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Guidelines

SCCT guidelines for the performance and acquisition of coronary computed tomographic angiography: A report of the Society of Cardiovascular Computed Tomography Guidelines Committee Endorsed by the North American Society for Cardiovascular Imaging (NASCI)

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ABSTRACT

In response to recent technological advancements in acquisition techniques as well as a growing body of evidence regarding the optimal performance of coronary computed tomography angiography (coronary CTA), the Society of Cardiovascular Computed Tomography Guidelines Committee has produced this update to its previously established 2009 “Guidelines for the Performance of Coronary CTA” (1). The purpose of this document is to provide standards meant to ensure reliable practice methods and quality outcomes based on the best available data in order to improve the diagnostic care of patients. Society of Cardiovascular Computed Tomography Guidelines for the Interpretation is published separately (2). The Society of Cardiovascular Computed Tomography Guidelines Committee ensures compliance with all existing standards for the declaration of conflict of interest by all authors and reviewers for the purpose ofclarity and transparency.

1. Preamble

In response to recent technological advancements in acquisition techniques as well as a growing body of evidence regarding the optimal performance of coronary computed tomography angiography (coronary CTA), the Society of Cardiovascular Computed Tomography Guidelines Committee has produced this update to its previously established 2009 “Guidelines for the Performance of Coronary CTA”.[1] The purpose of this document is to provide standards meant to ensure reliable practice methods and quality outcomes based on the best available data in order to improve the diagnostic care of patients. Society of Cardiovascular Computed Tomography Guidelines for the Interpretation is published

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separately.[2]

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2. Introduction

Since the first publication of recommendations for performance of coronary CTA in 2009,[1] further technological developments of multi-detector row computed tomography (MDCT) have significantly increased the ability to image the heart and coronary arteries noninvasively, supporting the clinical utility of coronary CTA to identify coronary artery stenosis, if image quality is adequate.[4–6] An expert consensus document has defined a number of clinically "appropriate", "inappropriate", and "uncertain" indications for coronary CTA.[3]

It is generally accepted that the diagnostic quality of coronary CTA images is highly dependent on a number of technical factors, including hardware, software, and acquisition protocols. These factors still continue to evolve at a rapid pace, resulting in the "state of the art" being in a continuous "state of flux". Several MDCT scanner geometries are currently utilized for coronary CTA, and provide a wide array of options. Technological advancements over the last decade include: a range of 64–320 detector row systems; dual source scanners; dual energy imaging; iterative reconstruction algorithms; and a variety of new 3D workstations and software programs for processing and reviewing scan data.

Therefore, this publication aims to establish an updated consensus of the minimally required standards for appropriate coronary CTA acquisition and data processing; and to provide recommendations for methods to achieve robust image data, optimize scan results, maximize image quality and avoid unnecessarily high radiation exposure within the limits of the currently available technology.

3. Physician and technologist competencies; institution and scanner standards

3.1. Physician standards

All examinations should be performed and interpreted by physicians adequately trained in coronary CTA including an ability to assess coronary arteries, cardiac and pericardial structures, great vessels, and extra-cardiac structures within the acquired field of view. The interpreting physician(s) should have adequate training as described in competency statements issued by medical specialty societies e.g. the ACC/AHA Clinical Competence Statement on Cardiac Imaging with Computed Tomography and Magnetic Resonance[7] or the ACR Practice Guideline for the Performance and Interpretation of Cardiac Computed Tomography.[8] This competency includes adequate knowledge of the ALARA ("As Low As Reasonably Achievable") principle from the standpoint of radiation exposure, among others. For pediatric coronary artery imaging, knowledge of age and size based modifications for patient preparation and image acquisition are required to decrease diagnostic risk.

An imaging center should accordingly have a supervising physician with advanced knowledge in cardiovascular CT and radiation issues. Certification of advanced expertise in cardiac CT is desirable, e.g. Diplomat of the Certification Board of Cardiovascular CT (CBCCT), holder of the ACR Certificate of Proficiency in Cardiac CT, or American Board of Radiology ABR/ABMS Focused Practice Recognition in Cardiac CT (FP-CCT).

3.2. Technologist and ancillary personnel standards

All examinations should be performed by technologists adequately trained in cardiac CT, including adequate knowledge of the ALARA principle. Moreover, technologists should receive additional training to perform coronary CTA on their respective equipment, including scanner and injection devices. Demonstration of advanced proficiency in cardiac computed tomography such as through holding of the Society of Cardiovascular Computed Tomography Technologist Certificate of Competency in Cardiovascular CT, or equivalent is desirable, but not required.

At least one person with appropriate training in inserting intravenous access (peripheral IV) is required for patient preparation, and at least one person certified in advanced cardiac life support (ACLS) has to be readily available during the acquisition. If additional medications are used, a person with adequate training in administering medications such as beta-blockers and nitroglycerin must be available. The above functions can be performed by a physician or physician assistant. If pediatric imaging is performed, at least one person certified in pediatric advanced life support (PALS) should be available during the scan, and pediatric specific emergency resuscitation equipment should be readily available.

3.3. Institution and equipment standards

The imaging facility should meet lab accreditation standards as set forth by the applicable body, e.g. the Intersocietal Commission for the Accreditation of Computed Tomography Laboratories (ICACTL), or the American College of Radiology (ACR). CT systems with fast gantry rotation (equal or less than 350 ms) should be utilized. The minimum detector requirement is a 64-slice scanner (collimations of 32×2 or 64×1, or newer generation, which typically have detector element widths of 0.625 mm or less). Dual head injection pumps that allow biphasic or triphasic injection protocols with high injection rates (4–7 cc/sec) are recommended, although single head injection pumps can yield appropriate results. For a detailed description of the different injection protocols, please refer to Section 5. Image data storage should be in the Digital Imaging and Communications in Medicine (DICOM) standard format. A picture archiving and communication system (PACS) or equivalent CT image data archiving system is required to allow storage and retrieval of the entire diagnostic image data set.

3.4. Radiation monitoring standards

Independent of local policy and legislation, it is recommended that the radiation dose estimates from each coronary CTA, as reported by the scanner after coronary CTA acquisition, should be recorded for each patient. Volume CT dose index (CTDIvol) and dose-length product (in mGy · cm) should be used; effective dose (in mSv) may be recorded, however the conversion factor for calculating effective dose is not unique to coronary CTA and as a result may change over time, giving discrepant results. The radiation doses need to be stored in a format that allows for retrieval and periodic review of representative samples of the data. Examples of formats for recording include, but are not limited to, a DICOM image/DICOM standard reporting template with radiation information in a PACS, a paper based logbook, hospital information system (HIS) or radiology information system (RIS), or a dedicated database or local registry. It is imperative that the lab director, or equivalent physician ensures (a) the presence of, and adherence to a periodic (e.g. biannual) review of the range of radiation doses, and the median and average radiation dose at the site and (b) comparison of the local data with national standards and other published references. This review process should trigger the review and

optimization of scanning protocols, especially if the site radiation dose is higher than comparable national or international references utilizing the same acquisition equipment that still meets the national standards. More details and recommendations regarding radiation dose optimization and reporting can be found in the dedicated Society of Cardiovascular Computed Tomography guideline document.[9]

For pediatric patients, the DLP and phantom size (16 cm or 32 cm) should be recorded. There is variation in the phantom size used to calculate DLP at different institutions, which results in variable estimates of patient dose for similar scanner outputs. If dose is reported in mSv for a pediatric patient, the conversion factor used in the calculation should be documented.

3.5. Recommendations

- The supervising physician (lab director, etc.) should have advanced knowledge and expertise in cardiovascular CT and medical radiation. Certification of advanced expertise in cardiac CT is desirable.
- The interpreting physician should have adequate training as described in competency statements.
- Technologists should be adequately trained to perform Coronary CTA on the respective equipment, including scanner and injection pumps. Certification of expertise is desirable.
- The institution should meet or exceed current standards for medical imaging facilities.
- CT scanner technology should meet or exceed current standards.
- Radiation dose estimates from coronary CTA should be recorded for all patients.
- Periodic review of the site's radiation levels and comparison with published references (and internal protocol review & optimization) is necessary and should be performed at least twice per year.
- Pediatric coronary artery imaging should be performed by physicians with training in scan preparation and dose optimization techniques for pediatric patients.

