Balancing Image Quality, Contrast Medium, and Radiation Dose: Coronary CT Angiography Applications

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Introduction

Image quality in multi-detector-row computed tomography (MDCT) depends on many factors, including the individual CT parameters and patient conditions (e.g., body size). Cardiac CT is a recent and sophisticated MDCT technique that is associated with a high radiation dose. For vascular studies, especially those carried out using cardiac CT angiography (CTA), image quality, and thus optimization of contrast injection, is of crucial importance for interpretation. The settings of the apparatus should be selected to minimize radiation exposure while insuring that a high-quality image, sufficient for diagnostic purposes, is obtained. In order to optimize both the contrast and the radiation dose, these parameters must be balanced for each individual patient.

Factors Influencing Image Quality in Cardiac CT

The factors influencing image quality and their relationships are discussed below and shown in Fig. 1.

Artifacts

Image quality may be impaired by extrinsic factors such as movement artifacts. Movement artifacts involving the heart are the most frequent factors affecting image quality in cardiac MDCT and occur most frequently for heart rates above 65 beats per minute (bpm) [1]. They can be prevented by lowering the patient's heart rate using drugs such as β-blockers. In our experience, 100 mg of metoprolol administered 45 min before the examination reduces the heart rate by a mean 20 bpm. Intravenous β-blockers, which have an immediate effect, also may be used. However, as there may be contraindications for the use of β-blockers (asthma, cardiac insufficiency, atrioventricular block, severe aortic stenosis), it is sometimes necessary to carry out cardiac CT at higher heart rates. In these cases, images free from heart motion are more readily acquired at end-systolic phase (generally 40% of the R-R interval) than at end-diastolic phase.

An irregular heart rate due to cardiac arrhythmia is also responsible for severe artifacts since, in this situation, the slices are not reconstructed during the same phase of the cardiac cycle for each beat. Dedicated reconstruction processes, including the ECG editing techniques proposed by some manufacturers, may then be very helpful in minimizing such artifacts. End-systolic phases, in absolute numbers (not the percentage of the RR cycle), were found to be the best times for achieving optimal image quality in patients with atrial fibrillation (Fig. 2) [2].

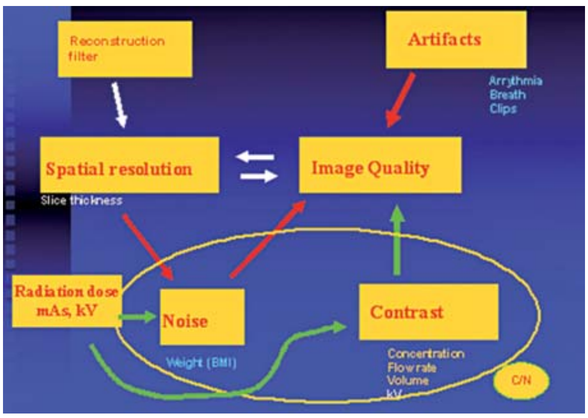

Fig. 1. Main factors influencing image quality. *Red arrows* indicate a negative effect; *green arrows*, a positive effect

