Minimizing radiation dose in coronary CT angiography with diagnostic imaging quality in routine investigation of coronary artery disease

By Dr CE Richards & Dr DR Obaid

The potential for cardiac imaging and evaluating coronary artery disease (CAD) non-invasively has been a key driver behind the advances in computed tomography (CT) technology over the last three decades.

Coronary CT angiography (CCTA) now has the diagnostic accuracy to be able to exclude CAD in routine use with high negative predictive power. To extend CCTA to wide-spread usage, including low-risk or even asymptomatic subjects, however requires that high quality images be produced with radiation doses low enough to reduce clinical risk to an absolute minimum [1].

Traditionally, fluoroscopically guided images from coronary angiography have defined the standard in diagnosing CAD. The use of intra-arterial contrast, however, is more invasive and requires longer patient preparation and recovery times. CCTA is a less invasive and viable alternative as a diagnostic procedure that uses only an intravenous injection of iodine-rich contrast. [Figure 1]

Figure 1. Comparison of right coronary artery stenosis detected with (A) invasive catheter angiography and (B) CCTA.

Despite the growing utilisation of CCTA, a number of challenges remain. Visualizing a 10% stenosis of a coronary artery requires a minimum isotropic resolution of 0.3 mm [2]. Differentiating submillimetre structures means that high spatial resolution is required while the rapid motion of the heart means that high temporal resolution is needed to reduce motion artefacts. Balancing the need for an image quality of approximately that of coronary angiography with the need to optimize image signal-to-noise ratio (SNR) has resulted in high radiation doses of up to 31.4 mSv [3] being used, so increasing the lifetime risk of radiation-induced malignancy [4].

Recent strategies have been developed to minimise radiation to "as low as reasonably achievable" (ALARA) levels. While submillisievert radiation doses have been reported in recent studies, the generalizability of these studies are limited by the fact that they generally involved only small cohorts of pre-selected patients with very low heart rates , small body habitus and a low prevalence of CAD. Patients with other characteristics, such as heart rate > 65 bpm, a body mass index > 30 kg m^{-2}, and arrhythmias, still present imaging challenges. The feasibility of CCTA low-dose scan modes and the effect on image quality and radiation exposure in these populations has yet to be fully investigated.

The Authors

Dr Caryl Elizabeth Richards[1, 2] & Dr Daniel Rhys Obaid[1]

1. Swansea University Medical School, Swansea University, Grove Building, Singleton Park, Sketty, Swansea SA2 8PP, UK

2. Morriston Hospital, Swansea SA6 6NL, UK

Corresponding author

Dr CE Richards email: carylerichards@googlemail.com

DOSE REDUCTION METHODS

Low-dose CCTA modes optimize the trade-off between the scan parameters that affect image quality while adhering to the ALARA principle [5,6]. Temporal and spatial resolution depend on several factors including the detector size and configuration, gantry rotation time, acquisition mode, and reconstruction method and interval. Image contrast is affected by noise, tube current and voltage [7]. We have demonstrated that diagnostic image quality is possible with low radiation doses in an unselected patient population using a combination of the following low-dose CCTA scanner modes

Z-axis coverage: volumetric CT field of view

The dimension of the z-axis (longitudinal) detector array determines the number of gantry rotations required to cover the entire cardiac volume. For cardiac imaging using previous generation CT scanners, where the z-axis detector length is shorter than 140 mm, several gantry rotations are required. At our institute, CCTA images are taken with a multidetector array CT (MDCT) 320-slice scanner with 320 × 0.5 mm detector array (Aquilion One, Toshiba Medical Systems, Japan). Z-axis coverage of 160 mm allows coverage of the full cardiac volume within a single non-helical rotation, reducing scan times.

A full 360-degree gantry rotation is limited to 350 ms due to mechanical stresses. For cardiac CT, a temporal resolution of 350 ms is not adequate, so half-segment reconstruction is used in which CT images are reconstructed from projection data covering 180° plus the fan angle of the CT detectors in the axial plane. Since the entire image of the heart is taken at the same time in one x-ray pulse there are no mis-registration artefacts, no banding artefacts, and perfect contrast uniformity. Patient-specific, preliminary CT radiographs or "scout views" are also used to select the scan field of views to the minimum volume coverage in the z-axis in a single complete acquisition, thus further reducing the radiation dose.

Prospective electrocardiogram-gating

Prospective electrocardiogram (ECG)-gated tube current modulation is one of the most effective radiation dose reduction strategies [8]. With ECG-gating software (SURE Cardio, Toshiba Medical Systems, Japan) the x-ray tube acquisition window can be reduced to 70–80% of the interval between two consecutive QRS complexes, rather than the whole cycle in patients with a heart rate below 65 bpm.

