Seminars in
ULTRASOUND
CT *and* MRI

Technical and Clinical Aspects of Coronary Computed Tomography Angiography

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Coronary computed tomography angiography is an emerging imaging technique that has attracted much scientific attention over the past years. Improved scanner technology and dedicated protocols have made noninvasive coronary a reliable diagnostic test in patients with suspected coronary artery disease (CAD). Several technical steps such as the introduction of 64-slice scanners, multisegment reconstruction, and dual-source computed tomography have substantially improved temporal and spatial resolution. With these sophistications, coronary computed tomography angiography enables reliable exclusion of CAD in patients with low to intermediate pretest probability of having CAD or with inconsistent ischemia test results.
Semin Ultrasound CT MRI 29:167-175

Since coronary artery disease (CAD) is the most common cause of death in the Western world[1] and conventional invasive coronary angiography a costly procedure[2] and potentially dangerous for patients,[3] much recent clinical research has focused on the development of noninvasive approaches to assess the coronary arteries. Noninvasive coronary angiography is technically demanding because of the nature of its targets, the continuous motion of the heart, and the small size of the coronary arteries. A noninvasive approach must also be reasonable for patients with suspected heart disease. To meet these challenges, noninvasive coronary angiography must fulfill four major technical requirements: high spatial resolution, high temporal resolution, fast continuous coverage within one acceptable breath-hold period, and synchronization to the heart beat to cope with the heart's motion. Multislice computed tomography (MSCT) has the potential to achieve these requirements and has overtaken magnetic resonance angiography[4] and electron beam computed tomography[5] in the field of noninvasive coronary angiography. Magnetic resonance angiography is at present not able to cover the whole coronary artery tree with a spatial resolution comparable to that of computed tomography (CT),[6,7] and EBT is mainly limited by a spatial resolution of only 1.5 to 3 mm in the *z*-axis of the patient.[8,9] Major disadvantages of MSCT are the radiation exposure and the need for administration of contrast agents and in most cases beta-blockers. Efforts have been undertaken recently to reduce these disadvantages and improve image quality and diagnostic accuracy; these efforts are discussed in this article.

Large data sets are acquired during a single coronary computed tomography angiography (coronary CTA) so that efficient postprocessing techniques are needed to ensure adequate image interpretation within a reasonable time. Different options are available and in clinical use; these options are another focus of this article.

Coronary CTA has different indications and contraindications that are important to know for the referring physician to achieve optimal results; these indications are also comprehensively presented.

Spatial Resolution

The coronary arteries are very small vessels and have a complex anatomy in all three dimensions. The proximal segments have lumina of 1.5 to 4.5 mm and a mean diameter of approximately 2.5 mm.[10] It is therefore obvious that a high spatial resolution is necessary to depict the whole coronary artery tree. The in-plane resolution of CT depends on the system geometry and the reconstruction kernel selected. Axial image series in *x*- and *y*-axis are reconstructed within a defined field-of-view (FOV). The size of each pixel depends on the size of the selected FOV; with a standard matrix of 512 × 512 in a standard FOV for chest CT of 35-40 cm, each pixel has a size of approximately 0.8 × 0.8 mm, which is too large for adequate coronary artery assessment. To increase spatial resolution of coronary CTA, the patient is positioned off-center on the table so that the heart is in the gantry rota-

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doi:10.1053/j.sult.2008.02.002

tion center. A scan FOV of 32 mm is applied to cover the whole chest diameter and the adjoining parts of the lung. For coronary analysis a small reconstruction FOV of 18-22 cm results in a minimal in-plane resolution of 0.35 mm. In z-axis pixel size depends on detector collimation width. Different CT vendors introduced different detector designs: General Electric[11] and Philips[12] use detectors with 64 × 0.625 mm collimation, Toshiba detectors with 64 × 0.5[13] mm collimation, and Siemens 32 × 0.6 mm collimation,[14] which results in an effective collimation of 64 × 0.6 mm when combined with z-flying focal spot technology.[15] In conclusion, nearly isotropic resolution of 0.35 × 0.35 × 0.5 mm is optimal for coronary CTA.

Sublingual nitroglycerine administration immediately before the examination facilitates analysis by increasing coronary vessel diameters and improves comparability with invasive coronary angiography, which is performed with intracoronary nitroglycerine injection.[16] The examiner must carefully exclude contraindications to nitroglycerine such as phosphodiesterase inhibitors (eg, sildenafil, Viagra™), as this medication is not uncommon in patients with atherosclerosis, and interaction might be fatal.[17]

Temporal Resolution

Mean arterial motion velocity is about 50 mm/s for the small coronary arteries[18,19] requiring high temporal resolution to display the coronary arteries without motion artifacts. The standard of reference, invasive coronary angiography, has a temporal resolution of approximately 10 milliseconds.[20] MSCT is not able to reach this benchmark, even with the most modern scanners. However, reliable coronary CTA is possible using sophisticated reconstruction techniques and concentrating on specific time points within the cardiac cycle.

