

# **Safety Reports Series**

**No. 58**

## **Radiation Protection in Newer Medical Imaging Techniques: PET/CT**



**IAEA**

International Atomic Energy Agency

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**RADIATION PROTECTION  
IN NEWER MEDICAL IMAGING  
TECHNIQUES: PET/CT**

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SAFETY REPORTS SERIES No. 58

**RADIATION PROTECTION  
IN NEWER MEDICAL IMAGING  
TECHNIQUES: PET/CT**

INTERNATIONAL ATOMIC ENERGY AGENCY  
VIENNA, 2008

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## FOREWORD

A major part of patient exposure now arises from practices that barely existed two decades ago, and the technological basis for their successful dissemination only began to flourish in the last decade or so. Hybrid imaging systems, such as the combination of computed tomography (CT) and positron emission tomography (PET), are an example of a technique that has only been introduced in the last decade. PET/CT has established a valuable place for itself in medical research and diagnosis. However, it is an application that can result in high patient and staff doses.

For practitioners and regulators, it is evident that innovation has been driven both by the imaging industry and by an increasing array of new applications generated and validated in the clinical environment. Regulation, industrial standardization, safety procedures and advice on best practices lag (inevitably) behind the industrial and clinical innovations. This series of Safety Reports (Nos 58, 60 and 61) is designed to help fill the growing vacuum, by bringing up to date and timely advice from experienced practitioners to bear on the problems involved.

The advice in this report has been developed within the IAEA's statutory responsibility to establish standards for the protection of people against exposure to ionizing radiation and to provide for the worldwide application of these standards. The Fundamental Safety Principles and the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) were issued by the IAEA and co-sponsored by organizations including the Food and Agriculture Organization of the United Nations (FAO), the International Labour Organisation (ILO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO), and require the radiation protection of patients undergoing medical exposures through justification of the procedures involved and through optimization. In keeping with its responsibility on the application of standards, the IAEA programme on radiation protection of patients encourages the reduction of patient doses without losing diagnostic benefits. To facilitate this, the IAEA has issued specific advice on the application of the BSS in the field of radiology in Safety Reports Series Nos 39 and 40. This Safety Report is a further contribution to the resources provided by the IAEA in support of the implementation of the BSS. In addition, it has embarked on a series of coordinated research projects in radiology, mammography, fluoroscopy and interventional radiology, and CT, the results from which will appear in other IAEA publications.

The International Action Plan for the Radiological Protection of Patients, approved by the General Conference of the IAEA in September 2002, requires that:

“The practice-specific documents under preparation should be finalized as guidance rather than regulations, and they should include input from professional bodies, from international organizations and from authorities with responsibility for radiation protection and medical care.”

This Safety Report, and the other two related reports (Nos 60 and 61), are issued in this spirit. They provide guidance and advice for those involved in one of the most dose intensive areas developing in radiology and nuclear medicine today.

The IAEA thanks D. Townsend for his role in compiling the initial text. In addition, the major role of J. Malone in bringing the final draft to fruition is gratefully acknowledged. The IAEA officer responsible for this publication was M.M. Rehani of the Division of Radiation, Transport and Waste Safety.

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# 1. INTRODUCTION

## 1.1. BACKGROUND

The Fundamental Safety Principles [1] and the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2] of the IAEA represent the culmination of efforts over the past decades towards harmonization of radiation protection and safety standards internationally. These publications were jointly sponsored with other organizations including the Food and Agriculture Organization of the United Nations (FAO), the International Labour Organisation (ILO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO). The publications have also enjoyed much support from other bodies, including the European Union. Their purpose includes establishing basic requirements for protection against the risks associated with exposure to radiation and the safety of radiation sources. The requirements are based on basic principles clearly enunciated, in somewhat different ways, in both publications.

The IAEA Safety Standards can only be implemented through an effective radiation safety infrastructure that includes adequate laws and regulations, an efficient regulatory system, supporting experts and services, and a 'safety culture' shared by all those with responsibilities for protection, including both management and workers.

