ESC European Society of Cardiology

European Heart Journal (2017) **0**, 1–11
doi:10.1093/eurheartj/ehx582

CURRENT OPINION

Strategies for radiation dose reduction in nuclear cardiology and cardiac computed tomography imaging: a report from the European Association of Cardiovascular Imaging (EACVI), the Cardiovascular Committee of European Association of Nuclear Medicine (EANM), and the European Society of Cardiovascular Radiology (ESCR)

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Reviewers: This document was reviewed by members of the 2016–18 EACVI Scientific Documents Committee: Bernhard Gerber, Erwan Donal, Frank Flachskampf, Kristina Haugaa, Victoria Delgado and by external experts: Juhani Knuuti, Paul Knaapen, Pal Maurovich-Horvat, Stephen Schroeder

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Received 18 July 2017; revised 8 September 2017; editorial decision 20 September 2017; accepted 26 September 2017

The opinions expressed in this article are not necessarily those of the Editors of the *European Heart Journal* or of the European Society of Cardiology.

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Introduction

The radiation burden due to cardiovascular imaging in Europe

Cardiovascular diseases (CVDs) are the leading cause of death in Europe (5 million deaths per year) at a cost of €196 billion in 2009.[1] Imaging techniques such as computed tomography (CT), single photon emission computed tomography (SPECT), and positron emission tomography (PET) play an increasingly important role in the diagnosis of CVD.

Regarding myocardial perfusion imaging, scan volume has grown rapidly worldwide over the past two decades to 15–20 million procedures annually and diffusion of technology and expertise has led to its continued adoption across the developing world.[2] However, there are concerns regarding the radiation burden associated with these diagnostic modalities.

During the past 10 years, numerous technologies and data acquisition protocols for low-dose imaging have become available. The implementation of these technologies is always a balance between the long-term risk associated with exposure to ionizing radiation and the short-term risk related to impaired diagnostic accuracy. Furthermore, an important aspect to keep the dose as low as possible is to choose the most appropriate test for an individual patient using the correct acquisition protocol. From a clinical point of view, this implies to select the diagnostic test that is most likely to influence and direct patient care to improve outcome. From a technical point of view, this implies knowledge on differences between protocols and applying the protocol that results in the highest image quality with the lowest radiation exposure.[3] Dose reduction is a multidisciplinary effort. For this reason, this article provides a consensus of three professional associations in the field of cardiac imaging—the European Association of Cardiovascular Imaging (EACVI), the Cardiovascular Committee of European Association of Nuclear Medicine (EANM), and the European Society of Cardiovascular Radiology (ESCR)—focusing on the balance between radiation dose and diagnostic accuracy, in agreement with the European guidelines endorsed by the involved associations.

Radiation risk

When considering the clinical indication for diagnostic procedures that use radiation, it is important to balance the short- and mid-term risks of the diseases remaining undetected and untreated against the long-term risk associated with radiation exposure.[4] While ionizing radiation applied in the context of novel imaging technologies enables anatomical, functional, and molecular characterization of the whole heart with high accuracy, it poses a potential health risk because it may damage living tissues by changing cell structure and altering DNA. Sievert (Sv) is the unit of effective radiation dose in the International System of Units. One milliSv (mSv) corresponds to 10 J of energy of radiation transferred to 1 g of living tissue.

The potential damage depends on not only the amount of absorbed energy and the different types of radiation but also the susceptibility of the tissue exposed to radiation. It has been shown that high-dose radiation exposure causes adverse health effects including an increased risk of cancer induction. Much of our knowledge about the risks from high-dose radiation is based on studies of survivors of the atomic bombs at Hiroshima and Nagasaki, as well as on the experiments with fruit flies performed by Hermann Muller, which built the basis for the linear non-threshold (LNT) model.[5] The LNT model states that any radiation dose—no matter how small—may cause cancer. The LNT model currently still serves as the basis for international recommendations for radiation protection. This seems reasonable, despite some uncertainties about the accurate estimation of radiation-induced cancer risk. These uncertainties arise from the fact that the calculations are mainly based on data extrapolated from very high-dose exposure and only consider radiation dose while completely neglecting dose rate.[6] Following the as low as reasonably achievable (ALARA) principle, contemporary cardiovascular examinations need to be performed with a radiation dose as low as possible. Recent literature indicates a median radiation exposure of 2–8 mSv for a nuclear myocardial perfusion scintigraphy (MPS),[2] 2–5 mSv for a cardiac PET,[7] and 0.5–7 mSv for a coronary CT angiography (CCTA) scan.[8] Moreover, in the setting of exclusion of clinically relevant coronary artery disease, the latest technologies in nuclear perfusion imaging and CT angiography enable examinations of <1 mSv.[9,10] Estimation of risk from low-dose radiation exposure remains exceptionally difficult, but the risks are most likely small. Prospective trials focusing on adverse events associated with radiation exposure related to diagnostic procedures are difficult to perform. Randomized prospective data will probably hardly ever be available. A very recent study by Leuraud *et al.*[11] followed over 300 000 radiation-monitored workers up for a total of 8.22 million person-years hinted a potential positive association between protracted low-dose radiation exposure and leukaemia, thus lending support to the concept of a linear dose response at low doses. The results from the ongoing studies, such as the Epi-CT study,[12] which is currently recruiting over one million children or young adults who had CT scans in nine European countries with the aim of evaluating the radiation-related risk of cancer, may provide more solid evidence.