4. Patient screening and preparation

4.1. Introduction

The decision to order a coronary CTA examination should be made by a qualified physician or under supervision of a qualified physician following current national guidelines. Coronary CTA should only be performed if the results of the test have the potential to impact patient management or prognosis and if sufficient image quality can reasonably be expected.

Patient preparation should be performed by a qualified individual. Patients should be screened for contraindications to contrast-enhanced CT in general, or for factors that may interfere with image quality in coronary CTA. Blood pressure and heart rate prior to administration of heart rate-slowing medication and/or nitroglycerin should be noted. The following is a description of standard procedures that are required prior to a coronary CTA.

4.2. Initial screening

Coronary CTA is generally contraindicated in the following clinical scenarios, however, on a case-by-case basis, coronary CTA may be pursued in some of these scenarios if clinically warranted. Contraindications include a known history of severe and/or anaphylactic contrast reaction; inability to cooperate with scan acquisition and/or breath-hold instructions; pregnancy; clinical instability (e.g. acute myocardial infarction, decompensated heart failure, severe hypotension); and renal impairment as defined by local protocols. Regarding pregnancy in particular, a chest CT results in low radiation exposure to the fetus, however, a negative long term effect even from low level radiation cannot be excluded.[10] Furthermore, small amounts of absorbed iodine from the contrast material may affect fetal thyroid function.[11] While coronary CTA in pregnant women may not be absolutely contraindicated, the indication should be critically reviewed. As with every procedure, alternative imaging modalities should be considered and the study with the best benefit-risk ratio should be employed. Screening for potential pregnancy by history and/or pregnancy testing should be performed according to the local imaging facilities policies for undertaking radiological examinations that involve ionizing radiation in women of child-bearing age. For breast feeding mothers it is reassuring to note that iodine accumulation in the breast milk is considered too low to warrant interruption of their breast feeding schedule.

In addition to the above contraindications, there are also a number of patient related variables that affect the diagnostic accuracy of coronary CTA. The presence of such factors (in conjunction with scanner variables) should trigger reconsideration of the risks and benefits of coronary CTA with the decreased accuracy in mind. These variables include obesity; difficulty following breath-hold commands, maintaining body position, raising one or both arms, or lying supine for scanning; contraindication to beta-blockade in the presence of an elevated heart rate and no alternative medications available for achieving target heart rate; heart rate variability and arrhythmia; and contraindication to nitroglycerin. Regarding obesity in particular, scan restrictions for upper weight limits depend on scanner dimensions and characteristics. Many scanners are approved to accommodate patients of up to 450 pounds body weight or more. Certain scanner systems provide acquisition modes specifically adapted to improve image quality in these scenarios. However, image quality for coronary assessment in such patients may be inadequate even with maximum scanner output. It is the attending physician's responsibility to consider the scanner's characteristics appropriately for the probability of imaging success.

Anesthesia with suspended respiration may be required for pediatric patients unable to cooperate with breath holding instructions. Scanners capable of high pitch spiral acquisition mode may allow image acquisition without breath hold for some indications. If anesthesia is required, both the imaging and anesthesia risk must be taken into consideration in determining the appropriateness of pediatric coronary CTA.

It is recommended to evaluate for the following items prior to coronary CTA:

- Pregnancy or potential pregnancy: According to ACR recommendations[12] “All imaging facilities should have policies and procedures to identify pregnant patients prior to imaging, and to consider any possible risks to the fetus of any planned administration of contrast material, taking into consideration the potential clinical benefits of the examination.”
- Presence of contraindications to contrast media or other medications including heart-rate slowing medications (e.g. beta blockers) and nitroglycerin.
- Renal impairment and risk of contrast induced nephrotoxicity (CIN)
- Prior allergic reactions to any allergens
- Active bronchospastic disease, hypertrophic cardiomyopathy, severe aortic valve stenosis, or other precautions or contraindications to beta-blockers
- Current medications (especially sildenafil, vardenafil, tadalafil, or metformin)

- Any other pertinent medical history
- Assessment of the ability to follow breath-hold commands and perform sufficient inspiratory breath-hold. If pediatric patients are unable to cooperate with breath holding, anesthesia with suspended respiration may be required.
- Body weight and height.
- Assessment of heart rate (preferably following inspiration) and arrhythmia
- Assessment of blood pressure if beta blockers and/or nitroglycerin will be administered

4.3. Pre-test instructions

Pre-test patient instructions are best given at the time when the procedure is scheduled. The following is a list of the typical set of instructions:

- No food for 3–4 hours prior to exam.
- May drink water or clear fluids without caffeine up until time of exam (patient should be well hydrated for renal protection, for ease of establishing venous access, and to avoid post-procedure hypotension).
- No caffeine products for 12 hours prior to exam in the non-acute setting, because they might hinder efforts to reduce the heart rate before scanning. This includes coffee, tea, energy drinks, energy pills, diet pills and most soda.
- Take all regular medications the day of exam, especially blood pressure medicine.
- Take pre-medications for contrast allergy as prescribed by the ordering physician. As an example, the standard Greenberger regimen is prednisone, 50 mg by mouth, 13, 7, and 1 hour prior to contrast exposure, in addition to diphenhydramine 50 mg by mouth 1 hour prior to contrast exposure.[13]
- It is reasonable to suspend metformin for at least 48 hours after contrast administration. Metformin itself is not nephrotoxic, but is exclusively cleared by the kidneys. If renal failure is precipitated by iodinated contrast, a toxic accumulation of metformin may result, which can induce lactic acidosis. There is no evidence that withholding metformin *before* a contrast procedure is protective although this approach has been adopted by some in the past.
- If a pediatric patient requires anesthesia, institutional NPO guidelines should be followed as directed by the anesthesia staff.

Instructions should also include information of the potential administration of pre-procedure medications (i.e. beta-blockade and nitroglycerine) in order to prevent patient irritation, as patients may not associate the performance of a coronary CTA with the necessity of potential medication administration.

4.4. Informed consent

Whether or not informed consent prior to performance of coronary CTA should be required may be regulated by institutional, regional or state regulations. A consent form, if used, should explain in simple terms the procedure and the reasonably expectable risk to the patient.

4.5. Intravenous access

Intravascular access should be established using the facility's protocol and adequate flow should be ascertained prior to injection. Cannula size and position should be adequate for the high flow rate of power injector bolus intravenous administration of contrast and in accordance with the individual facility policy. A short 20 gauge IV catheter may be sufficient in normal or small patients but an 18 gauge catheter is often necessary in adults to achieve rapid infusion rates (4–7 cc/sec). For pediatric patients, a 22 gauge IV is often sufficient for the contrast injection rate required. New high flow IV catheters are available that offer the potential to use a smaller bore while maintaining high flow rates. The right antecubital vein is preferable (median, cubital, basilic and cephalic veins), followed by a left antecubital vein. Contrast injection via the left antecubital vein can result in a larger amount of streak artifact from the contrast bolus as it passes through the left brachiocephalic vein, potentially degrading image quality. Hand veins (metacarpal and dorsal) should be avoided, unless no other suitable access can be established. This generally requires a 20 gauge or smaller catheter and slower flow rates. Unless specifically labeled for power injection, central lines should not be utilized.

4.6. Renal precautions

Pre-test determination of estimated glomerular filtration rate (GFR) is not required for all patients, but should be performed for patients considered at increased likelihood of renal impairment on the basis of age and history, because impaired renal function is a relative contraindication to coronary CTA. Calculation of GFR, rather than creatinine alone, is encouraged.[14–16] The incidence of contrast induced nephropathy (CIN) increases in patients with impaired kidney function (estimated GFR < 60 cc/min/m^2) and other co-morbidities such as cardiomyopathy (left ventricular ejection fraction $< 40\%$) and diabetes mellitus. The risk is higher in the elderly as well as in patients with a low BMI. Patients who are dehydrated or volume depleted prior to contrast exposure have an increased risk and any condition that decreases renal blood flow (hypotension, non-steroidal anti-inflammatory use) is also likely to increase the risk of CIN.