The BSS cover the application of ionizing radiation for all practices and interventions and is, therefore, basic and general in nature. The detailed requirements established in Appendix II of the BSS are applicable, in particular, to radiology and nuclear medicine. In addition, recent publications from the IAEA describe approaches to implementation of the BSS in nuclear medicine [3] and in diagnostic radiology [4]. These also seek to involve organizations outside the regulatory framework, such as professional bodies, whose cooperation is essential to ensure compliance with the BSS for medical exposures.

## 1.2. GROWTH IN POSITRON EMISSION TOMOGRAPHY/ COMPUTED TOMOGRAPHY

The past 15 years have seen the transition of positron emission tomography (PET) from the research domain into mainstream clinical applications, particularly for oncology [5–9]. The emergence of PET as a functional

imaging modality for diagnosis, staging, monitoring therapy and assessment of recurrence in cancer has led to increasing demand for this new imaging technology. It is important to recognize that functional imaging modalities such as PET, in some instances, may provide an earlier diagnosis and more accurate staging than conventional anatomical imaging with computed tomography (CT). Moreover, the recent introduction of hybrid systems, where the PET component is coupled with a CT scanner, has enabled the addition of the precise anatomic detail provided by CT to the metabolic imaging provided by PET. As a consequence, the number of new PET facilities has steeply increased worldwide.

PET imaging in oncology is based on the increased uptake of glucose by cancer cells which has, for many years, been well known to be related to one of the biochemical characteristics of malignant cells: an enhanced rate of glucose metabolism due to an increased number of cell surface glucose transporter proteins and increased intracellular enzyme levels of hexokinase and phosphofructokinase which promote glycolysis. This enhanced glycolytic rate of malignant cells facilitates their detection utilizing PET  $^{18}\text{F}$ -2-deoxy-D-glucose (FDG) imaging. Once inside the cell, FDG is phosphorylated by hexokinase into FDG-6-phosphate. FDG-6-phosphate is not further metabolized and accumulates intracellularly.

The fluorine labelled analogue of glucose, FDG, although not a specific identifier of cancer, is now widely used for whole body PET scanning. The use of FDG is facilitated by the half-life of  $^{18}\text{F}$  (110 min) that enables transport from a remote cyclotron (typically not further than a 2–3 h travelling distance). Since close to 100% of the workload in a typical clinical PET/CT facility involves the use of FDG, this publication focuses primarily on radiation protection issues related to FDG–PET imaging.

The recent combination of PET imaging with CT may be considered to be an evolution in imaging technology where fusion of two established modalities offers more than the sum of the parts. Both modalities have their strengths: CT scanners image anatomy with high spatial resolution; thus, malignant disease can only be readily identified with this modality from the presence of abnormal masses or from size changes of lymph nodes. PET, on the other hand, can identify a functional abnormality even in a normal sized lymph node — although localization of the node may sometimes be less accurate from the PET scan alone. The combination of the two approaches thereby offers accurate spatial localization of functional abnormalities and, conversely, functional assessment of abnormalities identified on anatomical scans. The use of the same patient couch for both scans and the minimization of the effects of uncontrollable internal organ movement ensure accurate alignment of the PET and CT images in most studies. Furthermore, for non-specific tracers such as

FDG, that demonstrate metabolism in many tissues and organs, it is important, particularly for abdominal and pelvic regions, to distinguish normal uptake from disease, a distinction made easier with the advent of PET/CT than with PET alone.

For these reasons, PET/CT has now become one of the most rapidly growing medical imaging modalities in terms of market share. In the years since it became commercially available, stand-alone PET scanner sales have been almost entirely replaced by PET/CT machines with new shipments currently standing at some 400–500 units/a. With well over 1000 PET/CT scanners now installed worldwide, this represents over 95% of PET sales — and over 10% of CT sales. Since the first commercial PET/CT was introduced, the modality has, therefore, had a far-reaching impact on medical imaging, particularly for diagnosis and staging malignant disease, and monitoring response to cancer therapy.