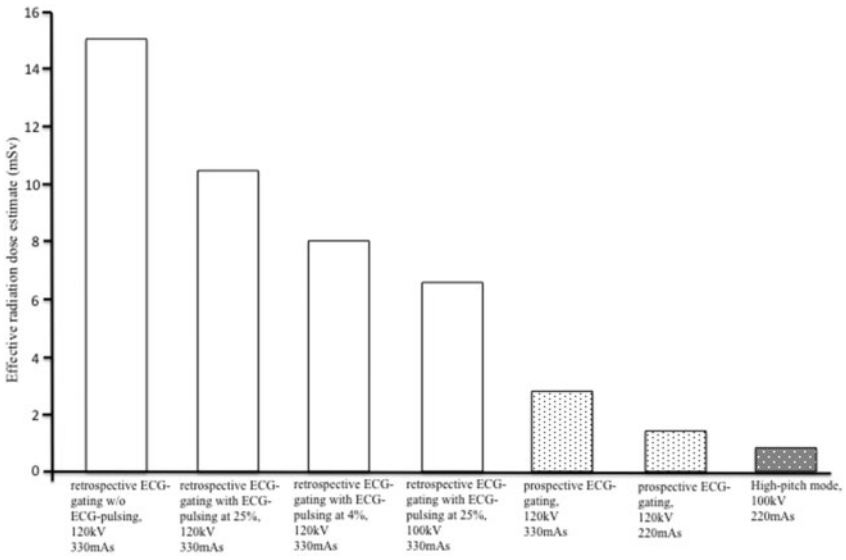

Figure 1 Bar graph illustrating the average effective radiation doses of cardiac CT applying the various radiation dose reducing algorithms. Adapted from reference.[14]

State-of-the-art technologies and their impact on radiation dose

In the last 15 years, a fast technological evolution of scanners, hardware as well as software for image acquisition and reconstruction, has allowed a dramatic improvement of efficiency and quality of cardiac imaging resulting in progressive reduction of radiation doses to the patient[2,7,8] which are becoming comparable to natural radiation exposure.[13]

This fast technological evolution may cause an imbalance between the natural life cycle of technological equipment and the need for updating to the state-of-the-art technology. We will summarize in the subsequent paragraphs the major evolutions in nuclear cardiology and cardiac CT technology, which have an impact on radiation dose reduction (*Figures 1* and *2*).

New gamma camera detectors and software dedicated to cardiac imaging

A growing number of nuclear medicine departments in Europe are now using a new generation of gamma cameras for cardiac imaging. In these so-called 'CZT cameras', the conventional sodium/iodine (Na/I) crystal used for the detection of gamma rays has been replaced by a cadmium–zinc–telluride (CZT) crystal. This crystal transforms directly the signal induced by gamma rays into electric impulses without the need for photodetectors. Manufacturers have taken advantage of these much thinner and more flexible CZT detectors to design the gamma cameras dedicated to cardiac imaging offering a larger surface for signal detection while focused on the heart region.[16,17] The CZT gamma cameras provide a four- to seven-fold higher system sensitivity compared with Na/I-based cameras.[18] This increase in signal detection efficiency has translated into a significant decrease in the dose of radiotracer required for cardiac scintigraphy. In turn, this has resulted to lower radiation exposure of patients and partly in shorter duration of acquisitions with preserved or even improved image quality and increase in the detection of coronary artery disease[19] (*Figure 3*).

Another significant evolution has been provided by new reconstruction algorithms. Novel iterative reconstruction methods with resolution recovery and noise reduction provide higher image contrast (with sharper defects and borders) and significantly improve image quality, particularly for low-count imaging studies from half- and quarter-dose radiotracer protocols.[20] The value of the novel software is that existing scanners can be upgraded with advanced software to reduce radiation dose, a much smaller capital investment than buying a new scanner.

Positron emission tomography systems for cardiac imaging

Thanks to the development of more efficient crystals and electronics, cardiac PET imaging has shifted from a 2D detection mode to a 3D detection mode.

