CARDIO TC: STATE OF THE ART AND FUTURE SCENARIOS

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ABSTRACT

Computed tomography of the heart (CCT) has become an effective tool in different clinical contexts. The development of the technology has led to a progressive expansion of the indications with a concomitant reduction of the radiation dose necessary for the execution of the investigation.
Computed tomography (CT) is, in fact, destined to consolidate as a pillar of cardiovascular diagnostics for a number of practical reasons. These include the robustness and reproducibility of performance, the fairly low cost compared to magnetic resonance imaging, the great flexibility of use that puts it at the center of multifunctional diagnostic structures. To this is added the fact that with each new generation of computed tomography devices the real and potential applications expand further.

INTRODUCTION

Coronary angiography with computed tomography (CTCA) is one of the major innovations in diagnostic medicine and is one of the methods of non-invasive investigation of the heart and coronary heart. The first experiments date back to 1999 with 4-layer computed tomography equipment while current technology can exploit equipment up to 320 layers. From the first experiences with 4-layer CT we have reached the dawn of the era of low-dose CT radiation, this means that one of the greatest reserves that have limited until now the extensive application of this mode is about to be removed. Among the major problems that need to be addressed for the clinical use of CCT have an essential role: radiation dose, training, logistics and implementation. These factors are interrelated and will have a significant impact on future diagnostic scenarios and radiology departments.

MATERIALS AND METHODS

Technology and hardware requirements

The most important components of a TC apparatus are the X-ray tube and the system of detectors. The combination of fast tube-detector rotation time and multi-layer acquisition is the starting point for cardiological applications.
64-layer CT equipment meets the basic criteria for conducting cardiological and coronary examinations. In particular, the hardware requirements of CT for cardiological imaging are:

- high temporal resolution and synchronization with the phases of the heart cycle: the heartbeat requires that the method is able to capture images in a sufficient time to minimize or avoid movement artifacts altogether. In addition, in order to avoid such artifacts, image scanning/reconstruction must be synchronized with the ideal cardiac cycle phase, that of the least residual movement;
- high spatial resolution: the structures under investigation and in particular the coronaries are characterized by reduced calibre (<5 mm). Therefore, the spatial resolution of the method should be able to form images with spatial resolution appropriate to the visualization of the structures and their main characteristics;
- high contrast resolution: the distinction between the structures being studied (e.g., vascular lumen, ventricular cavities, cardiac muscle, adjacent soft tissues) requires a contrast resolution that is appropriate to the distinction of the structures themselves and their measurement;
- High scanning speed: Scanning speed becomes important due to the fact that breathing movement determines movement artifacts. Therefore, the ability to conduct the survey in the shortest possible time (e.g., in apnea) is a factor that determines the final quality of the images.

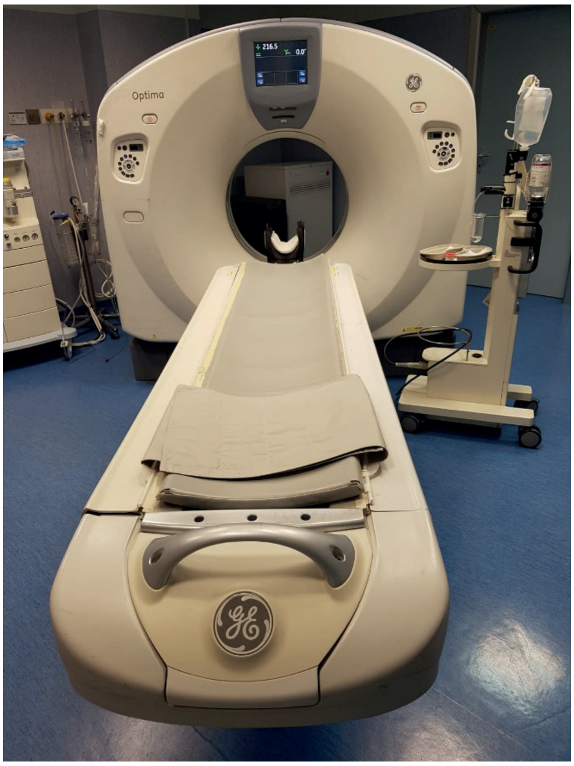

Fig. 1 - *TC OPTIMA 64 GE layers.*

Inclusion and exclusion criteria

Normally the inclusion criteria for scanning are:

