality. Modification of the reconstructed FOV, the region over which image data are reconstructed, is typically restricted to a value less than or equal to the acquisition FOV and has no effect on the radiation dose.

Iterative reconstruction algorithm

One option for decreasing x-ray exposure is to use noise-reducing statistical iterative reconstruction algorithms.⁹¹ In general, iterative reconstruction algorithms assume initial attenuation coefficients for all voxels and use these coefficients to predict projection data. Predicted projection data are compared with actual, measured projection data, and voxel attenuations are modified until the error between estimated and measured projection data is acceptable.

Several different iterative reconstruction techniques are currently available from scanner manufacturers. Iterative reconstruction of CT images can be performed on image data, raw (projection) data, or both. Compared with standard analytical reconstruction methods that are based on filtered back projections, statistical iterative reconstruction produces equivalent signal-to-noise ratios at lower radiation doses without a loss in spatial resolution.⁹² Therefore, data can be acquired at lower tube parameter settings (tube current and potential). Algorithms that operate in part or in full on the raw data are more complex and more time consuming but may offer the additional advantages of improved low-contrast detectability and fewer streak artifacts. Although some experience with iterative reconstruction of cardiovascular CT data has been described in the literature,^{34,93–96} iterative reconstruction algorithms are in their infancy; further development of and experience with these algorithms may expand their use in cardiovascular imaging.

Reconstruction slice thickness

With filtered back-projection, the reconstructed slice thickness determines the number of absorbed x-ray photons contributing to the CT image and, subsequently, image noise. Noise is proportional to $1/\sqrt{\text{reconstructed slice thickness}}$, such that a 3-mm thick image has 73% less noise than a 1-mm thick image if the radiation dose level is maintained. With true iterative reconstruction, there is an uncoupling of noise and slice thickness, but the modified iterative reconstruction techniques currently implemented on clinical CT scanners preserve some dependency of noise on slice thickness.

This relationship between slice thickness and noise allows a decrease in radiation dose (through a reduction in x-ray tube potential or current) with an increase in slice thickness while maintaining the same image noise. However, because the decrease in radiation dose comes at the cost of decreased spatial resolution, this dose-saving strategy is not appropriate for evaluation of small cardiac structures such as the coronary arteries. The reconstruction of thicker images is indicated for non-contrast-enhanced evaluation of coronary calcium and the evaluation of larger cardiovascular structures (eg, aorta, pulmonary vein).

It should be stressed that increasing reconstructed slice thickness (a reconstruction parameter) has no direct effect on x-ray exposure. It is incumbent on the user to concurrently lower the x-ray tube potential or current (data acquisition parameters) with increased reconstructed slice thickness to lower the patient radiation dose.

Recommendation

Images should be reconstructed with the greatest possible slice thickness for the given cardiovascular CT indication, and the tube current should be adjusted with the understanding that a lower tube current can be used with the reconstruction of thicker slices.

Predictors of radiation dose with cardiovascular CT

Patient-related factors

Heart rate and regularity

Heart rate is the primary determinant of radiation dose and image quality for many patients imaged with ECG-synchronized scan modes. Across a broad spectrum of techniques and study sites, heart rate and heart rate regularity during scanning have been found to be significant independent predictors of radiation dose for coronary CT angiography,^{62,90} a cardiovascular application with little tolerance for motion artifacts. Most of the dose-reduction strategies described earlier depend on a steady and low heart rate (<70 beats/min, and preferably <60 beats/min in most cases), because a consistently wide diastolic time interval is needed with techniques such as ECG-based tube current modulation, prospective ECG-triggered axial scanning, and prospective ECG-triggered high-pitch helical scanning. Without adequate patient preparation (generally, β -blocker drugs), it is rare that this goal is achieved. It is important to remember that even with resting heart rates in the range of 50–60 beats/min, without modest β -blockade, adrenergic drive induced by intravenous contrast injection and other scan-related stimuli may result in rapid acceleration of heart rate, resulting in inconclusive results. Factors that affect

resting heart rate and heart rate response to β -blockade, such as anxiety, may lead to increased radiation dose, although this has not been rigorously studied.^{97,98}

Body size and weight

Body weight has a profound effect on the selection of parameters that influence radiation exposure in cardiovascular CT. Patient weight and BMI have been shown to be independent predictors of radiation exposure for coronary CT.^{62,90} Because of tissue attenuation and x-ray scatter, heavier patients tend to require higher tube potential and current settings to achieve acceptable noise levels and to make diagnostic results possible. In many cases, it is advantageous to use standard charts to calculate BMI. However, patients with similar BMI but substantially different weight distribution to the upper body may have significantly different noise levels at the same tube settings. For example, patients with low body weight or low BMI may still have large amounts of breast tissue and are more likely to have excessive noise levels at lower tube settings. Therefore, adjustment of x-ray parameter settings should be performed judiciously. As mentioned previously, higher x-ray exposure does not necessarily mean higher radiation risk for heavier patients (see “High-risk groups”).²⁹

Age

In one large-scale clinical study, increasing age was associated with higher radiation exposure, independent of other factors.⁹⁰ The reasons for this are not entirely clear, because multivariable analysis eliminated the confounding factors of protocol selections (eg, tube potential, scan length, use of ECG-based tube current modulation with helical scanning). It is possible that the lowered probability of long-term cancer induction in these patients (see “High-risk groups”) has led to the use of higher exposure protocols.