While a causal relationship between contrast material and nephropathy has been postulated on the basis of data extrapolated from intra-arterial administration,[17–20] some studies have suggested that this relationship is overstated in the setting of intravenous contrast administration.[29] Indeed, it has been shown that creatinine levels increase in patients who are not receiving contrast material at a similar frequency to patients that receive intravenous contrast.[21] Moreover, in a recent retrospective analysis of 21,346 patients undergoing CT at a single center over a 10 year period stratified based on whether contrast was administered and following propensity score based matching to account for differences in baseline risk, patients undergoing CT with contrast material were not at increased risk of acute kidney injury, dialysis or death compared to patients undergoing CT without contrast material.[22]

Nevertheless, the risks and benefits of contrast administration in patients with impaired renal function must be carefully considered. Patients considered to be at increased risk of CIN due to baseline renal insufficiency may benefit from preventative measures. Intravenous fluid volume loading is the single most important measure.[23] It is recommended that local protocols for pre-scan hydration are utilized (these may need to be modified to avoid volume overload in patients with reduced left ventricular function.[24] In addition, the following measures are recommended in patients with baseline renal insufficiency[23]:

Considerations when performing coronary CTA in patients at risk of CIN:

- Consideration of alternative imaging, such as stress testing, that does not require intravenous contrast

- Avoid dehydration
- Minimize the volume and frequency of contrast administration (avoid repeat injection within 72hrs)
- Avoid high osmolar agents. Iso-osmolar or low osmolar agents are recommended depending on institutional preference and availability
- Avoid nephrotoxic medications 48hrs before contrast administration, including nonsteroidal anti-inflammatory drugs (NSAIDs)
- Consider IV fluid administration in at-risk patients as per published guidelines focusing on the administration of IV contrast in at-risk patients

4.7. Recommendations

- The decision to order a coronary CTA should be made by a qualified physician or under supervision of a qualified physician following current national guidelines.
- Coronary CTA should only be performed if the results of the test have the potential to impact patient management or prognosis
- In the absence of national guidelines for pediatric and adult congenital patients, coronary CTA should be performed when the risk is considered less than, or the potential information gained superior to alternate modalities.
- If pediatric patients are unable to cooperate with breath holding, but coronary CTA has been determined necessary for clinical care, anesthesia for suspended respiration should be considered.
- Initial screening should take place for contraindications to coronary CTA and for factors that may reduce its diagnostic accuracy.
- Coronary CTA should not be performed in the presence of contraindications (eg. Renal impairment), unless careful deliberation demonstrates that the risks from coronary CTA are outweighed by the potential benefit and the risk from not performing the scan.
- In situations that increase the likelihood of non-diagnostic image quality, the relative merits of coronary CTA should be judged against the risks of additional radiation and nephrotoxicity.
- Intravenous access should be adequate for high flow and high pressure contrast injection.
- Glomerular filtration rate (GFR) should be determined for patients at increased likelihood of renal impairment.

4.8. Pre-procedure medications and instructions

4.8.1. Heart rate control

In general, optimal image quality is reliably achieved when the patient has a low heart rate and a regular cardiac rhythm during the scan.[25,26] The requirement for heart rate reduction varies dependent upon the scanner temporal resolution, the method of image acquisition, and the indication for imaging. However, even though some CT scan platforms are enabled with improved temporal resolution that may afford diagnostic image quality at higher heart rates, there remains a tangible benefit with heart rate control which includes both image quality but also the ability to employ dose reduction scan acquisitions that are not possible at higher heart rates.[27] A target heart rate for coronary CTA set at 60 bpm or less is usually appropriate. However, depending upon the scanner parameters listed above, scanning at a higher heart rate may be acceptable if a target heart rate of 60 bpm cannot be reached.

Beta-blockers are considered first-line for achieving short-term heart rate reduction for the purpose of coronary CTA and protocols may utilize oral, intravenous or both routes of drug administration. The administration of oral and intravenous beta-blockers requires compliance with institutional policies. Most beta-blocker protocols prior to coronary CTA involve oral premedication followed by supplemental IV beta-blocker if the target heart rate is not achieved in the monitoring area prior to image acquisition. For premedication, metoprolol is most commonly used due to its demonstrated safety and low costs.[28,29] Atenolol may be chosen in patients with significant hepatic dysfunction due to its renal route of clearance (the opposite is true for patients with renal impairment). The most common approach uses oral metoprolol with staggered dosage based on the presenting resting heart rate ranging from 50 to 100 mg given 1 hour prior to the scan followed by supplemental intravenous doses immediately prior to the CT scan if the target heart rate (<60bpm) is not achieved.[30] While patients presenting with resting heart rates of <60 bpm do not require beta blockade for heart rate reduction, many advocate that a low dose of metoprolol is helpful to reduce heart rate variability and improve image quality.[31] While oral drug administration 1hr prior to the scan is the usual practice (50–100 mg metoprolol by mouth), pre-medication during the 24 hour period before may be more effective at lowering heart rate at the time of scanning as well as the need for supplemental intravenous beta-blocker.[32,33] If premedication is considered safe, then a possible regimen would be to give 50 mg metoprolol by mouth 12 hours before the scan and another 50–100 mg metoprolol by mouth 1 hour before imaging. It is important to note that for premedication regimens, slow-release forms of beta-blockers should not be used. At the time of scanning, if the heart rate remains above target, supplemental IV beta-blockers can be administered.

Protocols that use IV beta-blocker alone can be used to shorten the overall preparation time required and have been shown to be effective and safe, even at high doses.[34] After the patient is placed on a cardiac monitor, 5 mg of IV metoprolol is given as an initial dose, followed by 5 minutes of monitoring to observe the heart rate response. Further repeated intravenous doses of 5 mg each may be administered as indicated to achieve the desired heart rate, typically up to a maximum dose of 20–25 mg. Esmolol may also be used in this setting. One reported protocol involves an initial dose of IV esmolol at 0.8 mg/kg. If the HR does not reach target within 20 seconds, another dose of IV esmolol can be administered (0.8 mg/kg)[35]). The main advantages of this approach include the rapid onset of esmolol compared to oral metoprolol and its short half-life, which results in avoidance of possible prolonged side effects observed with oral beta-blockers. In patients that are on chronic beta-blockade, supplemental oral or IV beta-blockers may be given.

Pediatric patients have higher resting heart rates but have been shown to respond to medical regimens to decrease heart rate. If given, a weight based approach to beta blockade should be used. Even with beta blockade, pediatric patients may have relatively a relatively high heart, and sinus arrhythmia with the breath hold. Initiating the breath hold earlier (with opacification of the pulmonary arteries) will decrease the sinus arrhythmia at the time of image acquisition and decrease radiation dose, but requires a slightly longer breath hold.

Ivabradine, a direct I(f) current inhibitor, has limited international approval for use in the treatment of congestive heart failure, but currently is in the investigational phase for use in coronary CTA (both in addition or as an alternative to beta blockers). Ivabradine is available in an oral or intravenous formulation. In contrast to beta-blockers, ivabradine lowers heart rate (especially high heart rates) without affecting myocardial contractility, impulse conduction, or blood pressure.[36] Importantly, ivabradine is ineffective in patients that are not in sinus rhythm due to its direct inhibition of current in sinoatrial node cells. The use of Ivabradine for heart rate control prior to coronary CTA has been investigated. Oral ivabradine can be

given as a premedication 2hrs before the coronary CTA with similar reduction in HR compared to metoprolol but less reduction in systolic blood pressure.[37] In the same study, ivabradine was more effective than metoprolol in patients treated with chronic beta-blockers. Possible ivabradine regimens prior to coronary CTA include: 15 mg or 7.5 mg (in chronic beta blockade) by mouth 1 h before scanning. It may also be used for oral pre-medication (5 days before) with supplemental IV metoprolol on the day of coronary CTA with good heart rate control in the majority of patients.[38] Further, in patients with contraindications to beta-blockers who present for coronary CTA, a bolus of IV ivabradine (10 or 15 mg) can be administered to rapidly and safely achieve target heart rate.[39]

Screening for absolute and relative contraindications to beta blockers and ivabradine should be performed prior to administration. Beta-blockers should not be used in patients with active bronchospastic disease.