1. Heart rate <65 beats per minute (bpm) (spontaneous or induced by administration of β-blockers or other negative chronotropic drugs).
2. Ability to hold breath for a period compatible with the scanning time. Bradycardization allows for a longer diastolic interval, which results in an increase in the duration of tele-diastole, at which time the heart and coronary arteries are almost devoid of movement. Although CCT can be diagnosed at higher heart rates, motion artifacts gradually reduce the number of segments that can be correctly displayed. The second criterion is to avoid artifacts related to respiratory movement. Inadequate breathing of the patient during scanning reduces the quality of the information acquired.

The exclusion criteria shall:

1. The exclusion criteria concern technical aspects related to heart rate (cardiac arrhythmias: nonsinus rhythm, frequent ectopic beats (extrasystoles), atrial fibrillation with high ventricular response), radio-protectionist aspects and law enforcement aspects. Patients with heart rate (FC) 65 bpm, known allergy to iodized contrast agent, kidney failure (serum creatinine >140 mmol/l), pregnancy, respiratory failure, clinical unstable state and severe heart failure, body weight >150kg, are normally excluded from the study by CCT. For the assessment of coronary calcium, the exclusion criteria for heart rate and contrast agent do not apply.

Border-line situations

Patients with FC >70 bpm should not be subjected to CTC. Only patients with mild irregular heart rhythm (e.g., premature heartbeat, atrial fibrillation, left branch block, elongation of the QRS complex, FC<40 bpm, etc.) may be included in the evaluation in this case, the scan should not be performed by using the X-ray dose reduction software based on the ECG plot, which consists in the prospective modulation of the dose emitted on the basis of the wave R. in the presence of abnormality of the FC the localization of the period with lower dose will be variable and can re-enter inside the diastole. A favourable situation for CTC scanning even in the presence of high FC (>70 bpm) is that of low ejection fractions and/or hypokinetic ventricles. In these conditions, in fact, even an FC of 80-90 bpm allows to obtain images of high diagnostic quality especially if you can use the time windows of telediastolic and telesistolic reconstruction. However, considerable experience is needed to achieve a high standard of quality in these conditions.

Pharmacological management

From the first experiences with 4-layer CT equipment to the most modern, the use of drugs to reduce FC has been a constant.

Medications that can be administered to the patient before scanning in order to reduce FC are:

- β-blockers;
- calcium antagonists;
- benzodiazepines;
- nitrates.

Outline of pharmacology

β-blockers

Oral: 45-60 minutes before scanning, methoprol-tartrate for os with dosage between 50 and 200 mg.

Intravenous: esmolol, characterized by a short half-life, is certainly the drug of choice. Intravenous administration under pressure and ECG control allows you to reach the reference FC quickly by facilitating the flow of patients on the machine. However, a preparation with β-blockers for os allows to carry out the examination in a patient with good β-blocker basal tone. Other β-blocker drugs, higher plasma half-life, may be used via V.V., such as metropolol, ethanol, and propanolol. The latter in particular has a superior bradycardization effect. Caution in administration should take into account a short monitoring period after examination.

Calcium antagonists

As a rule used in the case of contraindications to β-blockers.

Benzodiazepines

sometimes, especially in younger patients, the emotional component of "anticipation" of the examination is the prevailing one. In these cases, short-half-life benzodiazepines may be administered to reduce this component.

