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Trends in radiation protection of positron emission tomography/computed tomography imaging

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Abstract–Over the past decade, the number of positron emission tomography/computed tomography (PET/CT) imaging procedures has increased substantially. This imaging technique provides accurate functional and anatomical information, particularly for oncological applications. Separately, both PET and CT are considered as high-dose imaging modalities. With the increased use of PET/CT, one could expect an increase in radiation doses to staff and patients. As such, major efforts have been made to reduce radiation dose in PET/CT facilities. Variations in working techniques have made it difficult to compare published results. This study aimed to review the literature on proposed methods to reduce patient and staff dose in clinical PET/CT imaging. A brief overview of some published information on staff and patient doses will be analysed and presented. Recent trends regarding radiation protection in PET/CT imaging will be discussed, and practical recommendations for reducing radiation doses to staff and patients will be discussed and summarised. Generally, the CT dose component is often higher in magnitude than the dose from PET alone; as such, focusing on CT dose reduction will decrease the overall patient dose in PET/CT imaging studies. The following factors should be considered in order to reduce the patient's dose from CT alone: proper justification for ordering contrast-enhanced CT; use of automatic exposure control features; use of adaptive statistical iterative reconstruction algorithms; and optimisation of scan parameters, especially scan length. The PET dose component can be reduced by administration of lower activity to the patient, optimisation of the workflow, and appropriate use of protective devices and engineered systems. At the international level, there is wide variation in work practices among institutions. The current observed trends are such that the annual dose limits for radiation workers in PET/CT imaging are unlikely to be exceeded.

Keywords: PET/CT; Radiation protection; Staff dose; Patient dose; Radiation dose reduction techniques

1. INTRODUCTION

Over the last decade, there have been significant developments in medical imaging techniques. One of the main evolutions is the combination of positron emission tomography (PET) and computed tomography (CT) on a single gantry as a hybrid PET/CT scanner. This provides both anatomical and functional images of the patient as a fused image. Since its introduction in 1998 (Beyer et al., 2000), PET/CT has become an important imaging modality worldwide. PET/CT is one of the fastest-growing medical imaging modalities, with more than 5000 PET/CT systems installed worldwide (Beyer et al., 2011). PET/CT is widely recognised as the main imaging modality used in oncology for early diagnosis, staging, restaging, and monitoring the therapy of several types of tumours. Oncological applications account for more than 90% of PET/CT procedures, whereas other applications, such as cardiology, neurology, and psychiatry, account for 4% (IMV Medical Information Division, 2011). Due to the increased use of PET/CT with increased patient throughput, one could expect an increase in radiation doses to workers. Radiation protection issues in PET/CT have been addressed adequately, and significant progress has been made in reducing occupational radiation doses in PET/CT facilities. Applied measurement techniques and different working practices increase the variations in published data. Other factors, such as the level of experience of staff, type of PET/CT scanner, work practice, administered activity, procedure used during dose dispensing, time spent by worker close to patient, distance from the patient, workload, and CT parameters, are the causes of these variations.

There is a need to review the current literature and produce updated recommendations. The main aim of this study was to present and analyse published information on recent trends in radiation protection at PET/CT facilities, and discuss state-of-the-art radiation reduction techniques for staff and patients.

Separately, both PET and CT are considered as high-dose imaging modalities. However, a properly justified diagnostic CT examination must be taken as part of a PET/CT examination in order to avoid the radiation dose received subsequently from an additional CT examination.

Experience has shown real difficulty regarding CT procedure standardisation due to the wide variation in radiology practice worldwide. Most CT studies have adequate image quality, allowing the radiologist to make a proper diagnosis. Therefore, it is always possible to optimise the patient radiation dose by accepting a lower image quality. However, this task is extremely challenging to implement.

Primary tumour staging often requires a good-quality diagnostic CT scan. For cancer patients, the benefit from a CT examination is much higher than the risk associated with the radiation dose received during imaging.

2. CT DOSE COMPONENT IN PET/CT IMAGING

Data on the doses delivered during PET/CT imaging to patients and staff are available in the scientific literature. Implementation of the optimisation principles in PET/CT requires assessment of patient doses, exposed workers, and the operational aspects of radiation protection in the clinical environment.