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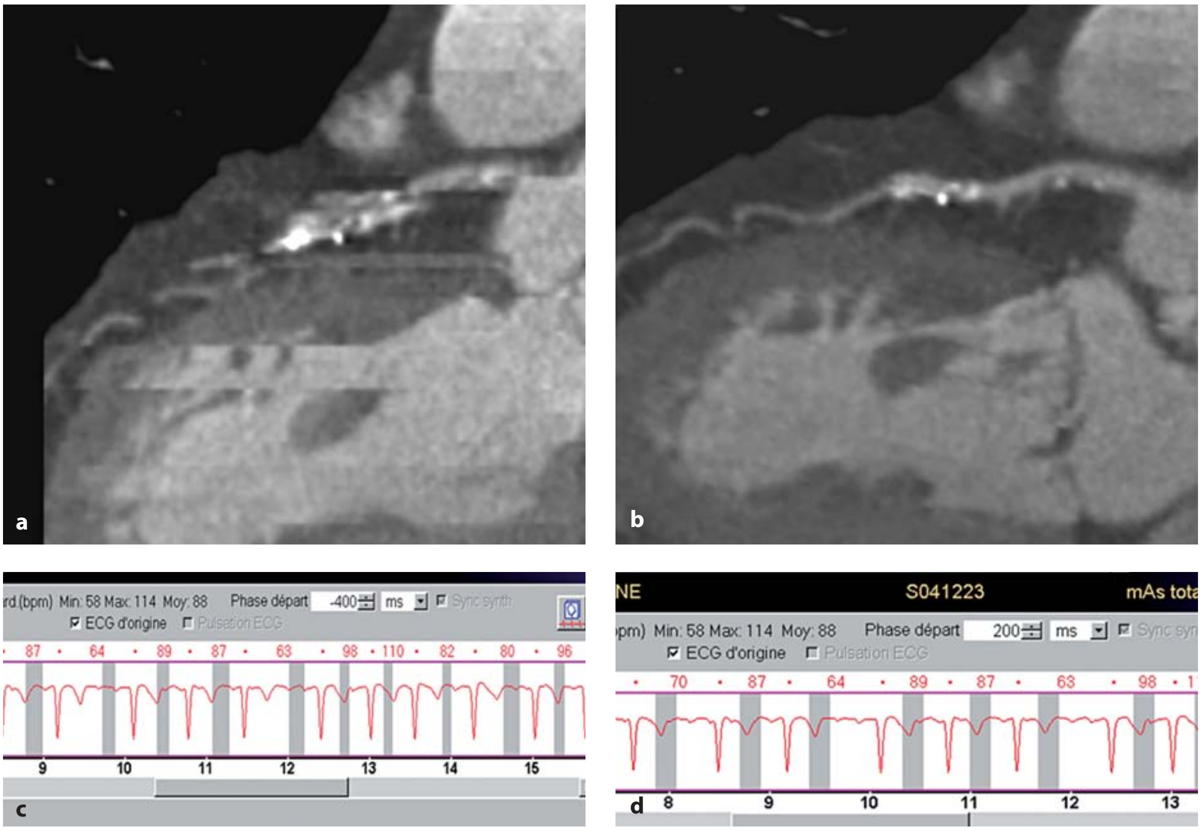


Fig. 2 a-d. a In a patient with arrhythmia, initial diastolic reconstruction (**c**) shows multiple movement artifacts. **b** Reconstructions from the same dataset in systolic phase (200 ms in the RR interval, see **d**), showing absence of movement artifacts

Respiratory motion is also a potential cause of substantial artifacts, with severe impairment of image quality. There is no way to correct these artifacts after image acquisition. Respiratory artifacts can be avoided by careful instruction of the patient before the acquisition. Most patients are able to hold their breath for a scan time of < 10 s (corresponding to the maximal time necessary for cardiac acquisition with a 64-slice CT).

Spatial Resolution

Image quality should be evaluated for a given spatial resolution. An image with high spatial resolution may seem noisier than another reconstructed image from the same dataset but with a thicker slice thickness. Thus, it is mandatory that the spatial resolution be the same when two different images are compared. Spatial resolution in the z axis depends on the collimation (size of the detector). Resolution in the x, y plane is defined by the field of view (FOV) during the reconstruction process. The smaller the FOV and collimation, the higher the spatial resolution. The spatial resolution also depends on the reconstruction filter. High-resolution filters minimize partial volume effects and enhance visualization of details in the CT image (Fig. 3).

MDCT coronary imaging requires high resolution (i.e., sub-millimeter images) since the sizes of the coronary arteries ranges from 1 to 7 mm. However, in daily practice, users may select slightly different slice thicknesses. For example, with the 64-slice CT from Siemens, 0.75- or 0.6-mm slice thicknesses are available. In practice, to obtain better image quality, a slice thickness of 0.75 mm, acquired with a medium filter (B30), may be preferable to a slice thickness of 0.6 mm. It should be noted that a 0.75-mm slice thickness obtained with a B30 filter results in the same noise level as a 0.6-mm slice thickness acquired with a smoother filter (B20). Higher resolution (for example, with a B46 filter) is recommended for stent visualization [3] (Fig. 4), to minimize partial volume effects, and thus to achieve better delineation of the stent structure. Also, coronary calcified plaques are better evaluated using high-resolution kernels.

