

## SPECT/CT radiation dosimetry

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**Abstract** Single-photon emission computed tomography combined with X-ray computed tomography (SPECT/CT) improves diagnostic accuracy by allowing better localization and definition of scintigraphic findings. However, the combined acquisition of functional and anatomical images can substantially increase radiation exposure to patients, particularly when using a hybrid system with diagnostic CT capabilities. At the same time, the introduction of new SPECT and CT reconstruction techniques (based on the use of iterative algorithms), and of CT automatic dose modulation techniques, has opened the way for possible reductions in patient dose and/or improvements of image quality. It is, therefore, essential to carefully balance the diagnostic needs and the radiation protection requirements, optimizing the choice of radiopharmaceutical and administered activity, and the image acquisition and processing modalities both in SPECT and in CT. This is particularly important in the case of pediatric examinations. In short, to maximize benefit to patients, SPECT/CT studies have to be optimized, adopting dose-reduction measures both from CT and SPECT practices. In SPECT, shorter lived gamma emitters should be preferred and the amount of activity administered must be carefully adjusted to the patient's size. In CT, scanning parameters (scanning length, tube current, tube voltage, filtration, collimation, slice thickness, pitch, automatic dose modulation method, reconstruction technique, and image processing) must be chosen carefully,

remembering that normally the scanned images are used only for the purposes of attenuation correction and/or a more precise localization of scintigraphic findings, which require lower quality and consequently entail a lower dose to the patient. On the other hand, good quality diagnostic CT images, obtained at higher dose levels, are necessary if a diagnostic CT examination must still be planned for the patient. The purpose of this review on SPECT/CT radiation dosimetry is to provide updated information on the total effective dose and total equivalent doses to critical organs due to both radiopharmaceutical administration and CT scan modality for both adults and pediatric patients. The use of new solid-state detectors (cadmium zinc telluride) for SPECT cameras will also be considered. Finally, the means of easily determining SPECT/CT dose to patients will be provided.

**Keywords** SPECT/CT · Radiation dosimetry · Effective dose · Injected activity

### Introduction

As is well known in general radiology and in diagnostic nuclear medicine, radiation doses must be kept as low as is reasonably achievable consistent with obtaining the required medical information. It is, therefore, very important, in all diagnostic procedures, to adjust radiation doses in order to meet this principle. It is particularly important in the case of pediatric examinations.

In recent years, there has been a constant development of the use of SPECT/CT hybrid systems which combine single-photon emission computed tomography (SPECT) with X-ray computed tomography (CT). These systems improve diagnostic accuracy by allowing better

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localization and definition of scintigraphic findings. However, the combined acquisition of functional and anatomical images can substantially increase radiation exposure to patients, particularly when using a hybrid system with diagnostic CT capabilities.

With SPECT/CT, the radiation dose to patients is the sum of the radiation dose due to the radiopharmaceutical administered for SPECT imaging and the radiation dose from the CT component of the study. Thus in SPECT/CT procedures, it is essential to carefully balance the diagnostic needs and the radiation protection requirements through optimization of both SPECT and CT practices. For this reason, the radiopharmaceutical used and its administered activity as well as the image acquisition and processing modalities both in SPECT and in CT must be carefully evaluated.

The purpose of this review on SPECT/CT radiation dosimetry is to provide updated information on the total effective doses and total equivalent doses to critical organs due to both radiopharmaceutical administration and the CT scan modality with reference to both adult and pediatric patients. To this end, the two components of the study, SPECT and CT, are dealt with separately.

In this context, we highlight the effect of new dose-reduction techniques and also consider the use of new solid-state detectors (CdZnTe) in cardiac SPECT imaging.

Finally, the means of easily determining SPECT/CT dose to patients will be provided.

## The SPECT component

### Administered activities

An adequate clinical result of a SPECT examination depends primarily on the statistical content of the images.

Thus, the administered activity is the most important factor determining SPECT image quality. However, the administered activity must be decided on the basis of a correct evaluation procedure, taking into account several clinical and technical aspects that also depend on patient characteristics. The most important factors that must be taken into account are scan duration, characteristics of the imaging system, image reconstruction, and image processing modalities.

Table 1 shows the injected activities for the most common SPECT/CT examinations recommended by the European Association of Nuclear Medicine (EANM) procedural guidelines [1–8], as listed on the EANM website (<http://www.eanm.org/publications/guidelines/index.php>), and by the Society of Nuclear Medicine and Molecular Imaging (SNMMI) in its Nuclear Medicine Radiation Dose Tool [9].

These values are compared with those obtained by Brix et al. [10] based on an evaluation of SPECT examinations carried out in 48 German hospitals and private practices in 2007–2008 and those obtained in a UK nuclear medicine survey carried out in 2003–2004 by Hart et al. [11]. They are also compared with those reported by Mettler et al. [12] as current representative activity values administered in diagnostic nuclear medicine, derived from peer-reviewed scientific literature published in the United States, Canada, Japan, Australia, and Western Europe between 1980 and 2007, and with other published data on currently injected activities in SPECT/CT examinations [13–17].