Algorithm of patient preparation

It has been described how high FC negatively affects the performance and success of scanning in terms of diagnostic quality. The best way to reduce FC in the patient is definitely pharmacology. Once FC is obtained, variability should be observed and, in addition, a test should be performed to assess whether the duration of the patient's apnea is compatible with the scanning time. Generally, with 64-layer or higher generation scanners apneas are 10 sec or lower and are unlikely to be compatible with stable apnea, except for the critical and/or non-cooperative patient. If at the end and during apnea the FC remains stable the patient can perform the investigation.

The good preparation of the patient comes from a thorough knowledge of the clinical conditions associated with coronary heart disease and those independent of it and from the adequate knowledge of the mechanisms of action and of the absolute and relative contraindications of drugs used.

Positioning of the patient

The patient is in a supine position with both arms raised above the head to avoid artifact from hardening of the beam because even though the arms will remain outside the FOV, if these should be lowered, in the processing of data will also be obtained information, albeit partial, of their presence giving rise to nuances or bands artifacts that will affect the quality of the image. It is preferable for the patient to enter the head for the simple fact of a more accurate visual contact.

Method of execution

Performing a typical coronary angio-CT examination (multislice CT-coronary angiography, MSCT-CA) involves performing a first direct scan (CA-Score), performed with high collimation thickness (3-5 mm), followed by a subsequent acquisition performed during

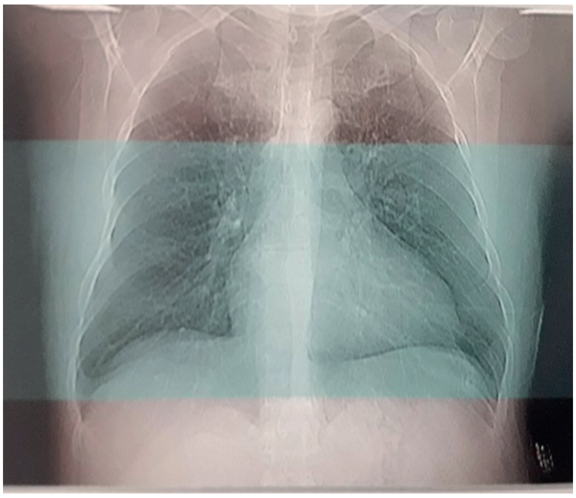

Fig. 2 - *Representation of the scout-view on which the CT exam is set. The area colored in blue represents the volume that is normally acquired during coronary angioTC examination.*

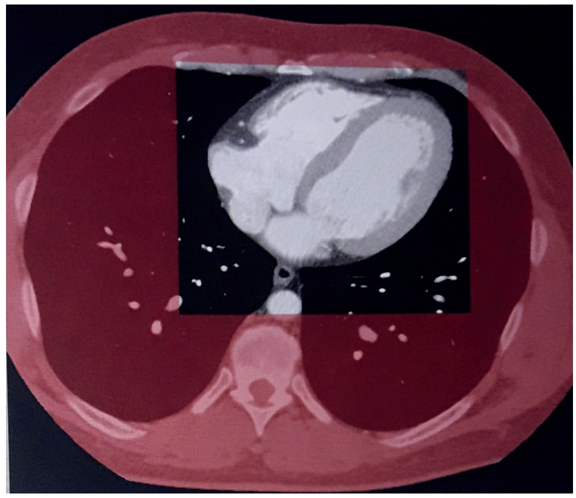

Fig. 3 - *In this axial image of the thoracic district is indicated the reconstruction FOV set around the cardiac structures. All the sector highlighted in red will be excluded from the reconstruction and therefore not evaluated, even if the information related to that district has been acquired.*

the administration of mdc, performed in the arterial phase with a thin collimation layer (0.5-0.6 mm). In the course of these investigations, a portion of the thoracic district is acquired between a plane passing under the aortic arch to the cardiac base, comprising a portion of the organs of the upper abdomen. The investigated district contains different anatomical structures:

- Heart
- Large vases
- Lymphatic structures
- Esophagus
- Tracheo-bronchial structures
- Lung parenchyma
- Pleural and pericardial leaflets
- Bone structures
- Nerve structures
- Diaphragm
- Liver
- Adrenals
- Kidneys
- Spleen
- Stomach
- Transverse colon

