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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Abstract

Cardiovascular diseases represent the leading cause of death in Europe. Radionuclide myocardial perfusion imaging and cardiac computed tomography (CT) play an important role in establishing the diagnosis and prognosis of patients with cardiac diseases, but require the use of ionizing radiation. Novel imaging technologies and protocols have recently become available that allow for a significant reduction in radiation exposure while maintaining diagnostic accuracy.

State-of-the-art nuclear cardiology and cardiac CT imaging requires embracing best practices for appropriate patient selection, patient-centered imaging protocols, use of novel protocols for traditional scanners, and adoption of laboratory practices in order to reduce lifetime radiation exposure of patients and staff members.

The specific knowledge on these different subjects is, however, spread across different medical professions. Therefore, a close collaboration between the three mainly involved European Societies, European Association of CardioVascular Imaging (EACVI), European Association of Nuclear Medicine (EANM) and European Society of Cardiovascular Radiology (ESCR) is mandatory. This would enable an adequate dissemination of the knowledge and would allow for an optimized education of both clinicians and clinical imagers.

The aim of this review is to summarize the recent developments in hardware and imaging protocols that allow for a significant reduction in radiation exposure while maintaining diagnostic accuracy.

Introduction

The radiation burden due to cardiovascular imaging in Europe

Cardiovascular diseases (CVD) 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 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, the present paper 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 risk of the disease 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 tissue 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 Joules of energy of radiation transferred to one gram of living tissue.

The potential damage not only depends on the amount of absorbed energy and the different types of radiation but also on 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 ALARA (as low as reasonable achievable) principle, contemporary cardiovascular exams 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 less than 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 leukemia, thus lending support to the concept of a linear dose response at low doses. The results from ongoing studies, such as the Epi-CT study (12) which is currently recruiting in 9 European countries over one million children or young adults who had CT scans with the aim of evaluating the radiation-related risk of cancer, may provide more solid evidence.

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 of software for images acquisition and reconstruction have 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 with natural radiation exposure (13).

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

New gamma cameras 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 of photo-detectors. Manufacturers have taken advantage of these much thinner and more flexible CZT detectors to design gamma cameras dedicated to cardiac imaging offering a larger surface for signal detection, while focused on the heart region (14, 15). CZT gamma cameras provide a 4- to 7-fold higher system sensitivity compared to Na/I-based cameras (16). 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 (17) (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 (18). 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 (19, 20). 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, 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 (21).

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 (22, 23). 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 (24).

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 datasets 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 (25) 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, as compared to 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 (26). All these lower-dose acquisition protocols require lowering of the heart rate (27, 28). 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 to the standard use of 100 or 120 kV, while high tube currents compensate for increased image noise (29). 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 to the filtered back-projection techniques, allow for cardiac imaging at lower radiation exposure (30-32).

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, are critical in reducing patient radiation dose. All these variables must be considered but 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).

SPECT 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) (33), acquisition protocol (1 or 2-day protocols, imaging time, pixel size, gated acquisition) and the type of equipment (multiple head scintillation camera, or a camera based on CZT detectors).

For example, a weight- or body mass index–based adjusted SPECT radiotracer dose may be better than a fixed dose, to balance low radiation (58% radiation dose reduction) with optimal image quality (34).

^{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 current models for the calculation of absorbed effective doses (35), 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 (approximately 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) (36). 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 (37, 38). 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, 39-42). Nevertheless, in light of the ALARA principle, this improved sensitivity should preferentially be used to reduce the amount of injected dose preserving image quality (43). Effective doses below 2 mSv can be achieved by administering low dose 99mTc-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 (36, 39-41, 43). Efforts should be directed towards reducing radiation exposure by taking advantage of the recent development in SPECT technology.

Key points: main steps to setup a nuclear cardiology protocol to minimize the radiation exposure

Best practice	Dose
Prefer radiotracers with low radiation exposure ^{99m}Tc (Stress/rest protocol, 4mCi/12mCi respectively)	2-8 mSv
Check the possibility to perform stress-only acquisition (4mCi)	≤ 2 mSv
Use weight based radiotracer doses	
Appropriate use of attenuation correction	0,5-1 mSv
Avoid ^{201}Tl (Stress/rest protocol)	>8 mSv
Avoid dual isotope imaging	>8 mSv

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. PET 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 (44-48) and for selected clinical conditions (balanced myocardial ischemia, microvascular disease). ^{15}O-water is the gold standard radiotracer for measurements 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 ^{82}Rubidium and 1-2 mSv for ^{15}O-water. New ^{18}F-labeled 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 (49).

