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ESC REPORT

The appropriate and justified use of medical radiation in cardiovascular imaging: a position document of the ESC Associations of Cardiovascular Imaging, Percutaneous Cardiovascular Interventions and Electrophysiology

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The benefits of cardiac imaging are immense, and modern medicine requires the extensive and versatile use of a variety of cardiac imaging techniques. Cardiologists are responsible for a large part of the radiation exposures every person gets per year from all medical sources. Therefore, they have a particular responsibility to avoid unjustified and non-optimized use of radiation, but sometimes are imperfectly aware of the radiological dose of the examination they prescribe or practice. This position paper aims to summarize the current knowledge on radiation effective doses (and risks) related to cardiac imaging procedures. We have reviewed the literature on radiation doses, which can range from the equivalent of 1–60 milliSievert (mSv) around a reference dose average of 15 mSv (corresponding to 750 chest X-rays) for a percutaneous coronary intervention, a cardiac radiofrequency ablation, a multidetector coronary angiography, or a myocardial perfusion imaging scintigraphy. We provide a European perspective on the best way to play an active role in implementing into clinical practice the key principle of radiation protection that: 'each patient should get the right imaging exam, at the right time, with the right radiation dose'.

Keywords Cancer • Cardiovascular disease • Imaging • Radiation • Radiological protection • Risk

Introduction

Medical radiation from X-rays and nuclear medicine is the largest man-made source of radiation exposure in Western countries, and accounts for a mean effective dose (ED) of 3.0 milliSievert (mSv) per person per year, equivalent to the radiation dose of 150 chest X-rays (CXR).[1] The natural background radiation worldwide is about 2.4 mSv [2] (*Figure 1*). Cardiologists are responsible for about

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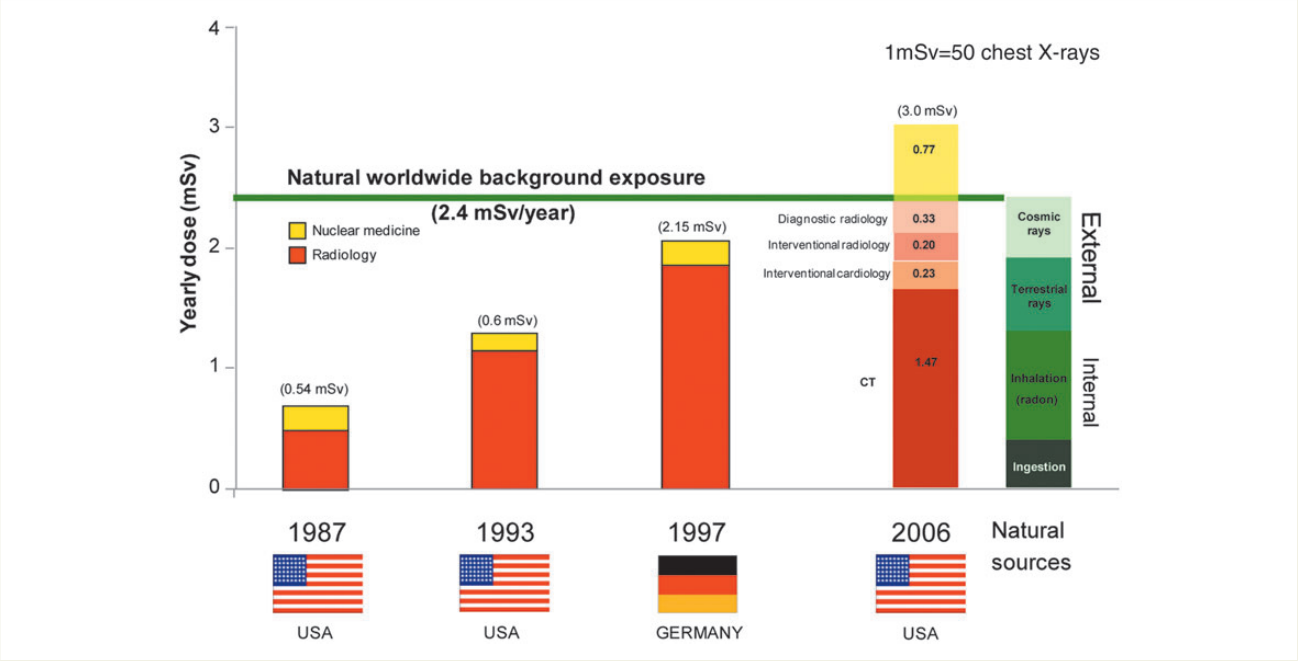

