Technical Principles of Computed Tomographic Angiography for Adult Congenital Heart Disease

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The computed tomographic angiography (CTA) imaging protocol must be tailored to the suspected cardiac lesion and the type of prior surgical repair. The relevant parameters that need to be selected prior to imaging are contrast volume, contrast injection speed, the timing of the scan, slice collimation, scan length, tube voltage (kV), tube current (mA), and pitch. In addition, the imager must decide on the use of non-ECG-synchronized acquisition versus ECG synchronization (prospective or retrospective). In general, multidetector scanner with ≥64 rows is preferred for evaluation of congenital heart disease (CHD).

CTA protocols for assessing adult patients with known or suspected congenital heart disease are similar to standard coronary artery CTA imaging protocols with one major exception. For coronary artery imaging, scan timing is adjusted to avoid right ventricular contrast opacification since it may interfere with assessment of right coronary artery anatomy. In imaging CHD, adequate contrast opacification of both the right and left ventricles is necessary to adequately visualize the complex right- and left-sided anatomy. Not only must scan timing be altered to allow this, but at times, a delayed scan is necessary to allow adequate recirculation of contrast through complex anomalies and their potential corrections such that all the necessary anatomy is adequately opacified.

6.1 Contrast Agent Administration

Low-dose pre-contrast imaging is indicated in patients who have prior surgical repairs as it allows identification of calcified conduits and septal patches and minimizes the risk of confusing these expected changes with true postoperative complications, particularly vascular leaks. For contrast administration, a right-arm injection is preferred to avoid contrast artifacts often associated with injection into the left brachiocephalic vein. To reduce artifacts from undiluted contrast material, a saline bolus chaser should be used. We prefer the automated bolus tracking technique to determine the appropriate imaging delay. In adults, the region of interest is placed in the ascending aorta, and the attenuation threshold is set at 140 HU. An appropriate, fixed delay time (generally 15 s) may be used when the right heart, superior vena cava, or complicated shunts such as the Glenn shunt or the superior limb of a baffle are areas of interest.

To achieve both right and left ventricular opacification, a biphasic contrast injection protocol (contrast followed by a saline injection) is appropriate. Monophasic injections (contrast only) should be avoided since these cause excessive streak artifacts. If complex shunts such as Glenn or Fontan are present, additional delayed scanning should be performed 60 s after start of the contrast injection to opacify the venopulmonary circuit.

Imaging protocols for patients with CHD should closely mimic standard coronary artery imaging protocols since the detection of coronary artery disease remains pertinent since the prevalence of coronary artery disease is similar to that of the general population. In fact, recent studies support coronary angiography in patients with CHD older than 40 years before corrective surgery [1]. It is not unusual to perform corrective surgery in adults with congenital heart disease simultaneously with coronary artery bypass grafting [2]. In order to diagnose coronary artery images, aggressive heart rate reduction is required to prevent motion artifact. We prefer a resting heart rate of ≤60 beats per minute which not only helps to prevent motion artifact but also allows the use of radiation reduction protocols.

6.2 Slice Collimation (Slice Thickness)

Thicker detector collimation (2 mm) is preferable to reduce radiation dose and improve image quality, although visualization of small structures is diminished. In addition, the CTA acquisition time is lower when using thicker collimation, and consequently radiation dose and respiratory motion artifacts are reduced. However, if evaluation of small intracardiac structures or the coronary arteries is indicated, thinner collimation should be used.

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Contrast volume is usually between 80 milliliters (ml) and 120 ml with higher volumes being used for more complex shunting anomalies to allow adequate mixing of contrast. The injection rate is generally between 5 and 7 ml/s.

6.3 Scan Length (Z-Axis Coverage)

Since the CTA radiation dose is directly proportional to the scan length, it is essential that the scan length be minimized to include only the area of interest. The typical scan length for adults is 12–13 centimeters (cm) and extends from just below the carina to slightly below the diaphragm. If great vessel anomalies are expected, a longer scan length extending superiorly may be required to allow visualization of the entire aortic arch area. A recent study has shown that for each 1 cm reduction in scan length, the retrospectively gated CTA radiation dose is reduced by 5 % [3].

6.4 ECG-Controlled Tube-Current Modulation

Modulating tube current during the R–R interval (ECG current modulation, ECG CM) has proven to be an effective dose reduction strategy in retrospective ECG-gated CTA [4]. Using ECG CM, the tube current outside the predetermined cardiac cycle is reduced relative to the current inside the pulsing window. In one series, tube current was maintained at its maximum during diastole and reduced to approximately 20 % of the maximum in systole. This approach has been shown to reduce radiation dose by as much as 40 % without loss of image quality [4]. The optimal ECG pulsing window for cardiac CTA depends on the patient's heart rate [5, 6].

6.5 Tube Voltage

Reducing the tube voltage from 120 to 100 kV can reduce radiation dose by up to 50 % [7]. Using a kV of 80 in appropriate patients may further reduce radiation exposure [7, 8]. In patients who weigh ≤85 kg or who have a body mass index (BMI) of ≤30 kg/meter $(m)^2$, a tube voltage of 100 kV is appropriate. Patients who weigh ≤60 kg or in those with a BMI ≤ 25 kg/m^2, a tube voltage of 80 kV may be used.