4.8.2. Nitrates

Nitrates are direct vasodilators and provoke their pharmacological vasodilator effects by vascular smooth muscle relaxation.[40] Similar to invasive coronary catheterization, nitroglycerin (glyceryl trinitrate) should be administered prior to coronary CTA to achieve coronary vasodilatation and in order to enhance coronary evaluation.[41,42] A commonly used regimen is 400–800 μg of sublingual nitroglycerin administered as either sublingual tablets or a metered lingual spray (commonly 1–2 tablets or 1–2 sprays) 5 minutes prior to coronary CTA with 800 μg dosing and metered lingual spray preferred. Due to the specific pharmacodynamics and time-dependency of the effect of nitroglycerine,[43,44] it should be administered approximately 5 minutes prior to the contrast-enhanced data acquisition with vasodilatory effect only lasting only for 20–30 minutes. Importantly, administration of nitroglycerine has been shown to improve the diagnostic accuracy of coronary CTA through improved vessel visualization and stenosis assessment.[45]

Nitrates may reduce blood pressure, but are considered safe in the supine position providing there is no severe hypotension or concomitant preload-dependent condition including severe aortic stenosis. While nitroglycerine may induce a temporary headache through its vasodilatory effect, it is generally safe among patients referred for coronary CTA and is essential for optimal image quality and thus accuracy. Use of nitroglycerin is contraindicated if the patient has recently taken a phosphodiesterase inhibitor (e.g. sildenafil, vardenafil, or tadalafil) for the treatment of erectile dysfunction or pulmonary hypertension.

The use of nitroglycerine should be documented by the technologist and reported by the interpreting physician.

4.8.3. Breath-hold training

It is essential to minimize respiratory motion during image acquisition. Coronary CTA should be acquired during an inspiratory breath-hold. Prior to scan initiation, patients should be provided specific instructions and offered practice in the form of a test breath-hold, ideally following ECG lead placement with the patient on the scanner table. The purpose of the test breath-hold is threefold: 1) to ensure appropriate quality of the breath-hold (patient should not perform a Valsalva maneuver), 2) to ensure adequate timing of the breath-hold, and 3) to observe fluctuations in heart rate and rhythm during the breath-hold exercise. Coronary CTA should not be performed if a patient cannot adhere to breath-hold commands. It is strongly advised that all steps of the scan protocol (scout topogram, calcium score and test bolus, if performed, as well as the coronary CTA acquisition) be performed using identical breath-hold commands.

4.9. Recommendations

- Beta-blocker use should be considered based upon its requirement as indicated by scanner and patient factors and the indication for imaging. A target heart rate for coronary CTA set at 60 bpm or less is usually appropriate. However, depending upon scanner parameters, scanning at a higher heart rate may be acceptable if a target heart rate of 60 bpm cannot be reached. A single low dose of oral beta blockade should be considered to reduce heart rate variability for patients presenting with low resting heart rates.
- The use of nitroglycerin should be the default protocol but should be withheld in the presence of circumstances of absolute contraindications. Importantly, image acquisition for coronary CTA should not begin until 5 minutes after the administration to ensure maximal effect.
- Explicit breath-holding instructions and breath-hold training must be provided prior to scanning.

4.10. Patient positioning

Proper patient positioning and electrocardiographic (ECG) lead placement are important to ensure adequate image quality in a gated cardiovascular CT acquisition. The major objectives for positioning of the patients are: 1) to minimize the presence of extraneous high density material (e.g. ECG leads) within the scan field (i.e. lower 2/3 of the chest) that may produce streak artifacts, and 2) to position the heart within the center of the gantry by adjusting the table height and lateral position of the patient on the scan table.

If possible, patients should be imaged supine and with both arms above the head, thereby removing the humeri from the field-of-view (FOV) and ultimately reducing streak artifact and image noise. The arms should be positioned comfortably to avoid pectoral fatigue or trembling, which can lead to ECG irregularities and gating errors. Care should be taken to keep the arm with the intravenous access as straight as possible to avoid line or vein kinking and facilitate contrast agent injection. The contrast pump and intravenous line should approach the patient from the cranial side so that the line does not cross through the gantry, which would produce streak artifact. The table height should be adjusted for each patient to center the heart within the gantry to optimize spatial and temporal resolution.[46,47] The horizontal positioning laser lights can be used for this purpose: when correctly positioned, the laser line lies at the junction of the anterior 1/3 and the middle 1/3 of the patient's thorax.[48] It is reasonable to offset patients laterally by a few centimeters in order to center the heart within the gantry, however, without resulting in contact between the patient and gantry during the acquisition. It is recommended to move the patient through the gantry for the expected respective scan range (i.e. a “test run”) to ensure that no lines or leads are tethered and that the patient does not contact the gantry. Contact of the patient with the gantry may result in passive or active (protective) body motion, producing artifacts that may not be correctable through post processing. The ECG leads should be straightened and care taken that the leads do not unnecessarily traverse the scan range to avoid streak artifact and image noise. Likewise any other leads, metal, or radio-opaque material should be removed (inferiorly onto the abdomen, or superiorly) from the scan field.

In order to obtain a reliable ECG tracing, proper placement of ECG leads is critical. The number and preferred location of leads depends on the scanner type and design. Care should be taken to place leads outside the imaging FOV to the extent possible to avoid streak artifact. Cleaning the skin with alcohol and shaving at the site of electrode placement may be necessary to ensure sufficient

electrode-to-skin contact. For best recognition of ECG trigger points, it is important to obtain a steep upslope towards the R-peak and sufficient R-peak voltage with minimal baseline noise. Repositioning of ECG leads is necessary if the baseline noise is relatively high compared to the R-peak amplitude, or of the amplitude of the T-wave is in a similar range as that of the R-peak because this may result in false triggering (R-peak detection).

4.11. Recommendations

- The preferred patient position is supine with arms raised above the head and the heart centered within the gantry.
- Special attention should be paid to ensure proper positioning and firm contact of ECG leads to ensure a high R-peak amplitude and low baseline noise.

4.12. Contrast injection protocols

4.12.1. Contrast type, delivery, volume and rate

Image quality is dependent on the contrast-to-noise ratio. Optimal images require high intra-arterial opacification of more than 250 Hounsfield Units (HU). Hence, contrast agents with high iodine concentrations are preferred (270–400 mg Iodine/cc). An injection rate between 5 and 7 cc/sec should be used for coronary CTA in most adults, although lower injection rates can be appropriate in low kVp acquisitions depending on body habitus or the IV line size (20G). Warming of contrast agent improves viscosity and allows higher injection rates at lower injection pressures. The overall contrast volume is a function of the injection rate and the injection duration. The injection duration should be as long as (or slightly longer than) the estimated scan duration. For very short scans, the injection duration should be at least 10 seconds. In patients with higher cardiac output, the injection rate should be increased to allow the arterial opacification to remain high. Typical contrast volumes range from 50 to 120 cc. Dual head injectors have the advantage of allowing contrast injection to be followed by saline injection, or in some cases to be followed by a mixture of contrast and saline.[49–52] A biphasic injection protocol consists of a first injection of contrast at a rate of 5–7 cc/sec (volume depends on scan duration) and subsequent injection of approximately 40–50 cc of saline, typically at the same injection rate. In these protocols, the right heart cavities typically appear washed-out, which generally reduces streak artifacts otherwise caused by dense contrast material in the right atrium. In certain settings it may be desirable to have some opacification of the right heart (e.g. for evaluation of LV geometry requiring delineation of the intraventricular septum, or evaluation of right ventricular structural abnormalities). In such cases, a triphasic injection protocol may be used, consisting of an initial high flow rate contrast injection (5–7 cc/sec), followed by a second injection of either a mixture of contrast and saline (5–7 cc/sec), or a contrast injection at lower injection rate (e.g. 2 cc/sec), followed by a third injection of a smaller volume of saline.

Flow rates as low as 1 cc/sec may be used in small pediatric patients through a small gauge IV. Contrast volume of 1–2 cc/kg can be used in pediatric patients depending on the anatomy requiring evaluation. For isolated coronary imaging 1 cc/kg is sufficient, for additional evaluation of complex anatomy a higher contrast load may be used (2 cc/kg).

4.13. Test bolus vs. bolus tracking

Accurate timing of the data acquisition to the arrival of the IV contrast in the target structures is necessary to ensure optimal intraluminal enhancement within the coronary arteries. Normally, the scan delay should equal the contrast travel time from the accessed vein to the ascending aorta plus 2–4 seconds to allow complete filling of the coronary arteries. In general, two strategies are commonly available to determine the vein-to-aorta travel time: bolus tracking, and the test bolus technique.