Figure 1 Medical and natural sources of radiation per person per year. Modified from Picano[1] and updated from Mettler *et al.*[2]

40% of the entire cumulative ED to the US population from all medical sources excluding radiotherapy.[3] In addition, the occupational radiation exposure of interventional cardiologists and cardiac electrophysiologists can be two to three times higher than that of diagnostic radiologists,[4] and their exposure has increased steadily in the past few decades.[5]

The increasing use and complexity of imaging and interventional techniques have not been matched by increasing awareness and knowledge by prescribers and practitioners. The majority of doctors—including cardiologists—grossly underestimate the radiation doses for most commonly requested tests.[6,7] The significant increase in the cumulative exposure of patients and population to ionizing radiation is likely to cause an increased incidence of cancer in years down the line, with an important yet potentially avoidable public health threat.[8] Cancer induction associated with radiation goes unrecognized because it is neither differentiable nor predictable for individual patients, and because clinically significant consequences do not become evident for many years. The balance between risks and benefits determines the appropriateness score of a test: the test is appropriate when benefit greatly exceeds the risks, and inappropriate when risk exceeds the benefit.[9] According to recent estimates, at least one-third of all cardiac examinations are partially or totally inappropriate,[10] i.e. risks and costs outweigh benefits. The risk–benefit assessment is a 'dynamic', tailored variable rather than an absolute, fixed concept, since the same test can have a favourable risk–benefit ratio in an individual with intermediate pre-test probability and equivocal ECG, and totally inappropriate in a middle-aged woman with atypical chest pain and maximal negative ECG stress test. The order of magnitude of the risks of several imaging techniques (or associated procedures, such as stress or contrast administration) may range between 1–10% (contrast-induced nephropathy) and 0.1–0.3% (severe reaction during stress administration of dobutamine or dipyridamole). Therefore, radiation risks are certainly not the only, and probably also not the most important of the risks to be included in the risk-side of our risk–benefit assessment. However, they are probably the least well known and the least considered in our daily decision making.[11]

Table 1 Biological effects of ionizing radiation

	Tissue reactions ('deterministic')	Chance damage ('probabilistic')
Dose level	Medium to high	Low
Latency period	Short (days or weeks)	Long (years)
Threshold dose	Yes	Probably not, but some uncertainty
Biological mechanism	Predominantly cell death	Cell damage
Sample clinical effects	Skin lesions; cataract	Cancer, inherited defect in offspring

Biological effects of radiation

There are two main biological effects of radiation (*Table 1*): tissue reactions (deterministic effects), which happen when the radiation dose exceeds a specific threshold and become evident days to months after exposure as they cause a predictable change in tissue,[12] and stochastic effects, which relate to the potential for future harm to the tissue and the body. Tissue reactions of most