It has been reported that low-dose CT used for attenuation correction (AC) and anatomical orientation may only account for 50% of the whole PET/CT dose, with an average PET dose of 7 mSv and an average low-dose CT dose of 2–3 mSv (total 9–10 mSv) (Mattson and Soderberg, 2012).

It has been reported that only 73% of PET/CT facilities use dedicated low-dose CT acquisition for AC of PET/CT studies (Beyer et al., 2011). The remaining 27% of PET/CT facilities should be encouraged to implement low-dose CT in routine practice in order to reduce the patient radiation dose.

Three different CT acquisition protocols were compared using a humanoid (Alderson-Rando) phantom equipped with thermoluminescent dosimeters (TLD-100) during a whole-body PET/CT scan; the CT dose component accounted for 54–81% of the total combined dose. The calculated effective dose from PET/CT scanning with a diagnostic CT protocol and an administered ^{18}F-FDG activity of 370 MBq was approximately 32 mSv for a whole-body diagnostic scan (Huang et al., 2009).

Brix et al. (2005) measured the effective dose from PET/CT examinations with four diagnostic CT protocols, and reported a range of 23.7–26.4 mSv. Wu et al. (2004) reported that the effective dose from diagnostic CT and PET was 18.9 mSv and 10.7 mSv, respectively.

When full CT is required along with whole-body PET, the advantage of conducting the CT scan before the PET scan is that the CT data can be used for AC, and misalignment artefacts will be minimised. On the other hand, if the CT scan is conducted after the PET scan, a smaller field of view can be selected and an optimised CT examination can be performed. Also, if the patient has an allergic reaction to the contrast media, this will not affect the PET study, but there may be more image misalignment artefacts.

3. JUSTIFICATION OF CT EXAMINATION IN PET/CT IMAGING

One important concern in diagnostic radiology is that all examinations should be justified to avoid unnecessary radiation exposure of the individual patient. To prevent unjustified examinations, close cooperation between radiologists, other clinicians, and medical physicists is required. In a recent survey about the justification of performing CT examinations in Sweden, it was reported that 20% of all CT examinations were unjustified, and that a major population dose reduction could be achieved by avoiding such unjustified examinations (Swedish Nuclear Safety Authority, 2009).

Efficient cooperation between nuclear medicine and radiology departments is necessary to use PET/CT investigations most appropriately. Efforts should be made to better inform referring physicians about various alternatives to radiological examinations and the criteria for their use. Radiologists and nuclear medicine physicians should establish evidence-based imaging parameters as a function of clinical indications for PET/CT imaging. The development of clear referral criteria for imaging will decrease the number of inappropriate examinations, and hence reduce collective dose to patients.

To reduce radiation dose, low-dose CT in combination with ultrasound and/or magnetic resonance imaging for the assessment of anatomy is often preferred to a full-dose examination (Biermann et al., 2013). Guidelines are difficult and expensive to produce and maintain. Such decision support must be comprehensive, user-friendly, relevant, and interactive. The current challenge in the area is the fact that the proposed guidelines must be based on sound methodology. In conclusion, there is a need for imaging referral guidelines in a useable format.

4. CT DOSE OPTIMISATION IN PET/CT IMAGING

CT technology is used in PET/CT to perform AC and anatomical reference localisation for the PET scan data set. Low-resolution CT imaging using multi-slice CT scanners, usually 64-slice scanners, is usually requested.

In CT imaging, proper selection of exposure parameters (e.g. kVp, mAs, scan length, pitch, and gantry rotation speed) is required. Dose reduction features such as automatic exposure control, conformal three-dimensional dose modulation, and new image reconstruction algorithms (e.g. iterative reconstruction techniques) must be applied when available. The use of these technologies will empower the end user to achieve patient and staff dose reduction and optimisation.

The relationship between justification and optimisation principles is complex; there is a need to establish proper clinical justification criteria for high-resolution or contrast-enhanced CT (CECT) examinations in PET/CT. There is also a need to avoid repeated prescriptions because these will increase patient dose.