Acquisition of PET images in a 3D mode increases the efficiency of signal detection by a factor of 2 and therefore requires, for similar image quality, the injection of only half of the dose of radiotracer formerly required in 2D mode.[21,22] PET images require correction for tissue attenuation, which is currently provided by using maps derived from low-dose CT acquisitions. This low-dose CT-related radiation exposure adds up to that from PET. Thus, PET–CT examination will most likely benefit from current progresses in CT image reconstruction to reach lower levels of radiation exposure. This is even more important in hybrid cardiac PET/CT imaging that is used to combine PET and coronary CT angiography information on myocardial function and coronary anatomy, which will benefit even more from CT dose-saving protocols.[23]

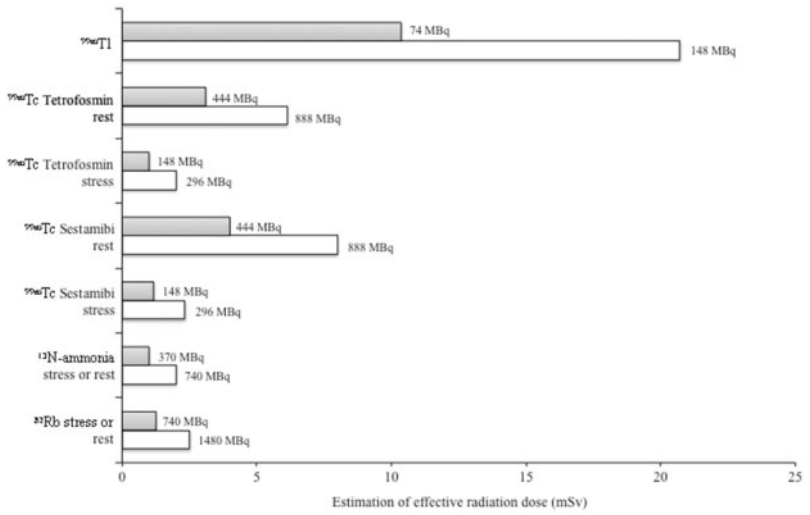

Figure 2 Recommended radiotracer doses for MPI conventional scanners (white bar) and for scanners with new softwares and/or hardwares (grey bar). Full-dose PET radiotracer is used for 2D imaging and half-dose for 3D imaging; typically, equal dose of radiotracer is administered for rest and for stress PET MPI. Estimated dose is effective dose multiplied by administered activity. Dose is calculated for rest and stress scans separately, considering a single day examination. Adapted from reference.[15]

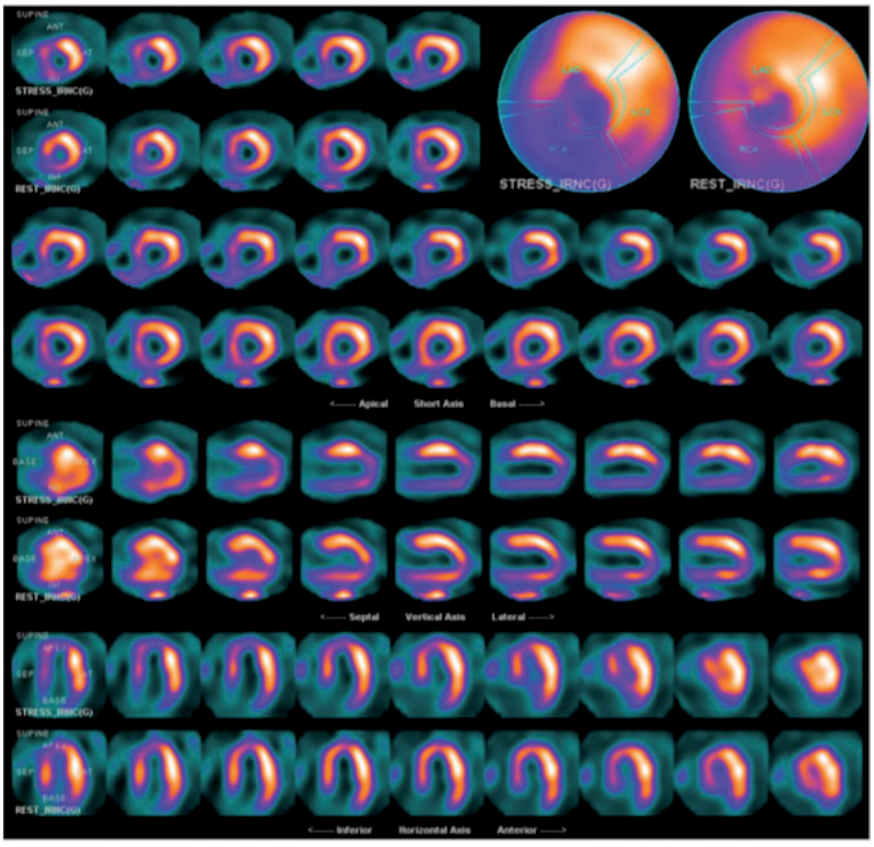

Figure 3 A 60-year-old gentleman with typical angina. A single-day stress–rest low-dose protocol with ^{99m}Tc-tetrofosmin was performed, injecting 130 MBq at peak of exercise stress test and 390 MBq at rest. Stress and rest images were acquired for 6 and 5 min, respectively. CZT images reveal the presence of a reversible perfusion defect involving the inferoseptal wall, the inferior wall, the distal portion of the anteroseptal wall, and the apex.