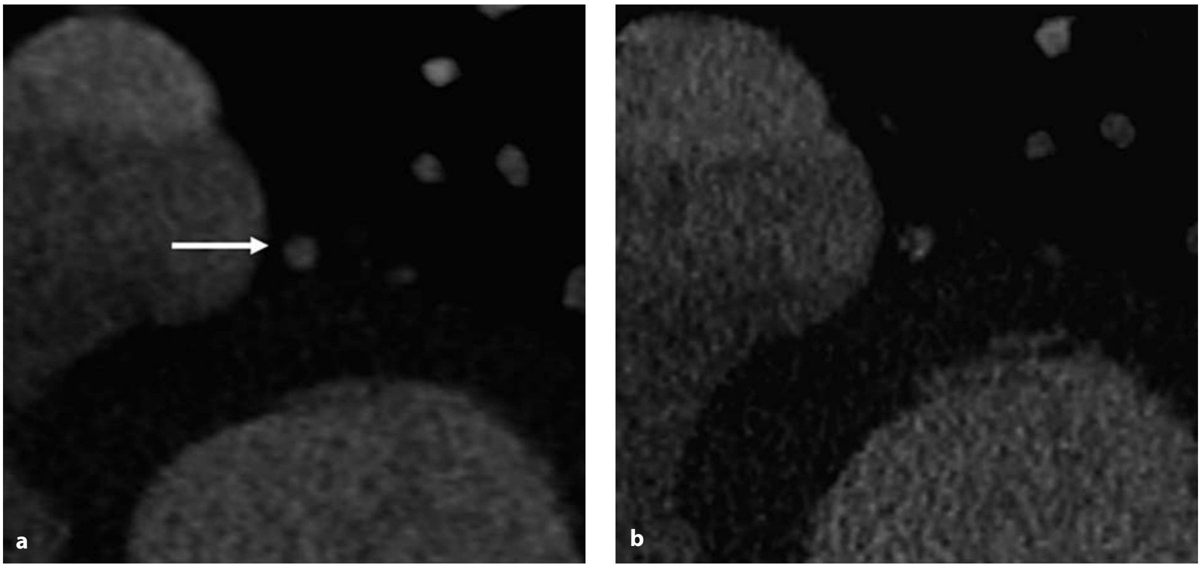
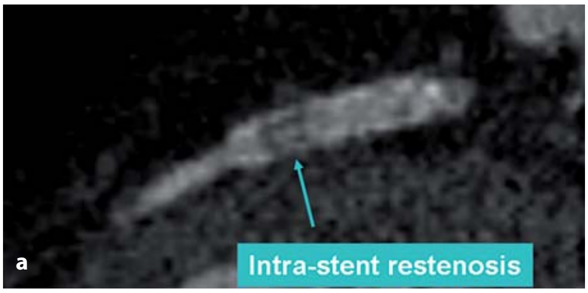


Fig. 3 a, b. Patient with a small dissection flap of the left anterior descending artery (LAD). **a** With a standard filter, the flap (*arrow*) is very difficult to detect. **b** The same image with a higher resolution filter allows clear visualization of the flap



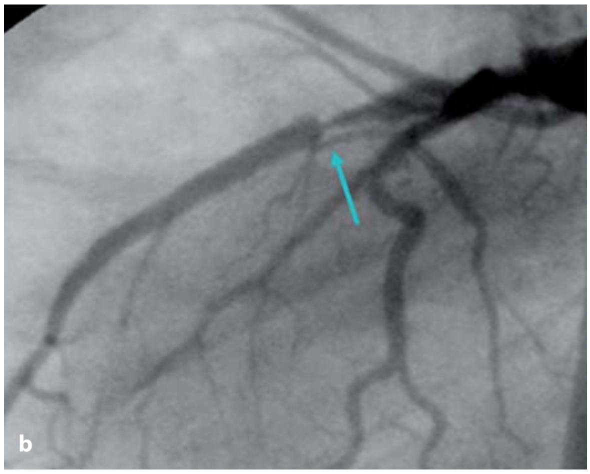


Fig. 4 a, b. **a** Coronary CT using a high-resolution kernel allows depiction of the in-stent stenosis. **b** The same stenosis was confirmed with CT angiography

Noise

Noise can be measured as the standard deviation of the pixel values in a homogeneous region of interest. The more noise, the lower the image quality. In coronary CT, images tend to be noisy because high spatial resolution is mandatory (0.5–0.8 mm depending on the manufacturer). An increase in radiation dose may lower the noise, but only part of the total radiation delivered is used to reconstruct the image in the current retrospective mode. The "useful" radiation corresponds to a temporal window of one phase of the cardiac cycle (for example, mid-diastole). This temporal window is determined by the rotation time of the machine and its value is about half the rotation time for a monophasic reconstruction. On average, only 20% of the radiation burden is used to reconstruct one phase of the cardiac cycle. The level of noise varies also with the patient's morphology. Finally, the acceptable noise level depends on the radiologist's preference and experience for reading images.