### 1.3. EMERGING ISSUES

The addition of FDG–PET in the evaluation of oncological patients with well defined algorithms, including a combination of imaging studies, seems to be cost effective. It accurately identifies patients who benefit from invasive procedures and saves unnecessary costly invasive procedures on patients who do not benefit from them. However, although the appropriateness of the use of PET/CT in well defined clinical applications has been extensively debated and assessed, its rapid diffusion into the clinical arena and its widespread adoption inevitably raises many new concerns about patients' exposure to ionizing radiation. For example, there are some issues relating to the role of the CT scan; is its role to be clinical and diagnostic, or is it a low dose scan for PET attenuation correction and localization only? Even a low dose CT scan represents some increased radiation exposure of the patient compared with the traditional PET transmission scans which have been used for attenuation correction.

Attenuation correction is needed since photons emitted from inside the body may be attenuated or absorbed before they reach the detectors, an effect that must be corrected for in order to obtain a true image of the positron emitting distribution within the patient. In previous PET-only devices, the information needed to correct the emission data for photon attenuation was obtained from a separate scan, termed a transmission scan, involving rotating 511 keV sources. A PET transmission scan is equivalent to a CT scan acquired at a monochromatic beam energy of 511 keV. For PET/CT scanners, the CT images are used to generate the attenuation correction factors after scaling

from the mean photon energy of the CT (about 70 keV) up to the PET photon energy of 511 keV.

Since the CT scan is much more rapid than a PET-only transmission scan (30 s instead of 15 min), the use of the CT scan for attenuation correction, as described in Section 2.2, significantly reduces the overall scan duration and, if desired, increases patient throughput.

#### 1.4. CLINICAL APPLICATIONS

Excellent reviews of clinical applications utilizing PET/CT imaging are available [5–9]. The applications for FDG–PET imaging are rapidly growing and being accepted in the field of oncology. FDG–PET imaging does not replace other imaging modalities, such as CT, but seems to be very helpful in specific situations where CT has known limitations. The application most used, currently, is in tumour imaging. PET/CT has been found to be invaluable in the management (early diagnosis, staging and restaging) of several malignancies which sum up to a large fraction of all cancer conditions. PET/CT has already found applications in cardiology, specifically in coronary artery disease, and this is expected to grow significantly in the next few years [10]. PET has also found applications in brain imaging, especially in the evaluation of dementia, seizure disorders and, more recently, movement disorders. A growing area of research is in psychiatric disorders that may eventually lead to clinical applications in psychiatry. Other applications, for example, in infection imaging are expected to become feasible in the future.

#### 1.5. RADIATION DOSE

The radiation dose to the patient, discussed in Sections 4 and 5, depends on the PET/CT protocol, and particularly on whether the CT is acquired at low dose or at full diagnostic scan dose. In addition, the high count rate performance of some PET scanner designs permits the administration of higher levels of activity to the patient (e.g. up to 550 MBq), and thus higher patient dose. Higher patient throughput comes at a cost of increased radiation exposure to the staff and a requirement for more shielded rooms where the patients wait for 45–90 min during the uptake phase.

## 1.6. OBJECTIVE

The objective of this report is to review current PET/CT technology and the radiation protection issues arising from its use. Associated radiation dose implications for both patients and staff will be discussed and guidelines offered on dose management and optimization. The report will conclude with some specific recommendations.

## 1.7. SCOPE

This report is directed primarily at Member States adopting PET/CT technology, and focuses on radiation protection issues. It is not a comprehensive source of information on the technology and methodology of PET/CT imaging.

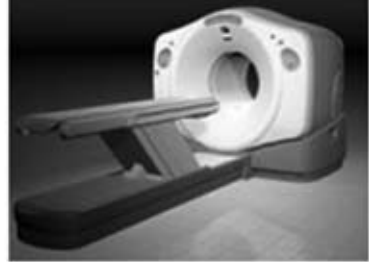
# **2. CURRENT PET/CT TECHNOLOGY**

## 2.1. DESIGN CONSIDERATIONS

Since the introduction of PET/CT into the clinical arena in 2001, all commercial designs consist of a CT scanner placed in tandem with a PET scanner. The CT scanner is positioned to the front, closest to the patient couch, and the PET scanner is positioned to the rear. In some designs, the CT and PET are placed as close together as possible and a single gantry cover over both systems creates the impression of a fully integrated device. An alternative, more open design adopted intentionally keeps the two systems physically separated allowing access to the patient inside the tunnel. An advantage of keeping the imaging components separate rather than well integrated is that, as the CT and/or PET technology improves, it is easier to incorporate new developments into the next generation of PET/CT designs. Thus, with multi-detector CT (MDCT) scanners of up to 64 slices being offered along with a range of different PET components, in 2006 there were over 20 different PET/CT configurations available from five different vendors, examples of which are shown in Fig. 1. The standard bore opening is 70 cm for most PET/CT scanners. Larger 80–90 cm bore CT scanners not only accommodate larger patients but also allow imaging of radiation therapy patients in the