In CT procedures, radiation dose can be estimated using the dosimetric quantities available as part of the image DICOM file, such as the CT dose index and the dose length product. The dose may also be measured using established reference dosimetry methods with body phantoms and pencil dosimeters coupled with electrometers. At the national level, a patient radiation dose survey will require application of a standardised acquisition protocol for all surveyed scanners, and adequate time for performance of the survey.

In order to evaluate the successful implementation of dose optimisation techniques, the standard imaging protocols in use must be examined. Medical institutions may customise the suggested optimised protocols to fit their scanners. However, training and awareness of technical and medical staff performing and reporting the PET/CT scan are vital. Vendors' cooperation during the implementation stage is also important.

4.1. Contrast-enhanced CT

CT scanners used in PET/CT imaging system are identical to any standard diagnostic CT scanner (modern multi-slice CT). These CT scanners are used to produce scans specifically for AC of the PET data. CT-based AC (CTAC) scans are usually lower-dose scanning parameters. The CTAC scans must not be used for other diagnostic purposes. On the other hand, a high-quality diagnostic scan can also be used for AC. Diagnostic scans should only be used if more clinical indications are required other than AC of PET images. In such case, diagnostic CT examination will replace the CTAC scan to avoid additional patient dose. CECT studies have shown some advantages, such as improved delineation of anatomical structures, increased sensitivity for detection of pathological lesions, and improved accuracy in lesion characterisation (Antoch et al., 2004).

In a study to evaluate low-dose non-enhanced CT (LDCT) and full-dose CECT, PET/CECT was found to be a more accurate imaging modality with higher confidence for assessing ovarian cancer recurrence than PET/LDCT (Kitajima et al., 2012).

Another study has clearly shown the usefulness of PET/CT for better evaluation and management of patients with fibroblast proliferative disease. Accurate determination of the level of inflammation was significantly improved when PET/CT and CECT were performed in the same study, and used for better delineation of areas of residual inflammation (Liu et al., 2012). When performing PET/CT, optimal detection and characterisation of liver lesions required the use of a fused CECT scan in patients with colorectal cancer (Ozkan et al., 2012).

The use of iodinated contrast media for small-animal PET imaging has been found to significantly improve tumour delineation and diagnostic performance, without significant alteration of small animal PET quantitative accuracy and National Electrical Manufacturers Association (NEMA) image quality parameters (Lasnon et al., 2013).

Other studies have shown that there is little advantage in using CECT (e.g. in staging malignant melanoma) in comparison with LDCT (Elstrom et al., 2008; Pfluger et al., 2011). Yoshida et al. (2009) reported that routine CECT is not justified for lesion detection in staging primary head and neck cancers with PET/CT.

While contrast CT examinations have good diagnostic value in PET/CT imaging studies, there is some disagreement on their role in AC. Clinical PET/CT studies have shown that contrast agents may result in overestimation of standardised uptake values on images corrected for attenuation with attenuation maps derived from CT (Berthelsen et al., 2005; Yau et al., 2005; Mawlawi et al., 2006; Bunyaviroch et al., 2008; Aschoff et al., 2012).

The mean and maximum standardised uptake values were significantly increased in contrast-enhanced PET/CT compared with non-enhanced PET/CT at each anatomical site (Prechtel et al., 2012). On the other hand, it has been reported that intravenous contrast does not have an adverse effect on the sensitivity and specificity of PET/CT (Hall et al., 2011). Non-AC PET images can also be used to solve potential image artefacts arising from CECT AC PET images in PET/CT.

4.2. Image reconstruction algorithms

Adaptive statistical iterative reconstruction (ASIR) has been reported to save dose in comparison with the known filtered back projection algorithm. The images produced have the appearance of noise-free images and may not be easily accepted by radiologists. A blended solution exists, composed of a linear combination of filtered back projection and ASIR, with a natural appearance and less noise. These preliminary results support body CT dose index reductions of 32–65% when ASIR is used. Studies with larger statistical samples are needed to confirm these findings (Hara et al., 2009). Using the iterative reconstruction technique, it has been shown that the temporal bone dose can be reduced by 50% in comparison with the conventional filtered back projection algorithm (Niu et al., 2012). Most CT vendors have now incorporated the iterative reconstruction technique into their scanners. Technical evaluations of the proposed iterative reconstruction algorithms showed reduced noise levels and increased signal-to-noise ratio in images while maintaining the same spatial resolution. The immediate benefit from applying this new reconstruction technique is the ability to use it extensively on obese patients, in paediatric examinations, on patients requiring multiple imaging studies for follow-up, and on patients unable to use magnetic resonance imaging as an alternative imaging modality (Silva et al., 2010).