Contrast

High vascular enhancement is required to visualize small vascular structures, such as the coronary arteries. Insufficient contrast in the coronary lumen may impair lesion detection [4] (Fig. 5). However, if the contrast is too bright (> 500 Hounsfield units), it may not be possible to distinguish calcified lesions in the coronary lumen, because calcium and iodine may have similar attenuation values (Fig. 6). In our experience, a target value of 400 ± 100 Hounsfield units (HU) is adequate for coronary-artery evaluation. In this range, the contrast is high enough for visualization of the main and side branches of the coronary artery, but not so high as to prohibit a clear distinction between the coronary lumen and calcifications. For stent visualization, a lower in-stent lumen attenuation (350 HU) showed substantially less artifactual stent stenosis than was a case with a high attenuation (550 HU) [6]. In cardiac CT, low enhancement in the right ventricle is also recommended to avoid beam-hardening artifacts from right cavities filled with dense contrast medium (Fig. 7). This can be achieved by appropriate adjustment of the injection time (in practice: injection time = scan duration + 5 s).

Compared to an image acquired at 120 kV, iodine enhancement is 50% greater at 80 kV and 25% greater at 100 kV. Conversely, the same contrast is decreased by 20% at 140 kV due to lower absorption of iodine at higher kilovoltages. Low-kilovoltage settings enhance iodine contrast and thus may improve image quality in selected patients.

Contrast to Noise Ratio: a Simple Way to Evaluate Image Quality

Intrinsic quality can be measured by the contrast-to-noise ratio (CNR) in a homogeneous region of interest (ROI). Since CNR is a reliable indicator of image quality, there is a link between iodine injection and radiation dose. In other words, improved contrast injection (using highly concentrated contrast medium and/or high rates of injection) facilitates radiation dose reduction, keeping CNR constant.

In our experience, CNR measured in the aortic root is a good indicator of image quality for coronary CTA (Fig. 8). This measurement is very simple to perform.

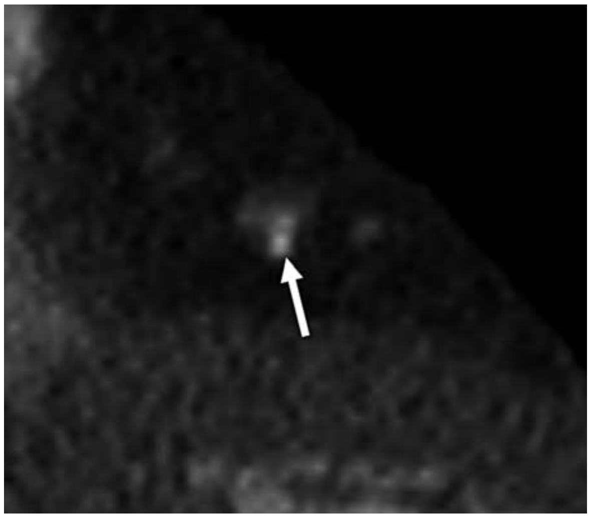


Fig. 6. Cross-sectional image of the LAD in a patient with significant stenosis: calcified nodule (*arrow*) shows more attenuation than the coronary plaque. The coronary lumen can still be distinguished. Higher contrast enhancement (> 500 HU) would have made the difference between calcium and lumen impossible