6.6 Pitch

Pitch is defined as the ratio of table travel (mm) per gantry rotation to scan length. The latest generation of dual-source CTA technology permits scanning at very high pitches. In single-source CTA, the maximum pitch is limited to approximately 1.5. In the high-pitch dual-source scanner, the second detector system is used to fill the imaging gaps created by high-pitch imaging [9]. By interweaving data from the two detectors, the pitch can be increased to as high as 3.4, thus reducing the acquisition time to image the entire chest to below 1 s [10]. The high-pitch mode has been demonstrated to provide artifact-free visualization of the coronary arteries at a radiation exposure less than 1 mSv [9].

6.7 Non-ECG-Gated Cardiac CTA

Since coronary artery anomalies are common in many types of congenital heart disease, ECG gating is often performed when CTA is used for the evaluation of CHD.

Non-ECG-synchronized CTA allows for fast acquisition of cardiac and extracardiac structures but limits the resolution of small cardiac and coronary structures because of cardiac motion artifacts. To improve image quality, detector collimation should be thicker in non-ECG-synchronized CTA. With current CTA systems, it has been shown that the origins and proximal segments of the coronary arteries are evaluable in 82 % of patients with CHD when non-ECG-synchronized CTA acquisition protocols are used [11].

6.8 ECG-Gated Cardiac CTA

Retrospective ECG-gated cardiac CTA uses oversampling of information across different phases of the cardiac cycle and across several consecutive heartbeats. Here, the data acquisition is obtained with continuous table motion and low-pitch scanning to allow overlap of slice data which results in higher radiation doses than when using non-ECG- synchronized CTA. However, synchronization to the ECG provides artifact-free visualization of cardiac and coronary structures even at elevated heart rates.

Although ECG synchronization allows for the assessment of left and right ventricular function, comparable information can be obtained by performing a non-ECG-synchronized scan to evaluate cardiac anatomy and morphology while utilizing echocardiography for functional information which cannot be obtained with non-ECG-gated scanning.

Prospective ECG-triggered CTA scanning is performed at user-selected predefined phases of the cardiac cycle. This acquisition mode uses the "step-and-shoot" approach, whereby radiation is delivered during a prospectively defined time window in mid-diastole. The table moves in a sequential manner and remains stationary while data are acquired. Because of the confinement of the radiation output to only a small part of cardiac cycle, prospectively triggered cardiac CTA may be performed with radiation doses as low as 1–5 millisieverts (mSv), compared to 12–15 mSv for a conventional retrospectively gated, helical scanning [12, 13].

Unlike retrospectively acquired scanning, prospective acquisition permits only static imaging of the heart since data are not acquired throughout every phase of the cardiac cycle. Thus, evaluation of cardiac function is not possible using prospective gating CTA techniques.

As a rule, gated studies are used as problem-solving techniques or when ventricular parameters are required. To date, prospective triggering has almost completely replaced retrospective triggering in patients with CHD if coronary artery evaluation is indicated. A retrospectively triggered scan should be used in patients with arrhythmia or in patients where artifact is expected so that reconstructions for a wider range of cardiac phases may be used to improve the diagnostic evaluation. If gating is to be performed in CHD patients with right heart failure, care must be exercised when using beta-blockers since their use can exacerbate the condition.

6.9 Padding

Radiation exposure from CTA can be minimized by shortening the time window during which images are acquired. Padding is the period of time during the cardiac cycle, beyond the minimum necessary, that the X-ray beam is activated for image acquisition. Padding is used to increase data collection and potentially improve the diagnostic value of the scan by increasing the number of possible phases that may be reconstructed and used for evaluation [14]. If all other scan parameters are kept constant, increased padding is associated with a greater radiation dose. Overall, the radiation dose increases by about 45 % for every 100 millisecond (ms) increase in the padding time ($p<0.001$) [14]. Without padding, the average radiation dose is 2.3 mSv in prospectively triggered scan. Conversely, when medium and long padding times are employed, radiation doses are 3.8 and 5.5 mSv, respectively [14].

6.10 Iterative Reconstruction

Traditionally, filtered back projection (FBP) is used to reconstruct the CTA scan data. Iterative reconstruction utilizes a computer model to reconstruct the CTA image. This more precise reconstruction method requires less signal to noise ratio (allowing reduced acquisition radiation doses) to accurately reconstruct a high-quality CTA image free of noise [15, 16]. The use of iterative reconstruction results in improved image quality with less noise than FBP while using lower radiation doses [16]. Iterative reconstruction is associated with a 27 % reduction in radiation dose compared with standard FBP methods ($p<0.001$) [15]. The median radiation doses are 2.3 mSv versus 4.1 mSv ($p<0.001$) for iterative reconstruction and FBP, respectively [15]. In addition, similar levels of image noise were achieved with 80 and 100 kV using iterative reconstruction compared to 120 kV with FBP, resulting in a 62 % reduction in effective dose [15, 16].

In summary, by combining several of the above-mentioned radiation-sparing methods, radiation doses in the 1 mSv range are now routinely possible, making CTA an attractive imaging technique for comprehensive evaluation of adults with CHD. Updated guidelines and comprehensive state-of-the-art review on radiation dose and dose-optimization strategies in CTA were published in 2011 [15].

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