As can be seen from Table 1, the administered activity ranges recommended by the EANM are generally aligned with those recommended by the SNMMI [9] with the sole exception of parathyroid examinations.

The data reported by Brix et al. [10] and Hart et al. [11] are generally aligned with the ranges recommended by the EANM and sometimes even lower, while a larger variability is present in the data reported by the other authors [12–17]. In any case, it has to be kept in mind that administered activities must respect any diagnostic reference levels established by the national legislation.

### Radiation doses

As is well known, the risk incurred by people exposed to ionizing radiation can be represented by the dosimetric quantity known as the “effective dose.”

Effective doses due to the administration of a radiopharmaceutical can be calculated simply by multiplying the administered activities by the effective dose coefficients per unit of administered activity. Table 2 shows the dose coefficients reported by the SNMMI. However, these coefficients generally refer to the values recommended by the ICRP publications 53 [20], 80 [21], and 106 [22] which are based on the old definition of effective dose (ICRP 60 [23]) and not on the most recent one (ICRP 103 [24]). Therefore, the dose coefficients calculated by Brix et al. [10] taking into account the new effective dose definition (ICRP 103) are also shown together with the mean absorbed dose per unit of administered activity to the critical organ [9].

### Measures to reduce the radiation dose in SPECT

As mentioned above, the radiation dose to the patient in SPECT examinations depends, in addition to the activity administered and the scan time, on several other factors. Among these we highlight in particular the following ones, which can be targeted in order to reduce the dose.

**Table 1** Injected activities (MBq) for the most common SPECT/CT examinations as recommended by the EAMN guidelines [1–8] and by the SNMMI Radiation Dose Tool [9]; as obtained by Brix et al. (German survey) [10] and by Hart et al. (UK survey) [11]; and as reported by Mettler et al. (literature review) [12]; and by other authors publishing data on injected activities in SPECT/CT examinations [13–17]

Examination/ organ	Radiopharmaceutical	Activity recommended by EAMN procedural guidelines [1–8]	Activity recommended by SNMMI Nuclear Medicine Radiation Dose Tool [9]	Brix et al. [10] median (interquartile interval)	Hart et al. [11] mean (range)	Mettler et al. [12]	Other SPECT/CT protocols (Larkin et al. [13], Mattsson et al. [14], Mhiri et al. [15], Montes et al. [16], Sharma et al. [17])
Brain	<sup>99m</sup> Tc-ECD (Neurolite)	740 (555–1,110) [4]	555–1,110	–	–	740	538.7 ± 230.1 (range 111–740) [14]
	<sup>99m</sup> Tc-HMPAO- exametazime	740 (555–1,110) [4]	555–1,110	–	488 (72–800)	740	740 [13] 800 [14]
	<sup>123</sup> I-ioflupane (DaTscan)	–	111–185	180 (176–188)	–	–	–
Thyroid	<sup>131</sup> I	–	37–185	–	–	–	74 [13]
	<sup>123</sup> I	–	15–185	–	–	25	–
	<sup>99m</sup> Tc-pertechnetate	–	74–370	–	–	370	–
Parathyroid	<sup>99m</sup> Tc-MIBI	600 (500–700) [7]	740–1,480	535 (438–688)	–	740	925 [13] 925 [15] 740 [16] 705.8 ± 76.6 (range 348–740) [14]
Cardiac rest- stress	<sup>201</sup> Tl-chloride	rest + stress 74–111 [1–3]	74–148	74 (70–94)	75 (55–80)	185	–
	<sup>99m</sup> Tc-sestamibi (1-day protocol)	rest 300–1,110 stress 300–1,110 [3]	740–1,480 (total)	970 (30 % stress and 70 % rest) (922–1,048)	403 (388–450) (each injection)	1,100	600 [14]
	<sup>99m</sup> Tc-sestamibi (2-day protocol)	rest 300–1,110 stress 300–1,110 [3]	rest <1,110 stress <1,110 [18]	738 (50 % stress and 50 % rest) (636–976)	–	1,500	–
	<sup>99m</sup> Tc-tetrofosmin	rest 300–1,110 stress 300–1,110 [3]	740–1,480 (total)	See <sup>99m</sup> Tc-sestamibi	407 (250–600) (each injection)	1,500	600 [14] stress 330 [16] stress + rest 330–1,000 [16]
Ventriculography	<sup>99m</sup> Tc-RBC	800 (500–1,050) [1]	555–1,110	700 (688–721)	–	1,110	–
Lung perfusion	<sup>99m</sup> Tc-MAA	40–120 100–120 [8] (after ventilation)	40–150	160 (114–190)	100 (–)	185	–