Continuous effort from major CT vendors in the area of reconstruction algorithm development is demonstrated by introduction of the model-based iterative reconstruction technique, which has shown good prospective achievement of image noise and patient dose reduction while maintaining good image quality (Pickhardt et al., 2012; Vardhanabhuti et al., 2013). This method can be applied to reconstruct low-dose acquired CT images (Katsura et al., 2012). The only drawback of the method is its longer computing time.

4.3. Optimisation of CT scan parameters

In PET/CT imaging, the CT scan is used mainly for AC of the PET images; such correction is achieved by using low-dose CT. Dose reduction in CT can be achieved by using adjusted examination acquisition parameters such as lower kVp and mAs, larger pitch for spiral acquisition, and, when possible, shorter scan length. A large number of studies covering the previously mentioned parameters have been published (Graham et al., 2011). The use of automatic tube current modulation has been recommended (Alessio et al., 2009).

Optimisation of scanning parameters is now possible due to numerous published studies using simulation tools, and such tools have shown that parameter optimisation will lead to reduced patient dose without affecting image quality. The simulation works simply by adding an artificial level of noise to the CT raw data in order to simulate a lower dose examination. As mAs is directly related to dose, a lower mAs examination will definitively produce a lower radiation dose scan (Kumar et al., 2012b). A specific level of image quality is desired by clinicians in order to acquire

valid CT studies that will answer the clinical question under investigation. Other reported parameters affecting patient dose are kVp, slice thickness, and scan length.

Automatic exposure control techniques are now integrated in all new CT scanners, and a large number of studies have shown their usefulness in patient dose reduction.

One important parameter affecting patient dose from CT is the scan length, as the effective dose is related to the dose length product using published conversion factors relating the two parameters. Proper scan length can be estimated easily from the internationally published dose reference levels, usually expressed using the CT dose index and dose length product.

Hence, administered activity for a PET scan cannot be reduced substantially because it is related to the patient's weight. The easiest way to decrease the patient radiation dose burden from PET/CT imaging is to optimise and adjust the CT scan acquisition parameters for each patient. There is a need for well-established clinical guidelines for CT examination requirements as part of the PET/CT examination.

5. PET DOSE COMPONENT IN PET/CT IMAGING

PET/CT procedures include many tasks that contribute significantly to the occupational radiation exposure of staff. These tasks include: (1) dispensing and preparation of individual patient dose; (2) dose administration; (3) measurement of residual activity; (4) patient contact during uptake period; (5) escorting the patient to the PET/CT scanner; (6) positioning the patient on the PET/CT couch and helping the patient to rise from the couch; (7) scanning of the patient (worker will not be exposed to x rays during the CT examination and the patient is exposed to external radiation); and (8) escorting the patient out of the department at the end of the PET/CT examination. The total radiation dose depends on the skill of the worker to implement the radiation protection principles of time, distance, and shielding. Therefore, reducing radiation dose to workers in a PET/CT facility is a complicated issue, and more effort is required to implement the ALARA (as low as reasonably achievable) principles and International Commission on Radiological Protection (ICRP) recommendations.

ICRP has recommended that the occupational dose limit for radiation exposure is 20 mSv $year^{-1}$ averaged over 5 years, and a maximum of 50 mSv in any single year (ICRP, 1991). According to the literature, the annual occupational dose to a PET/CT worker is always well below the 20 mSv dose limit. Seierstad et al. (2007) estimated the occupational dose to workers in PET/CT, and attributed approximately 60% of the occupational dose to the technologist handling the radioactive materials and 40% to close contact with the patient. This indicates that handling radioactive materials before and during injection, and dealing with the patient after the injection, are important aspects and must be addressed when attempting to reduce occupational radiation dose in PET/CT facilities.