Sex

Male sex has been associated with higher radiation exposures for coronary CT angiography independent of other patient or scan protocol characteristics.⁹⁰ Awareness of the potentially higher sensitivity of breast tissue to cancer induction may lead to an increased use of lower exposure protocols in women, although this information has not been verified in available studies.

One strategy that has been considered to reduce radiation exposure to breast tissue in women is the placement of breast shields. Shields placed superficially on the breast during cardiovascular CT scans can provide some protection from the entrance radiation dose. Studies have shown a substantial reduction in breast dose when bismuth shields are placed over the breast during chest CT scans, but image noise was increased.^{99–102} Further, shields may create image artifacts and reduced image quality beneath the shielded area.

When anatomic-based tube current modulation is to be used, the greatest dose reduction is achieved if the breast shields are placed after the completion of the scout/topogram scan, because most anatomic-based tube current modulation techniques estimate patient thickness and density on the basis of this initial scan. If the breast shields are placed before the scout scan, the scanner might increase the dose while scanning over the breast shields.

Unlike routine CT scans, cardiovascular CT scans are usually performed with ECG-based tube current modulation techniques instead of or in addition to anatomic-based tube current modulation techniques, making the challenges involved in breast shield use even greater. Because tube current modulation is performed on the basis of the patient's ECG signal, inclusion of breast shields may cause streak artifacts that might diminish image quality.¹⁰³ An additional concern about breast shield use is that there will always be some internally scattered radiation that cannot be avoided.¹⁰⁴

The use of breast shields should be evaluated carefully, taking into consideration the logistics of breast shield use, hygiene, and cost. Experts agree that all other steps to reduce overall radiation dose need to be implemented before the use of breast shields. Optimizing a protocol by reducing the tube current and other scan parameters may have a greater effect on radiation exposure to the patient than will the use of specific patient shields.^{100–102}

Recommendation

Use of breast shields is not recommended for cardiovascular CT.

CT imaging center-related factors

Imaging center experience and volume

As with other diagnostic and therapeutic procedures, quality assurance registry studies have confirmed that radiation dose is lower in imaging centers that have been operating longer and have a higher volume of cases.^{66,90} Thus, imaging centers initiating cardiovascular CT programs and those with lower case loads need to take advantage of additional training to overcome the hurdle these conditions impose.

Imaging center training

Cardiovascular CT, and in particular coronary CT angiography, is a difficult procedure to do well. Many protocol decisions are required to optimize dose and image quality. There is good evidence that special dose-reduction training results in sustained lower median doses, and this is especially true in lower-volume centers.⁹⁰

Imaging center staffing

The division of labor at a given imaging center can have a major effect on median dose. If the general staff of an imaging center rotates through the cardiac-capable scanner, or if cardiovascular CT is provided at multiple sites within a large institution, it is unlikely that all staff members will be highly skilled in dose-optimization procedures. Thus, a highly trained, specialized group of nurses and technologists to prepare and scan patients for cardiovascular CT is advantageous.

Scanner-related factors

Among vendors and specific scanner models, there are considerable differences in CT design and features (eg, number of x-ray sources, maximal x-ray tube output, gantry rotation speed, number of detector rows, maximal table speed, and available image reconstruction algorithms). Caution should be used when transferring scan protocols from one manufacturer and model to another, because optimal values for many imaging parameters are scanner specific.

Protocol-related factors

The specific CT protocol is obviously the ultimate determinate of radiation exposure. Specific parameter settings are influenced by patient-related factors, cardiovascular-related factors, and scanner-related factors, as described above. For cardiovascular imaging, selection of the acquisition mode and the exact implementation of ECG-based tube current modulation (helical scan) or the width of the data acquisition window (axial scan) typically have the biggest effect on radiation exposure, followed by selection of tube potential and tube current and planning of scan length. The effect of acquisition mode selection and parameter changes on radiation dose is described in detail in "General methods for radiation dose reduction".

Recommendation

Imaging centers (especially those initiating coronary CT angiography and those with lower case volumes) may participate in collaborative quality improvement programs.

Applying algorithms for dose optimization in clinical practice

This section discusses considerations for performing cardiovascular CT with optimal diagnostic image quality and radiation exposure as low as reasonably achievable. Although these general considerations and recommendations can be applied to most patients, the wide variety of CT scanners currently in use provide additional or slightly

different approaches or newer techniques for radiation dose optimization, which could be used in appropriate conditions.