Table 1 continued

Examination/ organ	Radiopharmaceutical	Activity recommended by EAMN procedural guidelines [1–8]	Activity recommended by SNMMI Nuclear Medicine Radiation Dose Tool [9]	Brix et al. [10] median (interquartile interval)	Hart et al. [11] mean (range)	Mettler et al. [12]	Other SPECT/CT protocols (Larkin et al. [13], Mattsson et al. [14], Mhiri et al. [15], Montes et al. [16], Sharma et al. [17])
Lung ventilation	$^{99m}\text{Tc}$ -technegas <sup>a</sup>	25–30 [8] (lung uptake)	–	390 (327–545) (activity in nebulizer, assumed 10 % uptake)	–	–	–
	$^{99m}\text{Tc}$ -DTPA (inhalation)	25–30 [8] (lung uptake)	900–1,300 (dispensed) 20–40 (inhaled) [19]	950 (855–1,045) (activity in nebulizer, assumed 4 % uptake)	–	40	–
Renal	$^{99m}\text{Tc}$ -DMSA		74–222	–	–	370	–
Bone	$^{99m}\text{Tc}$ -MDP	500 (300–740) [6]	740–1,110	510 (benign) (486–553) 661 (malignant) (602–700)	682 (500–800)	1,110 600 [14] 740 [15] 740 [16] 538 ± 230 (range: 236.8–925) [17]	1,110 [13] 600 [14] 740 [15] 740 [16] 538 ± 230 (range: 236.8–925) [17]
Infection/ inflammation	$^{67}\text{Ga}$	–	148–333	–	–	150	370 [13] 185 [16]
Octreoscan	$^{111}\text{In}$ -octreotide	200 [5]	–	167 (144–180)	–	222	222 [13] 150 [14] 185 [15] 185 [16]

<sup>a</sup> The Technegas Generator User Manual recommends crucible loading between 400 and 900 MBq of sodium pertechnetate ( $^{99m}\text{Tc}$ )

**Table 2** Effective dose coefficients per unit of administered activity (mSv/MBq) adapted by the SNMMI [9] from ICRP 106 [22] for men and women, and those calculated by Brix et al. [10] using the effective dose definition recommended in ICRP 103 [24]

Examination/organ	Radiopharmaceutical	Effective dose (ICRP 60) per MBq (mSv) (SNMMI [9])		Effective dose (ICRP 103) per MBq (mSv) (Brix et al. [10])	Critical organ	Mean absorbed dose per MBq (mGy) (SNMMI [9])	
		Men	Women			Men	Men
Brain	<sup>99m</sup> Tc-ECD (Neurolite)	0.008	0.010	–	Bladder	0.05	0.06
	<sup>99m</sup> Tc-HMPAO (Ceretek)	0.009	0.011	–	Kidneys	0.03	0.04
Thyroid	<sup>123</sup> I-ioflupane (DaTscan)	0.024	–	0.04	Bladder	0.05	–
	<sup>131</sup> I	0.072	0.088	–	Bladder	0.61	0.75
	<sup>123</sup> I	0.013	0.016	–	Bladder	0.09	0.11
	<sup>99m</sup> Tc-pertechnetate	0.013	0.017	–	Upper large intestine	0.06	0.07
Parathyroid	<sup>99m</sup> Tc-MIBI	0.009	0.012	0.0,068	Gallbladder	0.04	0.05
Cardiac rest-stress	<sup>201</sup> Tl-chloride	0.140	0.200	0.12	Kidneys	0.48	0.58
	<sup>99m</sup> Tc-sestamibi	0.0079 stress	0.010 stress	0.0059 stress	Gallbladder	0.03	0.04
		0.009 rest	0.012 rest	0.0068 rest			
	<sup>99m</sup> Tc-tetrofosmin	0.007	0.009	0.0058 stress 0.0062 rest	Gallbladder	0.03	0.03
Ventriculography	<sup>99m</sup> Tc-RBC	0.007	0.009	0.011	Heart wall	0.02	0.03
Lung perfusion	<sup>99m</sup> Tc-MAA	0.011	0.016	0.013	Lungs	0.07	0.10
Lung ventilation	<sup>99m</sup> Tc-aerosol (Technegas)	0.015	0.022	0.017	Lungs	0.11	0.16
	<sup>99m</sup> Tc-DTPA (inhalation)	0.006	0.008	0.0034	Bladder	0.07	0.08
Renal	<sup>99m</sup> Tc-DMSA	0.016	0.019	–	Kidneys	0.17	0.21
Bone	<sup>99m</sup> Tc-MDP	0.006	0.007	0.004	Bone surface	0.06	0.08
Infection/inflammation	<sup>67</sup> Ga	0.100	0.130	–	Bone surface	0.63	0.81
Octreoscan	<sup>111</sup> In-octreotide	0.054	0.071	0.059	Spleen	0.57	0.79

For each examination, the critical organ and the absorbed dose coefficients are also reported for men and women (SNMMI [9])

*Choice of radiopharmaceutical*

It is appropriate, when faced with comparable clinical information, to use radiopharmaceuticals with shorter physical and biological half-lives (e.g., <sup>99m</sup>Tc vs <sup>201</sup>Tl) and generally those that result in lower doses (Tables 1, 2).