6. PET DOSE REDUCTION TECHNIQUES

6.1. Administered activity

It has been reported that only 44% of PET/CT facilities employ weight-based radioactivity dose injection (Beyer et al., 2011). This indicates that the remaining PET/CT facilities should implement weight-based radioactivity dose injection in their practice in order to optimise radiation dose to patients. Given the availability of the three-dimensional acquisition mode, administered activity could be reduced without affecting image quality. For a standard adult patient (75 kg), the European Association of Nuclear Medicine recommends using 380 MBq for the two-dimensional mode and 190 MBq for the three-dimensional mode (Boellaard et al., 2010).

All new commercial PET/CT scanners offer time-of-flight (TOF) technology, which can help to overcome poor signal from large patients. TOF accurately measures the actual time difference between detection of the two annihilation photons, and this leads to improved image contrast and higher sensitivity. El Fakhri et al. (2011) reported that TOF reduces the injected dose, and therefore reduces the exposure of patients and workers to radiation. Etard et al. (2012) reported that new TOF technology can decrease average specific activity by approximately 20% (from 4.3 MBq kg^{-1} to 3.5 MBq kg^{-1}) while maintaining image quality.

Hydration and voiding are also important for patient preparation during PET/CT. The patient is encouraged to drink water after the ^{18}F-FDG injection and before scanning in order to limit the radiation dose to the bladder. The bladder is the organ that receives the largest radiation dose during PET/CT procedures. The estimated absorbed radiation dose to the bladder is 0.16 mGy MBq^{-1}, 0.21 mGy MBq^{-1}, and 0.32 mGy MBq^{-1} for an adult, a 15-year-old, and a 5-year-old, respectively (ICRP, 1998).

6.2. Extremity dose

Staff preparing and administering unsealed ^{18}F-FDG doses may receive a significant dose to their hands, especially their fingers. The location of the highest exposure to the worker's hand should be measured and monitored. ICRP has recommended that skin dose should be measured at a depth of 0.07 mm (the skin's basal cell layer is considered to be 70 μm), and should not exceed the annual dose limit of 500 mSv (ICRP, 2007). ICRP also recommends that ring dosimeters should be worn at the base of the middle finger, with the TLD facing the palm, and recommends a factor of 3 to estimate the highest extremity dose at the fingertip if the TLD faces the palm and a factor of 6 when the TLD faces the dorsal side of the hand (ICRP, 2008). The extremity dose to the fingers of workers dealing with ^{18}F-FDG is more than three orders of magnitude higher than the dose for workers handling ^{99m}Tc (3.0 μGy MBq^{-1} for ^{18}F and 0.0012 μGy MBq^{-1} for ^{99m}Tc) (Leide-Svegborn, 2012).

The skin dose due to contact with 5 ml of ^{18}F is eight times higher than the skin dose from ^{99m}Tc (2.88 mSv MBq h^{-1} for ^{18}F and 0.354 mSv MBq h^{-1} for ^{99m}Tc) (Delacroix et al., 2002). The skin dose limit is applied to dose averaged over an area of 1 cm^2 (ICRP, 1991). Therefore, it should be measured accurately at the location

that represents the highest skin dose. This is considered as the extremity dose and should be measured at the tip of the fingers or the thumb. Published studies for extremity dose indicate that there is a significant variation in the measured extremity dose in PET/CT imaging using ^{18}F-FDG. These variations are mainly due to position of the dosimeter (palmer or dorsal), location of the dosimeter (base of ring finger or wrist), choice of hand (dominant or non-dominant), exposure time (condition of the patient and experience of the worker), amount of activity, individual skills and habits of the workers, number of patients handled (or number of measurements per worker), total number of workers, distance between finger and radioactive source, and use of syringe shields. Exposure time may be affected by the inconvenience of TLD location on the finger and the experience (or skill) of the worker. The skill of the worker plays an important role in the dose received (ICRP, 2007). Carnicer et al. (2011) found that good working habits were more important than experience. More experienced PET/CT workers should be responsible for dealing with paediatric, disabled, and elderly patients.