Changes in the heart rate and arrhythmias pose further challenges for CCTA. Automatic arrhythmia rejection software (SURE Cardio, Toshiba Medical Systems, Japan) monitors the heart rate and terminates the radiation exposure if an arrhythmia occurs, before automatically detecting and acquiring the next normal beat for image reconstruction in real time.

Tube Current (mA) and Voltage (kV)

CT radiation is approximately proportional to the square of the tube voltage and decreases linearly with tube current. Automated modulation (SUREExposure, Toshiba Medical Systems, Japan) optimizes the tube current and voltage (100 kV–135 kV) according to the size and attenuation profile of each patient, based on the scout image. Reducing the tube voltage also increases the vessel lumen and cardiac chambers attenuation with iodinated contrast resulting in greater image contrast.

Iterative Reconstruction

A multidetector array arrangement improves spatial resolution compared to a single detector, where images can be reconstructed from a number (n) of thin-slice CT scans at a fixed radiation dose. However, a reduction in the number of x-ray photons by a factor n per slice yields an increase in noise by a factor $\sqrt{n}$. Images with the same noise level can be obtained by increasing the dose by a factor of n, or by using thicker CT slices, which is counterproductive [9]. This approach has since been offset by image reconstruction methods such as iterative reconstruction. Adaptive iterative dose reduction (AIDR-3D) uses an initial estimate of the image, which is then improved iteratively by comparing the synthesized image to the one acquired with projection data [10]. Improvements in SNR and contrast-to-noise ratio make it possible to maintain image quality at reduced currents [11].

Heart Rate control

Minimum cardiac motion occurs during the diastolic phase, which becomes smaller with increasing heart rate. Motion-free cardiac imaging in patients with heart rates up to 70 bpm, requires a temporal resolution of 250 ms. However, heart rates greater than 100 bpm require 150 ms temporal resolution, which is at the limit of gantry rotation. If necessary, rate-limiting beta-blockers can be administered to patients to achieve a heart rate below 65 bpm unless beta-blockers are contraindicated [12].

OUTCOME

We carried out a study of 543 consecutive patients in sinus rhythm who were referred to our institute between June 2012 and August 2016 for CCTA examination for suspected CAD. The mean subjective image quality was scored as 3.65 ± 0.61 on a four-point scale (4 = excellent, 1 = non-diagnostic) by two trained observers [13]. Of the patient CCTA images, 93% scored a rating of 3 ("good") or above and CAD was confirmed in 57 (10%) of patients.

The median effective radiation dose was 0.88 mSv, including what we believe to be the lowest ever-reported radiation dose for a routine CCTA (0.18 mSv) for clinically indicated CAD [10].

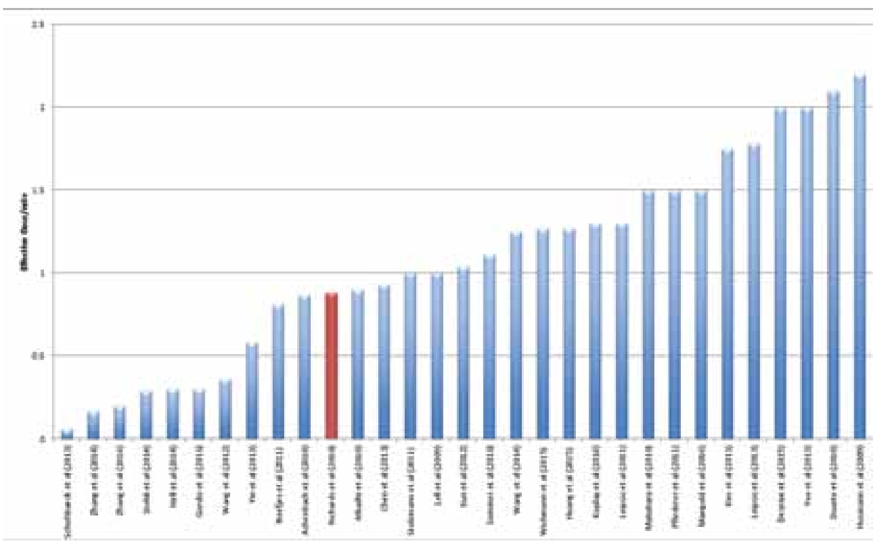

Figure 2. Review of CCTA studies from the literature over recent years showing the lowest effective radiation doses recorded and illustrating the variation in the recorded dose between studies. The red bar represents the study carried out in our institute in the Abertawe Bro Morgannwg health trust in the UK.

Figure 2 shows the lowest effective radiation doses recorded over recent