*New reconstruction algorithms*

The introduction of accelerated algorithms and advances in computing technology allowed the development of iterative image reconstruction with resolution recovery. Iterative reconstruction (IR) methods use slightly different algorithms but they are all based on the same concept: IR works in different loops, in which the image reconstructed from the projection data is compared to the “best estimate” of the image made by the software. According to the complexity of the process, corrections are made and the comparison is repeated until the deviation between the reconstructed image and the “best estimate” becomes

acceptable. The major manufacturers now offer implementations of the ordered subset expectation maximization (OSEM) reconstruction method with distance-dependent resolution modeling (Wide Beam Reconstruction—WBR™—Ultraspect, Haifa, Israel; Evolution for Cardiac—GE Medical Systems, Waukesha, WI, USA; Astonish—Philips Healthcare, Eindhoven, The Netherlands; Flash3D—Siemens Medical Solution USA, Inc.). The new algorithms are available in commercial software, and their use is feasible within clinically practical times.

These new algorithms are designed to reduce noise, improving lesion identification without affecting image resolution. They make it possible to obtain the same image quality with a smaller number of collected counts, in other words to reduce the injected activity or the acquisition time of the examination.

Different studies have been conducted in different fields of application.

- Leva et al. [25] and Marcassa et al. [26] showed that the use of new IR algorithms makes it possible to perform

either half-time or half-dose cardiac SPECT examinations, obtaining image quality and quantitative data comparable to those of standard-time or standard-dose SPECT.

- Livieratos et al. [27] assessed the commercial 3D-OSEM algorithm (Philips Astonish), evaluating its performance in bone scintigraphy ( $^{99m}\text{Tc}$ -MDP). The results of this study showed that OSEM with the distance-dependent spatial resolution model can be used for image reconstruction in bone  $^{99m}\text{Tc}$ -MDP SPECT studies at half the acquisition time or injected activity without compromising the image quality or reducing the diagnostic value of the examination.
- Albridge et al. [28] investigated “Evolution for bone SPECT” (GE Healthcare Technologies, Milwaukee, Wisconsin, USA), a new model-based corrective image reconstruction algorithm that compensates for image degradation due to collimator-detector characteristics, photon attenuation and scatter in the body, applying it to bone scintigraphic procedures as well as in parathyroid imaging. They demonstrated that the corrective algorithm improved image quality compared with filtered back projection (FBP) and OSEM. As a result of this study, this software is now routinely used in clinical practice, and SPECT acquisition time has been reduced from 30 to 15 min in the case of parathyroid SPECT examination and from 20 to 10 min for bone SPECT. This has improved patient comfort as the duration of scanning was one reason for non-compliance. In addition, potential movement artifacts are reduced as length of scanning time is decreased and patient throughput is increased. Of course, this potential for reducing scanning time while maintaining image quality can also be used for reducing administered activity and else patient dose.

#### High-sensitivity collimators

Special collimators, designed to magnify a specific region, provide higher acquisition sensitivity for specific organ examinations.

A variable focus collimator was developed by Siemens retaining the magnifying properties of a cone-beam collimator near the center of the field of view and eliminating the truncation artifacts at the edges of the field of view that are common to pinhole and focusing collimators. Imbert et al. [29] found a three-fold improved count sensitivity for this collimator with respect to conventional parallel-hole collimators. The use of this collimator, added to a cardio-centric acquisition and to the IQ SPECT reconstruction method, allowed the collection of up to four times as many

counts from the heart during a myocardial perfusion SPECT study (Slomka et al. [30]).

#### New high-efficiency camera systems with more sensitive detectors

New camera systems specifically for cardiac examinations were recently introduced. These systems are based on new multiple solid-state high-efficiency detectors (cadmium zinc telluride—CdZnTe) and optimized acquisition geometry, collimator design, and reconstruction software.

The CdZnTe detectors are pixelated and the number of photons, which are counted on each detector, results in a directly measurable electrical signal. CdZnTe detectors are characterized by an excellent energy resolution (typically <6 %), meaning that energy discrimination can be greatly improved, and by a very good response to high count rates.

These devices provide a four- to seven-fold improvement in sensitivity compared with a conventional dual-detector SPECT with higher resolution and contrast-to-noise ratio (CNR) (Imbert et al. [29]).

Using a GE Medical Systems Discovery NM 530c system with stationary pinhole collimators and an OSEM-type reconstruction algorithm, Duvall et al. [31] found, with respect to conventional SPECT at comparable or improved image quality and diagnostic accuracy, a significant reduction of administered activities (185 MBq for  $^{99m}\text{Tc}$  rest acquisition and 555 MBq for  $^{99m}\text{Tc}$  stress acquisition) and of scan times (5 min for  $^{99m}\text{Tc}$  rest acquisition and 3 min for  $^{99m}\text{Tc}$  stress acquisition, compared to a 15-min conventional SPECT acquisition).