Most hospitals do not perform extremity dose monitoring (Kemerink et al., 2012). Based on the ORAMED (Optimisation of RAdiation protection of MEDical staff) study, nearly 20% of nuclear medicine staff are likely to receive a skin dose that exceeds the annual skin dose limit of 500 mSv (ORAMED, 2011). This is because it is impractical to place the dosimeter at the fingertip, and inconvenient for the worker. The fingertip is the part of the hand that is likely to receive the highest radiation exposure due to its proximity to the radiation source. Therefore, in routine practice, extremity dose is measured by placing the dosimeter at the base of the ring finger (ring dosimeter) or at the wrist (wrist dosimeter), which underestimates the actual fingertip dose due to distance from the fingertip. There is a large discrepancy between finger doses received by the dominant and non-dominant hands. Withdrawal of activity can lead to a greater finger dose discrepancy between the dominant and non-dominant hands than injection and waste handling (Leide-Svegborn, 2012). This is likely to be due to use of the non-dominant hand to support the syringe during the removal of air bubbles, and to support the needle during withdrawal of activity from the vial into the syringe.

As a result, in routine daily practice, the majority of workers use ring dosimeters because they are convenient to wear. However, a corrective factor should be applied to estimate the highest finger (fingertip) dose. Correction factors of 6 (Carnicer et al., 2011) and 9 (Covens et al., 2007) have been reported in the literature. This indicates that there is a need to change the practice of wearing finger dosimeters from the wrist to the base of the index finger of the non-dominant hand (facing the palm) in order to give a more accurate estimate of the maximum finger dose (Carnicer et al., 2011).

Covens et al. (2007) studied the highest skin dose for seven workers (right-handed) performing ^{18}F manipulation (kit preparation, dispensing, and injection), and reported that the highest dose location was situated on the tip of the ring finger of the left hand. The highest skin dose for one worker was 850 μSv per handled GBq of activity when manipulating ^{18}F-FDG without radiation protection measures. This worker would easily exceed the annual dose limit. Carnicer et al. (2011) reported skin

doses of 930 μSv GBq^{-1} and 1200 μSv GBq^{-1} for the administration and preparation of ^{18}F-FDG, respectively, and showed that the dose to the hands might surpass the dose limit of 500 mSv. Leide-Svegborn (2012) reported that the finger dose might reach 420 mSv, which is close to the 500 mSv annual finger dose limit, and suggested that much has to be done in order to reduce the extremity dose from ^{18}F-FDG procedures.

Although use of a syringe shield is a practical solution to reduce radiation dose to fingers during manual injection, other efficient systems such as automatic (or semi-automatic) dispensing/injection systems have been recommended to limit the finger dose. Covens et al. (2010) studied one of these automated dispensing/injection systems, and found that extremity dose can be reduced by more than 95% with the use of an automated dispensing/injection system. Lecchi et al. (2012) studied the use of a combined dispensring/injector system, and reported that the extremity dose to the physician (when administration of ^{18}F-FDG was performed by a physician) was reduced by 93%. Prevot et al. (2012) reported that collective finger doses were reduced by 39% with the use of an automated dispensing/injection system.

6.3. Automated dispensing/injection systems

Most of the occupational radiation dose is received during dispensing and injection of ^{18}F-FDG. The extremity dose is mainly received during handling of the syringe. ^{18}F-FDG is often dispensed and injected manually. Recently, some manufacturers have developed automated combined dedicated dispensing/injection systems. Covens et al. (2010) studied one of these systems and reported that the dose was reduced by 20% during the ^{18}F injection phase and by up to 50% for the whole-body dose.

Schleipman and Gerbaudo (2012) studied occupational dose to workers from both automated infusion and manual injection protocols. Their study discovered a10-fold reduction in staff extremity and body dose with use of an automated infusion device compared with manual injection of ^{18}F-FDG radiotracers. Prevot et al. (2012) reported that collective whole-body exposure was decreased by 25% in 2 years with the use of an automated dispensing/injection system. Lecchi et al. (2012) reported that the whole-body radiation dose was reduced significantly by 38% with the use of a combined dispensing/injection system. These systems have some disadvantages, such as high capital cost, cost of consumables, cost of multi-dose vials from off-site cyclotrons, unfamiliarity with the system, and space requirement. Kumar et al. (2012a) studied dose rate to staff during different phases (injection, positioning, and scanning of the patient), and found that injected dose made a greater contribution to the total radiation dose. All these studies indicate the need to consider the use of automated injection systems, particularly in PET/CT facilities with high patient throughput.