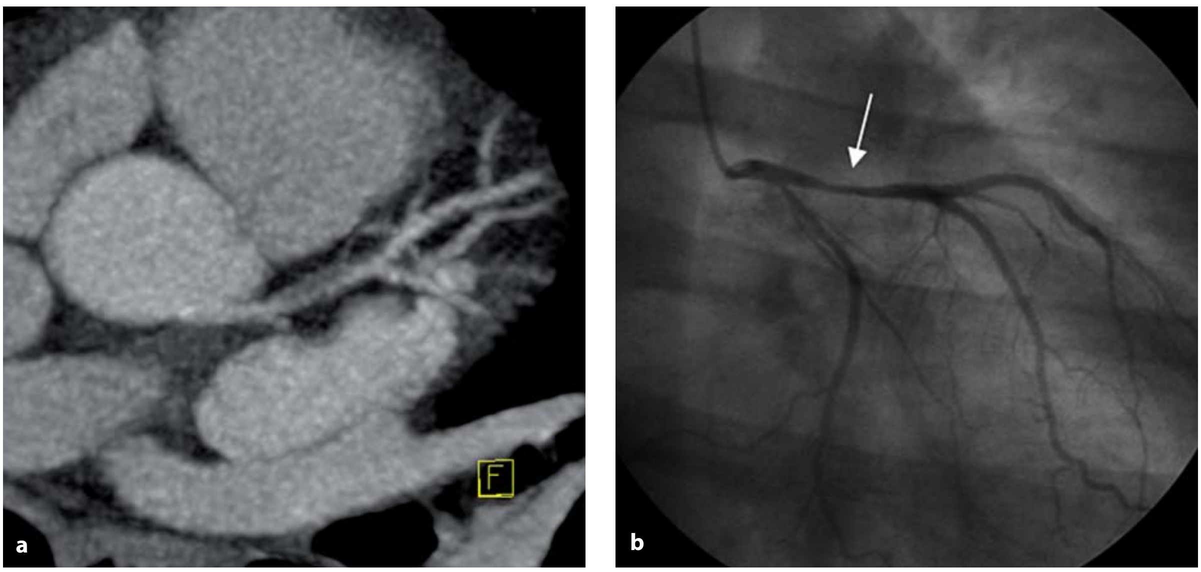


Fig. 5 a, b. **a** Coronary CT angiography shows poor vascular enhancement (210 HU in the aortic root). A coronary stenosis of the LAD is suspected, but the image quality is insufficient to make the diagnosis with confidence. **b** The suspected stenosis (*arrow*) was confirmed by conventional CT angiography

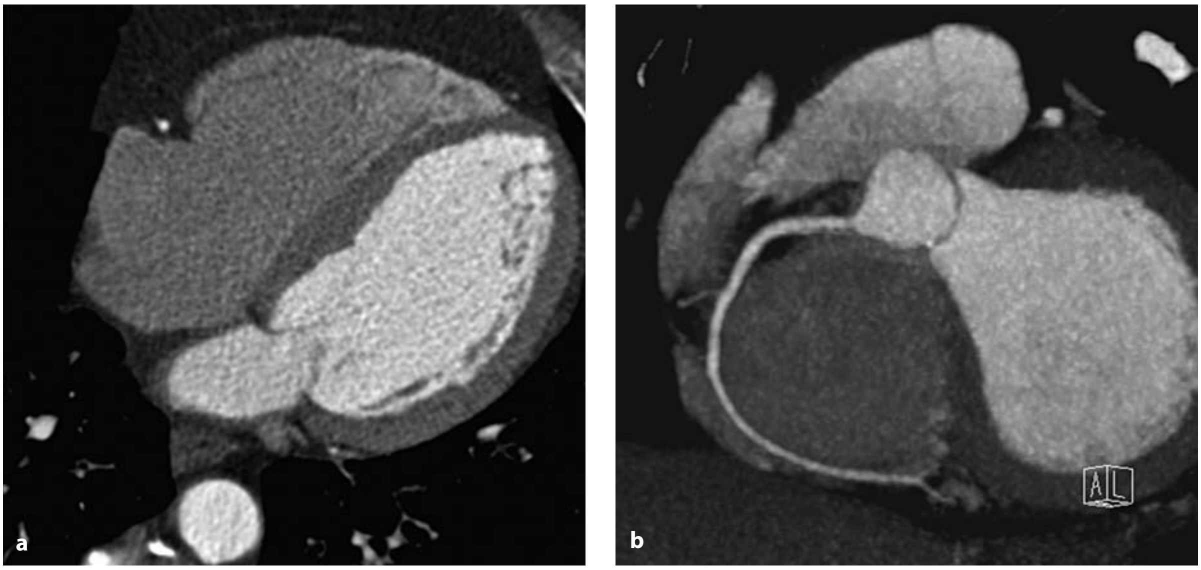


Fig. 7 a, b. Low contrast within the right ventricle facilitates visualization of the right coronary artery (RCA)

In our experience, a CNR > 8 in the aortic root is associated with adequate image quality while a CNR > 10 is associated with excellent image quality. Suboptimal images are obtained with a CNR < 7. CNR measurement converts a subjective evaluation into objective measurements, thereby allowing objective comparisons of image quality between different protocols and between different centers with different CT machines.