Individual sites should consider developing site-specific algorithms for radiation dose optimization that take into account the cardiovascular indication, scanner characteristics and capabilities, patient heart rate and variability, and patient body habitus. These settings should be tailored to individual patients, but a standardized algorithm may be helpful as a starting point in formulating dose-appropriate protocols.^{105,106} The information presented in this section provides a basis for the development of such algorithms.

Recommendation

Individual sites should consider developing site-specific algorithms for radiation dose optimization, which should be reviewed and revised if needed at least annually.

Considerations for coronary calcium scanning

Coronary calcium scanning has been shown to have significant prognostic value for future cardiac events independent of conventional cardiac risk factors.¹⁰⁷ Prognostic information about calcium scores is analogous to Framingham risk scoring, in that the data for both are based on asymptomatic patients undergoing screening for future coronary events.

At some centers, it is felt that the ability to precisely identify the upper and lower boundaries of the coronary arteries with a preliminary coronary calcium scan reduces scan length sufficiently to justify its use in every patient undergoing coronary CT angiography.¹⁰⁸ In addition, some centers use calcium scoring as a screening tool in selected patients before coronary CT angiography to determine the extent of calcification. If calcification is severe, the coronary CT angiogram is not performed. However, it is important to note that with the trend of decreasing dose for coronary CT angiography, the addition of a calcium scoring scan can significantly increase the relative radiation burden of the total examination. Thus, clinical judgment must dictate whether to perform a coronary calcium scan before coronary CT angiography.

Coronary calcium scanning was first performed with electronic beam CT before multidetector-row CT became available. At present, most coronary calcium scanning is performed on 64-slice or higher scanners; the dose is highly dependent on imaging technique but should range from 1 to 3 mSv for scans using an appropriate protocol.³ Prospective ECG-triggered axial scanning for coronary calcium scanning are available on most scanners; if this technique is available, it should be used to minimize dose. Alternatively, some dual-source scanners offer prospective ECG-triggered high-pitch helical scan modes that may also provide a lower

dose option for coronary calcium scanning. If only retrospective ECG-gated helical scanning is available, ECG-based tube current modulation should be used with the period of high tube current limited to the narrowest possible window and the lowest current setting chosen outside this window. With all techniques, the reconstructed slice thickness should be 3 mm, as submillimeter resolution is not necessary and requires increased dose to achieve acceptable image noise.

A recent study reported excellent correlation of Agatston scores in the same patients undergoing scans with tube potentials of 100 kV and 120 kV, with dose reductions of approximately 40% with the lower tube potential.¹⁰⁹ This lower tube potential approach was used regardless of body weight, unlike in coronary CT angiography. Because of the increased x-ray absorption of calcium at this lower tube potential (and the subsequent increase in calcium attenuation), modifications to standard analysis, including an increase in the threshold for calcium identification, are required. Although lowering the tube potential would provide significant dose savings, calcium scanning at 100 kV is not currently recommended for routine use because of the required modifications to image analysis and the paucity of clinical data available.

Recommendations

Coronary calcium scans should be performed with prospective ECG-triggered axial or prospective ECG-triggered helical techniques, a 120 kV tube potential, a patient size-adjusted tube current, and the widest beam collimation that allows for reconstruction of 3-mm slices.

If coronary calcium scans can only be performed with retrospective ECG-gated helical scanning, ECG-based tube current modulation should be used along with a 120 kV tube potential, a patient size-adjusted nominal tube current, and the widest beam collimation that allows for reconstruction of 3-mm slices.

Considerations for coronary CT angiography

Coronary CT angiography for the diagnosis or exclusion of obstructive coronary artery disease is the leading indication for performing cardiovascular CT studies. As the specific coronary CT angiography protocol is selected, the risk of nonevaluability of coronary segments has to be balanced with the minimization of radiation dose.

The main contributing factors to unevaluable coronary artery segments include significant motion artifacts,¹¹⁰⁻¹¹³ a low contrast-to-noise ratio,¹¹⁴ and the presence of dense calcification.^{111,112,115} Generally, the risk of finding nonevaluable segments on coronary CT angiography is determined on the basis of patient-specific parameters, such as patient heart rhythm, rate, and variability; patient size; and calcium burden. Therefore, before the initiation of

coronary CT angiography, these basic patient characteristics should be assessed.

The importance of controlling heart rate to minimize motion artifact and to reduce radiation exposure has been described in detail earlier and in the 2009 SCCT Guidelines for Performance of Coronary Computed Tomographic Angiography.⁷² The regularity of the heart rhythm and the heart rate are important guides for the selection of the scan protocol. Because diagnostic image quality is highly dependent on heart rate, it is strongly recommended that coronary CT angiography should be performed at heart rates below 65 beats/min or even 60 beats/min, if possible. If a stable sinus rhythm with a heart rate below 60–65 beats/min is present, scans with reduced radiation exposure, such as prospective ECG-triggered axial or helical scans, can be applied while image quality is maintained.