Bolus tracking implies semi-automated scan triggering by monitoring the arrival of contrast through a sequence of repetitive single slice scans at a pre-specified anatomical level and automated measurement of the contrast attenuation within a region of interest (ROI). The scan is triggered when the attenuation in the ROI exceeds a predefined threshold. The ROI can be placed in the ascending aorta, descending aorta or a cardiac chamber, depending on scanner geometry, acquisition mode and preferences. The delay time between passing the threshold and start of data acquisition must account for potential table position adjustment and breath-hold instructions. Commonly the threshold is below the target attenuation of the data acquisition as contrast is still arriving during the delay time, with exceptions in protocols employing volume scanners where the ROI may be placed in the left ventricle, no table position adjustment is required, and breath-hold instructions may be initiated prior to monitoring, so that data acquisition may instantly commence when reaching the attenuation threshold.

The test bolus technique consists of a small test bolus injection, typically 10–20 cc of contrast followed by a saline bolus of approximately 50 cc, both injected at the anticipated injection rate for the subsequent data acquisition. The test bolus images are acquired during an inspiratory breath-hold, with repetitive single slice acquisitions at a pre-specified anatomical level e.g. ascending aorta, every 1–2 seconds. An enhancement curve is then generated to determine the contrast transit time to peak enhancement. Commonly, 2–4 seconds are then added for calculation of the total delay time before data acquisition, to allow for peak enhancement in the coronary arteries.

Advantages and disadvantages as well as institutional preferences may favor one technique over the other. Advantages of the test bolus technique include an opportunity to acquaint the patient with the breathhold commands and the sensation of contrast injection, identification of contrast dilution complications, and establishing adequacy of IV access. In contrast, the bolus tracking technique offers the potential to reduce the overall contrast dose by eliminating the test bolus. However, it adds complexity to the scan protocol and may itself be a source for error.

4.14. Contrast volume reduction protocols

Contrast volume should be adapted to the duration of scan acquisition. Recently, a number of contrast volume reduction strategies have been proposed, although data examining their impact on clinical management are lacking. Monochromatic image reconstruction using dual energy coronary CTA (see below) may permit a 50% or greater reduction in contrast volume with no significant compromise on diagnostic interpretability and certainty.[53,54] Iterative reconstruction techniques may permit imaging at lower kVp, potentially allowing for a decrease in contrast flow rate and hence contrast volume by enabling scanning at lower energies closer to the k-edge of iodine.[55]

4.15. Contrast reaction protocols

The CT laboratory has to be equipped and staffed appropriately for handling the rare event of anaphylaxis.[56] Immediate treatment by appropriately trained personnel is necessary in case of anaphylaxis. ACR or ACC guidelines for management of contrast reactions should be followed in the appropriate settings.[57]

Recommendations:

- High iodine concentration contrast agents are preferred to achieve greater contrast to noise ratios.
- Higher injection rates of 5–7 cc/sec for coronary CTA are usually optimal in adults, although lower injection rates can be appropriate in low kVp acquisitions, depending on body habitus
- Contrast injection rates in pediatric imaging should be adjusted to patient size and IV gauge.
- Total contrast volume should be based on injection rate and scan duration, and is typically 50–120 cc.
- It is reasonable to use a total contrast volume of 1–2 cc/kg for pediatric patients until the standard adult volume is reached.
- Dual head power injectors are preferred over single head injectors.
- Biphasic or triphasic injection protocols should be used.
- Either bolus tracking or a test bolus protocol is acceptable. Timed scans (using empiric timing alone without either bolus tracking or a test bolus) are not recommended.
- The CT lab should be appropriately equipped and staffed to manage contrast reactions, including anaphylaxis.

5. Coronary CTA acquisition

Technical advances over the past decade have optimized CT systems for cardiovascular imaging. An understanding of these technical advances is important as the choice of the CT acquisition protocol determines image quality and diagnostic value, but also radiation exposure. It is imperative to balance these characteristics for individual patients and clinical indications as described below.

5.1. Overview of ionizing radiation

Ionizing radiation, which includes x-ray radiation, has the potential to cause harm and it is critically important for any physician ordering or performing coronary CTA to have a fundamental understanding of its risks and measures to minimize patient exposure.

The average annual radiation exposure arising from natural sources (radon, cosmic radiation, terrestrial, etc.) for an individual living in the United States accounts for an effective radiation dose of approximately 3.6 mSv.[58] While there are limited direct data available for the estimated risk from low-level radiation at the range of diagnostic CT studies, some controversies remain. The 'linear no threshold' theory assumes that there is a direct linear relationship between the radiation exposure and the risk of cancer.[59] Furthermore, it is assumed that any radiation exposure is potentially harmful.[60] The harmful effect is cumulative, i.e., the more radiation exposure one experiences in life, the greater the risk. In addition, there is long latency (>10–30 years) before the manifestation of radiation-induced cancer with available data suggesting that children and young adults are particularly at risk from radiation exposure.[61] Lastly, growing tissue and organs may be more susceptible to genetic damage induced by radiation than tissue with low turnover. Because of higher sensitivity of breast tissue to radiation, radiation risks of coronary CTA are higher for women than for men.

For all of the above reasons, it is imperative to assure that CT scanning is indicated for the individual patient, that the most appropriate protocol is chosen for the specific clinical indication, and that all possible precautions are applied to minimize radiation exposure. However, the potential increased risk from radiation has to be weighed against the requirement to acquire images that are of diagnostic quality. Diagnostic image quality is determined by multiple factors, including the absence of motion and other image artifacts, high contrast-to-noise, and high spatial resolution. For each patient, the acceptable limits for image quality should be determined a priori in order to tailor the CT scan technique and deliver the lowest possible radiation exposure, in keeping with the principles of ALARA (*A*s *L*ow *A*s *R*easonably *A*chievable) and the "Image Gently" campaign for pediatric patients.[62,63] For example, a coronary CTA to delineate the course of a coronary anomaly in a pediatric patient may be performed with less radiation exposure than a coronary CTA intended to evaluate for coronary artery stenosis in an adult patient, as the former protocol can tolerate higher image noise. Likewise, if scanning only for left atrial and pulmonary vein anatomy prior to an ablative procedure when knowledge of coronary artery anatomy is not needed, diagnostic image quality can be achieved at lower contrast-to-noise and higher motion tolerance than a coronary CTA for evaluation of coronary stenosis, and as such the CT scan can be performed at a lower radiation exposure.

5.2. Techniques to reduce radiation - general principles

Factors influencing the overall radiation exposure include the scanner type (single or dual source; scanner geometry; gantry rotation, available filters), tube voltage, tube current, scan range, scan acquisition time, gating (retrospective gating, prospective triggering, high-pitch helical acquisition), slice thickness, overlap and pitch (for helical scanning), and reconstruction method (filtered back projection, iterative reconstruction). All of these factors need to be optimized with the goal of minimizing radiation exposure as low as reasonably achievable without significantly compromising image quality.

Since the first edition of these guidelines, the ACR relative radiation level designation for coronary CTA has been lowered to 1–10 mSv for adult effective dose estimating the median radiation dose in the USA.[64] With the integration of recent technological advancements, including wide detector and high-pitch helical dual source CT, some patients can undergo coronary CTA with a radiation dose of less than 1 mSv.[65,66,68–70]

5.3. Scan range

Radiation exposure is proportional to the scan range. Therefore, the scan range should be limited to the extent that is necessary for addressing the clinical question and will enable radiation dose savings.[71] In the case of most coronary CTA scans of the native coronary arteries, the range should only include the heart. Obtaining a low dose scan to determine the smallest required scan field in order to minimize radiation dose is not recommended, because it does add radiation and utilization of anatomic landmarks is generally sufficient. The scan range for coronary CTA typically starts below the tracheal bifurcation or the mid-level of the left pulmonary artery and extends to just below the lower cardiac border. In limited clinical scenarios such as the assessment of coronary artery bypass grafts including the internal thoracic (internal mammary) arteries or in patients with congenital heart disease, an extended scan range may be required.

