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RADIATION DOSE MANAGEMENT IN CT, SPECT/CT AND PET/CT TECHNIQUES

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New imaging technologies utilising X rays and radiopharmaceuticals are continuously under development. The benefit of computed tomography (CT) has been so dramatic that there is a tendency to overuse it and not to place enough efforts into optimisation of the technique. It is also now more and more common to combine two imaging techniques into a single investigation, such as PET/CT and SPECT/CT—the so-called 'hybrid imaging'. The increasing radiation exposure from CT has been of concern for some years and is now receiving increased attention from health professionals, authorities, manufacturers and patient groups. The relatively high radiation doses from PET and SPECT investigations have only recently been discussed. The aim of this article is to provide information on developing technologies and clinical techniques for 3D imaging using ionising radiation and their associated radiation dose to patients and staff. Tools for improved dose management are also discussed.

INTRODUCTION

Medical imaging provides tremendous and undeniable benefit in modern health care. It is used for disease detection, classification, prognostic staging, treatment planning and to validate therapeutic response[1, 2]. During recent years, there have been dramatic developments in imaging techniques and this progress continues today. Since its introduction in the 1970s and 1980s, respectively, computed tomography (CT) and magnetic resonance imaging (MRI) have become important tools in medical imaging and have supplemented planar X ray, nuclear medicine and ultrasound. After the introduction of multi-slice CT[3] in 1997, the number of slices acquired per rotation has—until recently—doubled every 18 months, resulting in improved temporal and spatial resolution and shorter scan times[4]. Modern, dual energy, 64-slices spiral CT can scan a whole body in 25 s using a gantry rotation time of 0.33 s. Multislice CTs recording up to 128 and now even 320 slices per revolution are available (www.medical.toshiba.com). These improvements in CT technology lead to increased use of CT as a tool for early diagnosis of various diseases, particularly through high-sensitivity virtual imaging of the colon and lung for cancer detection. High-quality images are also the base for planning of therapies such as surgery and radiotherapy.

Large-area flat panel detectors in combination with cone beam X-ray fields (cone-beam CT, CBCT) are now used more frequently as an alternative to conventional CT[5]. Examples of its application include: (1) routine interventional and intraoperative imaging using C-arm-based interventional flat panel detector CT, e.g. in connection with brachytherapy; (2) CT image-guided external tumour therapy, which is one of the most rapidly growing applications. Attaching a standard X-ray tube and a flat panel detector to a rotating linear accelerator allows for CT imaging of the patient on the therapy couch; (3) CT for dedicated maxillo-facial scanning; and (4) CT for dedicated imaging of the breast. Moreover, flat panel detector technology is also applied to standard CTs.

Tomosynthesis is a form of limited angle tomography that produces 'slice' images from a series of projection images acquired as the X-ray tube moves over a prescribed angular range, in relation to the angle for the ordinary projection image. By reducing visibility of the overlapping normal tissue, the detection of pathological lesions is improved when compared with projection radiography. Up to now, tomosynthesis has been applied primarily in breast and chest examinations and, to some extent, for orthopaedic, angiographic and dental investigations. For chest imaging, tomosynthesis is used as an alternative to CT with significantly lower radiation dose to the patient[6]. Breast tomosynthesis has, in several studies, proved to be an effective tool for improving detection of breast lesions and an interesting modality for screening[7, 8].

The evolution of diagnostic imaging now goes from standalone techniques to 'hybrid imaging' using SPECT/CT and PET/CT for many applications—and now also PET/MR (www.siemens.com/mMR). The concept of PET/CT has become so successful that none of the major manufacturers of medical imaging equipment now offers stand-alone PET scanners. This has also stimulated the use of SPECT/CT

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devices. The complementary anatomical, functional and molecular information provided by these hybrid techniques—all facilitating quantitative imaging—has proved clinical importance.

The significant increase in the use of CT, alone or in combination with SPECT or PET has raised concerns about patient radiation exposure and the consequent increased risk of malignancy later in life[9, 10]. For CT to be fully used in the diagnosis of disease, dose reduction is necessary. A further problem is that some of the PET- and SPECT- investigations give a comparatively high patient dose.

A report from the Swedish Radiation Safety Authority showed that CT and nuclear medicine constituted 16 % of all radiological investigations (mammography not included) and contributed to 64 % of the collective radiation dose in Sweden in 2005[11]. The National Council on Radiation Protection and Measurements in the USA reports that CT and nuclear medicine constituted 22 % of all radiological investigations, but 75 % of the collective US radiation dose in 2006[12].