The evaluation of a cardio-CT examination involves the execution of several reconstructions using multiplanar techniques (MPR), curved multiplanars (cMPR), MIP and volume rendering, all aimed at defining the patency of the coronary tree or assessing the functionality of the heart muscle.
These methods of reconstruction are aimed at optimizing as much as possible the visualization of the vascular structures under examination, but at the same time they involve an exclusion of part of the tissues and extracardial structures that do not appear in the reconstructed images or appear there with a distorted anatomy not useful for the recognition of ancillary pathologies.
The method of carrying out the examination and its reconstruction may hinder this assessment as some thoracoabdominal sectors may not appear in the reconstructed axial images. This is because in order to obtain greater spatial resolution in the anatomical areas of interest the field of view (FOV) of reconstruction is sized to include only the mediastinal structures concerned (heart and large vessels). It will then be necessary to perform a second reconstruction using a large reconstruction FOV that contains the entire chest.

Contrast agent administration and general principles of contrast media attenuation to CT

Synchronized intravenous injection of the bolus of contrast agent useful to the angiographic phase, must necessarily be entrusted to the aid of an automatic injector capable of delivering a flow of at least 6ml sec. Bearing in mind that the MDC must be preheated to the average body temperature of 37 years. so that the low viscosity can be maintained. This device should preferably be equipped with a double head, in order to have a secondary bolus based on 40 50ml saline solution, useful for the function of pushing the mdc in the veins of the arm. The connection of the injector to

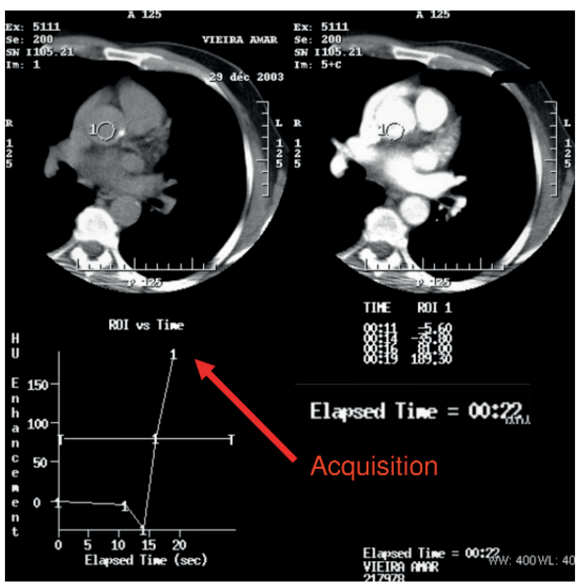

Fig. 4 - *Acquisition Enhancement Point.*

Fig. 5 - *Automatic Injector.*

Fig. 6 - *MDC organ iodate Iomeron 400*

the vein of the patient, will be entrusted to a device for spiraloid infusion, of adequate length and equipped with an antireflux valve. The agocanula to be used will be an 18 gauge gauge (green venflon). The particular anatomy of the anonymous vein on the right suggests preferring the antecubital vein of the homolateral arm (the way to the right atrium is shorter). This will avoid artifacts due to high contrast density in the vein, which could compromise the visualization of the aortic arch and the origin of supraortic trunks due to the fact that the blood route is longer. Since the journey time is shorter we will be able to have a bolus of contrast well concentrated without being diluted so much during the journey.

CCT scanning and synchronization with cardiac cycle and image reconstruction

The ideal protocol for CCT is one that allows a high spatial resolution (finer collimation), a high temporal resolution (faster rotation of the tube-detector system), lower exposure to ionizing radiation (prospective modulation of the current of the tube synchronized to the electrocardiogram, etc.) compatibly with a good signal/noise ratio.