(a)



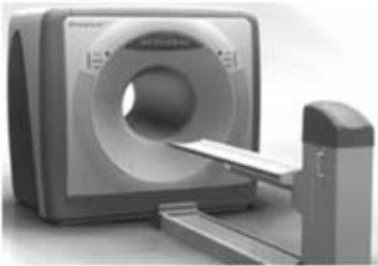
(b)



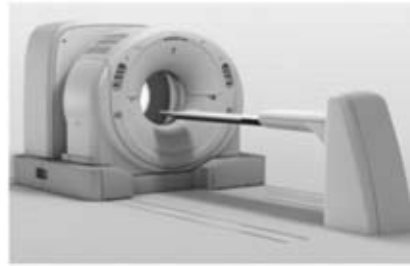
(c)



(d)



(e)



(f)

*FIG. 1. Current commercial PET/CT scanners from five major vendors of medical imaging equipment: (a) Discovery LS (GE Healthcare); (b) Discovery ST (GE Healthcare); (c) Gemini (Philips Medical Systems); (d) Biograph (Siemens Medical Solutions); (e) SceptreP3 (Hitachi Medical Systems); (f) Aquiduo (Toshiba Medical Corporation).*

teletherapy treatment body position, although such large bore CT scanners have yet to be incorporated into PET/CT designs. The vendors have adopted different designs of patient couch to minimize the weight associated downward deflection of the pallet as it advances through the tunnel (Fig. 2).



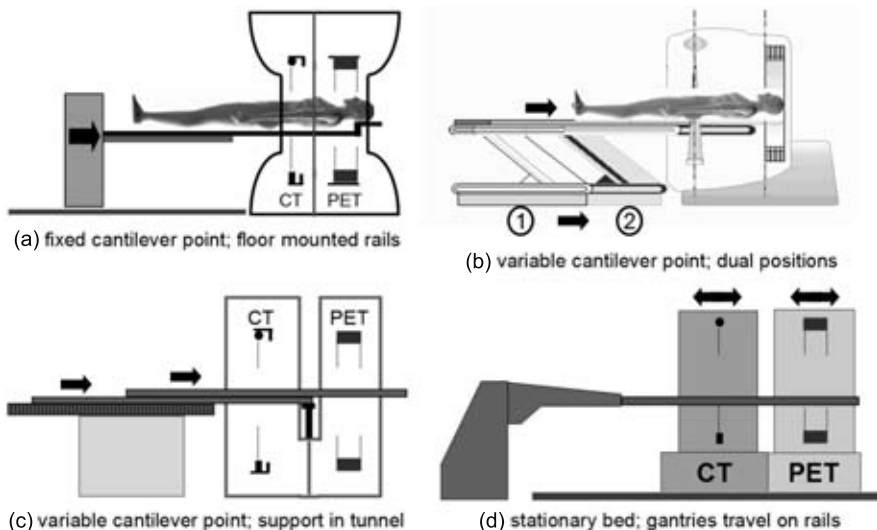


FIG. 2. Four different solutions to the patient handling system (PHS) that minimizes variable vertical deflection of the pallet as it advances into the tunnel of the scanner. The designs include (a) a bed with a fixed cantilever point where the entire couch assembly moves on floor mounted rails (Biograph and SceptreP3); (b) a dual position bed with one position for CT and one for PET (Discovery LS and ST); (c) a patient couch that incorporates a support throughout the tunnel (Gemini); and (d) a fixed couch with the scanner travelling on floor mounted rails (Aquiduo).