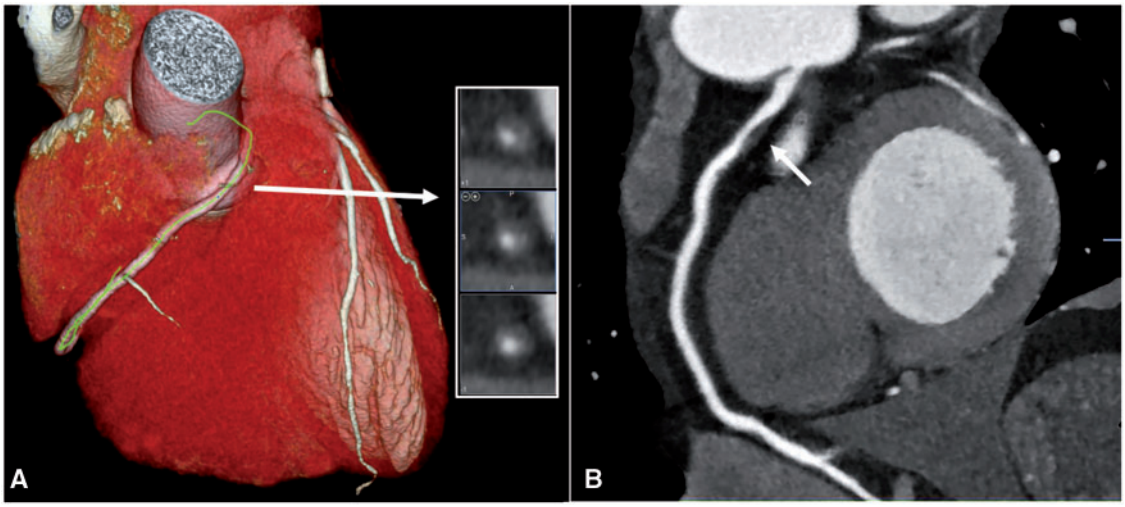

Figure 4 Ultralow-dose coronary CTA performed in a 67-year-old female (BMI 20) with a 320-row multidetector CT scanner, using a single heartbeat acquisition technique. By combining an 80-kVp tube voltage with third-generation iterative reconstructions, a sub-mSv radiation dose was obtained (0.7 mSv) with a high diagnostic quality of the examination. Volume rendering (*A*) and curved planar reconstruction (*B*) images show the presence of a high-risk, eccentric, soft tissue lesion in the proximal right coronary artery causing a high-grade stenosis.

The emerging digital PET detector technology based on silicon photomultipliers will allow for a further substantial reduction of injected dose and therefore decrease radiation exposure. Recently, a new generation of scanners has entered the clinical arena, integrating a magnetic resonance (MR) with a PET device into a hybrid PET/MR scanner.[24,25] The preliminary results show that attenuation maps can be obtained from MR, avoiding the need for CT attenuation maps, therefore reducing the ionizing radiation to the patient.[26]

Cardiac computed tomography

State-of-the-art cardiac CT scanners are equipped with 64 or more detector rows. Several technological advances can and should be used to acquire cardiac CT data sets at low radiation doses. Among them, fast scanner rotation with high temporal resolution has been important, as it permits prospectively electrocardiographically (ECG)-triggered image acquisition. In fact, it has been the introduction of prospective ECG triggering,[27] which has paved the way for low radiation dose scanning in daily practice. Although this technique has less flexibility regarding the cardiac phase in which images are reconstructed, when compared with helical or spiral acquisition protocols with retrospective ECG gating, it results in substantially lower dose. Prospectively ECG-triggered high-pitch spiral acquisition protocols can further reduce the dose.[28] All these lower dose acquisition protocols require lowering of the heart rate.[29,30] The fact that modern X-ray tubes generate higher tube currents at the same potentials can also be used to reduce patient radiation exposure: low tube potentials—such as 70 or 80 kV—substantially reduce dose compared with the standard use of 100 or 120 kV, whereas high tube currents compensate for increased image noise.[31] Dedicated roentgen tube filters can further reduce dose by effective shielding and modification of the X-ray spectrum. Various types of tube current modulation, to continuously adjust the tube output depending on the type and amount of tissue to be penetrated, can further reduce dose. Finally, iterative reconstruction algorithms, which improve image quality compared with the filtered back-projection techniques, allow for cardiac imaging at lower radiation exposure (*Figure 4*).[32–34]

A brief description of the main metrics used for characterization of CT radiation dose is depicted in *Table 1*.