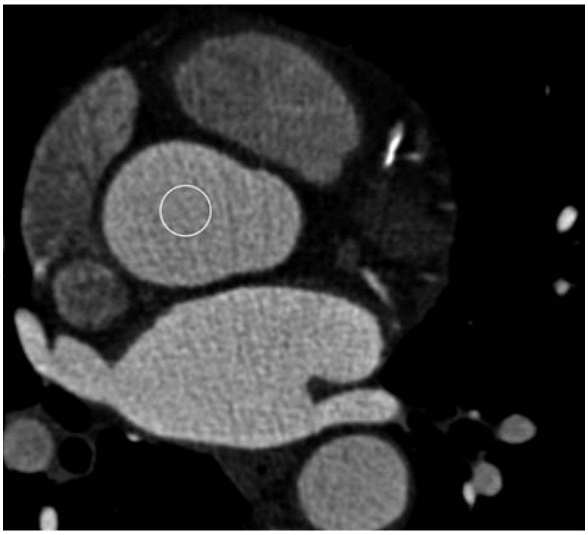


Fig. 8. Measurement of the contrast-to-noise ratio (CNR) within the aortic root is an indicator of image quality. In this case CNR=12

Radiation Dose vs. Image Quality: a Major Concern

Radiation dose to patients is a major concern for coronary CT imaging [7, 8]. There are substantial differences in X-ray attenuation between patients due to body size; therefore, individual adaptation of the tube current to the patient can substantially decrease the radiation dose, in many cases without impairment of image quality [9]. Generally speaking, standard CT protocols lead to higher radiation doses for slim than for normal or overweight patients, because attenuation of X-rays is lower in the former. As this is particularly true for coronary CT imaging, adaptation of the parameters (mAs and kilovoltage) is essential for optimizing radiation dose while preserving image quality. Indeed, it has been established that mAs can be lowered according to the patient's BMI or weight without impairment of image quality [10-12]. Individually weight-adapted protocols have been successfully applied to coronary CTA by adjusting mAs to the patient's weight: the corresponding dose reduction was 17.9% for men and 26.3% for women, and noise was consistently unaffected [9]. More recently, the use of a lower kilovoltage has been shown to be possible, with additional benefits with respect to iodine dose [13] since iodine absorption is higher at lower kilovoltage settings. A weight-adapted low-kilovoltage protocol was initially described for chest CT, and benefits for low-weight patients were demonstrated using 80 kV without impairment of diagnostic image quality [13]. The 80-kV protocol was also applied to cardiac MDCT, with delayed acquisition for analysis of left-ventricle post-infarction changes [14-16]. A setting of 80 kV has been successfully used for coronary studies, especially in slim patients and children [17]. Since the radiation dose is proportional to the square of the kilovoltage, a reduction from 120 to 80 kV at the same current setting allows a 65% decrease in radiation dose.

Coronary CT Optimization Based on a Multiparametric, Individually Adapted Protocol

We aimed to develop an individually adapted radiation dose in combination with a contrast-adapted protocol. Radiation-exposure settings were based on the noise measured on the pre-contrast image [18] (Fig. 9) (Table 1). The selected image was over the heart, and the amount of noise reflected the local attenuation in each patient. The amount of contrast depended on the weight of the patient (400 mg iomeprol/ml, 1 ml per kg body weight) and was administered over a period of 17 s, with the flow rate adapted for each patient.

This protocol was successfully applied in a large cohort of patients, with comparable CNR for all groups except the 100-kV and 140-kV groups. The highest CNR was found at 100 kV (mean CNR: 12), and the lowest at 140 kV (mean CNR: 7.9). Although noise was similar in both groups, contrast enhancement was higher at 100 than at 140 kV. All patients scanned at 140 kV were overweight. Thus, scanning obese patients remains difficult for coronary CT imaging and requires large amounts of contrast administered at high injection rates.

Clinical Situations

The following three examples of clinical situations illustrate the judicious use of scan parameters and iodine dose.