concern for patients and operators include skin injuries (reported in patients undergoing long, repeated and complicated interventional procedures[13]) and cataract (present in one-third to half of interventional cardiologists or radiologists[14]). The stochastic effect of most concern is a carcinogenic effect. It occurs when the cell is modified by damage to its DNA but remains viable, the harm eventually being expressed through cell proliferation.[15] Ionizing radiation damages DNA molecule either directly (through ionization of DNA molecule) or indirectly (through generation of free radicals and reactive oxygen species in the surrounding medium). Cancer may occur after a latency period of many years. The reduction of risk of cancer is at the core of the radiation protection system for patients and staff.[16] The available epidemiological evidence linking increased cancer risk to radiation exposure is now strong for doses >50 mSv,[17,18] also for diagnostic medical exposures.[19] In contemporary imaging practice, doses >50–100 mSv are sometimes reached after cumulative exposures[20] in a single hospital admission[21] and not infrequently by a patient in multiple examinations and diagnostic or interventional procedures for a single imaging technique[22] and even in a single examination.[23] For any given radiation exposure, the cancer risk is higher in females than in males, in children than in adults, and in adults than in elderly, and may differ among individuals (*Figure 2*). From a radiation sensitivity standpoint, not all tissues have the same risk of radiation-induced cancer (*Table 2*). The radiation-induced cancer is clinically undistinguishable from a spontaneously occurring cancer. Out of 100 subjects exposed to 100 mSv (roughly equivalent to 5000 CXRs), 42 will develop a spontaneous cancer anyway (independently of radiation exposure), and the radiation exposure may induce 1 additional cancer (*Figure 3*). These estimates have a considerable margin of uncertainty, with a 2 to 3 confidence interval of attributable risk estimates,[18] which translates in the example above into an additional risk as high as 1 in 30 or as low as 1 in 300.

Non-ionizing radiation is generally considered safe, but radiofrequency fields used in CMR are a possible (class IIb) carcinogen according to the International Agency of Research on Cancer, and the World Health Organization has urgently called an action in order to evaluate adverse biological effects of clinical MR scanning,

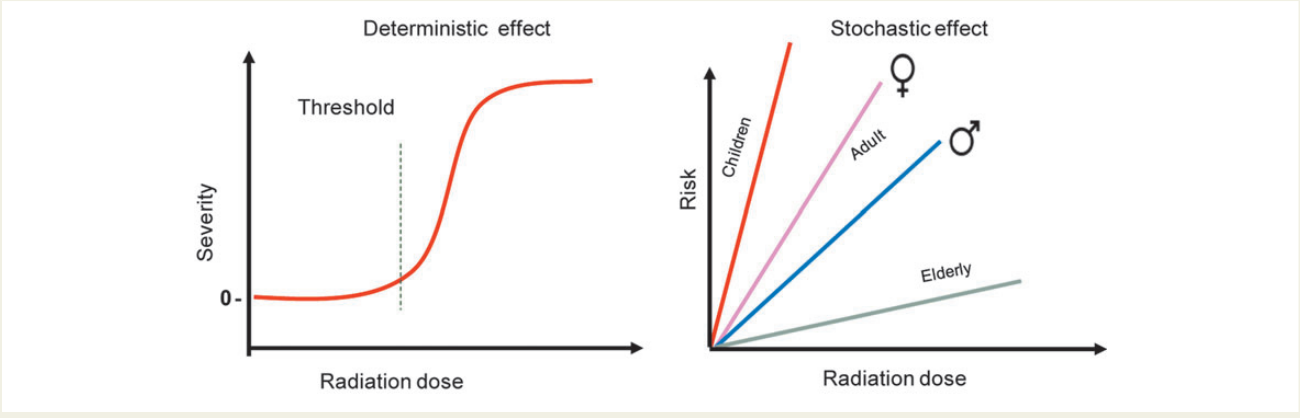

Figure 2 Deterministic vs. stochastic effects (representative, not scaled). The stochastic risk is highest in children, higher in women than in men, and reduced by one-half in the elderly (>80 years old). Modified from original data of Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII, Phase 2[18], BEIR VII

Table 2 Radiation sensitivity and tissue weighing factor

Radiosensitivity (tissue weighing factor)	Organ				
Highest (0.12)	Breast	Colon	Lung	Stomach	Bone marrow
High (0.08)	Ovaries	Testes			
Moderate (0.04)	Thyroid	Bladder	Oesophagus	Liver	
Low (0.01)	Bone	Salivary glands	Skin	Brain	
Very low (0.008)	Heart	Kidneys	Pancreas	Prostate (male)	Uterus (female)