Changed protocols, which have impact on dosimetry and patients

Appropriate selection of radiotracer and acquisition protocols is critical in reducing patient radiation dose. All these variables must be considered while keeping in mind that diagnostic accuracy of the imaging test should be maintained (*Table 2*). As a good clinical practice, the overall radiation dose to the patient resulting from the given imaging procedure should be clearly indicated in the clinical report as recommended by current international procedures.[3]

Single photon emission computed tomography protocols and tracers

Currently, it is not possible to issue precise recommendations regarding the doses of radiotracers for SPECT myocardial perfusion imaging (MPI) due to the lack of strong evidence linking a better performance of the test to specific injected doses. The dose of radiotracer to be administered is a compromise between image quality and radiation exposure and depends on patient characteristics (e.g. body weight), choice of radiopharmaceutical (^{99m}Tc compounds or ^{201}Tl chloride),[35] acquisition protocol (1 day or 2 days protocols, imaging time, pixel size, and gated acquisition), and the type of equipment (multiple head scintillation camera or a camera based on CZT detectors).

Table 1 Description of the main metrics used for characterization of CT radiation dose

Computed tomography dose index (CTDI)	Area under the radiation dose profile for a single rotation and fixed table position along the axial direction of the scanner divided by the total number of detectors for slice thickness and is expressed in coulomb/kg
CTDI100	Integrated radiation dose from acquiring a single scan over a length of 100 m
CTDIw	Average radiation dose to a cross-section of a patient's body determined with the equation CTDIw=2/3CTDI100 at periphery+1/3CTDI100 at centre
CTDIvol	Average radiation dose over the volume scanned determined by the equation CTDIvol=CTDIw/pitch, where pitch is defined as table movement expressed in millimetres for each 360° gantry rotation, divided by the product of the number of slices and slice width. It is measured in milligray
Dose length product (DLP)	Integrated radiation dose for a complete CT examination measured in milligray×centimetres and calculated by the formula DLP=CTDIvol×length irradiated
Effective dose (ED)	Measured as the product between DLP and k, the region-specific conversion factor

Table 2 Practical ways to reduce radiation exposure

Before the test	• Consider implementing new imaging technologies allowing for radiation exposure • Select the optimal test for the individual patient and situation, guided by clinical guidelines and appropriateness criteria • Check for recently performed cardiac evaluations to avoid duplicate testing • If the clinical question is not clear or the test ordered is not the most appropriate test, discuss with the referring physician (consider a multidisciplinary approach) • Plan a personalized imaging protocol according to age, weight, and estimated prevalence of CAD • Avoid repeating examinations as a routine for unselected patients
At the time of the test	Myocardial scintigraphy: check the possibility to perform stress-only acquisition
After the test	(These recommendations do not reduce radiation exposure, but make others aware for potential future radiation exposure) • Report dose of radiotracers and total radiation exposure • Provide easy access to imaging and reports • Monitor trends in radiation exposure at your laboratory and compare with other laboratories

For example, a weight- or body mass index (BMI)-based adjusted SPECT radiotracer dose may be better than a fixed dose to balance low radiation (58% radiation dose reduction) with optimal image quality.[36]

^{99m}Tc agents are to be preferred over ^{201}Tl because of their shorter half-life, significantly lower effective dose, and superior image quality. Based on the current models for the calculation of absorbed effective doses,[37] for ^{99m}Tc-labelled tracers, the effective dose for a full stress–rest protocol with 1000 MBq is approximately of 6–7 mSv.[6] For a stress–rest protocol using 111 MBq of ^{201}Tl (74 MBq for stress and 37 MBq at rest), the effective dose (~11 mSv) is increased of almost a factor of 2.

Stress-first enabling stress-only MPI using ^{99m}Tc tracers can significantly reduce the radiation dose compared with standard dose rest–stress MPI protocols. If the stress MPI results are normal, the rest scan can be omitted, with significant savings in cost, time, and radiotracer exposure to the patient (35% dose reduction) and to the laboratory staff (40% dose reduction).[38] Prone imaging can be used as an alternative strategy for troubleshooting attenuation-dependent inferior wall perfusion defects. The attenuation correction CT scan results in an additional dose of 0.5–1.0 mSv. However, attenuation correction using radionuclide or CT-based transmission scans may reduce the need for rest MPI imaging in a significant percentage of patients, thus limiting the overall radiation dose.[39,40] In patients with increasing body weight, such as in obesity or body habitus in women, the image quality may be limited, reducing the possibility to perform routinely stress-only protocol.