5.4. Tube potential

Typically, 100–120 kV tube potential is sufficient for cardiac imaging in most patients. Increasing the tube voltage to 140 kV leads to a higher energy X-ray beam with better tissue penetration and a reduction in image noise, which may be necessary in very large patients. However, increasing the tube voltage typically a increases radiation exposure proportional to the square of the tube voltage change.[72] In smaller patients and children, reducing the tube potential to 100 or 80 kVp can substantially lower radiation exposure by 30–50%, while maintaining adequate contrast-to-noise and diagnostic image quality.[67,73–75] Recently released CT

platforms supported by improved detector technology and specific tube designs that maintain the ability to use high tube currents at low tube potential permit coronary CTA at 70 kVp, although there is limited data on the diagnostic performance at this tube potential.[76,77] While 120 kV is often considered the "standard" tube potential for coronary CTA, tube potential should be reduced from 120 kV to 100 kV when the patient's weight is below 100 kg and the body mass index (BMI) is below 30 kg/m^2, particularly considering recent advancements in iterative reconstruction techniques (discussed below), which preserve image quality at lower tube potentials.[78] In favorable situations (e.g. body weight below 60 kg), it should be considered to lower tube potential even further. In addition to BMI-based tube voltage selection, the use of automated methods for kVp selection based on attenuation values in the scout images may facilitate low radiation exposure in patients undergoing coronary CTA, especially women.[79]

5.5. Tube current

More commonly, the tube current (mA) is modified to adjust for patient size/weight and desired image noise. Increase in tube current results in more photons per exposure time leading to less image noise, but greater radiation exposure. In contrast to the tube voltage, the increase in radiation dose is approximately directly proportional to the change in tube current. In general, larger patients need greater tube current to reduce image noise (generated by more tissue penetration) to an acceptable level. It has to be emphasized again, that tube current should only be increased to a level necessary for acquiring images of adequate quality. Since the previous guidelines, the major advance in relation to lowering tube current has come through the integration of iterative reconstruction methods, which improve image quality such that lower tube current scanning is feasible without a significant compromise in diagnostic image quality. Tube current needs to be selected based on the iterative reconstruction capabilities of the relevant CT scanner platform being used. Similar to automatic kVp selection above, patient attenuation data from the scout images may also be used to select tube current and reduce dose.[79]

5.6. Anatomy-based tube current modulation

While the tube current should be adjusted for each patient according to the patient's size and scan indication, many scanners have additional features that can lower the tube current during the image acquisition, called "tube current modulation". One form of tube modulation, also called "automatic exposure control", lowers the tube current when the X-ray beam is penetrating less dense tissue (i.e., lungs) and increases the current when more solid tissue is penetrated.[80] The selection of tube current is typically determined by the estimated patient attenuation from the acquired scout/localizer scans in conjunction with the technologist's indication of a target image noise level. During CT acquisition, tube current automatically increases or decreases longitudinally in accordance with the degree of attenuation. Lastly, the tube current can be modulated as a function of x-ray source angle (or "X,Y modulation"). Tube current modulation can significantly lower radiation exposure and should be strongly considered when available on the respective CT scanning platform.

5.7. ECG-based tube current modulation

In general, ECG-based tube current modulation should be applied during retrospectively ECG-gated coronary CTA. The principle of ECG-based tube current modulation considers the fact that coronary motion is low during limited phases of the cardiac cycle (end-systole and diastole) and image reconstruction during other cardiac phases frequently results in motion artifacts, thus generating non-diagnostic images of the coronary arteries. Accordingly, tube current is reduced during phases of the cardiac cycle when coronary motion is likely greater (early- and mid-systole) while reserving full-dose tube current to limited phases of the cardiac cycle when coronary motion is minimal. Dose savings of up to 50% can be obtained using ECG-based tube current modulation, although the reduction in radiation exposure depends on several factors, including heart rate (greater dose savings in patients with low heart rates) and CT scanner used.[81]The disadvantage of ECG-based tube current modulation is greater noise in images reconstructed during phases of the cardiac cycle utilizing a lower tube current. However, the increase in image noise does not usually hinder cardiac function analysis since ventricular contours can still be delineated.

6. Modes of data acquisition

6.1. Prospectively ECG triggered axial acquisition

Prospectively ECG-triggered axial acquisition should be considered for coronary CTA as the default scan mode of choice in patients with adequate heart rate control. With prospectively ECG-triggered axial acquisition, the X-ray tube is activated only during a pre-specified phase of the cardiac cycle (R-R interval). There is no table movement during this time interval. X-ray data are obtained during the phase of the cardiac cycle with presumably the greatest likelihood of minimal coronary motion. The acquisition window can be as narrow as required to reconstruct one phase of the cardiac cycle (approximately one-half of the gantry rotation time), but this leaves no flexibility to select additional phases of the cardiac cycle for image reconstruction in the event that coronary segments are degraded by motion. However, it is possible to widen the acquisition window for a longer interval of the cardiac cycle ("padding"), which allows for reconstruction of images at different time instants so as to reduce the risk of a non-diagnostic exam at the expense of greater radiation exposure.[82] Since no X-ray data are acquired during the remainder of the cardiac cycle, the savings in radiation exposure compared to retrospective ECG-gating can be substantial (up to 90%). Prospectively ECG-triggered axial acquisition is recommended in patients with a regular heart rhythm. In heart rates <60 bpm, prospectively ECG-triggered axial acquisition with a narrow acquisition window during mid-diastole should be applied, whereas in higher heart rates, the acquisition window may be widened so as to include end-systolic phases.

Large detector scanners with broad Z-axis coverage have recently been introduced into clinical practice.[83] The detectors may be wide enough to cover the entire volume of the heart and hence offer the opportunity for single heartbeat acquisitions, eliminating the risk of misalignment artifact and allowing for homogeneous blood pool attenuation.[84]

6.2. Retrospectively ECG-gated helical or spiral acquisition

In retrospectively ECG-gated coronary CTA, x-ray data are acquired throughout the entire cardiac cycle while the patient table is subjected to constant, slow motion. This generates an x-ray data set with substantial oversampling and for image reconstruction; only data acquired during the cardiac phase with the least motion are used. Retrospective ECG-gating in coronary CTA should be considered in cases where a regular heart rhythm cannot be obtained or if the heart rate is high. In addition, retrospective ECG-gating should be considered when seeking evaluation of ventricular or valvular function. ECG-based tube current modulation should always be

considered when retrospectively ECG-gated helical or spiral acquisition is used for coronary CTA.

6.3. Prospectively ECG-Triggered high-pitch helical or spiral acquisition

High-pitch spiral coronary CTA is a recent scan mode developed specifically for low-dose imaging and is currently available on dual source CT platforms.[85] Dual-source CT technology enables seamless z-sampling at helical pitch values of 3.4 by interleaving data acquired from the two detector systems. Scan acquisition with high-pitch spiral coronary CTA is most commonly triggered during early diastole (60% of the R-R interval) and completed within one cardiac cycle. At higher heart rates it may be more appropriate to trigger during end-systole. High-pitch spiral coronary CTA may be applied in patients in whom excellent image quality is expected (regular heart rate <60 bpm, BMI <30 kg/m^2). The major advantage of this protocol is the generation of very low-dose coronary CTA images with radiation exposures often less than 2 mSv. The disadvantage of high-pitch spiral coronary CTA is that only one phase during the cardiac cycle is available for image reconstruction. In addition, the process of image acquisition is triggered several heartbeats before data acquisition actually occurs, so that the protocol is not suitable for patients with any variability in heart rates, nor is it useful in cases seeking evaluation of ventricular function.

7. Shielding

Intuitively, shielding of radiosensitive organs within (breast, lung) or outside (thyroid, intestine, gonads) the scan field by protective materials (lead, bismuth, tungsten-antimony) should help minimize radiation exposure to the patient. Yet, the potential benefits of shielding must be weighed against evidence that shielding impairs CT image quality by increasing noise, reducing image signal and by the introduction of streak artifacts.[9] While phantom models and dosimetry studies suggest that shielding yields modest reductions (30–60%) of radiation exposure during CT imaging, further evidence is needed to demonstrate if any biologic benefits may offset impaired image quality. While a White Paper of the American College of Radiology suggests that “technologists may need to use individualized shielding”,[86] until more conclusive data are available, shielding is not considered a routine tool to lower radiation exposure for coronary CTA.