If the CT scanner does not support prospective ECG-triggered data acquisition, then retrospective ECG-gated helical scan protocols with an “aggressive” ECG-controlled tube current modulation should be used in patients with a stable sinus rhythm and a heart rate below 60–65 beats/min (Fig. 1). Such aggressive algorithms for ECG-controlled tube current modulation are characterized by two features: a very narrow diastolic phase in which the full tube current is applied and a maximally reduced

tube current in the remaining time of the R-R interval. The very narrow time period during which the full tube current is applied usually allows for assessment of the coronary arteries at one or two closely related phases of the R-R interval (eg, 65% and 70%); the maximally reduced tube current still allows for functional analysis of ventricular wall motion and ejection fraction, if desired.

Options for dose reduction are more limited in patients with higher-than-ideal heart rates or without a stable sinus rhythm. In patients with tachycardia, the likelihood of obtaining diagnostic image quality without motion artifacts for the assessment of coronary arteries is decreased because of the limited temporal resolution of CT. Thresholds for heart rates above which the likelihood of nondiagnostic image quality is high may vary among CT scanner systems, resulting in considerably higher dose levels. Patients with frequent premature beats represent a similar patient population, in which the reconstruction of diagnostic images is often difficult. In such patients with tachycardia or arrhythmia, the need for >1 reconstructed phase of the R-R interval for accurate assessment of the coronary arteries is increased. Therefore, retrospective ECG-gated helical scan protocols are thought to provide the highest likelihood of yielding diagnostic coronary images. The use of ECG-controlled tube current modulation is still feasible in most

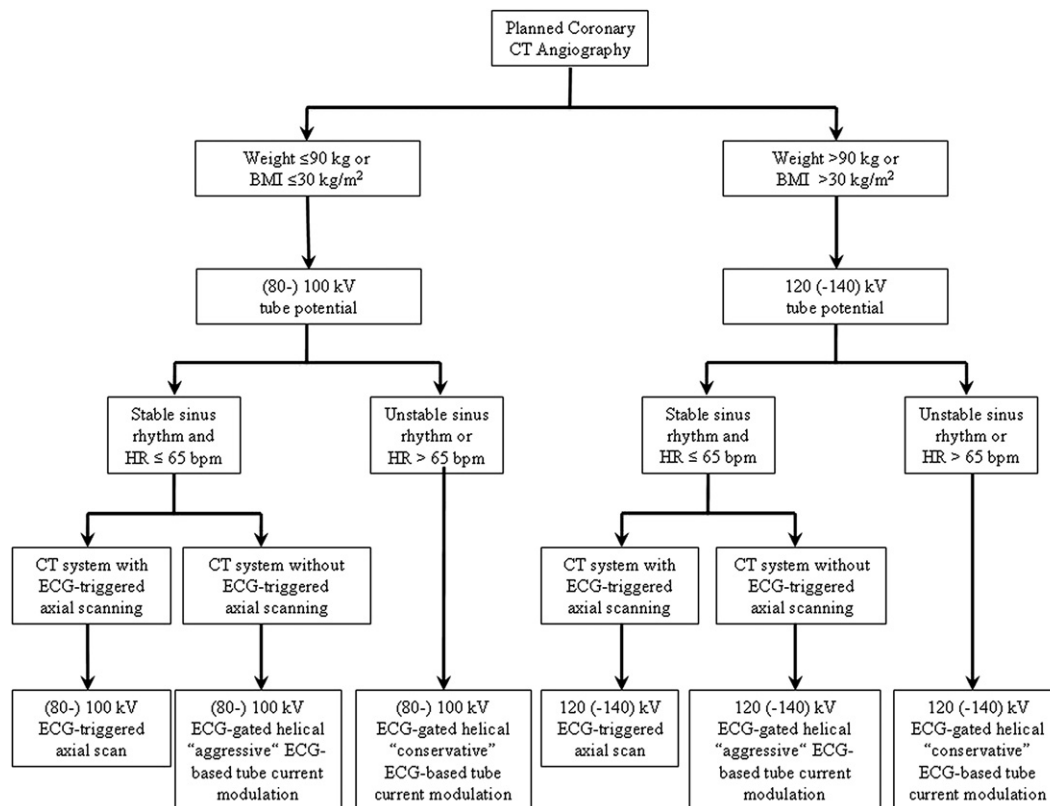


Figure 1 Example of flow chart to optimize radiation exposure for coronary CT angiography with the use of the ALARA principle. “Aggressive” ECG-based tube current modulation refers to use of a narrow window of high tube current and selection of the minimum tube current available outside the window. “Conservative” ECG-based tube current modulation describes the use of a wider window of high tube current and, possibly, the selection of a higher minimum tube current value.

patients because the currently available algorithms modify the tube current modulation in the event of arrhythmias. However, the phase of the full tube current may need to be widened, allowing for multiple data reconstructions (also referred to as conservative tube current modulation). Still, a coronary CT angiogram should only be performed in these patients after sufficient administration of β -blocking medication. Light sedation might also be considered in anxious patients with high heart rates.