The technology of the gamma cameras is another variable that may help reducing the radiation dose. Low radiotracer dose protocols (half-dose or less than half-dose) using novel scanners, collimators, or software are increasingly utilized. Camera systems based on new technologies (e.g. CZT cameras) have improved count sensitivity for the detection of gamma rays. The increased sensitivity enables shorter image acquisition duration.[12,41–44] Nevertheless, in light of the ALARA principle, this improved sensitivity should preferentially be used to reduce the amount of injected dose preserving the image quality.[45] Effective doses below 2 mSv can be achieved by administering low-dose ^{99m}Tc tracers (lower than 148 MBq) and combining stress-only protocols with new scanner technologies.

Taken together, there are plenty of opportunities to reduce patient radiation burden without major impact on image quality and

thereby maintaining diagnostic accuracy.[38,41–43,45] Efforts should be directed towards reducing radiation exposure by taking advantage of the recent development in SPECT technology.

The key points include main steps to set-up a nuclear cardiology protocol to minimize the radiation exposure.

Best practice	Dose (mSv)
Prefer radiotracers with low radiation exposure ^{99m}Tc (stress/rest protocol, 4 mCi/12 mCi, respectively)	2–8
Check the possibility to perform stress-only acquisition (4 mCi)	≤2
Use weight-based radiotracer doses	
Appropriate use of attenuation correction	0.5–1
Avoid ^{201}Tl (stress/rest protocol)	>8
Avoid dual isotope imaging	>8

Positron emission tomography protocols and tracers

Estimated whole-body effective radiation dose is directly related to the half-life of the radiotracer and dose of radiotracer administered. In general, PET myocardial perfusion tracers have the advantage of their short to very short half-lives.

For the evaluation of myocardial perfusion ^{82}Rb and ^{13}N-ammonia, the most commonly utilized tracers for clinical imaging provide high image quality and low radiation exposure. Positron emission tomography protocols allow for quantitation of absolute myocardial blood flow (MBF) in mL/min/g, and MBF reserve providing additional relevant information in different patient populations[46–50] and for selected clinical conditions (balanced myocardial ischaemia and microvascular disease).[17] O-water is the gold standard radiotracer for the measurement of MBF with PET and provides parametric quantitative representation of MBF with low radiation exposure. A complete stress–rest study can be performed with a total radiation exposure of 2–4 mSv for ^{13}N-ammonia, 3–5 mSv for 82Rb and 1–2 mSv for ^{15}O-water. New ^{18}F-labelled PET radiotracers for MPI are currently under evaluation and can be used with exercise stress testing because of their longer half-life and longer retention times.[51]

The use of ^{13}N-ammonia and ^{15}O-water requires an on-site cyclotron for the synthesis of radiotracer. 82Rb can be produced in a generator, which is relatively cheap even if the monthly costs of precursor are high requiring high patient throughput to be cost-effective. As for SPECT, a weight- or BMI-based adjusted PET radiotracer dose is recommended to reduce radiation dose and preserve optimal image quality.

Moreover, as recently demonstrated by Danad *et al.*,[52] further reduction of radiation exposure can be achieved by a stress-only protocol. The use of a quantitative cut-off for absolute hyperaemic myocardial blood flow may provide even a superior accuracy for diagnosing haemodynamically significant coronary artery disease (CAD) when compared with quantification of flow reserve that requires rest/stress protocol. For evaluation of myocardial viability, the typical protocol includes a PET perfusion study and a PET metabolic study using ^{18}F-fluorodeoxyglucose (18 F-FDG). A strategy to reduce radiation exposure is the use of ^{18}F-FDG without PET MPI, as preserved uptake of FDG can be regarded as a sign of viability.[53] A typical ^{18} F-FDG cardiac study results in ∼3–5 mSv.

In PET/CT scanners, accurate attenuation correction of cardiac PET image is provided by CT, with a small increase in radiation dose. Using a single CT scan for attenuation correction of multiple PET acquisitions can further reduce the global dose.[54] Recent developments in PET technology (e.g. 3D detection mode and silicon photomultipliers) may allow to further reduce the injected dose and hence the radiation exposure.

The key points include main steps to set-up a cardiac PET protocol to minimize the radiation exposure.