#### Pregnancy

Compared with routine medical radiation practices, the medical radiation exposure of a pregnant patient carries additional ethical considerations. This situation demands stricter application of the principle of justification and greater attention to optimization even though most nuclear medicine procedures do not cause large fetal doses [32].

For most of the radiopharmaceuticals used, which do not cross the placenta, the fetal dose is due to radioactivity in maternal tissues. There are, however, some radiopharmaceuticals, such as  $^{131}\text{I}$ -sodium iodide, which do cross the placenta and concentrate in specific organs or tissues. In such cases, the fetal self-dose contribution must be added. Table 3 shows absorbed doses to the fetus per unit of administered activity to the mother at different stages of gestation (from the early stages of pregnancy up to nine months) for the radiopharmaceuticals most widely used in SPECT/CT examinations as reported by the SNMMI [9].

Since radionuclides in maternal tissues contribute to the fetal dose; maternal hydration and frequent voiding can reduce the fetal dose after the administration of a number of radiopharmaceuticals. Absorbed dose to the fetus can also be reduced using longer imaging times and thus smaller administered activities.

Pediatric examinations

Although radiation exposures in children undergoing diagnostic nuclear medicine studies are low [34], such exposures can be further reduced by optimizing routine protocols, by applying advanced image processing, and potentially using advanced imaging systems.

Despite the longstanding use of nuclear medicine in pediatrics, the question of the standardization of pediatric-administered radiopharmaceutical activities has only recently been addressed. In 2014, the EANM and the SNMMI both suggested changes in their respective guidelines on administered activities for pediatric nuclear

medicine in order to achieve a level of harmonization [35].

The SNMMI developed a tool that provides recommended injected activity for pediatric patients based on the North American consensus guidelines and the European Association of Nuclear Medicine guidelines (<http://www.snmmi.org/ClinicalPractice/PaediatricTool.aspx>).

Table 4 shows the administered activities for the most common pediatric examinations together with the effective dose coefficients. Data are reported for four different ages: 1, 5, 10, and 15 years. Effective dose (ICRP 60) coefficients were obtained from ICRP publications 80 [21] and 106 [22] and were calculated considering the mathematical phantoms described by Cristy and Eckerman [36].

Administered activities can be reduced through conventional system optimization by selecting the most appropriate collimator in relation to the patient size and the clinical task [34].

Using advanced image processing and reconstruction techniques in SPECT, as already outlined for adults, it is

**Table 3** Absorbed doses to the fetus per unit of activity administered to the mother at different stages of gestation (first stages of pregnancy, 3, 6, and 9 months) for the radiopharmaceuticals most widely used in SPECT/CT examinations as reported by the SNMMI [9]

Examination/ organ	Radiopharmaceutical	Fetus of a woman in early stages of pregnancy: absorbed dose per MBq (mGy/ MBq)	Fetus of a 3-month pregnant woman: absorbed dose per MBq (mGy/MBq)	Fetus of a 6-month pregnant woman: absorbed dose per MBq (mGy/MBq)	Fetus of a 9-month pregnant woman: absorbed dose per MBq (mGy/MBq)
Brain	<sup>99m</sup> Tc-ECD (Neurolite)	0.0114	0.0091	0.0056	0.0042
	<sup>99m</sup> Tc-HMPAO (Ceretek)	0.0087	0.0067	0.0048	0.0036
Thyroid	<sup>131</sup> I	0.0668 (0.072 <sup>a</sup> )	0.051 (0.068 <sup>a</sup> )	0.213 (0.23 <sup>a</sup> )	0.259 (0.27 <sup>a</sup> )
	<sup>123</sup> I	0.0196 (0.02 <sup>a</sup> )	0.0087 (0.014 <sup>a</sup> )	0.0062 (0.011 <sup>a</sup> )	0.0062 (0.0098 <sup>a</sup> )
	<sup>99m</sup> Tc-pertechnetate	0.011	0.022	0.014	0.0093
Parathyroid	<sup>99m</sup> Tc-MIBI	0.015	0.012	0.0084	0.0054
Cardiac rest– stress	<sup>201</sup> Tl-chloride	0.097	0.058	0.047	0.027
	<sup>99m</sup> Tc-sestamibi	0.012 stress	0.0095 stress	0.0069 stress	0.0044 stress
		0.015 rest	0.012 rest	0.0084 rest	0.0054 rest
	<sup>99m</sup> Tc-tetrofosmin	0.0096	0.007	0.0054	0.0036
Ventriculography	<sup>99m</sup> Tc-RBC	0.0064	0.0043	0.0033	0.0027
Lung perfusion	<sup>99m</sup> Tc-MAA	0.0028	0.004	0.005	0.004
Lung ventilation	<sup>99m</sup> Tc-aerosol (Technegas)	0.0005	0.0004	0.0005	0.0006
	<sup>99m</sup> Tc-DTPA (aerosol)	0.0058	0.0043	0.0023	0.003
Renal	<sup>99m</sup> Tc-DMSA	0.0051	0.0047	0.004	0.0034
Bone	<sup>99m</sup> Tc-MDP	0.0061	0.0054	0.0027	0.0024
Infection/ inflammation	<sup>67</sup> Ga	0.093	0.2	0.18	0.13
Octreoscan	<sup>111</sup> In-octreotide	0.082	0.06	0.035	0.031