Coronary CT angiography in patients with atrial fibrillation is challenging; sometimes, even in the most experienced hands, it is impossible to obtain diagnostic CT images. Although some CT scanner technologies, including those with high temporal resolution¹¹⁶ or full organ detector coverage,¹¹⁷ might offer advantages over others in imaging these patients, these scan protocols are usually associated with higher radiation exposures. Thus, if suitable imaging conditions for coronary CT angiography data acquisition cannot be achieved or if the likelihood for obtaining diagnostic images is low, cancellation of the study should be considered, and the patient should be referred to alternative imaging methods that are less sensitive to heart rate and rhythm.

Body weight and BMI can affect the scan protocol and therefore radiation exposure. Tube potential and tube current should be adjusted to the patient size (Fig. 1). Adjustments of the tube current should be considered after the tube potential is set. The level of the tube current as set by the CT manufacturer in standard coronary CT angiography protocols typically allows for image acquisitions with diagnostic levels of image noise over a wide range of body weights or BMI. However, weight- and BMI-dependent adjustments of the tube current may allow for a better balance of low radiation dose and acceptable image noise. Because of the differences among CT systems, however, it is impossible to include a general recommendation for adjustments of the tube current within this guideline.

Recommendation

If possible, the patient's heart rate during scanning should be <65 beats/min and ideally <60 beats/min for coronary CT angiography (specific values depend on specific scanner characteristics and cardiovascular indication) to provide the best image quality and to allow use of lower-dose acquisition modes.

Considerations for triple rule-out and emergency department scanning

A single scan to exclude acute pulmonary embolism, acute aortic dissection, and coronary artery disease (also known as, triple rule-out) is feasible with modification of the injection protocol to allow for enhancement of the right

heart and pulmonary vasculature in addition to the coronary arteries and aorta. Most important, a longer scan length is needed to cover the pulmonary arteries and aorta, which leads to an increase in radiation exposure compared with a coronary-specific scan in the same patient. Surveys have shown a very low yield of unexpected diagnoses in such cases (ie, an aortic dissection in intermediate-risk patients with acute chest pain).^{118,119} This result argues against routine use of this procedure.

However, there are cases in which prudent medical practice requires performing both a coronary CT angiography and another test; in these cases, the triple rule-out protocol reduces both radiation exposure and contrast dose compared with two separate examinations.¹²⁰ Despite previous concerns about possible pulmonary side effects from β -blockade in patients with suspected pulmonary emboli, in practice it has been possible to follow the same prudent guidelines to control heart rate in triple-rule-out examinations as in dedicated coronary evaluations.⁷² If clinical judgment rules out the use of β -blockers, the triple rule-out procedure should probably not be performed unless the patient's heart rate is especially low or a scanner with high temporal resolution is available.

Considerations for noncoronary cardiovascular CT

CT imaging requirements for the large number of noncoronary cardiovascular indications such as myocardial disease, pericardial disease, valvular heart disease, cardiac masses, congenital heart disease, aortic disease, and venous disease are varied.¹²¹ Many indications (eg, identification of a small, focal intimal aortic tear after traumatic injury, assessment of valvular disease) have the same requirements as coronary artery imaging. However, some noncoronary cardiovascular indications (eg, evaluation of aortic size) may permit imaging with lower spatial or temporal resolutions and higher noise levels compared with those necessary for coronary evaluation.

For many noncoronary cardiac indications, less-demanding requirements for spatial resolution permit the reconstruction of thicker slices and the lowering of x-ray tube potential or current during data acquisition. It is important to reiterate, however, that increasing reconstructed slice thickness (a reconstruction parameter) has no direct effect on x-ray exposure (see "Reconstruction slice thickness"). It is incumbent on the user to also lower the x-ray tube potential or current (a data acquisition parameter) to decrease patient radiation exposure.

An additional consideration for imaging of the left atrium and pulmonary veins in patients with atrial fibrillation and a poorly controlled, irregular heart rate is the acquisition of data with the use of a lower-dose, non-ECG-gated protocol. Typically, cardiac patients with high or irregular heart rates are restricted to higher-dose, retrospective ECG-gated helical scan modes. However, because of the lack of synchrony between the motion of the heart and

the ECG signal and no significant change in left atrial volume over the cardiac cycle in patients with atrial fibrillation,¹²² non-ECG-gated imaging may actually be preferable. Non-ECG-gated helical imaging has been shown to provide images relatively free of motion artifacts with low radiation exposure.^{123,124}

Recommendations

For some noncoronary cardiovascular CT studies, lower-dose settings can be used and thicker slices reconstructed to achieve acceptable image noise.