Most PET/CT scanners acquire PET data in a high sensitivity 3D mode only, whereas one scanner (the GE Discovery, Fig. 1(b)) incorporates retractable septa and can acquire data in both 2D and/or 3D modes. While debate continues as to whether 2D or 3D acquisition yields better image quality, particularly for larger patients, significant improvements in 3D image quality and signal to noise have been achieved through the use of faster scintillators and statistically based reconstruction algorithms. Use of new fast PET scintillators (gadolinium orthosilicate (GSO) and lutetium oxyorthosilicate (LSO)) have resulted in lower rates of non-causally related coincidences compared to bismuth germanate (BGO). They also offer superior performance for 3D whole body imaging.

While there has not yet been much effort to increase the level of hardware integration, there has been significant effort to reduce the complexity and increase the reliability of system operation by adopting a more integrated software approach. In early designs, CT and PET data acquisition and image reconstruction were performed on separate systems accessing a common database. Increasingly, functionality has been combined so as to reduce cost

and complexity, and increase reliability. Similar considerations of cost and complexity for the hardware may, in the future, lead to greater levels of integration. The likelihood is that newer designs will be more application specific, incorporating a 6, 8 or 16 slice MDCT for oncology and a 64 slice MDCT for cardiology. There will also be a demand for more cost effective, entry level PET/CT designs for oncology, with the likelihood that they will, progressively, replace all stand alone PET scanners.

Even though all PET/CT scanners can provide clinical quality CT images, many centres elect to acquire a low dose, non-diagnostic CT for attenuation correction and spatial localization of the PET data. The trade-off in the potential reduction of ancillary incidental findings due to the reduction in CT image quality must be weighed against the increase in dose required for generating diagnostic quality CT scans. This risk–benefit determination becomes increasingly important as more PET/CT scans are being used to assess the efficacy of therapy.

PET/CT is playing an increasing role in cancer management. Using PET with low dose CT for monitoring therapy response may have the advantage of reducing the radiation exposure to the patient compared to the current procedure of repeat diagnostic CT. There is also the possibility of further limiting the radiation exposure to the patient by reducing the number of repeat diagnostic CT examinations and replacing them with a low dose PET/CT.

## 2.2. CT BASED ATTENUATION CORRECTION

The acquisition of accurately co-registered anatomical and functional images is a major strength of combined PET/CT systems. A further important advantage is use of the CT images for attenuation correction of the PET emission data [11], eliminating the need for a separate lengthy PET transmission scan. The use of the CT scan for attenuation correction not only reduces whole body PET scan times by at least 40%, but also provides essentially noiseless attenuation correction factors compared to those from standard PET transmission measurements. Since attenuation values are energy dependent, the correction factors derived from a CT scan at the mean photon energy of the polychromatic X ray beam (~70 keV) must be scaled up to the 511 keV PET photon energy.

The scaling algorithm uses a bilinear function to transform the attenuation values above and below a given threshold with different factors. The composition of biological tissues other than bone exhibit little variation in their effective atomic number and can be well represented by a mixture of air and water. Bone tissue does not follow the same trend as soft tissue because the

calcium and phosphorus content requires a different scaling factor that reflects a mixture of water and cortical bone. The breakpoint between the two mixture types is set at around 100 Hounsfield Units (HU) as shown in Fig. 3.

Intravenously injected iodinated contrast is used in CT to enhance attenuation values in the vasculature. At the PET photon energy (511 keV), the presence of iodinated contrast only has a 2% effect on attenuation. However, if contrast enhanced pixels are misidentified as bone, the applied scaling factor will be incorrect and the erroneously scaled pixels could, in theory, generate artefacts in the PET image. Many thousands of PET/CT scans have been performed in the presence of intravenous contrast and experience has shown that contrast administration does not cause problems that affect its diagnostic accuracy [12, 13].

Oral contrast is administered to visualize the gastrointestinal tract and the distribution of the contrast material is rather variable, both in spatial distribution and level of enhancement [14]. It is not clear whether contrast medium produces significant diagnostic effects on the PET scan.