To calculate the effective dose (i.e. the biological risk corresponding to any given physical dose), the individual organ dose values are multiplied by the respective dimensionless tissue weighing factor (taken from ICRP 2007[17]). The higher this factor, the more radiosensitive the tissue, i.e. allowing a rough estimation of biological risk corresponding to any given radiation dose. The sum of the tissue weighing factors is unity so that a uniform dose distribution in the whole body gives an effective dose numerically equal to the radiation-weighted dose in each organ and tissue of the body.

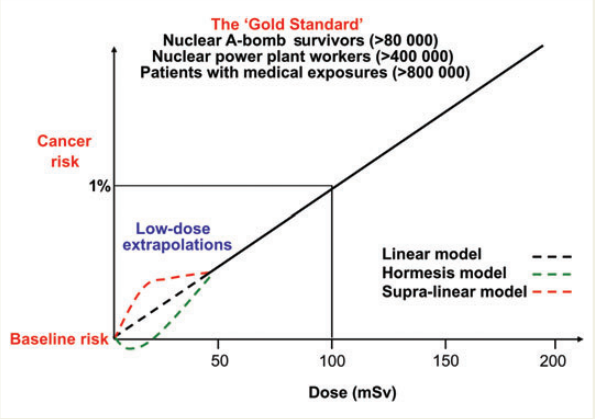

Figure 3 The dose–effect relationship between radiation exposure and cancer risk over background levels. The solid line indicates the epidemiological evidence, which is conclusive for doses >50–100 mSv. The dashed line indicates the dose range with inconclusive evidence. Below 50 mSv, the currently accepted linear no-threshold model (continuous line) is based on the assumption that the dose level (*x*-axis) is directly proportional to the cancer risk (*y*-axis). In the supra-linear model, the risk is higher for any given dose. In the hormetic model, low doses might even have a protective effect. Modified from original data of Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII, Phase 2[18], BEIR VII.

which is capable of producing detectable damage to human lymphocyte DNA integrity.[24]

Nuclear medicine: doses and risks

In the USA, nuclear cardiology accounts for >50% of all nuclear medicine procedures and 85% of the entire cumulative ED due to nuclear medicine, which accounted for 26% of the overall medical exposure of patients in 2006.[2] *Table 3* summarizes the ED for commonly performed studies.[25,26,27] A number of strategies can be used to minimize dose in cardiac nuclear imaging, such as the use of ^{99m}Tc (technetium) sestamibi or tetrofosmin agents as preferred radiopharmaceuticals in single-photon emission computed tomography (SPECT) and the use in patients with low pre-test probability of disease of stress-first/stress-only protocols.[28] Radiation exposure can be decreased by 75% using a protocol whereby stress imaging is performed first ('stress first'), with rest images eliminated in patients with normal stress images ('stress only')—but in current practice in the USA, it is seldom used due to gaps in practitioners' knowledge pertaining to radiation safety.[7] This same knowledge gap leads to the 15% rate of dual radioisotope testing, which is unacceptably high due to high ED involved (~30 mSv). The new SPECT detectors with cadmium zinc telluride technology can be used to considerably decrease the ED and acquisition time for myocardial perfusion SPECT with preserved image quality.[7,26] A strategic target of the nuclear cardiology community is that for the population of patients referred for SPECT or positron-emission tomography (PET) myocardial perfusion imaging, on average a total radiation exposure of <9 mSv can be achieved in 50% of studies by 2014.[29]

Computed tomography: doses and risks

Use of computed tomography (CT) for diagnostic evaluation has increased dramatically over the last two decades, from approximately 3 million in 1980 to nearly 70 million in 2007 in the USA, but the dose per examination showed a clear downward trend, with a reduction of three quarters of radiation dose in the last decade through increasing use of dose-saving measures and evolving scanner technology.[30] The ED of a calcium score study is substantially less (2–3 mSv) than a coronary CT study (*Table 3*). The patient dose as expressed by dose-length product can be converted into mSv (ED) with appropriate conversion factors, specific for the type of examination (chest vs. coronary artery)[31,32] (*Table 4*).