<sup>a</sup> Maternal and fetal self-dose contribution [33]



**Table 4** Administered activities and effective dose coefficients [21, 22] for the most common pediatric examinations

Examination/organ	Radiopharmaceutical	Age (weight)	North American consensus recommendations (MBq)	EANM recommendations (MBq)	Effective dose coefficients (mSv/MBq)
Lung perfusion	$^{99m}\text{Tc}$ -MAA	1 year (9.1 kg)	15	14	0.063
		5 years (18.1 kg)	20	25	0.034
		10 years (30.6 kg)	34	39	0.023
		15 years (54 kg)	60	64	0.016
Renal	$^{99m}\text{Tc}$ -DMSA	1 year (9.1 kg)	19	19	0.037
		5 years (18.1 kg)	33	30	0.021
		10 years (30.6 kg)	57	48	0.015
		15 years (54 kg)	100	78	0.011
Bone	$^{99m}\text{Tc}$ -MDP	1 year (9.1 kg)	84	85	0.027
		5 years (18.1 kg)	167	155	0.014
		10 years (30.6 kg)	283	245	0.011
		15 years (54 kg)	500	400	0.007

Data are reported for four different pediatric ages: 1, 5, 10, and 15 years

**Table 5** Effective doses delivered to patients in the most common SPECT/CT examinations, as reported in recent literature

Study type	Effective dose from radiopharmaceuticals (mSv)	Effective dose from CT component (mSv)	% increase due to CT
$^{99m}\text{Tc}$ -MIBI	8.3	5.4	65.1 %
parathyroid [13, 16, 17]	6.4	1.6	25.0
	6.4	1.2	18.8
$^{99m}\text{Tc}$ -MDP [13, 17]	6.3	3.8	60.3
	4.1	4.2	102.4
$^{111}\text{In}$ -octreotide [13, 16]	12	7.0	58.3
	8.5	2.6	30.6
$^{67}\text{Ga}$ llium [13, 16]	37	8.5	23.0
	26.5/18.9 <sup>a</sup>	2.6	10/13.7 <sup>a</sup>

<sup>a</sup> Lymphoma and infection, respectively

possible to achieve significant reductions in radiopharmaceutical administered activities, without any loss of diagnostic information, also for children.

Sheehy et al. [37] compared two methods of reconstructing  $^{99m}\text{Tc}$ -DMSA renal SPECT data—3D-OSEM and FBP—in children, considering their capacity to improve image quality and reduce the radiopharmaceutical activity and radiation dose. The results of the study demonstrated the possibility of obtaining, with 3D-OSEM, superior SPECT image quality with fewer counts than are used in FBP. The ability to reconstruct SPECT data with 50 % fewer counts made it possible to simulate a corresponding 50 % reduction in administered radiopharmaceutical activity, which in turn would lead to a 50 % reduction in radiation dose to the patient. Alternatively, still using 3D-

OSEM, it is possible to reduce scanning times by half and thus effectively increase patient comfort and potentially minimize the need to sedate young patients who undergo  $^{99m}\text{Tc}$ -DMSA SPECT examinations.

The same issue was validated by Stansfield et al. [38] using 3D-OSEM with resolution recovery in skeletal  $^{99m}\text{Tc}$ -MDP SPECT examinations.

### The CT component

In hybrid SPECT/CT imaging, functional information provided by SPECT is complemented by structural information provided by CT that serves different purposes such as attenuation correction (AC), anatomical localization, and sometimes even diagnosis.

The first SPECT/CT systems were equipped only with older CT devices and thus produced low-quality clinical images suitable only for AC and localization, but not for additional diagnostic purposes.

The most recent SPECT/CTs, however, incorporate last-generation CT scanners, which provide detailed anatomical images of patients and thus allow further clinical CT diagnoses. As regards their dose contribution, these scanners can account for a considerable percentage of the dose of the whole SPECT/CT examination, as reported in Table 5 [13, 16, 17]. Buck et al. [39], with reference to SPECT-guided diagnostic CT, report a radiation dose, additional to that of the radiopharmaceutical, of 6–14 mSv depending on the field of view in z-axis.

It is therefore very important that, rather than applying standard protocols, combined SPECT/CT procedures can be selected on an individual basis and reflect clinical needs.



As a general rule, low-dose acquisition is suggested when recent diagnostic CT data are available and when follow-up studies are to be performed (monitoring of response to treatment). Moreover, low-dose CT is indicated for further anatomical localization or characterization of focal pathology present on planar or SPECT images. SPECT-guided diagnostic CT is instead suggested when a recent diagnostic CT is not available and when detailed anatomical information is mandatory to address clinical needs.