In coronary CTA images are generated from data acquired during a half gantry rotation. It is obvious that gantry rotation time is the main predictor of temporal resolution. The first generation of MSCT scanners with four detector rows had a gantry rotation time of 500 milliseconds, resulting in an image acquisition time of 250 milliseconds. This time is sufficient to assess the coronary arteries in patients with low heart rates. Only 78% of the coronary artery segments scanned could be analyzed in the first studies performed on four-slice CT scanners.[21] The next scanner generations decreased gantry rotation time to a minimum of 330-350 milliseconds, resulting in image acquisition windows of 165-175 milliseconds using half-scan reconstruction. With systematic beta-blocker administration nearly 98%[14,22] of the coronary artery segments could be assessed. Beside faster gantry rotation, the vendors of CT scanners developed different technical approaches to reduce image acquisition time. Image data from a half-gantry rotation can be collected either by partial rotations in consecutive heartbeats or by two separate X-ray tubes rotating with an angular offset of 90 degrees, collecting data of two partial rotations within the same heart beat.

The first approach is referred to as multisegment reconstruction[23-25] and uses image data collected from up to five partial rotations in up to five consecutive heartbeats (depending on the heart rate). Resulting image acquisition time depends on the number of segments used for reconstruction and the intersection of the segments. An image acquisition time of 50 milliseconds can be reached under optimal conditions, when five partial rotations complement one another over five consecutive heartbeats with a gantry rotation time of 350 or 400 milliseconds. Image acquisition time is longer when the heart beat is exactly synchronized to tube rotation and segments of consecutive heartbeats overlap each other, resulting in an acquisition time equal to that of half-scan reconstruction. Optimal temporal resolution can be achieved by adjusting the gantry rotation time to the individual heart as shown in Fig. 1. At our institution we simulate the breath-hold period prior to the scan to identify the individual patient's heart rate and heart rate variability during apnea and then determine optimal gantry rotation time and pitch level. Adaptive multisegment reconstruction is less dependent on variations because it is able to react to heart rate variability so that either two, three, four, or five segments in consecutive heartbeats are used to reconstruct axial images.

Dual-source computed tomography is a second and more recent approach. It uses two X-ray tubes, acquiring data within a quarter rotation. With a gantry rotation time of 330 milliseconds, image acquisition windows of 82.5 milliseconds are reached, independently of the heart rate. This technique seems to be robust at heart rates ≥65 bpm, and initial studies without beta-blocker administration reported excel-

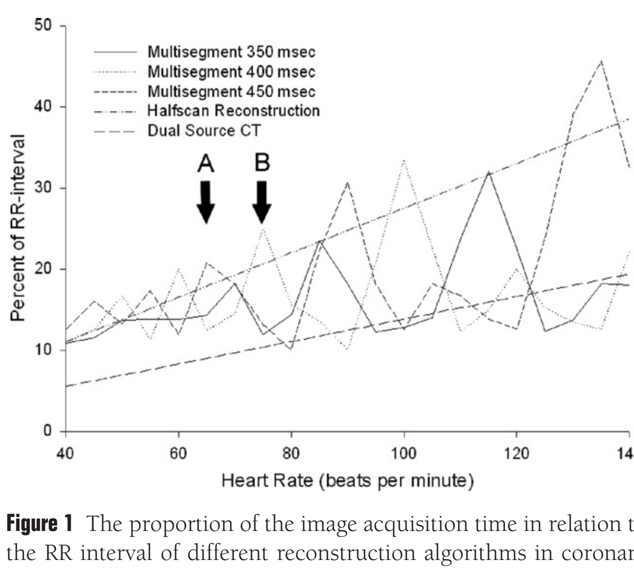

Figure 1 The proportion of the image acquisition time in relation to the RR interval of different reconstruction algorithms in coronary CTA for a heart rate range of 40 to 140 bpm. Conventional half-scan reconstruction acquires data within a half gantry rotation, dual-source CT within a quarter rotation shortening the temporal resolution significantly. Multisegment reconstruction can be performed with different gantry rotation times like 350, 400, or 450 milliseconds, resulting in optimal image acquisition at specific heart rates. The arrows illustrate two examples: at a heart rate around 65 bpm (A), 400 milliseconds gantry rotation time should be selected, and at a heart rate of 75 bpm (B), a gantry rotation time of 350 milliseconds. With these gantry rotation times, acquisition can be significantly shortened and approximates that of dual source CT.