Imaging in CCT scanning should be synchronised to the heartbeat and possibly to the phase of the cardiac cycle characterized by less residual movement. For this purpose, two main scanning techniques are adopted: retrospective cardiac gating and prospective cardiac triggering. In the first case the scan is continuous spiral at low pitch (0.15-0.4) and the data can be reconstructed at any stage of the cardiac cycle, by shifting the start point of the image reconstruction relative to the R wave. In the second the scan is sequential and the acquisition time window must be determined before the start of the scan. Retrospective cardiac gating is more flexible and allows better optimization of the reconstruction time windows at the price of an average higher radiation dose; Prospective cardiac triggering is less flexible but significantly reduces the radiation dose.

Generally, the cardiac cycle stages in which images are acquired/reconstructed are the telediastolic phase (60%-80% of the RR interval; -300/-400 ms before the next R wave) and the tele-systolic phase when available (20%-40% of RR interval; +175/+325 ms after the previous R wave). The other reconstruction parameters are relevant for the production of an image that can be considered diagnostic. In particular, the actual layer thickness may be equal to or slightly larger than the minimum possible collimation in order to improve the signal/noise ratio of the image. The reconstruction increment should be about 50% of the actual layer thickness (thus increasing the spatial resolution along the z-axis). The field of view should be as small as possible including the entire heart, so that the image matrix that is constant (512 512 pixels) can be fully exploited. The convolution filter should be intermediate (medium-smooth) and still in a good balance between noise and signal. When the coronary arteries are very calcific or stents are present, higher convolution filters, even if they increase the image noise, improve the visualization of the vessel wall or stent structure and the lumen inside.

Evaluation of the image

The image evaluation of a CCT survey is not yet performed using a standardised technique. In terms of reproducibility, the performance of the CCT is currently operator-dependent. Evaluation is generally performed by classification of the American Heart Association in 14-17 coronary segments. CCT is used for the identification of significant stenosis (ie reduction of the vasal lumen 50%) and the assessment is generally semi-quantitative. Images are evaluated on the axial dataset, then reconstructed using multiplanar

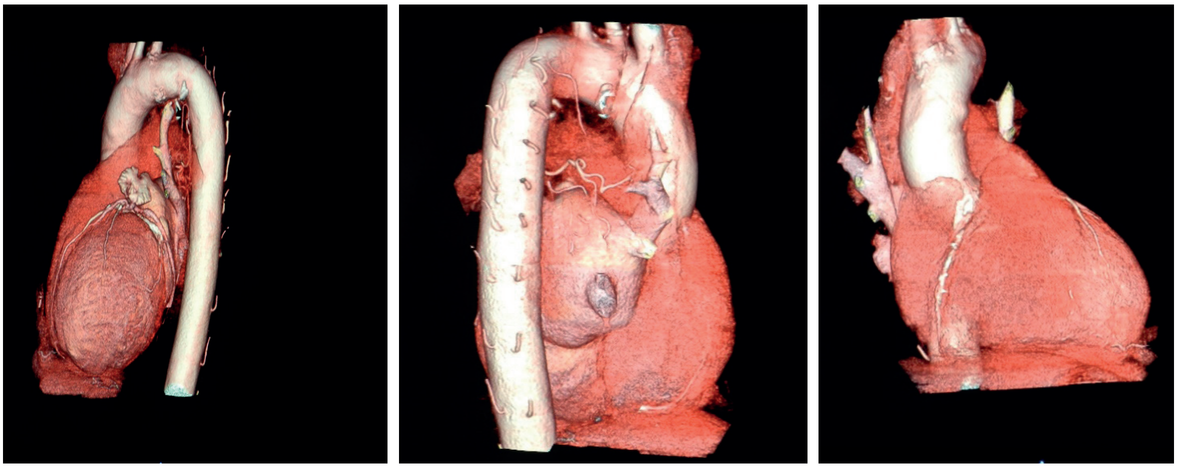

Fig. 7 - *Reconstruction of cardiac images.*

reconstructions (MPR), maximum intensity projections (MIP) and volume rendering (VR). The coronaries can also be displayed along the longitudinal axis, either manually or semi-automatically (curved MPR).