Recent emphasis on radiation exposure due to CT scanning has engendered a competitive effort on the part of manufacturers to reduce the dose while still providing images with sufficient diagnostic quality. As a result, if the heart rate is sufficiently slow and regular, cardiac CT angiography with a gated acquisition of a single frame in end-diastole can now be performed producing high-quality diagnostic images with a mean effective radiation dose of <2 mSv or even ≤1 mSv.

Interventional cardiology and electrophysiology

Among adult cardiology patients, fluoroscopically guided diagnosis and intervention account for 12% of all radiological examinations performed, and 48% of their total collective dose.[20] There are established correlation factors between ED and dose-area product (DAP) or kerma-area product (KAP) values displayed by the equipment as to indicating total energy imparted to the patient for a given IC procedure. The wide range of EDs corresponding to common examinations is reported in *Table 3*.[33–36] As a general rule, ED can be estimated approximately as follows: ED (mSv) = DAP (Gy × cm^2) × 0.2 (mSv/Gy cm^2).[37] The conversion factor (from DAP to mSv) is age-specific,[38] and increases with decreasing age (*Table 4*). Consequently, DAP quantity represents a relevant dosimetry index, the value of which should be optimized against the diagnostic reference level, which varies for each procedure and can be used as a tool to comply with the ALARA (As Low As Reasonable Achievable) principle.

Specific estimations of patient radiation dose for typical EP procedures are listed in *Table 3*.[39] The introduction of non-radiology-based methods of cardiac mapping and the use of co-registration of CT or CMR images of the target structures (for instance, the left atrium) have the potential to drastically reduce these doses.

Protection of personnel

The protection of doctors is just as important as protection of patients. With conventional radiology and CT, occupational radiation exposure is minimal since the staff leaves the room during the procedure. In nuclear cardiology, professional exposure can be as high as 2–5 mSv per year, although more frequently it