The introduction of PET and PET/CT techniques and the increasing use of positron emitters have also increased radiation dose to hospital staff as well as at the cyclotrons and hot laboratories used for production of the radiopharmaceuticals.

The topic of justification for medical exposures and the role of the referring physician and the radiologist/nuclear medicine specialist at the radiology/nuclear medicine department are currently topics of great discussion. The meaning of justification of an investigation and the role of the involved staff are clarified in ICRP Publication 103[10] and is further discussed and developed in the new European basic safety standards. This information must be disseminated to referring physicians for proper clinical integration to occur.

The aim of the present work is to provide an overview of clinically used CT-, PET-, SPECT-, PET/CT and SPECT/CT for X ray and nuclear medicine imaging, to inform the reader concerning the magnitude of radiation exposure, and to discuss various methods to reduce exposure of patients and staff in connection with these 3D investigations.

COMPUTED TOMOGRAPHY

Methods for patient dose estimation and magnitude of patient dose

In CT, the estimates of absorbed doses to organs and tissues and effective doses are based on the quantities[13]: the weighted CT air-kerma index ($C_{K,PMMA}$, mGy) and the CT air kerma-length product (P_{KL}, mGy). P_{KL} represents the average absorbed dose along the *z*-axis from a series of contiguous irradiations and is measured in cylindrical acrylic phantoms representing head and body using a pencil ionisation chamber with an active length of 100 mm. As the radiation beam widths of multi-slice scanners get wider, this method of estimation may no longer be adequate. A recent report of the American Association of Physicists in Medicine task group 111 introduced an alternative to the $C_{K,PMMA}$ method and suggests a new system for CT dosimetry[14].

The $P_{KL,CT}$ is a measure of the total energy deposited in the phantom or patient and broad estimates of effective dose may be obtained by multiplying with a conversion factor appropriate to different anatomical regions[15]. The factors are averaged over all photon energy distributions used in different scanners and obtained from Monte Carlo simulation and mathematically describable phantoms. The factors are useful for quick dose estimates and for large patient groups. For more detailed assessment of effective dose and organ doses, dose assessment software such as CT Expo[16], ImPACT CT[17] and NRPB SR-250[18] patient dosimetry calculators are recommended.

The effective dose from a CT investigation typically ranges from 2 (head) to 10 mSv (abdomen and pelvis) (Table 1), but with large variations between patients and hospitals. A total body investigation (brain, chest, abdomen and pelvis) provides ~20–30 mSv[3, 19]. This is roughly a factor of 10 higher than conventional planar X-ray investigations (range of 0.01–10 mSv). The CT doses are highly dependent on the characteristics of the CT scanner, patient size, anatomical region under investigation and technical factors used in each examination. For some individuals, local organ and tissue doses from a CT investigation can be up to 100 mSv[3, 19–21].

Methods to reduce CT doses

The gradually increasing awareness of the radiation exposure from CT has forced manufacturers to

Table 1. Typical effective doses and examples of some of the highest organ absorbed doses for common diagnostic single detector CT (SDCT) and multidetector CT (MDCT) investigations.

Investigation	Effective dose (mSv)[3, 18–21, 55]	Organ absorbed doses (mGy)[19]
Head CT	1–2	Lens of the eye, 50; thyroid, 2
Chest CT	5–8	Breast, 20, thyroid 2, lens of the eye, 0.1
Abdomen CT	5–10	Uterus and ovaries, 8
Pelvis CT	5–10	Uterus and ovaries, 25
Total body	20–30	

development techniques to reduce CT doses. The following section will review various dose reduction strategies. The implementation of these methods requires close collaboration between medical physicists, manufacturers, radiologists, technologists and referring physicians in order to be effective.

Optimise scanning parameters

There are a number of scanning parameters that influence radiation dose and image quality: tube current, tube voltage, filtration, collimation, reconstruction filter, slice thickness, pitch and scanning length. The operator can monitor most of these parameters and modify them to obtain the necessary image quality with a minimum of radiation dose to the patient.

Together with number of scans, tube current and tube voltage are the most important factors that affect radiation dose. There is a simple relationship between the tube load (the product of tube current and the exposure time per rotation, mA s) and the radiation dose to the patient. A 50 % reduction in tube load reduces the radiation dose by half, but also increases the noise level by a factor of $\sqrt{2}$. Determination of an adequate mA s level can be performed using recently available dose reduction simulation software[22–24]. The software adds artificial noise to measured CT raw data to simulate a scan acquired with lower dose (mA s).