Pulmonary vein anatomic mapping CT studies may be best performed with non-ECG-referenced or single heartbeat techniques for patients with atrial fibrillation.

Considerations for myocardial CT perfusion and myocardial CT delayed-enhancement imaging

Coronary CT angiography provides anatomic visualization of the location and extent of coronary artery disease but provides no information on its physiologic significance. Intermediate stenosis on a CT angiogram is a poor predictor of inducible ischemia.¹²⁵ However, CT angiography shows not only the coronary arteries but also the myocardium, such that areas of hypoperfusion from an infarct can be visualized.¹²⁶ Early clinical data have suggested that cardiac CT angiography can detect stress-induced perfusion defects.^{127–129} Hence, CT has the potential to evaluate the presence and severity of coronary artery disease and myocardial perfusion during one evaluation. One significant clinical limitation of this technique has been radiation dose; however, this area of concern is being addressed with the latest technologic advancements, including wide-area detectors and second-generation dual-source systems. Radiation doses can be minimized by reducing tube potential and with the use of prospective ECG-triggered axial scan modes. Currently, stress myocardial CT perfusion is still an investigational research tool.

The percentage of viable myocardium in patients affects both revascularization and long-term survival. Cardiac magnetic resonance is considered the “gold standard” for viability imaging; CT delayed-enhancement imaging is also feasible, but this technique has a low contrast-to-noise ratio. Reducing the tube potential to 80 or 100 kV increases the iodine attenuation and iodine contrast; however, there is then increased image noise, necessitating an increase in the tube current. Overall, reducing the tube potential with a corresponding increase in tube current improves myocardial CT delayed-enhancement imaging contrast-to-noise ratio and reduces radiation exposure.¹³⁰ Viability assessment by CT is feasible but not routinely used clinically because of limited published data.

Dose monitoring

Widespread concern about increased exposure of the population to ionizing radiation from CT and the variability in exposure for a given CT indication across institutions has prompted CT imagers and their professional societies, along with regulatory bodies such as the United States Food and Drug Administration (FDA), to advocate the monitoring and recording of patient radiation dose.^{131–134} This practice is already mandatory in some European countries.¹³⁵ Two primary purposes are served by monitoring and recording dose information, one related to documenting individual dose burden and a second related to quality control.

Inclusion of dose in patient medical record

Inclusion of dose information in the patient medical record is recommended and may soon be required by regulatory bodies, particularly in the United States. The best radiation dose descriptors currently available to the average CT imager are $CTDI_{vol}$ and DLP (“Radiation dose standards and measurements”).

Recommendation

$CTDI_{vol}$ (expressed in mGy) and DLP (expressed in mGy-cm) should be recorded for each patient.

Continuous feedback loops on radiation exposure

Systematic monitoring of adherence to institutional dose-optimization guidelines and resulting radiation dose values provides a continuous feedback loop and is an important dose-reduction strategy. Without systematic monitoring, the feedback loop from physician to technologist is often only closed in cases of poor image quality, in which an increase in x-ray output (increase in radiation dose) might have been indicated. Readers do not often report back to the technologists that, for example, a lower tube potential or tube current would have been sufficient. In addition, the technologist may tend to choose higher-than-necessary x-ray parameter settings to provide the physician with the most aesthetically pleasing images.

Systematic monitoring should include recording of dose descriptors in a format that allows for retrieval and periodic review of representative samples of the data. Example formats include a Digital Imaging and Communications in Medicine (DICOM) image with radiation information in a picture archiving and communication system (PACS), a paper-based logbook, hospital information system (HIS) or radiology information system (RIS),

or a dedicated database or local registry. A periodic (eg, biannual) review of the range of radiation doses and the median and average radiation dose at the imaging center should be performed. Local data should also be compared with national standards and other published references. This review process should trigger the review and optimization of scanning protocols, especially if the imaging center's radiation dose is higher than comparable national or international references.⁷²

Recommendation

Review of sites' radiation levels and adherence to institutional algorithms for radiation dose optimization should be performed at least twice per year.

Dose registries

The availability of radiation dose data allows imaging centers to compare CT dose descriptors recorded for their patients with regional, national, and international values contained within dose registries and to obtain information for purposes of quality control. Two large multicenter registries exist for coronary CT angiography. PROTECTION I, an international dose survey for coronary CT angiography that includes 50 study sites, and has collected representative radiation dose-relevant data for coronary CT angiography in >1960 patients.⁶⁶ This study has shown that coronary CT angiography performed in 2007 was associated with a median DLP (value does not include radiation exposure from a localizer, coronary calcium scan, or contrast bolus timing scan) of 885 mGy-cm, which corresponded to an effective dose of approximately 12 mSv. A second large registry included >4800 patients who underwent coronary CT angiography in 2007/2008. Data were collected as part of a large multicenter, interventional study by the Advanced Cardiovascular Imaging Consortium (ACIC) to investigate the effect of a formal program for lowering the radiation exposure from coronary CT angiography.⁹⁰ During a study period of 1 year, the investigators showed a 53% reduction in radiation exposure without impairment of image quality. The median total DLP (including radiation exposure from a localizer, coronary calcium scan, or contrast bolus timing scan, when performed) was reduced from 1493 mGy-cm in the initial control period to 697 mGy-cm in the final follow-up period.