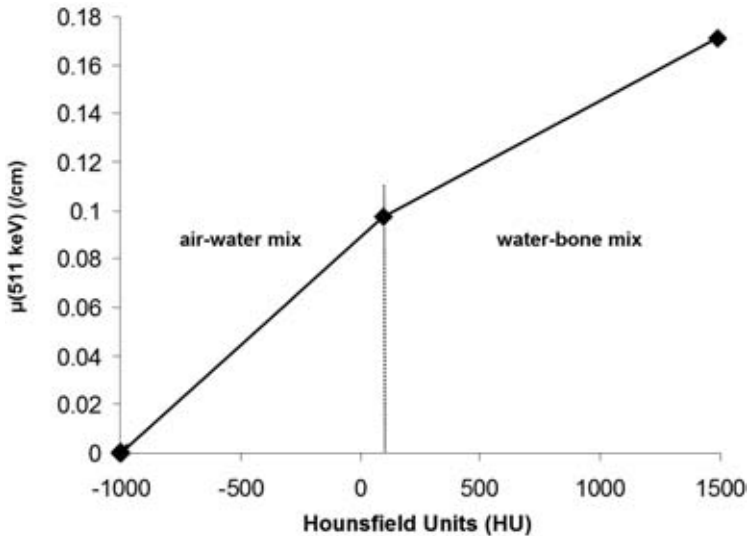


FIG. 3. The bilinear scaling function used to convert CT numbers to linear attenuation values at 511 keV. The graph shows the linear attenuation coefficient at 511 keV as a function of the corresponding CT value (HU), based on measurements made with the Gammex 467 electron density CT phantom using tissue equivalent materials. The separation between soft tissue (air–water mixing model) and bone like tissue (water–bone mix) is around 100 HU.

Avoiding the administration of contrast would reduce the likelihood of such problems; however, the decision to administer contrast depends on whether or not the CT scan has been requested as a diagnostic clinical CT scan and is, therefore, subject to specific CT protocol requirements. One suggestion to avoid such potential problems is to perform two CT scans: a clinical CT with appropriate contrast administration, and a low dose, non-contrast CT for attenuation correction and co-registration. This dual scan approach will, however, increase the radiation exposure to the patient (see Section 4).

### 3. CLINICAL METHODOLOGY

#### 3.1. RADIOPHARMACEUTICALS

Positron emitting isotopes that can easily be produced using either a small medical cyclotron (11 MeV) or a generator system are shown in Table 1. These include carbon, oxygen and nitrogen, the natural building blocks of all compounds in the human body. In addition,  $^{18}\text{F}$  can be substituted for hydrogen so that all compounds used by the human body can potentially be labelled.

The expertise and availability of a radiochemist is the determining factor in the number of compounds that can be labelled. To date, over 1000 compounds have been prepared. The most common and important is  $^{18}\text{F}$  labelled FDG. Other compounds that have found applications in clinical medicine include those listed in Table 2. The cyclotron and associated radiochemistry are outside the scope of this document.

TABLE 1. THE MAIN POSITRON EMITTING ISOTOPES CURRENTLY USED FOR MEDICAL APPLICATIONS

Nuclide	Half-life (min)	Positron emission (%)	Max. energy (MeV)	Production
$^{18}\text{F}$	109.8	97.0	0.633	Cyclotron
$^{11}\text{C}$	20.4	99.8	0.959	Cyclotron
$^{13}\text{N}$	9.96	100.0	1.194	Cyclotron
$^{15}\text{O}$	2.04	100.0	1.738	Cyclotron
$^{82}\text{Rb}$	1.27	96.0	3.40	Generator

TABLE 2. COMPOUNDS LABELLED FOR PET APPLICATION

<sup>11</sup> C thymidine	<sup>18</sup> F fluorothymidine
<sup>11</sup> C methionine	
<sup>11</sup> C choline	<sup>18</sup> F fluorocholine
<sup>11</sup> C tyrosine	<sup>18</sup> F fluorotyrosine <sup>18</sup> F fluoroethyltyrosine
<sup>18</sup> F fluorodihydroxyphenylalanine (FDOPA)	
<sup>18</sup> F fluoromizonidazole	
<sup>18</sup> F uracil	
<sup>18</sup> F annexin	
<sup>11</sup> C acetate	
<sup>13</sup> N ammonia	
<sup>15</sup> O water	<sup>15</sup> O oxygen gas
<sup>18</sup> F fallypride	
<sup>82</sup> Rb rubidium chloride	

A more detailed description of the mechanism of action, effects and potential for future applications for some of the above agents can be found in the recent article by Juweid and Cheson [5].