The tube voltage determines the energy of the emitted photons from the X-ray tube; variation in tube voltage causes a change in radiation dose and image quality. Several studies demonstrated the ability to affect radiation dose and image quality by using lower tube voltage[25, 26].

Automatic exposure control

Automatic exposure control (AEC) is a technique that adapts the tube current relative to the patient attenuation in the x–y plane (angular modulation), along the scanning direction (z-axis; longitudinal modulation), or both (combined modulation). The principle of this technique is that the operator selects an indicator of the required image quality and the system then adapts the tube current to obtain the predetermined image quality with improved radiation efficiency[27]. The use of an AEC system is an effective method for patient dose reduction; several studies documented its potential. Results from a study performed by Söderberg *et al.*[28], valid for an anthropomorphic chest phantom representing a standard male patient, showed dose reductions in the range of 35–60 %.

Iterative image reconstruction

Iterative image reconstruction methods have played a role in SPECT and PET for many years, but only recently were made available for CT, thanks to improved computer capacity. The conventionally used filtered back-projection (FBP) procedure is now being replaced. The iterative algorithms have potential advantages including lower image noise, improved spatial resolution and reduced image artefacts (beam hardening, 'windmill' and metal artefacts), allowing for reduction of radiation dose. Recently published clinical studies showed dose reductions of >25 % and improved image quality with iterative reconstruction compared with FBP[29, 30]. Additional similar studies can be expected in the near future, as the iterative algorithms become more widespread.

Organ dose reduction

Protection of radiosensitive organs such as the breast, eye lens and gonads is especially important in paediatric patients, adolescents and young adults. Hohl *et al.*[31] demonstrated an 87 % reduction in absorbed dose to testes using a gonad lead shield during abdominal-pelvic CT investigation. The use of bismuth shields to cover sensitive organs during CT investigations is, however, controversial. Some studies demonstrated its efficacy for dose reduction to the lens and breast without significant adverse effects on image quality[32, 33], while other groups have questioned its value and even reported that it increased radiation dose[34, 35]. It is important to take into account the possibility of interaction with the AEC system and applying the bismuth shield first after the scan projection radiograph has been taken.

Recently, organ-based tube current modulation was developed, where the tube current is reduced for a certain range of the rotation to protect radiosensitive organs from direct exposure (Figure 1). This is the method of choice for organ-specific dose reduction. Schmidt *et al.*[36] reported dose reductions to the breasts of ~30 % using noise-optimised image reconstruction techniques in combination with organ-based tube current modulation. This method provided a noise level similar to that produced with constant tube current.

Adaptive collimation to reduce effect of 'overscanning'

Overscanning is the exposure of tissue for which no reconstruction of tomographic images is performed. Due to reconstruction requirement, helical CT scans start and end beyond the region of reconstruction (Figure 2). As the X-ray beams in modern CT

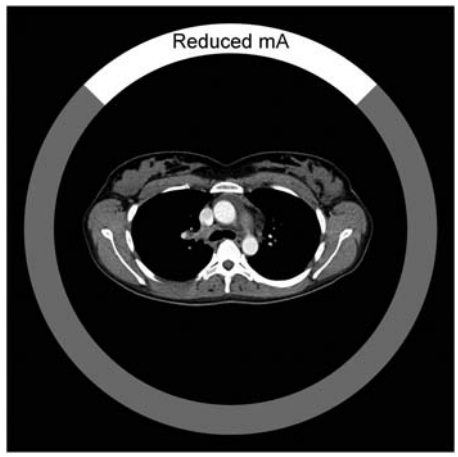

Figure 1. The X-ray tube current can be reduced for a certain range of the rotation to protect radiosensitive organs such as breasts, thyroid and eye lenses from direct exposure.

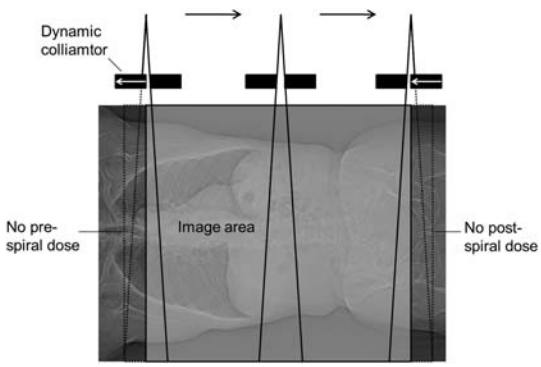

Figure 2. The excess exposure in the beginning and end of the helical scan can be reduced by using dynamic collimator control.

scanners become broader, more and more wasted radiation dose is delivered to the patient by over-scanning[37]. Both a software solution[38] and a hardware solution to this issue have been presented. Christner *et al.*[39] showed dose reductions of up to 40 % (using high pitch and short scan length) using dynamically adjustable *z*-axis collimation.