As an alternative to breast shielding in female patients, displacement of mobile breast tissue outside the CT scan range may be considered. Breast displacement may lower radiation exposure to breast tissue and improve CT image quality by reducing photon attenuation, while minimizing the radiation dose required to achieve a diagnostic CTA.[87]

7.1. Other considerations

Scatter from patient clothing, jewelry, and ECG leads should be considered and avoided by having patients change into hospital gowns prior to CT scanning, and carefully reviewing scout/localizer images for high attenuation objects within the scan volume.

7.2. Monitoring radiation exposure

Current scanners display the estimated radiation exposure for each component of the scan as well as the total estimated dose for each study. The standard radiation dose parameter is the CT dose index, CTDI, which represents the estimated dose delivered to a CT phantom for given scan parameters (tube voltage, current, rotation time, etc.). However, the CTDI does not account for the scan length and thus should not be taken as a surrogate for total delivered dose. The closest estimate to the actually delivered dose is the dose-length-product, DLP, which takes into consideration a weighted CTDI (accounting for dose heterogeneity in the scan field), the scan length and pitch/scan overlap. From the DLP, an estimation of effective radiation dose can be derived by multiplying the DLP by a conversion factor for thoracic imaging (currently 0.014 is being used for adult patients).[88] These values can be obtained during the planning stage of the scan, i.e., after determining the scan range, heart rate during breath-hold, and should be considered for applying the least radiation to address the test indication. It is important to note however, that the derived numbers are only rough estimates because they are based on phantom studies and the anatomic assumptions are frequently not met in clinical practice. It is also important to note, that radiation dose estimates typically underestimate the true radiation dose, when actually measured.[9] Thus, the DLP should serve as a rough guide of estimated radiation dose delivered and one should assume that the actual delivered doses exceed these estimates. The DLP is most useful to assess the relative dose reductions with alterations of the image acquisition, i.e., change in tube voltage and current, implementing dose modulation etc., for optimized scan planning. It is therefore recommended to document DLP for every coronary CT angiogram and to institute periodic review of radiation exposure.

Pediatric DLP estimates are often based on a 16 cm phantom, which will increase the estimated dose for the same exposure of a 32 cm phantom by a factor of 2.2. Thus, it is suggested that DLP, scan range and the phantom size used for DLP and CTDI estimates are reported for pediatric patients undergoing coronary CTA.

8. Scan protocols

8.1. Overview image

Imaging starts typically with obtaining an anterior-posterior projection overview image (scout, topogram, topographic scout image, etc.) that allows prescription of the scan range. Generally the coronary CTA scan range begins at the level of the tracheal bifurcation or the mid-level of the left main pulmonary artery and ends just below the diaphragm, usually 12–15 cm in length.

8.2. Coronary calcium scan

A coronary calcium scan is a non-enhanced ECG-synchronized scan for the detection and quantification of coronary calcium. In general, prospectively ECG-triggered axial acquisition should be used. The optimal phase of the cardiac cycle depends upon the heart rate observed during the test breath-hold and typically ranges between 65 and 80% of the R-R interval. Whether to proceed with a coronary CTA in the presence of extensive coronary calcification on the coronary calcium scan remains controversial. Coronary calcification leads to high X-ray attenuation that can result in partial volume averaging artifacts.[9] Some studies have demonstrated a higher incidence of non-diagnostic coronary segments in the presence of significant coronary calcification.[89] At the same time, more extensive coronary calcification increases the likelihood that the patient has obstructive coronary artery disease.[90,91] Accordingly, some centers do not proceed with coronary CTA in the presence of an Agatston score exceeding 600–1000. However, such approaches have not been adequately studied nor validated. For selected patients in whom good image quality is expected (regular heart rate <60 bpm, low to moderate body weight, and optimal patient corporation), coronary CTA may yield useful information despite extensive coronary calcification. The decision to proceed with coronary CTA in the presence of a high coronary

calcium score should be left to the discretion of the referring and attending physician.

9. Coronary CT angiography

9.1. Heart rate considerations

The heart rate and its variability obtained during breath-hold are critically important for planning the scan. In general, routine lowering the heart rate for coronary CTA substantially contributes to radiation dose saving. A regular heart rate (preferably <60 bpm) allows one to obtain diagnostic images using conventional prospectively ECG-triggered or high-pitch spiral coronary CTA in most patients. Depending on the scanner type and software specifications, higher heart rates may require the acquisition of data from both late systole and diastole, which may be achievable using prospectively ECG-triggered axial acquisition with a wide acquisition window or through retrospectively ECG-gated helical or spiral acquisition, usually performed with ECG-correlated tube current modulation. Irregular heart rhythms may also require retrospectively ECG-gated acquisition. The development of dual-source CT and wide-detector scanners may allow imaging of selected patients with higher and irregular heart rates such as atrial fibrillation with diagnostic imaging quality.[92,93] It should be acknowledged, however that coronary CTA in high or irregular heart rates typically is associated with a higher radiation dose. Moreover, in the event of irregular heart rates or atrial fibrillation it is essential that other determinants of image quality such as coronary calcification, body weight and patient cooperation are taken into consideration before deciding whether to proceed with the scan. The presence of frequent premature complexes prior to scanning therefore should trigger consideration of aborting the examination.

9.2. Weight considerations

Scan settings should be adjusted to the patient's body weight. Both tube voltage and tube current should be optimized to deliver the least necessary radiation for adequate image quality. In obese patients, higher tube current and tube voltage are required in order to preserve contrast to noise ratio. More importantly, tube current should be adjusted to the total volume of soft tissues within the scanned region. The specific adjustments are dependent on the scanner specifications.

9.3. Dual energy CT

In 2008, dual energy CT was introduced into clinical practice with a dual source CT platform. Alternative approaches include rapid kVp switching (rapidly toggling between 80 and 140 kVp) as well as the use of a dual layer detector.

Dual energy CT strategies have the capacity to reduce image artifacts for myocardial assessment with a particular focus on reducing beam-hardening artifact.[94] However, the role of dual energy CT for evaluation of coronary stenosis is not well defined and no specific recommendations can be made.

Recommendations.

- Physicians operating MDCT must be intimately familiar with the concepts of risks from radiation exposure.
- Every effort must be undertaken to allow the lowest radiation exposure as reasonably achievable while maintaining diagnostic image quality.
- Tube potential and current should be adjusted for each individual patient according to patient characteristics and test indication with the lowest settings necessary to achieve good image quality. When appropriate, use of 100 kVp is recommended to reduce radiation dose when the patient's weight is below 100 kg and BMI is below 30 kg/m^2. Automated scan parameter selection tools should be considered when available
- The scan range should be as short as reasonably possible.
- Prospectively ECG-triggered axial acquisition is recommended as the first choice protocol for coronary CTA. Alternatives such as high-pitch spiral acquisition or retrospectively ECG-gated helical or spiral acquisition with ECG-based tube current modulation may be applied in selected cases.
- High-pitch spiral acquisitions should be considered for stable heart rates $\leq$60 bpm
- If the patient's heart rate and/or rhythm remain unfavorable (given the site's scanner hardware) despite all efforts of heart rate control, alternative diagnostic imaging strategies should be considered, although coronary CTA may remain the appropriate test.
- The imaging physician has to be familiar with specific technical limitations and strengths of the site's CT scanner system and has to adjust patient selection according to determinants of image quality (heart rate, coronary calcification, weight, and patient cooperation) and acquisition protocols accordingly.

10. Image reconstruction and post-processing

10.1. Introduction

The immediate result of CT data acquisition is a raw attenuation data set, commonly referred to as 'raw data', and not actual viewable images. Viewable images are computed from the raw data by means of 'image reconstruction', producing digital images in which each pixel is assigned a digital numerical value (CT value), expressed in Hounsfield units. The default orientation of image reconstruction is commonly axial (transverse). However, images in any orientation can be reconstructed directly from the raw data. In the past, image reconstruction has predominantly been performed by a method referred to filtered backprojection. With increasing computational power, most hardware systems allow for iterative image reconstruction.

Alterations in the reconstruction method can influence the final appearance of the reconstructed images, in regard to image quality, image artifact, edge enhancement, and resolution. In most cases axial image reconstruction is pre-programmed into the scan protocol and takes place with minimal input from a technologist. However, it is advisable to be familiar with the image reconstruction process so that modifications to image reconstruction can be made when necessary. This section will address the factors that influence the final resulting image data set, and will make recommendations for certain actions in certain scenarios.