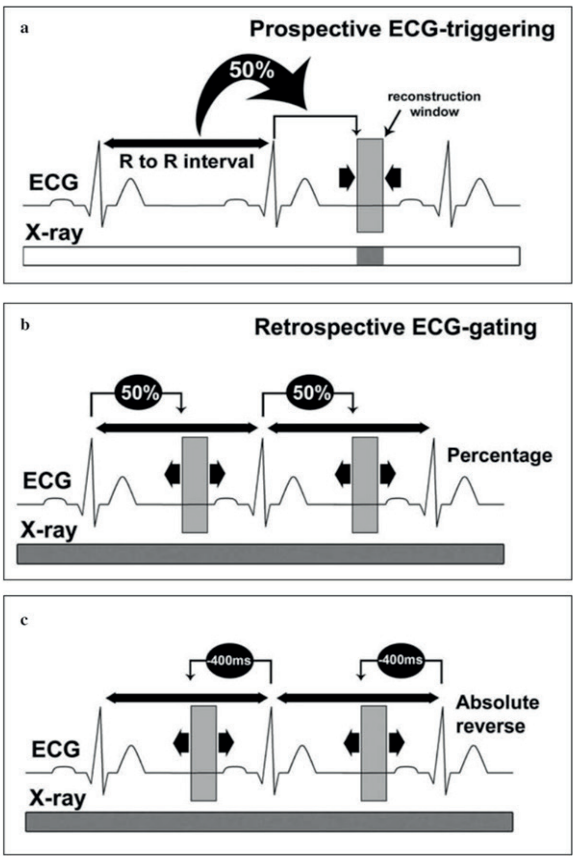

Fig. 8 a-c. - *Synchronization techniques for the CTCA. The synchronization techniques for the CTCA are essentially two: a prospective ECG triggering in which the scan is performed with sequential axial mode (step and-shoot) calculating the position of the time window on the RR interval of the beat preceding the acquisition itself; b,c gating retrospective ECG in which scanning is performed in low pitch spiral mode and images are retrospectively synchronized with the cardiac cycle phase. The first technique allows reduced exposure to ionizing radiation but is more sensitive to moving artifacts due to the reduced or absent flexibility in the reconstruction phase. The second requires high exposure but allows a wide freedom of choice of the optimal time window. CTCA, coronary angiography with computed tomography; ECG, electrocardiogram.*

Catalogue of artifacts, methods to avoid them and possible remedies

Artifacts from movement

Motion artifacts are generated by the voluntary and/ or involuntary and/or intrinsic movement of an organ within the district being examined or the patient.

- Type I: Volunteer. Typical example of the first case is the interruption of the inhalation apnea during the scanning phase by the patient.
- Type II: Involuntary. Typical example of the second case is slow diaphragmatic slipping (diaphragmatic drift) during the patient's apnea.
- Type III: Intrinsic. An example of the third case is the natural motion of the coronaries that generates an artifact due to an inadequate ratio of vessel velocity to raw data acquisition rate (temporary resolution).

Type I artifacts are generally due to errors or lack of patient compliance and result in blatant and severe alterations in image quality. Voluntary movement artifacts of the patient can be distinguished from artifacts related to cardiac movement because in the first case the artifact is present in the anterior thoracic wall, along the cardiac margin.

Some manufacturers, to compensate for motion artifacts, propose the use of "overscan" capture modes, correction software, and "cardiac gating".