Best practice	Dose
Check the possibility to perform stress-only acquisition (^{99m}Tc tracers, 4 mCi)	50% dose reduction
Use weight-based radiotracer doses	
Appropriate use of attenuation correction	0 5–1 mSv
Avoid dual isotope imaging of viability when possible (FDG only, 10 mCi)	3–5 mSv
Know the radiation dose associated with each radiotracer in a typical perfusion study	
^{13}N-ammonia (10 mCi) (stress or rest)	2 mSv
^{15}O-water (24 mCi) (stress or rest)	1.5 mSv
^{82}Rubidium (20 mCi) (stress or rest)	2.5 mSv

Computed tomography protocols

Until approximately 2006, most coronary CT angiograms were acquired using a retrospectively ECG-gated spiral scan mode. The principle of this scan mode is the continuous table movement and data acquisition over several cardiac cycles, after which cardiac phase-consistent projections are combined using a recorded rhythm trace to reconstruct the images. For image reconstruction, the desired phase of the cardiac cycle is specified and only X-ray data acquired during this phase is used for image reconstruction while the remaining data are often discarded. If desired, multiple reconstructions at various time points of the cardiac cycle can be obtained. This allows for selecting the phase with least motion artefacts and, within limits, permits to correct for arrhythmias and other artefacts.

The major drawback of this protocol is the high radiation exposure caused by temporal and spatial oversampling. Modifications have been designed to reduce overall radiation exposure. ECG-triggered X-ray tube current modulation is an algorithm that can reduce the tube output during the phases that are less likely to be used for the reconstruction.

This approach is effective in terms of radiation dose reduction and should be considered as a standard practice with retrospectively gated spiral CT protocols.

In patients with stable and low heart rates (usually below 65 b.p.m.), prospectively ECG-triggered axial scan protocols, also known as ‘sequential’ or ‘step-and-shoot’ protocols, have largely replaced spiral protocols. The advantage of the axial scan protocol is that exposure only occurs during the phase that is intended for reconstruction, minimizing the overall radiation exposure. Also the z-axis oversampling is less using axial scan protocols. The drawback is

that it relies on a regular and relatively low heart rate. Depending on the system, no alternative cardiac phases may be available in the case of suboptimal image quality. More recent systems operate axial scan protocols that allow for prolonged sampling and reconstruction of additional phases (also known as 'padding') and are also equipped with arrhythmia detection and handling algorithms. In the event of an irregular heartbeat, the acquisition at a given location is interrupted and/or repeated.

An additional strategy to reduce the radiation exposure is based on reduction of scan time. Wide detector array scanners (256–320 rows) and second- and third-generation dual-source CT scanners with high-pitch spiral scan protocols allow for complete coverage of the heart in a single gantry rotation. Single-beat acquisition avoids 'step' or 'misalignment' artefacts seen on image acquisition during multiple heartbeats and is generally associated with a lower radiation exposure.

Radiation exposure is very low due to the lack of oversampling. The prospectively ECG-triggered high-pitch spiral protocol on dual-source scanners results in substantially lower doses but requires a slow and regular heart rhythm.[55,56]

Absorbed doses from CT coronary angiography (CTCA) depend on the system and imaging protocol used and can be estimated between 2 and 5 mSv using commonly available single-source 64-slice CT scanners with a prospectively ECG-triggered step-and-shoot acquisition protocol.[57,58] In suitable patients, the acquisition protocols allowed by the newest CT hardwares and softwares enable even lower absorbed doses <1 mSv.[9,28]

Finally, if the lowering of tube voltage is a very effective radiation dose-saving strategy in CCTA due to the correlation between effective dose and the square of tube voltage, this is not possible for calcium score. Indeed, the change of scan parameter can influence the CAC value, and therefore, in this setting, only tube current optimization can be performed.

The key points include main steps to set-up a CT protocol to minimize the radiation exposure.

Perform scan length optimization	**Perform a topogram before the contrast-enhanced scan to minimize scan length and overall ED**
Set-up tube voltage and tube current	Consider a trade-off between higher image noise and lower contrast resolution For clinical practice: tube voltage of 100 and 120 kVp for patients with BMI <30 and >30 kg/m^2, respectively
Choice of ECG triggering	High heart rate: retrospective ECG triggering with tube current modulation Low heart rate: prospective ECG-triggering Last-generation scanner: single-beat acquisition

Fusion computed tomography/single photon emission computed tomography–computed tomography/positron emission tomography imaging imaging

'Fusion' or 'hybrid' imaging describes the integration of complementary imaging modalities to improve yield, accuracy, clinical, and prognostic impact of single imaging modalities. Early studies dating back nearly a decade have reported radiation doses from hybrid CT/SPECT imaging in the range of 15–25 mSv[59] and in the range of 9–15 mSv for hybrid CT/PET imaging.[23] Due to the added radiation exposure, sensible and careful patient selection for hybrid imaging procedures remains crucial. Even if large trials have yet to be conducted, it seems reasonable to address to hybrid imaging studies for those patients in whom perfusion defect allocation and assessment of the haemodynamic significance of individual lesions will play a determining role for further treatment and particularly for guiding revascularization procedures.[60,61] A potential strategy to reduce the added radiation exposure is to perform sequential imaging studies, where CTCA is used as a gatekeeper for SPECT or PET imaging.[62] As previously described, a number of extremely effective strategies and protocols are now available for reducing radiation exposure of both radionuclide imaging and CTCA. When all the aforementioned dose reduction strategies are exploited, full and comprehensive hybrid imaging studies may be obtained at a cumulative radiation dose as low as 4 mSv.[63] At such doses, hybrid imaging can be considered in wider patient populations with a very acceptable safety profile.