Table 3 Standard average reference doses of common cardiological examination

	Diagnostic procedures	Effective dose (mSv)	Equivalent CXRs	Background radiation (years)	Reference
Adult	**Conventional radiography**				
	CXR (PA)	0.02	1	2–3 days	Mettler *et al.*[25]
	Invasive fluoroscopy				
	Diagnostic coronary angiography	7 (2–16)	350	2.9	Mettler *et al.*[25]
	PCI	15 (7–57)	750	6.3	Mettler *et al.*[25]
	Thoracic angiography (pulmonary or aorta)	5 (4–9)	250	2.1	Mettler *et al.*[25]
	Abdominal angiography or aortography	12 (4–48)	600	5.0	Mettler *et al.*[25]
	Pelvic vein embolization	60 (44–78)	3000	25.0	Mettler *et al.*[25]
	TIPS placement	70 (20–180)	3500	29.3	Mettler *et al.*[25]
	Aortic valvuloplasty	39	1950	16.2	Signorotto *et al.*[33]
	Dilation chronic coronary occlusion	81 (17–194)	4050	33.7	Suzuki *et al.*[34]
	ETAAAR procedure	76–119	3800–5950	31.6–49.5	Panuccio *et al.*[35]
	Renal angioplasty	54	2700	22.5	Rehani *et al.*[37]
	Iliac angioplasty	58	2900	24.1	Rehani *et al.*[37]
Paediatric	Diagnostic cardiac catheterization	6.0 (0.6–23.2)	Age-dependent	2.5	Bacher *et al.*[36]
	Closure of ASD	2.8 (1.8–7.4)	Age-dependent	1.1	Bacher *et al.*[36]
	Patent ductus arteriosus occlusion	7.6 (2.1–37)	Age-dependent	3.2	Bacher *et al.*[36]
	Balloon valvuloplasty	8.1 (2.9–20)	Age-dependent	3.3	Bacher *et al.*[36]
Adult	**Cardiac electrophysiology**				
	Diagnostic EP studies	3.2 (1.3–23.9)	160	1.2	Heidbuchel *et al.*[39]
	Ablation procedure:	15.2 (1.6–59.6)	760	5.7	Heidbuchel *et al.*[39]
	AF	16.6 (6.6–59.2)	830	6.9	Heidbuchel *et al.*[39]
	AT-AVNRT-AVRT	4.4 (1.6–25)	220	1.8	Heidbuchel *et al.*[39]
	VT	12.5 (3 to ≥45)	625	5.2	Heidbuchel *et al.*[39]
	Regular PM or ICD implant	4 (1.4–17)	200	1.6	Heidbuchel *et al.*[39]
	CRT implant	22 (2.2–95)	1100	9.1	Heidbuchel *et al.*[39]
	CT				
	64-slice coronary CTA	15 (3–32)	750 (150–1600)	6.25	Mettler *et al.*[25]
	Calcium score	3 (1–12)	150	1.25	Mettler *et al.*[25]
	Nuclear cardiology				
	PET F-18 FDG rest (400 MBq, viability)	8	400	3.3	ARSAC[26]
	PET Rubidium-82 stress–rest (3700 MBq)	4.6	230	1.9	Gaemperli *et al.*[27]
	PET N-13 ammonia stress–rest (1100 MBq)	2.4	120	1	Gaemperli *et al.*[27]
	PET ^{15}O-H_2O stress–rest (2200 MBq)	2.5	125	1.04	Gaemperli *et al.*[27]
	^{99m}Tc-labelled erythrocytes (1110 MBq, cardiac function)	7.8	390	3.25	Gaemperli *et al.*[27]
	SPECT-^{201}Tl stress/redistr. (130 MBq, single injection)	22	1100	91.6	Gaemperli *et al.*[27]
	^{201}Thallium stress/rest reinj. (185 MBq, double injection)	40.7	2035	16.9	Mettler *et al.*[25]
	^{99m}Tc -Sestamibi (1100 MBq, 1 day) stress–rest	9.4	470	3.9	Mettler *et al.*[25]
	^{99m}Tc -Tetrofosmin (1500 MBq, 1 day) stress–rest	11.4	570	4.7	Mettler *et al.*[25]
	Lung scintigraphy				
	^{99m}Tc -MAA (185 MBq, lung perfusion)	2	100	0.8	Mettler *et al.*[25]
	^{133}Xenon (400 MBq, lung ventilation)	0.4	20	0.2	ARSAC[26]

AF, atrial fibrillation; AT, atrial tachycardia; ASD, atrial septal defect; AVRT, atrio-ventricular reciprocal tachycardia; CXRs: chest X-rays; CRT, cardiac resynchronization therapy; ETAAAR, endovascular thoraco abdominal aortic aneurysm repair; FDG, fluorodeoxyglucose; MAA, macroaggregated albumin; PCI, percutaneous coronary intervention; CT, computed tomography; PET, positron-emission tomography; SPECT, single-photon emission computed tomography.

remains <1 mSv. Most experienced (and most exposed) interventional cardiologists and electrophysiologists have an exposure per annum of ~5 mSv, two to three times higher than diagnostic radiologists, with a typical cumulative lifetime attributable risk on the order of magnitude of 1 cancer (fatal and non-fatal) per 100 exposed subjects.[40] Operator dose per procedure correlates somewhat with the patient dose, but may be typically 1000 times lower depending upon the shielding employed (one unit of incidence scatter dose for the operator when 1000 units of incident dose are given to the patient).[41] However, adequate radiation