Reduction of CT doses in recent years

Recent rapid technologic advances have increased the number of clinical applications for CT. Due to the increased number of performed examinations, radiation exposure has increased on a population level. The reduction of CT doses during recent years, mainly due to improved technology from manufacturers and increasing awareness at operator's level of the importance of acquisition parameters on the patient dose[3], has however been significant. Several studies demonstrated that adequate diagnostic information could be obtained at lower doses than previously used[27, 29, 30, 36, 38, 39]. Technological advancements have resulted in increased scan speed, capacity to provide large scan coverage, better contrast utilisation, less image noise, increased spatial resolution and temporal resolution improvement. For example, today a cardiac CT scan can be performed at an effective dose of <1 mSv using electrocardiogram-based tube current modulation and a CT colon investigation can be performed with an effective dose of <2 mSv.

HYBRID IMAGING

In PET/CT and SPECT/CT, the two techniques give complementary information on structure and function, anatomy and physiology/biochemistry. Hybrid imaging with PET/CT and SPECT/CT, in combination with more advanced reconstruction software, respiratory or cardiac gating and new tracer substances has increased the accuracy of imaging and enabled disease diagnosis at earlier stages[4, 40–42]. It has improved the management of patients with cancer over stand-alone CT- and PET images. Hybrid cardiac imaging shows cardiac and vascular abnormalities and their physiological effects in a single investigation and has become an alternative to catheter examination for cardiac and cardiovascular investigations[4, 42]. In PET/CT and SPECT/CT systems, attenuation mapping is performed based on available CT transmission data. Earlier techniques using different types of flat sources and line sources have been replaced by CT, as the improved attenuation correction in PET and SPECT give superior quantification possibilities[43].

Methods for patient dose estimation and magnitude of patient dose

Any efforts to reduce the patient dose from PET/CT and SPECT/CT investigations must account for the dose contribution from each of the two imaging methods. The dose from the CT unit is characterised in the same way as from a stand-alone CT using the CT dose index ($C_{K,\ PMMA}$) and the dose length product (P_{KL})[13].

For PET and SPECT investigations, the administered activity is the basic measurable quantity. Using standardised biokinetic and dosimetric models, organ/tissue doses and effective doses per unit of administered activity are given by the ICRP[44–46]. Recently, a new addendum to ICRP Publication 53

has been published under the title ICRP Publication 106[10]. Dose calculations were performed for adults and 15-, 10-, 5- and 1-y-old children. Updated information concerning mean absorbed doses to organs and tissues of patients of various ages are available for over 40 radiopharmaceuticals in common use. There are also a number of generic models and realistic maximum models covering other large substance groups.

According to ICRP[10], the quantity 'effective dose' can be of practical value for comparing the relative doses related to stochastic effects from different diagnostic examinations and interventional procedures and the use of similar technologies and procedures in different hospitals and countries. Effective dose is also useful in the comparison of different technologies for the same medical examination, provided that the representative patients or patient populations for which the effective doses are derived are similar with regard to age and gender. However, comparisons of effective doses are inappropriate for risk assessments when there are significant dissimilarities between the age and gender distributions of the representative patients or patient populations being compared (e.g. children, all females and elderly populations) and the ICRP reference distribution of both genders and all ages. This is a consequence of the fact that the magnitudes of risk for stochastic effects are dependent on age and gender. Risk assessment for medical uses of ionising radiation is best evaluated using appropriate risk values for the individual tissues at risk, and for the age and gender distribution of the population groups undergoing the procedures.

PET/CT has now replaced stand-alone PET for many applications. Its most common application is in oncology, but it is growing in use in the fields of cardiology and neurology. The effective doses from PET investigations are considerable. An investigation with 350 MBq of ^{18}F-FDG gives, for example, an effective dose of 7 mSv[46]. The highest (mean) organ/tissue doses are 20–50 mGy (Table 2). If a PET study is combined with a 'regular' CT investigation, which gives an additional effective dose of 10 mSv, this together comes up to an effective dose of 17 mSv. If the PET study instead is combined with a 'low-dose' CT for attenuation correction and

Table 2. Typical effective doses and examples of some of the highest organ absorbed doses for common PET investigations.