6.4. Shielding

Use of primary syringe shields (dedicated for 511 keV) can reduce the average dose per injection by approximately 44% (from 6.8 nSv MBq^{-1} with unshielded syringe to 3.8 nSv MBq^{-1} with shielded syringe) (Roberts et al., 2005). The

wrist dose was reduced by approximately 50% by the use of syringe shields (15 nSv MBq^{-1} with unshielded syringe to 7.5 nSv MBq^{-1} with shielded syringe) (Amaral et al., 2007). Reductions of 35% in the left hand and 33% in the right hand were obtained by shielding the syringe (Demir et al., 2010). It has been reported that use of a syringe shield can reduce finger doses, yet the finger doses for some workers are still high. This is due to improper use of syringe shields, where workers position their fingers around the needle during injection with a syringe shield (Carnicer et al., 2011).

6.5. Other techniques to minimise radiation exposure in PET/CT

The main principles of radiation protection (time, distance, and shielding) should be followed when working with ^{18}F-FDG radiopharmaceuticals and injected patients. Explaining the procedure to the patient before the injection is considered to be a practical method to reduce radiation exposure to workers. After ^{18}F-FDG injections, the patient should be viewed and communicated with remotely through a closed-circuit television camera and two-way intercom systems when possible. This will reduce contact time and increase distance from the patient. The staff or family member who escorts the patient when leaving the PET/CT facility at the end of the procedure should keep a distance of >0.5 m in the first 2 h after the injection, and the patient should stay away from children and pregnant women for at least 6 h (Demir et al., 2011). There are some PET/CT facilities where one technologist performs all tasks, and this significantly increases the whole-body dose to the worker. Sharing patient injections with other staff, such as nurses and doctors, can reduce the technologist's dose. Staff education on radiation protection issues on a regular basis with updates on radiation dose reduction techniques can promote safer practices. New workers should learn how to perform dispensing and injection procedures with dummy sources in order to become more familiar and improve their handling technique. Rotation of the work tasks between staff can help to reduce occupational dose. For individual members of staff, reducing the workload can help to reduce staff dose.

7. PET/CT FACILITY WITH HIGH PATIENT THROUGHPUT

Clearly, increasing the number of PET/CT procedures will lead to proportional increase in occupational dose to workers. The annual dose to workers should be estimated and monitored before increasing the number of PET/CT procedures. Orlacchio et al. (2012) reported that the maximum number of PET/CT examinations should be 14 examinations day^{-1}. Based on the data presented by Guillet et al. (2005), the effective whole-body dose to a technologist handling all tasks was 2.95 μSv $patient^{-1}$ (per 309 MBq administered activity), and using the assumption of 14 patients day^{-1}, 5 days $week^{-1}$, and 43 weeks $year^{-1}$, the annual occupational dose for an individual worker would be approximately 8.88 mSv. This value is still below the annual occupational dose limit (20 mSv). Demir et al. (2010) reported that the whole-body dose will exceed the ICRP limit after 4300 patients (working 12 h

day^{-1}, five technologists, and administered activity of 518 MBq). Seierstad et al. (2007) reported that the annual body dose limit is reached after handling approximately 3000 patients or after injection of 1 TBq. The previous assumption did not consider variations in administered activity.

With regard to skin dose, assuming a finger dose of approximately 2–3 μSv MBq^{-1} for 350 MBq for 500 patients day^{-1} as reported by Leide-Svegborn (2012), the annual finger dose limit will be reached after handling approximately 2400 patients year^{-1} (Mattsson et al., 2011). Demir et al. (2010) reported that the skin radiation dose limit will be exceeded after 3000 episodes. This indicates that the maximum number of ^{18}F-FDG injections should not exceed 2400 patients year^{-1} during 8 working h/day (for manual injection only) in order to remain below the annual finger dose limit.