Table 4 Conversion factors: from jargon to effective dose

CT	Conversion factor	Reference
DLP (for chest)	mSv = DLP (mGy × cm) × 0.021	Christner *et al.*[31]
DLP (for coronary arteries)	mSv = DLP (mGy × cm) × 0.030	Geleijns *et al.*[32]
Radiology		
KAP in adults	mSv = KAP (Gy cm^2) × 0.2	Rehani[37]
KAP in 15 year olds	mSv = KAP (Gy cm^2) × 0.4	Karambatsakidou *et al.*[38]
KAP in 5 year olds	mSv = KAP (Gy cm^2) × 1.0	Karambatsakidou *et al.*[38]
KAP in <1 year olds	mSv = KAP (Gy cm^2) × 1.9	Karambatsakidou *et al.*[38]
KAP in newborns	mSv = KAP (Gy cm^2) × 3.7	Karambatsakidou *et al.*[38]
Nuclear cardiology		
SPECT ^{99m}Tc–sestamibi (rest)	mSv = MBq × 0.0092	Einstein *et al.*[28]
SPECT ^{99m}Tc–sestamibi (stress)	mSv = MBq × 0.0078	Einstein *et al.*[28]
SPECT ^{99m}Tc–tetrofosmin (rest)	mSv = MBq × 0.0073	Einstein *et al.*[28]
SPECT ^{99m}Tc–tetrofosmin (stress)	mSv = MBq × 0.0065	Einstein *et al.*[28]
SPECT-^{201}Tl (stress-redistribution)	mSv = MBq × 0.22	Gaemperli *et al.*[27]
PET ^{13}N-ammonia (stress–rest)	mSv = MBq × 0.0022	Gaemperli *et al.*[27]
PET ^{15}O-H_2O (stress–rest)	mSv = MBq × 0.0011	Gaemperli *et al.*[27]
PET ^{82}Rb (stress–rest)	mSv = MBq × 0.0036	Gaemperli *et al.*[27]
PET ^{18}F-FDG (rest)	mSv = MBq × 0.0189	Gaemperli *et al.*[27]

CT, computed tomography; KAP, kerma-area product; DLP, dose-length product; PET, positron-emission tomography; SPECT, single-photon emission computed tomography.

protection training and diligent protection can reduce the radiation exposure by 90%.[42]

Cardiac imaging in paediatric cardiology

For any given radiological ED, the risk for some organs, including the brain, is three to four times higher in children than in adults.[17,18] Children are at substantially higher risk than adults because they have more rapidly dividing cells and a greater life expectancy, allowing the clinical manifestation of radiogenic cancer with long latency periods of decades. Thus, an infant or a child patient has a longer lifetime risk for developing radiation-induced cancers than adult patients. At the age of 15–20 years, grown-up congenital heart disease patients have already cumulated an ED exposure corresponding to 20–40 mSv, with an estimated lifetime attributable extra-risk of cancer of 1 in 10 to 1 in 100.[43] Among paediatric cardiology patients with congenital heart disease, fluoroscopically guided diagnosis and interventions account for 3.5% of all radiological examinations performed and 84% of their total collective dose.[43] In the USA, this issue of radiological responsibility was addressed with the Image Gently, Step Lightly Campaign, especially focused on the risks of unnecessary and excessive medical radiation exposure from interventional radiology administered to paediatric patients.[44] Typical EDs for common paediatric examinations are reported in *Table 3*. In paediatric catheterization, the conversion factor from DAP to mSv (mSv = DAP × 0.20 in adult cardiology patients) is higher (*Table 4*).

Cardiac imaging in women and in pregnancy

For any given radiation exposure, the cancer risk is higher in females (by ~38%) than in males at all ages. In women in childbearing age, the dose to gonads should also be known[45] and minimized (*Table 5*).