- Overscan: for the reconstruction of the images at the ends of the scan, additional rotations are made. This is due to the fact that the maximum discrepancy between the readings of the detectors occurs at the beginning and end of the rotation. Some models use this mode, which involves the acquisition of about 10% more rotation that is added to the 360 ºµ standard: the repeated data are then "weighed" and used to reduce the severity of the artifacts by movement.
- Correction software: Used in most scanners, they automatically weigh the initial and distal scans, reducing their contribution to the final image. However, this processing results in increased image noise.
- Cardiac gating: the synchronization of the data acquisition with the ECG allows to obtain images of the heart in (relative) immobility, employing for the reconstructions only the data coming from the phase of the cardiac cycle with the least degree

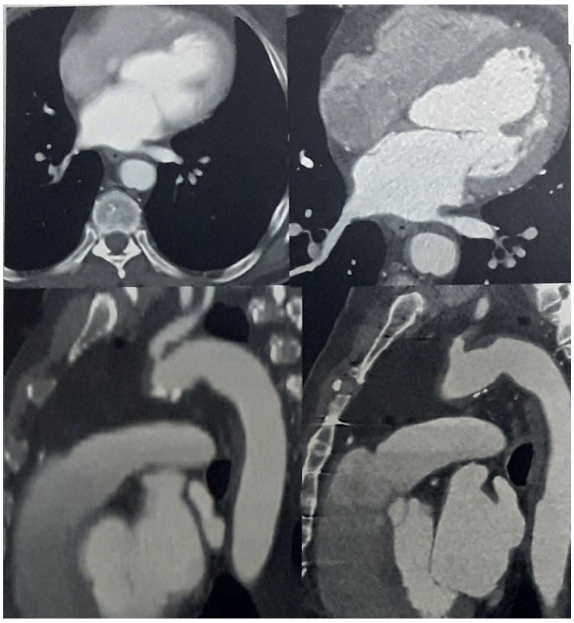

Fig. 9 - *Blurring and step artifact: typical appearance of two frequent movement artifacts. Blurring or blurring occurs when the motion of heart structures is greater than the temporal resolution of the scanner. The step-by-step appearance of the artifact is instead due to an interruption of the inspiratory apnea.*

of motion; this allows to avoid the onset of the severe artifacts of movement due to the rapid and wide movements of the Heart.

Artifacts from noise

Noise in a TC image is the variability of attenuation values around the average of pixels in a homogeneous region of interest (ROI). In fact, noise can be measured by the standard deviation of the attenuations measured in an ROI located in the evaluation area. One of the main factors influencing noise is the milliamperage per second (mas) produced by the X-ray tube. Increasing the mas will increase the number of photons that hit the patient and then the detector, so as to increase the signal/noise ratio (S/R).

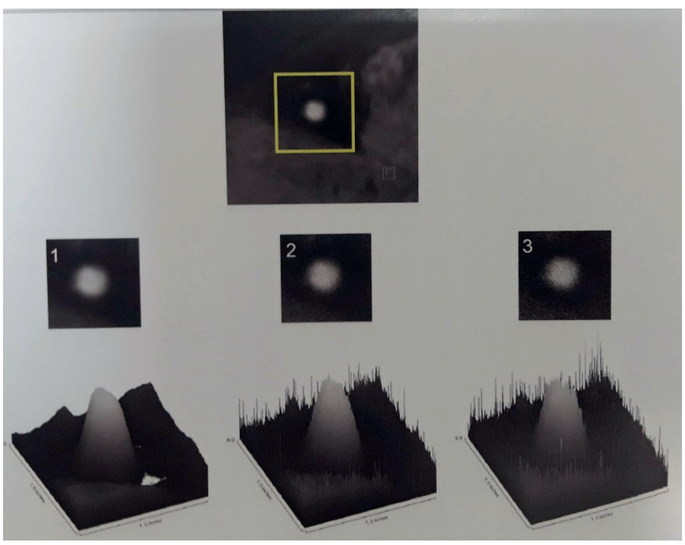

***Fig. 10** - Noise: Graphic representation of image noise. The frame represents a region of interest (ROI) obtained from the reference image at the level of the middle segment of the right coronary artery. The area attenuation values within the individual ROI (1-3) have been reported on an attenuation graph. The increase in noise results in a progressively larger oscillation of the attenuation values. This example explains why noisy images are more difficult to evaluate.*

Artifacts from partial volume

The partial volume (also known as “averaging volume”) is an artifact that occurs in all voxels of all images when there are two or more objects with different attenuation values inside a voxel. It depends on the fact that the voxels are larger than the structure you intend to represent. Another type of partial volume artifact, conceptually different from “averaging volume”, occurs when a dense object is only partially included within the X-ray beam and only when the tube-detector system is in certain positions. The inconsistency between the various points of view, in fact, determines artifacts that are appreciated as nuances in the images.