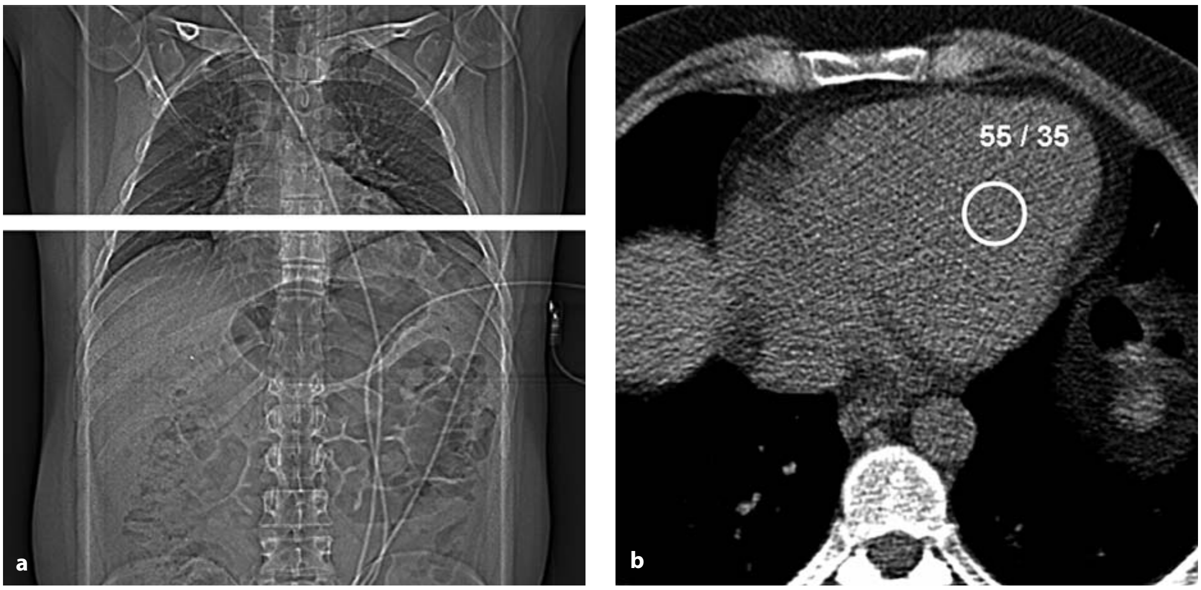


Fig. 9 a, b. **a** According to the topogram, a slice is positioned at the base of the heart. **b** A slice is acquired at the level defined in **a**; noise is measured in the left ventricle as the standard deviation of the value of the pixels within the region of interest (*circle*). Here, the standard deviation was at 35, which implied radiation dose parameters of 120 kV and 900 mAS (see Table 1) for the subsequent contrast-enhanced coronary CT

Table 1. Adaptation of the mAs and kV settings depending on the noise measured on a precontrol image realized at 120 kV and 20 mAs, on a Sensation 64 CT. In our population, this rule leads to a mean radiation dose of 9.5 mSv, by combination with ECG modulation technique. In a study of 270 consecutive patients, the noise was found similar in the 6 different groups, except at 80 kV

Noise on precontrol (HU)	Tube current-time product (mAs)	Tube power (Kv)	CTDI vol (mGy)	Mean noise on coronary CT angiography (HU)
< 15 HU	700	80	14	54
15-19	700	100	32	39
20-24	500	120	39	40
25-29	700	120	54	38
30-34	900	120	70	36
> 35	700	140	84	41

Case 1: Coronary CTA in a 3-week-old newborn (Fig. 10): In newborns and children, 80-kV protocols are always sufficient to obtain good image quality with a low radiation dose. ECG-gated protocols improve coronary visualization even at very high heart rates.

Case 2: Coronary CTA in a 13-year old patient presenting with acute myocardial infarction (Fig. 11): parameters were selected in order to minimize radiation exposure. In this patient, 80 kV and 500 mAs with ECG-pulsing were adequate. The flow rate was 3.5 ml/s. The radiation dose was estimat-