There is also a large-scale initiative by the American College of Radiology (ACR) to collect information related to dose indices for all types of CT examinations from institutions across the United States.¹³⁶ Participating institutions will be provided with periodic feedback reports that compare their data by body part and examination type with aggregate results. Data from the registry will be used to establish national benchmarks.

Diagnostic reference levels

Additional quality control information can be obtained by comparing radiation dose descriptors from individual imaging centers with diagnostic reference levels (DRLs) established from registry data. The DRL is the radiation dose level for a typical-sized patient and for a certain radiologic procedure. With the use of DRLs, it is possible to identify situations in which patient dose is unusually high. This comparison information allows imagers, regulators, and accrediting organizations to identify groups that deliver radiation doses far above or below their peers. The DRL is not the recommended or preferred dose, but rather an action level with respect to which investigations into radiation exposure used should be performed. If a DRL is consistently exceeded, the CT scan protocol should be reviewed, and appropriate measures taken for radiation dose reduction.⁷² The use of DRLs has been shown to decrease the mean radiation dose and the range of dose distribution of radiographic imaging procedures.¹³⁷

DRLs should be selected by medical bodies on the basis of large surveys of representative sites and reviewed at appropriate time intervals. The DRL is typically set at the 75th percentile dose level of large representative surveys with a broad range of examinations. Currently, no DRLs are available for cardiovascular CT procedures. From PROTECTION I data, the 75th percentile DLP for coronary CT angiography in a typical-sized patient was found to be 1152 mGy-cm, corresponding to an effective dose of approximately 16 mSv. From ACIC data, the 75th percentile total DLP (including radiation exposure from a localizer, coronary calcium scan, or contrast bolus timing scan, when performed) for coronary CT angiography in the follow-up period was found to be 1163 mGy-cm, corresponding to an effective dose of approximately 16 mSv and closely matching the results from PROTECTION I. Therefore, the available data support consideration of a DLP value of 1200 mGy-cm for a DRL for coronary CT angiography. However, it should be noted that reported evidence has shown a steady reduction in coronary CT angiography doses since data were collected in 2007/2008.¹³⁸ Data from forthcoming registries, including the ACR Dose Index Registry, may support a lower DRL.

One cautionary note for DRLs is that reference levels might have to be unreasonably high to work for all scan modes and for all scanner models. Scan mode- and scanner-specific DRLs would be preferable, but sufficient data from large surveys of representative sites are not currently available for these subcategories.

Discussion

Determining whether cardiovascular CT should be performed requires a comprehensive, individualized review of the clinical scenario and reference to published

guidelines and appropriate use criteria. The clinical usefulness of CT for the assessment of cardiovascular disease must be weighed against the required exposure to ionizing radiation and the small but potential risk of incident cancer.

With the introduction of 64-slice CT scanners, a substantial increase in radiation exposure was observed when compared with former 16-slice technologies.³⁴ This increase in radiation exposure was mainly driven by increases in temporal and spatial resolution with 64-slice CT systems. As a consequence, many studies have been performed to assess the effect of newer scan techniques and technical developments on the ability to reduce radiation exposure with CT while maintaining image quality.

Although these techniques and developments provide the opportunity to decrease radiation exposure in the individual patient, the ambition to obtain high-quality images and to cover a larger extent and detail of the patient's anatomy often leads to the opposite result in clinical practice. It is increasingly being documented that patient doses are higher than necessary and that the image quality in CT often exceeds the level needed for confident diagnosis.¹³⁹ These results also explain the >7-fold variability in median radiation doses for coronary CT angiography in the PROTECTION I survey.⁶⁶ These findings need to penetrate widely among imaging specialists, including cardiologists, radiologists, and radiographers. Large coordinated efforts aimed at increasing radiation dose awareness have been launched by the ACR, including the Image Gently campaign for pediatric patients and the Image Wisely campaign for adult patients. These programs encourage practitioners to avoid unnecessary ionizing radiation scans and to use the lowest optimal radiation dose for necessary studies.