Appropriate clinical use of non-invasive cardiac imaging for reducing global radiation exposure

Nuclear and CT imaging are included in the management flow charts of patients with different cardiovascular diseases providing unique or alternative information when compared with other imaging modalities. Current international guidelines and recommendations include nuclear cardiology techniques and cardiac CT as appropriate modalities for different clinical scenarios (see Supplementary material online, *S1*). Nevertheless, selection of functional cardiovascular imaging by nuclear modalities and anatomical imaging by CT depends on multiple factors including the clinical question, the age of the patient, the estimated pre-test probability of the disease, costs, availability and local expertise for each imaging technology, physician preferences, and patient convenience.[64] Some of these factors determine the overall radiation exposure that the patient will receive and, following the most recent clinical guidelines from the European Society of Cardiology (ESC) can be favourably modified taking into account the ALARA principle.

However, as underlined in a recent joint position document on three main different associations of the ESC: 'All other considerations being equal, it is not recommended to perform tests involving ionizing radiation when the desired information can be obtained with a non-ionizing test with comparable accuracy. If you perform a test that utilizes ionizing radiation, choose the one with the lowest dose and be aware of the many factors modulating dose'.[3] In the current ESC guidelines on stable CAD,[64] stress echocardiography, stress MRI, and stress MPS have the same level of recommendation for diagnosis and are considered as equally valid alternatives and should be taken into account to reduce radiation exposure. However, it should also be considered that imaging tests may carry risks not only related with radiations such as those associated with stressors, contrast agents, or other energy sources. For example, the induction of DNA

double-strand breaks has been described after exposure to non-ionizing radiation from cardiac MR scanning[65,66] even if its impact on long-term risk is not clear and has not yet been sufficiently explored. The knowledge of all advantages and pitfalls for each imaging technique should be well known to select the best one for each patient.

A brief description of the role of nuclear diagnostic imaging in several clinical scenarios, as indicated in the current ESC guidelines and recommendations, is summarized in Supplementary material online, *S1*.[67–77]

Impact on costs

Total expenditures related to advanced imaging show an increasing trend in Europe, raising concerns among health care providers.[78] As a consequence, evaluation of diagnostic tests is shifting to an assessment of their effect on clinical outcomes in relation to treatment and in particular cost-effectiveness rather than on their diagnostic accuracy alone. Although most of the publications using non-invasive testing indicate cost-effectiveness over strategies without non-invasive tests, the overall published data are conflicting, particularly regarding the question which non-invasive strategy is the most cost-effective. Moreover, the definition of effectiveness often includes diagnostic accuracy or downstream utilization of resources and rarely more relevant endpoints such as efficacy on clinical outcome. In addition, the definition of costs generally does not include those related with missed/over diagnosis or with the risks potentially associated with the procedure.

There are no studies available on the cost-effectiveness of radiation dose reduction strategies. Due to the present uncertainty of the risks associated with low radiation doses, the results of long follow-up studies assessing the impact on health and related costs are essential. However, lower dosages of the specific and most often expensive radiopharmaceuticals will most likely result in lower costs even if this assumption is dependent on local and national differences. In contrast with nuclear cardiology procedures, it is more difficult to predict the effects on costs in relation to a reduction in radiation dose with CT-driven protocols.

Conclusions

The increasing awareness of procedure-associated radiation has triggered the introduction of novel imaging protocols, and the development of new imaging technologies aiming at lowering radiation dose with further optimization of image quality. The state-of-the-art nuclear cardiology and cardiac CT imaging require embracing best practices for appropriate patient selection, patient-centred imaging protocols, use of novel protocols for traditional scanners, and adoption of laboratory practices to reduce lifetime radiation exposure for patients and staff members. This strategy requires a close collaboration between the three main European Societies (EACVI, EANM, and ESCR) to disseminate and educate the different myocardial imaging professionals as well as the referring clinical cardiologists.

Supplementary material

Supplementary material is available at *European Heart Journal* online.

Acknowledgements

All the authors would like to thank Rozemarijn Vliegenthart for her substantial help in the revision of the manuscript.

Conflict of interest: none declared.

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