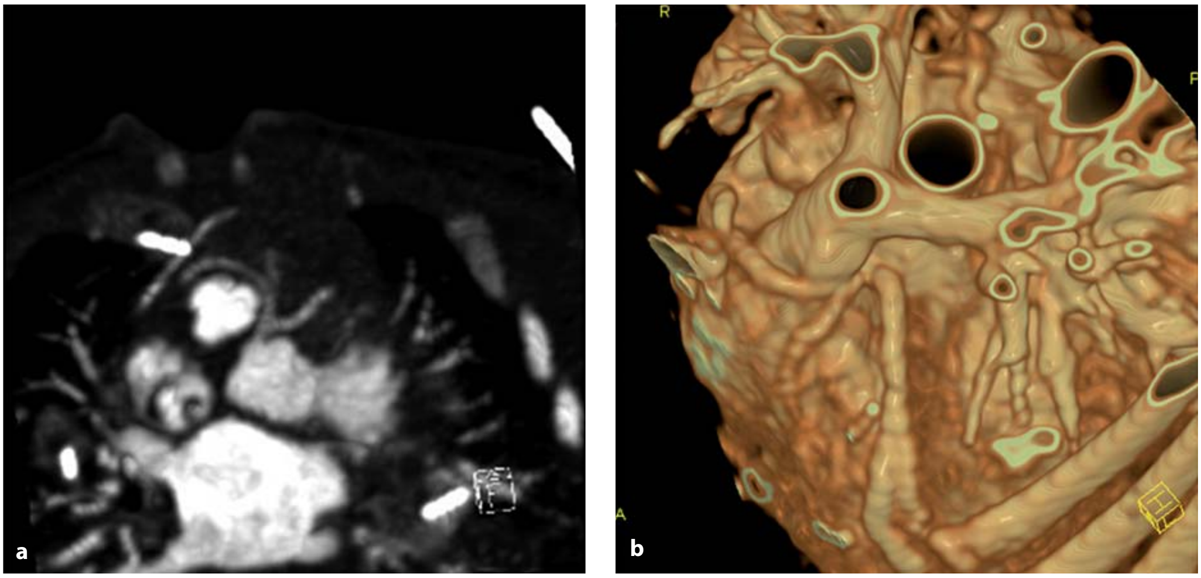


Fig. 10 a, b. Coronary ECG-gated angiography shows successful coronary reimplantation after switch intervention in a 3-week-old baby. The parameters were: 80 kV, 100 mAs, 10 ml of contrast medium (300 mg/ml at 0.9 ml/s). Image quality was excellent despite a heart rate > 120 bpm

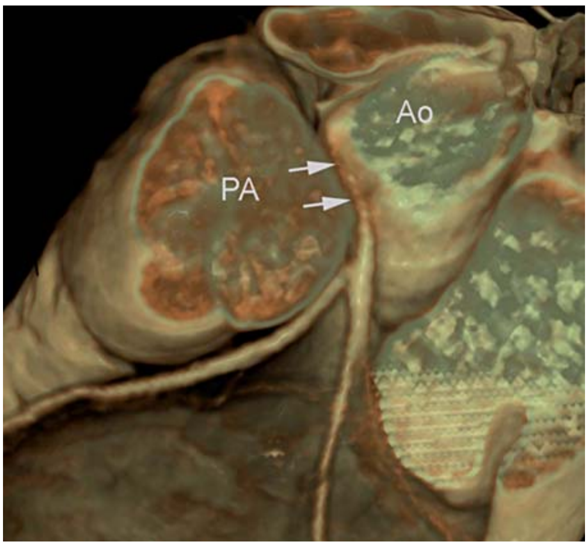


Fig. 11. Example of 3D coronary images from a 13-year-old patient presenting with acute myocardial infarction. Images were obtained at 80 kV and 500 mAs using a 16-slice CT. Patient was 42 kg; the noise on the pre-control image was 11. Abnormal left main coronary origin from the right sinus was correctly depicted. The dose-length product (DLP) of contrast-enhanced acquisition was 118, accounting for an estimated dose of 2 mSv. *Ao* aorta, *PA* pulmonary artery

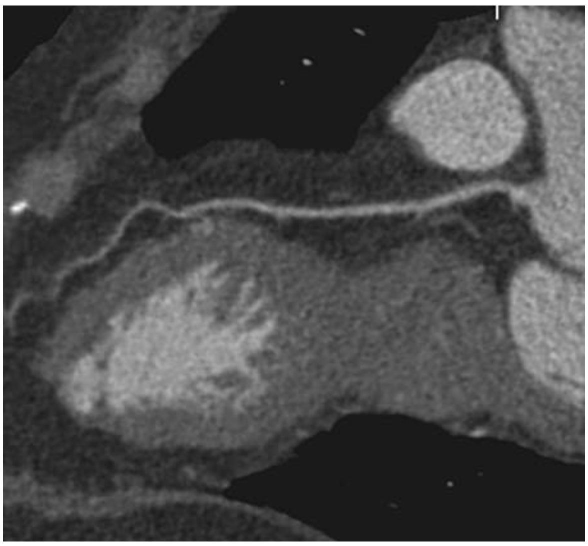


Fig. 12. Example of a curved multi-planar reconstruction (MPR) coronary image in a 49-year-old obese (98 kg) female presenting with atypical chest pain. Images were obtained at 120 kV and 600 mAs using a 64-slice CT. Slice thickness was increased at 1 mm to reduce the noise; however, image quality was still adequate to rule out coronary stenosis. The DLP of the contrast-enhanced acquisition was 429, accounting for an estimated dose of 8.5 mSv

ed at 2 msV (i.e., lower than for coronary angiography).

Case 3: Coronary CT in an obese patient (Fig. 12). A large amount of contrast agent (120 ml) and a high flow rate (6 ml/s) were necessary for sufficient attenuation in the coronary arteries. CNR was also preserved by lowering the spatial resolution.

In conclusion, a balance between contrast injection and radiation exposure (including different kilovoltage settings) may be reached by individually considering the status of each patient. Individual adaptation of radiation dose and the amount of contrast medium avoids unnecessary radiation exposure and iodine load to a large number of patients, while retaining image quality.

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