Study	Radionuclide	Radio-pharmaceutical	Activity (MBq)	Effective dose (mSv)[44–46]	Examples of organ doses (mGy)[44–46]
Tumour	^{11}C	Acetate	400	1.4	Kidneys, 21; heart, liver, 5.2; pancreas, 4.8
Tumour	^{11}C	Choline	300	1.4	Bladder wall, 4.8; kidneys, 5.4; liver, 4.2; spleen, 2.9
Tumour	^{18}F	Choline	300	5.7	Bladder wall, 20; kidneys, 24; liver, 18; spleen, 10
Tumour	^{18}F	FDG	400	7.6	Bladder wall, 50; ovary, 6; testes, 5, red bone marrow, 4
Cardiac	^{15}O	Water	1100	1.2	Heart, 2.1; kidneys, stomach, 1.9; liver, lungs, spleen, 1.8
Alzheimer	^{11}C	PiB	300	1.3	Bladder wall, 10; brain, 1.6

Table 3. Typical effective doses for common SPECT investigations.

Study	Radionuclide	Radio-pharmaceutical	Activity (MBq)	Effective dose (mSv)[44, 45]	Examples of organ doses (mGy)[44, 45]
Bone	^{99m}Tc	Phosphonates	600	3.4	Bladder wall, 30; red bone marrow, 6; ovary, 2; testes, 1.4
Myocardial perfusion	^{99m}Tc	Tetrofosmin Sestamibi	600	4.2–4.6	Gall bladder, 16–22; bladder wall, 10–16
Brain	^{99m}Tc	HMPAO	800	7.4	Kidneys, 27; thyroid, 21; bladder wall, 18
Tumour	^{123}I	MIBG	400	5.2	Liver, 27; bladder wall, 19
Tumour	^{111}In	Octreotide	150	8.1	Spleen, 86; kidneys, 62; liver, 15
Myocardial perfusion	^{201}Tl	Chloride	80	11	Kidneys, 38; bone surfaces, 30; colon, 20

anatomical orientation only, the CT contribution can be reduced to 2–3 mSv and the total effective dose to 9–10 mSv.

From a radiation protection point of view, PET/CT is the combination of two high-dose investigations, with effective doses up to 30 mSv and organ doses up to 100 mGy, as is seen in Tables 1 and 2 for the mean absorbed dose to the urinary bladder wall at a PET/CT investigation with ^{18}F-FDG. The use of ^{11}C-labelled substances gives in most cases a lower dose contribution than ^{18}F-labelled substances[44–46] (Table 2).

SPECT is superior to planar imaging with gamma camera for a number of investigations using ^{99m}Tc-, ^{123}I-, ^{111}In- and ^{201}Tl substances. SPECT/CT is used for bone scintigraphy, myocardial perfusion imaging, functional brain imaging, somatostatin receptor scintigraphy, parathyroid scintigraphy, adrenal gland scintigraphy and detection of sentinel nodes, among other applications[4, 40–42]. Table 3 reports typical effective dose and organ absorbed dose values for common SPECT investigations[44, 45]. For the majority of ^{99m}Tc substances, the effective dose per unit activity administered is very similar from substance to substance (0.005–0.01 mSv MBq^{-1}).

The use of the ^{201}Tl chloride for myocardial perfusion studies is associated with a lower effective dose than the use of ^{99m}Tc-labelled substances.

Dose management

One of the obvious limitations of hybrid imaging using PET/CT or SPECT/CT is related to the patient radiation exposure. For SPECT- and PET investigations, there are few observer performance studies relating diagnostic outcome to administered activity for an investigation.

Dose reduction for PET or SPECT can be achieved by using tracers with shorter physical and biological half-lives, by scaling injected activity by patient weight or body milliamperes per second index or body area or by using high-sensitivity PET scanners or high-sensitivity SPECT collimators. As technology and staff awareness increases, the recommended activities of different radiopharmaceuticals may be decreased. For SPECT examinations, the use of ^{99m}Tc-labelled substances is associated with a lower effective dose than the use of ^{201}Tl. The radiation dose at a SPECT investigation can be reduced with a combination of new iterative reconstruction methods and dedicated collimators and detectors. The omission of the remaining study when the stress study is normal reduces of course the dose.