Hulme et al. [40] demonstrated that AC is achievable with ultra-low-dose CT, despite the high CT image noise, without compromising the quality of the SPECT image. In fact they showed that, in the case of the Symbia True Point (T16, Siemens Medical Solutions USA, Inc.) system, CT noise levels corresponding to CT dose indexes ( $CTDI_{vol}$ ) down to  $\approx 4 \mu\text{Gy}$  did not affect SPECT quantification. Therefore, the need of higher doses for the CT component of SPECT/CT is imposed by image quality requirements for anatomical localization and artifact reduction.

While Buck et al. indicate a dose range from 2 to 4 mSv for SPECT-guided low-dose CT [39], Roach et al. showed that CT scans used for anatomical localization in the chest or abdomen release up to 1–2 mSv [41], Sawyer et al. [42] reported typical values of around 1.1 mSv for the chest, around 1.3 mSv for abdomen–pelvis and around 0.2 mSv for the head, and Montes et al. [15] reported similar values ( $\approx 1.2$  mSv) for chest and abdomen–pelvis and 0.6 mSv for the head–neck region.

Miller [43] showed even lower radiation exposure for the CT scan of the SPECT/CT examination: 0.47 mSv for an abdominal non-diagnostic localization and AC scan. The datum was also confirmed by Kneifel who assessed an effective dose of 0.5 mSv with the GE Hawkeye equipment [44].

#### CT dose optimization

The dose dependence, in CT, on acquisition parameters such as tube potential, tube load, rotation time, beam width, pitch, and reconstructed image thickness should be considered when addressing the need for CT dose optimization [45].

Furthermore, it is well known that CT scanning is also a patient-dependent modality: patient size can greatly influence the acquisition for particular body regions, necessitating different settings in different patients. In abdominal CT, for example, the tube potential should be adjusted from 80 kVp for very thin patients to 140 kVp for severely obese patients.

In particular, special care should be taken with children, who, due to the higher radiosensitivity of growing tissues and their longer life expectancy, are exposed to a higher radiation risk in a CT examination [46].

Good image quality in children can be achieved with lower tube potential and tube load values, thus reducing the dose delivered.

Dose increase in CT practice [47], combined or not with other modalities, has prompted manufacturers to study and propose new dose-reduction methods in order to limit the individual radiation exposure. This reduction should, however, be performed without sacrificing the diagnostic quality of the images, which must remain acceptable.

Three main improvements have been introduced for this purpose: automatic tube current modulation (ATCM), automatic tube voltage selection (ATVS), and IR algorithms instead of the “classic” FBP method.

#### *Automatic tube current modulation (ATCM)*

Automatic tube current modulation is a solution, now implemented in all commercial CTs, whose aim is to reduce the dose delivered to the patient fixing the image quality and adapting tube current (mA) to the patient’s size and anatomy and generating images of diagnostic quality.

ATCM can work in three dimensions by combining patient size-modulation, z-axis-longitudinal modulation adjusting current during table feed, and xy-axis-angular modulation with current adjustment during gantry rotation.

The ATCM uses the attenuation information from one or both scouts and also takes into consideration the operator-chosen image quality, selecting the vendor’s specific parameter: reference mAs (Siemens), standard deviation (Toshiba), Noise Index (General Electric), and reference images (Philips).

If properly used, ATCM allows, compared with a fixed tube current (FTC), a better dose distribution with higher mA to denser tissues and lower mA to more radiotransparent ones, like the lungs.

The dose-reducing effectiveness of ATCM compared to FTC has been demonstrated in several studies [48–50] with Lee et al. [48] showing an average reduction of 45 % in the abdomen and pelvis CT with images of an acceptable diagnostic level.

#### *Organ-based and automatic kV selection*

Some systems also provide for organ-based tube current modulation, which can reduce the dose to radiosensitive organs close to the surface of the body. The mammary glands, thyroid glands, and eye lenses thus receive a lower dose as the system reduces the tube current when the tube comes close to these organs. To compensate for this reduction, the tube current in the X-ray projection from the opposite side is increased thus leaving mean image noise constant [51, 52]. This application can be very useful in

SPECT/CT systems for sparing the lens in CT head acquisitions, as SPECT/CT can acquire only axial and not transaxial images with tilted gantry, because of problems in image registration. Bismuth shielding, placed over the organ of interest to attenuate the X-ray beam entering the patient, has also been used to reduce the dose from CT to anterior radiosensitive organs, such as the breast, lens of the eye, and thyroid [53]. However, the AAPM [54] recommends that the use of bismuth shielding should be carefully considered and that organ-based tube current modulation should be implemented when possible.

Since the radiation dose changes with roughly the square of the tube potential, attention turned to the possibility of introducing automatic tube voltage selection (ATVS) [55, 56] in addition to ATCM in order to acquire low-tube-voltage images.