The use of ^{13}N-ammonia and ^{15}O-water requires an on-site cyclotron for the synthesis of radiotracer. ^{82}Rb 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 body mass index–

based adjusted PET radiotracer dose is recommended to reduce radiation dose and preserve optimal image quality.

Moreover, as recently demonstrated by Danad et al (50), further reduction of radiation exposure can be achieved by a stress only protocol. The use of a quantitative cut-off for absolute hyperemic myocardial blood flow may provide even a superior accuracy for diagnosing hemodynamically significant CAD as compared with quantitation of flow reserve which 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 18F-FDG without PET MPI as preserved uptake of FDG can be regarded as a sign of viability (51). A typical ^{18}F-FDG cardiac study results in approximately 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 (52). Recent developments in PET technology (e.g. 3D detection mode, silicon photomultipliers) may allow to further reduce the injected dose and hence the radiation exposure.

Key points: main steps to setup a cardiac PET protocol to minimize the radiation exposure

Best practice	Dose
Check the possibility to perform stress-only acquisition (^{99m}Tc-tracers, 4mCi)	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 (10mCi) (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 is often discarded. If desired, multiple reconstructions at various time points of the cardiac cycle can be obtained. This allows 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 bpm), 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 heart beats, 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 (53, 54).

Absorbed doses from CT coronary angiography (CTCA) depend on the system and imaging protocol used and can be estimated between 2-5 mSv using commonly available single-source 64-slice CT scanners with a prospectively ECG triggered step-and-shoot acquisition protocol (55, 56). In suitable patients the acquisition protocols allowed by the newest CT hardwares and softwares enable even lower absorbed doses <1 mSv (9, 26).

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.

Key points: main steps to setup 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
Setup tube voltage and tube current	Consider a tradeoff between higher image noise and lower contrast resolution. For clinical practice: tube voltage of 100 kVp and 120 kVp for patients with BMI <30 and >30, 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 CT/SPECT CT/PET 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 (57) and in the range of 9-15 mSv for hybrid CT/PET imaging (21). 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 those patients in whom perfusion defect allocation and assessment of the hemodynamic significance of individual lesions will play a determining role for further treatment and particularly for guiding revascularization procedures (58, 59). A potential strategy to reduce the added radiation exposure is to perform sequential imaging studies, where CTCA is used as a gate-keeper for SPECT or PET imaging (60). 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 (61). 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 as compared with other imaging modalities. Current international guidelines and recommendations include nuclear cardiology techniques and cardiac CT as appropriate modalities for different clinical scenarios (supplementary materials). Nevertheless, selection of functional cardiovascular imaging by nuclear modalities and anatomic 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 (62). Some of these factors determine the overall radiation exposure that the patient will receive and, following the most recent clinical guidelines from European Society of Cardiology (ESC), can be favorably modified taking into account the ALARA principle. However, as underlined in a recent joint position document on three main different associations of the European Society of Cardiology: “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 coronary artery disease (62) 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 in order to reduce radiation exposure. However, it should also be considered that imaging tests may carry risks not only related with radiations such 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 (63, 64) 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 in order 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 Supplement material (S1) (65-75).

Impact on costs

Total expenditures related to advanced imaging show an increasing trend in Europe, raising concerns among health care providers (76). 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 end-points 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 to the procedure.

There are no studies available on the costs-effectiveness of radiation dose reduction strategies. Due to the present uncertainty of the risks associated to 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. State-of-the-art nuclear cardiology and cardiac CT imaging requires embracing best practices for appropriate patient selection, patient-centered 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.

Legend of figures

Figure 1 (Adapted from reference 77): Bar graph illustrating the average effective radiation doses of cardiac CT applying the various radiation dose reducing algorithms.

Figure 2 (Adapted from reference 78): Recommended radiotracer doses for MPI conventional scanners (white bar) and for scanners with new softwares and/or hardwares (gray 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 exam.

Figure 3: A 60 years 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 minutes, respectively. CZT images reveal the presence of a reversible perfusion defect involving the infero-septal wall, the inferior wall, the distal portion of the antero-septal wall and the apex.

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

Supplement material

S1: A brief description of the role nuclear diagnostic imaging in several clinical scenarios, as indicated in the current ESC Guidelines and recommendations is summarized in Supplement material (S1) (References from 62 to 72).

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