Using PET/CT and SPECT/CT, there are two alternative goals of the CT investigation: just to produce an image that can serve as a base for the attenuation correction of the PET or SPECT image ('low-dose CT') or to provide a diagnostic image ('diagnostic CT'). From the radiation protection point of view, it is essential that if a 'diagnostic' CT is needed, this be taken as part of the PET/CT or SPECT/CT investigation to avoid the need for an additional CT in the same patient. This requires cooperation between radiology and nuclear medicine departments, if they are separated. Sometimes, there is a need for a contrast-enhanced scan. When both contrast and non-contrast images are needed, the non-contrast CT image should be done first (and also serve for the PET or SPECT attenuation correction). A contrast-enhanced CT image could be used for attenuation corrections but there is a risk for contrast-induced correction artefacts.

OCCUPATIONAL EXPOSURE

Methods to estimate exposure of personnel

The main occupational dose contribution is associated with external exposure during the nuclear medicine part of the investigation. Programmes for routine monitoring of external exposure are in use in most nuclear medicine departments, with the most common method being personal TL dosemeters placed on the chest and evaluated monthly. Directly read electronic digital pocket dosemeters based on Si-diodes are becoming more common. For specific measurement on fingers, hands, near the eyes, etc., TL dosemeters are normally used.

At work with SPECT/CT and PET/CT, the occupational exposure from the CT units is trivial and controlled by structural shielding and a well-collimated X-ray beam. Moreover, the staff leaves the room during the patient imaging if not the patient's condition forces them to stay in spite of that, personal monitoring could be applied to radiology staff as well. In specific situations, extremity dosemeters should be used.

Doses from ingestion or inhalation from contamination in connection with SPECT or PET measurements are very small.

Occupational exposures at PET and SPECT investigations

The shielding of PET and PET/CT facilities presents special challenges as the 511-keV annihilation photons have much higher energy than other types of radiation used for nuclear medicine diagnostics. Earlier studies demonstrated that the occupational exposure in connection with the very frequent use of ^{99m}Tc-labelled substances is low[47]. This is also the case for the use of ^{99m}Tc and other low-energy photon-emitting radionuclides such as ^{123}I, ^{111}In and ^{201}Tl for SPECT/CT investigations. SPECT/CT facilities generally will not require shielding beyond that for the CT scanner. For positron emitters,

however, barrier shielding may be required in floors and ceilings as well as in adjacent walls. However, shielding requirements, facility design, site planning, workflow and other parameters are not yet standardised. Therefore, dose measurements for staff members show different values. From filling of syringe to patient departure, the effective dose to technicians from ^{18}F-FDG is ~15 nSv MBq^{-1}[48–52], with an essential dose contribution coming from interaction with the radioactive patient. For an annual number of less than 500 patients, the annual individual effective dose for the technicians would realistically be <3 mSv, which is low but still 50 % higher than that of technologists performing general nuclear medicine. Contributions to staff in wards may be about the same, 15 nSv MBq^{-1}. The exposure of hands and especially fingers may, however, be a greater problem. Finger doses to technicians working under good normal nuclear medicine laboratory standard is around 2–3 μSv MBq^{-1}[53, 54]. The use of syringe-drawing device and semiautomatic injector can reduce this value to 0.2–0.6 μSv MBq^{-1}[50] and with fully automatic dispensing technique it can be almost totally eliminated (<0.02 μSv MBq^{-1}). For an average injected activity of 350 MBq per patient and for the three categories mentioned, the dose limit (500 mSv to fingers) is reached after handling of 500, 2400 or many more patients annually.

CONCLUSION

Clinical application of CT has revolutionised medical imaging and plays an enormous role in routine medical care. Due to technical improvements, spatial and temporal resolutions have continuously improved. In spite of significant reduction of CT doses during recent years, mainly due to improved technology, CT is still a dominating source of radiation exposure in the population. With SPECT/CT and PET/CT, significant additional information about physiology and cellular and molecular events are provided. However, significant dose contributions from SPECT and PET occur, making PET/CT and SPECT/CT truly high-dose investigations. Fewer optimisation trials in the form of observer performance studies have been performed for PET and SPECT than for X-ray imaging and more investigations should be done to find optimal activities for various patients and investigations.

An efficient cooperation between nuclear medicine and radiology departments is necessary to use CT, PET/CT and SPECT/CT investigations most appropriately. Efforts should be made to better inform referring physicians and patients concerning various radiological examinations, criteria for their use and their dose contribution when optimised.

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