Artifacts from beam hardening

The beam hardening artifact occurs when the radiation is completely absorbed by an object with extremely high attenuation values. The beam hardening artifact can give rise to two types of effects: the so-called cupping artifact and the dark band or stripe appearance between dense objects in the image (streak artifact). In cardiac imaging, these types of artifacts can occur in various situations, such as:

1. Pace-maker filaments, metal valve prostheses, metal surgical clips, etc.
2. The bolus of MDC in the upper vena cava and right atrium can cause beam hardening artifact, with uncomfortable interpretation of more cranial scans of the heart in the anatomical region of the right coronary.
3. The presence of calcific atherosclerotic plaques may prevent a proper assessment of the vascular lumen.

Artifacts from MDC

The alteration, in excess or defect, of the parameters that regulate the MDC causes artifacts from MDC.

Volume: The causes of poor enhancement are generally related to inadequate administration and/or quality of MDC. A technical error in the administration procedure is generally the cause of not displaying MDC itself in the large vessels of the chest.

Speed: various studies have reported the advantages of using high concentration of iodine MDC (>350 mgi/ml) and a high flow of administration (>4.5 ml/s) to increase the visibility and therefore the diagnostic accuracy of the vessels, species that contain a small blood volume.

Saline solution: the use of a bolus saline solution following the injection of MDC (bolus chaser) has the effect of pushing MDC and keeping it compact in its intravenous course. The bolus chaser reduces the occurrence of beam hardening artifacts and represents an advantage especially for the visualization of the right coronary artery, subject to significant hardening artifacts when hyperconcentrated MDC is located in the vena cava and right cavities of the heart.

Radiation dose reduction strategies

The reference technique for the execution of the CCT is the low pitch spiral (0.2-0.35). The radiation dose

Technique	Dose reduction	Notes
Triggherate ECG prospective modulation	<50%	With FC<65 bpm and stable
Automatic Exposure Control (AEC)	~33%	
Low voltage	50%	With patients of medium-small build (BMI<30=100 kV; BMI<25=80 kV)
Triggering prospective ECG	>50%	With FC<65 bpm and stable
Dual/single-beat with prospective ECG triggering and prospective ECG triggering high-pitch spiral	>80%	With FC<60 bpm e stable
Iterative reconstructions	15%–25%	-

Tab. 1 - *Dose reduction techniques.*

was about 3-5 times that which normally served for a similar anatomical coverage with standard thorax protocol. With 64-layer equipment the average effective dose is about 12 mSv (range 8-18 mSv) at a stage where the prospective technique has already been introduced. With the reintroduction of the prospective acquisition mode combined with an effective heart rate control, it was possible to drastically reduce the effective dose. Other techniques and methods of acquisition associated with improvements in the reconstruction phase have allowed a progressive reduction of the dose.

Arguing

CTC is a non-invasive method for the diagnosis of coronary heart disease that is rapidly expanding both in terms of availability on the territory and in terms of clinical indications. In the future, clinical applications of the method are likely to extend in parallel with technological improvements and literature evidence. The reliability and accuracy of the method will be further increased by the introduction of new solutions, such as the dual source, allowing the implementation in the field of acute chest pain. The method is increasingly becoming a new reference point for the clinical management of follow-up of patients with coronary heart disease. In this perspective, the optimization of the individual dose will become increasingly important also in the possibility of a further diffusion of the method with potential further increase of the collective exposure from medical radiation. At present, in order to be effective, this method must be used in specialized environments and by personnel with long-term training.

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