Knowledge of foetal and mother dosimetry may affect the choice of testing in the pregnant patient. This is especially relevant in

Table 5 Gonad dose for diagnostic examinations

Diagnostic exposure	Gonad dose (mSv)
Abdominal X-ray	0.7
Pelvis and hip X-ray	4
Lower GI series (M/F)	90/36
CT chest	0.02
CT abdomen	3.7
CT pelvis and hips	20
Lower limb angiography	5.1
Body scintigraphy	3.0
Nuclear stress test (M/F)	2/13
PET scan	4

CT, computed tomography; PET, positron-emission tomography.
Adapted from Latini *et al.*[45]

Table 6 Terminology that should be used

Investigation (example)	Effective dose range	Additional lifetime risk of fatal and non-fatal cancer	RCR symbolic representation	Proposed risk term
CXR	<0.1 mSv	1:1 million	☢	Negligible
Abdominal X-ray	0.1–1 mSv	1 in 100 000 to 1 in 1 million	☢☢	Minimal
Chest CT	1–10 mSv	1 in 10 000 to 1 in 1000	☢☢☢	Very low
PCI	10–100 mSv	1 in 1000 to 1 in 100	☢☢☢☢	Low

These examples relate to a healthy 50-year-old man. Multiply by 1.38 for women, by 4 for children, and by 0.5 (reduced by 50%) in an 80-year-old man. Adapted from references 18,48, and 49.
CXRs, chest X-rays; RCR, Royal College of Radiology; PCI, percutaneous coronary intervention.
☢, <0.1 mSv; ☢☢, 0.1–1 mSv; ☢☢☢, 1–10 mSv; ☢☢☢☢, >10 mSv.

pulmonary embolism, which is the leading cause of maternal mortality in the developed world. Also on the basis of radioprotection considerations, strong recommendations were made by the American Thoracic Society for three specific scenarios: performance of CXR as the first radiation-associated procedure; use of lung scintigraphy (with a breast dose to mother 20 to 100 times lower than CT pulmonary angiography, with only slightly higher foetal dose) as the preferred test in the setting of a normal CXR; and performance of CT pulmonary angiography (whole-body maternal ED = 4–18 mSv) rather than digital subtraction angiography (7–28 mSv) in a pregnant woman with a non-diagnostic ventilation–perfusion result.[46]

For professionally exposed workers, pregnant workers can continue to work with radiation limits <1 mSv (foetal dose during full pregnancy) in many European countries, with the recommendation to communicate one's pregnancy to the competent hospital service. Allowed doses are higher in the USA, up to <5 mSv (measured by a waist dosimeter) for the entire pregnancy.[47]

Informed consent form

In radiological informed consent, the communication of doses and risks is often based on a highly specialized technical language, often difficult to understand even for practitioners and radiologists. As a result, both patients and doctors often are unaware of what they are doing, in terms of doses and radiation risks.[6,7] The informed consent form should spell out, in tabular form and possibly with a figure, the specific reference dose.[48] After the examination, the actually delivered dose should be stored in the patient's and laboratory's records. The jargon information should be translated into mSv, equivalent number of chest radiographs, and equivalent periods of natural background radiation (*Table 6*). After the procedure, the patient should be provided with dose information if he/she asks and this has become a requirement enforced by law in many countries. Effective dose has the advantage that it is not modality-specific and can be cumulated between different imaging modalities over time. This simple consent process will gently force the doctor to learn what he/she already should know, enabling him/her to make more responsible choices.[49]

Take-home message

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. The actual delivered dose should always be recorded and included in patients' records. Because of the numerous sources of variability, there is no clear threshold between acceptable and unacceptable exposure for any given examination, but the dose that is not even considered is certainly unacceptable.

X-rays and γ-rays used in radiology and nuclear medicine are proven (class 1) carcinogens, and cardiologists should make every effort to give 'the right imaging exam, with the right dose, to the right patient'.[50] The priority given to radioprotection in every cardiology department is an effective strategy for primary prevention of cancer, a strong indicator of the quality of the cardiology division, and the most effective shielding to enhance the safety of patients, doctors, and staff. A smart cardiologist cannot be afraid of the essential and often life-saving use of medical radiation, but must be very afraid of radiation unawareness.

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