ATVS automatically maintains a constant CNR, defined for a reference patient, by adjusting the scanning parameters, e.g., tube voltage (kV) and tube current (mA), taking into account the examination type, the body region, and the patient's body habitus.

#### Iterative reconstruction

Although FBP is the standard image reconstruction technique in CT, it presents limitations, namely image noise increase and a worsening of the image quality on dose lowering.

Recently vendors, in order to overcome this problem, as already seen with tomoscintigraphic reconstruction, have developed new IR algorithms for reconstruction techniques, which in the past were avoided because of their excessively long computational time. These algorithms are often divided into hybrid IR and pure IR. The hybrid IR algorithms involve blending with FBP in order to keep the noise characteristics and image texture that radiologists are accustomed to. In pure IR algorithms, there is no blending with FBP.

Several systems are available commercially that feature different mixes of IR and FBP and thus result in diagnostic

images having different appearances and allowing different dose savings [57, 58].

The role and the impact of IR algorithms have been investigated in several studies.

Christe et al. [59] reported an average dose reduction of up to 25 % with IR, while maintaining the same subjective (i.e., evaluated by radiologists) image quality on a chest phantom acquired with different kVp/mAs combinations. Kalmar et al. [60] studied the effect of the IR on 100 thoracic and abdominal CT scans, finding a dose reduction of 64 and 58 %, respectively, compared with FBP, with no clinically significant impact on image quality. Klink et al. [61] confirmed this trend after a study involving both phantom CT (CTDI<sub>vol</sub> reduction of 26–50 % using IR instead of FBP) and patient chest and abdominal CT, in which IR allowed lower tube voltage and current with the same image quality.

It has been found that ATCM, ATVS, and IR algorithms work even better together, allowing greater dose reductions in examinations of the chest [62–64], abdomen [62, 65], pelvis [65], and in coronary CT [66].

#### Dose assessment in CT

The two main dose descriptors in CT are the CTDI<sub>vol</sub> and the dose-length product (DLP). The CTDI<sub>vol</sub> indicates the estimated mean dose for a single slice, while the DLP, obtained by multiplying the CTDI<sub>vol</sub> by the scan length, estimates the overall radiation absorbed by the patient. The DLP is also useful for obtaining an approximate estimate of the effective dose to the patient. In fact the effective dose ( $E$ ) can easily be evaluated by multiplying the DLP by a conversion coefficient  $k$  specific for the anatomical region under examination ( $E = k \times \text{DLP}$ );  $k$  coefficients for adults (standard physique) and pediatric patients of various ages over various body regions, reported in the AAPM Report no. 96 [67], are shown in Table 6. Conversion factors for adult head and neck, and pediatric patients are referred to the head CT dose phantom (16 cm), while all other conversion factors are referred to the 32-cm-diameter

**Table 6** Normalized effective dose per dose-length product (DLP) for adults (standard physique) and pediatric patients of various ages over various body regions

Region of body	k <sub>ICRP60</sub> <sup>a</sup> [67]					k <sub>ICRP103</sub> <sup>a</sup> [70] Adult	k <sub>ICRP103</sub> <sup>a</sup> [71] Adult
	0-year old	1-year old	5-year old	10-year old	Adult		
Head and neck	0.013	0.0085	0.0057	0.0042	0.0031	–	0.045
Head	0.011	0.0067	0.0040	0.0032	0.0021	0.026	0.024
Neck	0.017	0.012	0.011	0.0079	0.0059	–	0.053
Chest	0.039	0.026	0.018	0.013	0.014	0.0199	0.0204
Abdomen and pelvis	0.049	0.030	0.020	0.015	0.015	0.0163	0.0171
Trunk	0.044	0.028	0.019	0.014	0.015	0.0178	0.0186

<sup>a</sup> mSv/mGycm

CT body phantom [68, 69]. Those coefficients ( $k_{ICRP60}$ ) refer to the effective dose as defined in ICRP 60. Recently, conversion coefficients were also evaluated by some authors taking into account the ICRP 103 definition [70, 71]. These ( $k_{ICRP103}$ ) are also shown in Table 6 for comparison. A more detailed analysis has also been done by Deak et al. [72] who determined, for spiral scanning protocols with different voltages, sex- and age-specific conversion factors taking into account both the ICRP 60 and ICRP 103 effective dose definitions.

## Conclusions

This review has provided ample information on the activities normally administered in SPECT/CT examinations and on the possibilities for patient dose optimization, which can be achieved both by carefully selecting and using appropriate equipment and by carefully considering each individual examination to be carried out.

It has also highlighted, with reference to the CT component, the importance, in the context of dose optimization, of taking into account the clinical need for the CT acquisition, as well as the use of the possible technological tools that can reduce patient exposure.

Finally, it has shown how patient dose can easily be determined in individual SPECT/CT examinations simply by considering administered activities and the DLP values reported in each CT examination.

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