With the use of semi-automatic injectors, finger doses can be reduced from 2–3 μSv MBq^{-1} to 0.2–0.6 μSv MBq^{-1} (Guillet et al., 2005). This will enable PET/CT facilities to increase the number of PET/CT procedures performed per year without exceeding skin dose limits.

It is recommended that each PET/CT facility should define their workload, taking into consideration the administered activity and the use of automated dispensing/injection systems. Additional staff should be considered to manage the extra radiation dose from high workloads.

8. RESULTS

Table 1 summarises the recommendations suggested to optimise radiation protection practice in PET/CT imaging.

9. CONCLUSIONS

Occupational radiation dose can be decreased by reducing the time that workers spend near the radioactive source (this includes the patient after administration), by increasing the distance from the radioactive source, and by using dedicated shielding tools. Extremity dose for workers in PET/CT is an issue that needs to be considered carefully in routine daily practice, and the highest radiation dose should be estimated. Use of automated dispensing/injection systems significantly reduces the extremity dose of workers. All manufacturers should invest in research that focuses on improving the sensitivity and efficiency of PET/CT scanners.

There is also a need to focus on educating and training PET/CT staff to pay more attention to practical aspects of radiation protection. There is an urgent need for international efforts to standardise and optimise the use of PET/CT imaging techniques in order to keep the radiation dose as low as reasonably achievable while optimising image quality. The international effort should focus on accurate monitoring of extremity doses, and increased awareness of high extremity doses.

Table 1. Practical radiation dose reduction techniques in positron emission tomography/computed tomography (PET/CT) imaging.

Preparation phase	• More communication between the referring physician and the nuclear medicine physician to reduce unjustified procedures
	• Patient instructions should be given to the patient prior to injection of the radiopharmaceutical
	• Establish clear intravenous access before the injection to avoid the need for repeat injection
	• Workers must wear an extremity dosimeter in PET/CT imaging practice
Dose injection	• Administered activity of the radiopharmaceutical should be minimal
	• Use unit doses instead of multi-dose
	• Use distance tools such as forceps
	• Use automated dispensing (or/and injection) system
	• Use radiation-shielded tools (syringe shields, syringe carriers, carts, waste containers, etc.)
Uptake phase	• Minimise time near the patient after the injection
	• CCTV and intercom facility should be used in the uptake room to minimise contact time with the patient
	• During uptake time, the patient should be encouraged to drink fluids and void frequently in order to reduce the radiation dose to the urinary bladder
Imaging phase	• Maximisation of distance when escorting and positioning the patient
	• Increase the acquisition time per bed position
	• During positioning of the patient on the PET/CT scanner, workers are encouraged to stand to the right of the patient and to minimise close contact time
	• Positioning time of the patient on the PET/CT table should be short
CT dose optimisation	• Use low-dose non-enhanced CT for AC
	• Use dose optimisation techniques by adjusting scanning parameters
	• Use automatic exposure control and dose modulation techniques
	• Use iterative reconstruction techniques
	• Encourage medical organisations and involved groups to develop CT examination prescription guidelines for PET/CT
Patient discharge	• Use other personnel for escorting the patient
	• For nursing mothers, expressed milk should be discarded for 2 h after the scan
	• Injected patients should keep a distance of >0.5 m from others in the first 2 h after the injection, and stay away from children and pregnant women for at least 6 h

Staff-related issues	• Fluorodeoxyglucose preparation and administration by a skilled worker
	• Training and rotation scheme within workers (divide responsibilities between staff)
	• Practical continuing education of PET/CT staff to reduce the extremity dose
	• Increase the number of PET/CT technologists in a department with high throughput
	• Optimisation of the individual workload is often used to restrict staff doses
	• Harmonising a competency-based programme for the certification of personnel in radiation protection (dual certificate on radiation safety in PET/CT imaging)
	• Workers should gain experience and improve their skills in handling radioactive material (e.g. more practice with non-radioactive materials)
Technology-related issues	• Vendors, workers, and inventors should collaborate to develop equipment, software, and protocols that deliver less radiation
	• Use of three-dimensional PET acquisition mode and time-of-flight technology
	• Perform regular quality control and preventive maintenance of PET/CT scanner

CCTV, closed-circuit television; AC, attenuation correction.

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