If cardiovascular CT is the appropriate test and scan parameters are optimized with respect to radiation exposure, the benefit to the patient should outweigh the potential risk of future stochastic events. Of course, the optimal benefit of testing would be in those indications for which evidence clearly establishes a link between CT and improved outcomes when compared with other diagnostic imaging modalities or in a no-testing strategy. Additional value may also be realized for indications for which high diagnostic and prognostic accuracy has been established. Although an abundance of data is available that note substantive diagnostic and prognostic evidence, no or minimal comparative effectiveness data are available for cardiovascular CT. Ideally, for an optimal benefit–risk evaluation, we would understand the added contribution in terms of life-years saved in relation to the observed cancer risk.

Radiation dose-reduction strategies for CT include tailoring the imaging protocol to the clinical question. Assessment of the coronary arteries, for example, requires high spatial resolution and, subsequently, high tube settings to achieve acceptable image noise. However, some cardiovascular CT indications have less-demanding imaging

requirements and may permit lower-dose protocols. This is an important point, because there is a tendency to use coronary protocols for all cardiovascular imaging examinations, an occurrence that should be strictly avoided in the absence of a clear indication for evaluation of the coronary arteries. Outcome data do not exist to support imaging the coronary arteries in the context of every cardiovascular CT examination (eg, for pulmonary vein isolation).

Radiation dose-reduction strategies also include modifying the CT imaging protocol on the basis of individual patient characteristics. Lower-dose options, including prospective ECG-triggered axial and high-pitch prospective ECG-triggered helical scanning, are available to some cardiovascular patients, namely those with lower heart rates. Although higher-dose, low-pitch retrospective ECG-gated helical scanning is required on all commercially available scanners for patients with very high or irregular heart rates, most cardiovascular CT patients can be imaged with the lower-dose techniques. In addition, x-ray parameters such as tube potential and tube current should be adjusted according to patient size.

Customization of the CT imaging protocol requires much more time and effort than a “one-size-fits-all” approach. However, careful consideration of parameter settings could spare many patients a significant amount of radiation without compromising image quality. Patient-specific scan protocols can and should be used, particularly in those patients at greatest risk of harm from x-ray exposure to the chest such as women and younger patients.⁸

To help insure adherence to good practice, radiation dose monitoring for CT procedures has been adopted voluntarily by many imaging centers but may soon be required by regulatory bodies in some countries (eg, the United States FDA). The recording of basic radiation dose descriptors allows for quality control and auditing at the site level. Additional information may be gained by comparing these site data with national or international standards.

Application of appropriate use criteria¹⁴⁰ to the individual clinical scenario can help to determine the benefit of the cardiovascular CT examination. Customization of scan parameters according to the clinical question and patient characteristics ensures the lowest acceptable exposure during the cardiovascular CT examination and, therefore, the lowest acceptable risk. The benefit of the procedure can then be balanced with the risk of forgoing a medically necessary examination, as well as the potential risk of future stochastic events.^{9,32} In particular, there are few data to support repeat or follow-up testing on a routine basis for most indications; this can be an important means to decrease radiation exposure.

Because of known uncertainties in dose estimates and risk models, the leap from radiation exposure to the risk of stochastic effects such as cancer is controversial, particularly for individual patients. The effective dose is the dose quantity most commonly used to relate exposures from low

doses of ionizing radiation to the probability of detrimental health effects. However, it must be recognized that this value is associated with a level of uncertainty on the order of $\pm 40\%$ when it is used to quantify dose for medical exposures.¹⁴ Further, cancer risk from the relatively low doses of ionizing radiation used during medical imaging is linearly extrapolated from the radiation risk data of atomic bomb survivors, who were subjected to much higher doses of radiation. The validity of this approach relies largely on the controversial linear-no-threshold theory, which assumes a linear relationship between dose and cancer risk even at the smallest doses. Therefore, estimations of risk from low doses of radiation delivered during medical imaging examinations must be interpreted with regard to the imprecision of the calculation.

Further, it is important to note that exposure to ionizing radiation during cardiovascular imaging is not limited to CT.^{5,9} Reported effective dose values for diagnostic invasive coronary angiography range from 2 to 16 mSv. Average values for cardiovascular nuclear medicine procedures (myocardial perfusion and myocardial viability studies) vary considerably, ranging from 5 to 41 mSv, depending on the pharmaceutical used.

In summary, the Radiation Committee believes that the benefit of the potential knowledge acquired by a cardiovascular CT procedure should be weighed against the potential risk of forgoing a medically necessary examination or obtaining a nondiagnostic examination because of excessive dose reduction, as well as the potential risk of future stochastic events, for each patient. Further, we support dose-reduction strategies for cardiovascular CT that consider applied radiation in the context of the clinical indication and the characteristics of the patient. We encourage imagers to use the evidence-based information contained in this statement along with the referenced literature to provide patients referred for cardiovascular CT with the lowest radiation dose that preserves diagnostic image quality. We also encourage institutional radiation dose monitoring to help insure adherence to good practice.

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Appendix 1. Guideline Committee of the Society of Cardiovascular Computed Tomography

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Appendix 2. Disclosure of Conflicts of Interest for Writing Group

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