10.2. Temporal resolution

Image reconstruction requires a minimum of 180° plus the width of the fan angle of raw-data projections necessitating only 180° of tube rotation. The rotation time of the gantry dictates how much time is needed to acquire 180° of projections. The approximate temporal resolution of the reconstructed images is thus dependent on the rotation time employed and, for the center of rotation, is calculated as rotation time/2 for an image reconstruction utilizing 180° of projections. To compensate for cardiac motion, the minimum rotation time should be employed for routine coronary CTA.

10.3. Half-scan (180°) vs. full-scan (360°) reconstruction

180-degree reconstructions are commonly referred to as a half-scan reconstruction. However, images can be reconstructed using a wider array of projections, e.g. 270° or 360°, the latter referred to as a full-scan reconstruction. Adding projections beyond 180° to the image reconstruction improves the signal-to-noise ration but decreases the temporal resolution. Half-scan reconstruction is the default mode for coronary CTA image reconstructions, as it optimizes the temporal resolution and reduces temporal averaging. Full-scan reconstructions can be employed obese patients to decrease image noise, but image degradation due to motion artifacts has to be considered.

10.4. Field of view and image matrix

The field of view (FoV) refers to the portion of the scan field comprising the image reconstruction, with certain, individually selected in-plane dimensions. The reconstructed FoV can be rectangular or circular. The image matrix refers to the number of pixels along both in-plane dimensions. The default matrix in coronary CTA is 512 × 512. A lower matrix resolution (e.g. 256 × 256) decreases the images resolution if the same FoV is employed and is not recommended for coronary artery evaluation. For image reconstructions dedicated to coronary artery evaluation the FoV should be limited to the cardiac structures (usually 200–250mm) using a 512 × 512 matrix. Holding matrix size constant, increasing the FoV will reduce spatial resolution of the data set. A 256 × 256 matrix can be employed for adjunct reconstructions, e.g. multiphasic reconstructions for cardiac function analysis, in order to limit the file size.

10.5. Slice width (slice thickness) and overlap

For coronary artery evaluation, axial image reconstructions should be performed with the smallest possible slice width (or thickness), varying between 0.5mm and 6.25mm, depending on vendor and CT system. A thicker slice width results in lower image noise, but also lower spatial resolution as compared to thinner slice width, resulting in volume averaging and decreased anatomical detail. In obese patients, image reconstructions employing a larger slice thickness may be employed to reduce image noise. However, the same effect may be obtained by generating 'thick' or 'averaged' multiplanar reformatted images based on thin sliced axial reconstructions using contemporary post-processing work-stations.

10.6. Reconstruction kernel

The reconstruction kernel is the mathematical algorithm used to compute the CT values of the pixels within the CT data set. "Soft" kernels produce an image of lower noise and lower spatial resolution, while "sharp" kernels increase resolution at the cost of higher image noise. In addition, algorithms can be designed specifically for reducing metal artifact or calcium blooming or to enhance the appearance of contrast and the vascular structures.[95,96] Understanding these differences is essential to selecting and applying the correct kernel for a given set of patient factors (e.g. body habitus) and clinical scenarios (e.g. imaging heavily calcified arteries). It is important to also note that attenuation values may vary from one scanner to the next.

10.7. Cardiac phase

The heart's continual cyclical movement provides brief periods of minimal motion during end-systole and mid-to-late diastole. Proper selection of these time intervals for motion-free image reconstruction is crucial to obtaining high-quality diagnostic images.[27] Identification of this time is based on cardiac cycle length and is expressed as a percentage of the cardiac cycle length (R-R interval) or as an absolute time (in ms) after the R-peak. The use of absolute times for selection of image reconstruction (e.g., 700 ms after the R-peak) may produce higher quality images, but has not been shown to significantly impact to make a difference diagnostic accuracy.[27] The optimal time for image reconstruction depends on the patient's heart rate during the acquisition, and this holds true for dual-source as well as single-source scanners.[27,97] There is general agreement that at lower heart rates (<65 bpm), the optimal timing is during late-diastole, while at higher heart rates (>65 to 70 bpm) the optimal timing is more frequently (but not always) during end-systole.[27,97] If the original data set is not free of motion artifact, additional datasets at different phases of the cardiac cycle (R-R interval) must be reconstructed. In these cases, it is not sufficient to rely solely on phases automatically selected by the reconstruction software or on a pre-determined, fixed range of phases applied to all cases. If motion artifact is present, tailored image reconstruction must be repeated in intervals that correspond to 5% of the cardiac cycle or less until a data set without motion artifact is obtained or the phase with least motion is identified. It may be necessary to use different phases of the cardiac cycle for various segments of the coronary arteries.

10.8. Multi-segment reconstruction

Multi-segment reconstruction can be utilized during retrospectively ECG-gated spiral acquisition or if more than one rotation is performed in axial acquisition to improve the effective temporal resolution. Because multiple detector rows are stacked in the z-axis, any given location in the body will pass multiple detector rows at the same point in the cardiac cycle but during different, contiguous heart beats. Rather than using the half-scan data from one cardiac cycle to reconstruct an axial image, multi-segment reconstruction uses data from multiple (contiguous) cardiac cycles and pieces them together to recreate a half-scan of data and hence an axial image. This reduces the effective acquisition time within each cardiac cycle, and improves temporal resolution and image quality. Especially at higher heart rates, the use of multi-segment reconstruction can significantly improve image quality and diagnostic accuracy.[98] Caveats regarding this technique include the requirement of an absolutely regular cardiac rhythm, and the assumption (not always true) that the cardiac position will not vary between heart beats during acquisition. Multi-segment reconstruction can only be applied when using retrospective ECG-gating.

10.9. ECG editing

In cardiac CT, acquisition of ECG data occurs simultaneously with the acquisition of attenuation data, and the axial reconstruction process uses both sets of data. Hence, the ECG data set must be reviewed if artifacts occur in the reconstructed image data set. If the capability exists, errors that are due to incorrect triggering should be corrected by "editing" the trigger instants in the ECG data and "tagging" or "removal" of trigger instances attributable to ectopic beats should be performed if they cause artifact. This can often salvage what would otherwise be an uninterpretable scan.[99]

10.10. Image review

It is recommended that axial images should be reviewed immediately after reconstruction, either by a technologist or physician trained in cardiac CT, while the patient is still on the

scanner table in order to confirm sufficient quality of data acquisition.

10.11. Recommendations

- Half-scan reconstruction should be used by default for all coronary CTA examinations.
- The reconstructed field of view should be reduced to maximize number of pixels devoted to depiction of the heart, usually a FOV of 200–250 mm for coronary CTA studies of native coronary arteries.
- If extra-cardiac structures are of interest then a second data set with a larger FOV (x-y plane) should be reconstructed.
- Axial images should be reconstructed with a slice width <1.0 mm for most coronary CTA studies of native coronary arteries. Minimum slice thickness (0.5–0.6 mm) should be considered for studies that require maximum spatial resolution, insofar as image noise permits. A thicker slice width (1.0–1.5 mm) should be considered in obese patients to reduce image noise due to body habitus.
- A slice increment of 50% of the slice width should be used.
- A semi-sharp reconstruction kernel should be used for most patients. For cases that require maximum spatial resolution, a sharp kernel may be used to reduce blooming and increase edge definition. For obese patients, a soft or smooth kernel may be used to reduce image noise.
- A sufficient number of phases should be reconstructed in order to find the optimal phase of the cardiac cycle (R-R interval) with the least amount of coronary motion.
- Multi-segment reconstruction should be considered, especially at higher heart rates, to improve temporal resolution and improve image quality.
- ECG-editing, if available, should be used to correct errors or artifacts occurring during acquisition, and to designate ectopic beats for exclusion or special handling during data reconstruction.

11. Conclusion

Recent advances in CT technology have greatly improved image quality, feasibility, and accuracy of coronary CTA. A clear understanding of the technique's capabilities and limitations, and an appreciation of the details of patient selection, preparation, scan acquisition, and image reconstruction are required to develop and sustain a successful coronary CTA program. Supervision and care must be taken at every step in the process to ensure that high quality results are achieved in all patients. These guidelines provide general instruction for the performance and acquisition of coronary CTA, but proper execution of the procedure for any patient requires expertise of all involved practitioners and staff, and recognition of patient factors and clinical scenarios which will require tailoring of the coronary CTA protocol.

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