### 3.2. WHOLE BODY IMAGING

The following points should not be taken as suggested protocols, but rather as an indication that they have an impact on patient dose and, thus, might be usefully considered when preparing the patient and/or performing the scan:

- Overnight (or at least 4 h) fasting prior to the start of the study to avoid repeat study.
- Measurement of blood glucose level. If glucose level is greater than 8 mmol/L (150 mg/dL), proceeding with the scan is dependent on the actual glucose level. If very high, control of the diabetes should be considered before performing the scan.
- 185–555 MBq (5–15 mCi) of FDG is administered intravenously. The injected dose is sometimes based on body weight and if so, values in the range of 3–4.5 MBq/kg (80–120  $\mu$ Ci/kg) are used. In some countries, use of lower activities may be required by regulations.

- Patients are placed in a quiet, dimly lit room at rest for 45–90 min to avoid brain and muscle stimulation during the FDG uptake period.
- Patients are then asked to void to minimize bladder radiation and are placed in the PET/CT scanner – arms down for head and neck, arms up for the rest of the body.
- Patients referred for radiotherapy planning are positioned to reflect their treatment positioning.
- Low dose CT scans are performed without intravenous contrast for attenuation correction and for anatomical localization.
- Patients are scanned from the pelvis to the head, avoiding high bladder activity that can produce reconstruction and anatomical registration errors.
- Diagnostic CT with intravenous contrast is sometimes required. In some institutions, the low dose CT may be replaced by this diagnostic CT. Diagnostic reference levels as established by national and international organizations should be used for guidance.

Additional advice is available from professional bodies in many countries and should be considered. In practice, many factors influence image quality and may compromise accurate image interpretation. This may necessitate repeat scanning that would increase patient dose.

### 3.3. CARDIAC IMAGING

The two most frequently used cardiac protocols incorporate FDG for glucose metabolism studies and  $^{13}\text{N}$  ammonia or  $^{82}\text{Rb}$  rubidium chloride for rest–stress myocardial perfusion studies. The following points might be usefully considered when preparing the patient and/or performing the scan:

- Start an intravenous line (20 G) and leave in place;
- Check baseline glucose;
- Give 25–50 g of glucose in 100–150 mL of water to drink;
- Wait 10 min and recheck glucose;
- Give remainder of bottle of glucose if required;
- Monitor the increase of glucose;
- Administer 370 MBq (10 mCi) FDG when glucose falls between 5 to 7 mmol/l (100–140 mg/dL);
- Wait 60 min for uptake of FDG;
- Position patient in scanner with arms up;
- Acquire low dose CT scan;

- PET acquisition: centred over heart, one bed position for 10 min;
- Check glucose level after scan.

If the blood sugar is above 7 mmol/L, then insulin will be required according to local practice. The cardiac PET radiation dosimetry is identical to that for an oncology scan with 370 MBq injected, whereas the CT scan is limited to a single bed position and consequently the effective dose will be 15–20% of that for a whole body oncology scan.

A cyclotron in close proximity to the PET/CT scanner is required for the  $^{13}\text{N}$  production due to the 10 min half-life.  $^{82}\text{Rb}$  is produced from a generator that usually needs to be replaced about once per month. The combined imaging of metabolism and perfusion is termed a ‘cardiac viability’ study and is used to distinguish myocardial segments that are metabolically viable but poorly perfused from those segments that are poorly perfused and no longer viable.

An example of a protocol for a typical rest–stress rubidium myocardial perfusion study is shown in Fig. 4. For  $^{82}\text{Rb}$ , typical injected doses are in the range of 1110–2220 MBq (30–60 mCi) administered at a rate of 50 mL/min not to exceed a cumulative volume of 200 mL. Appropriate protocols for cardiac applications of PET/CT are currently being developed, whereby  $^{82}\text{Rb}$  is used for rest–stress perfusion imaging and a 64 slice CT scanner for CT angiography and attenuation correction.

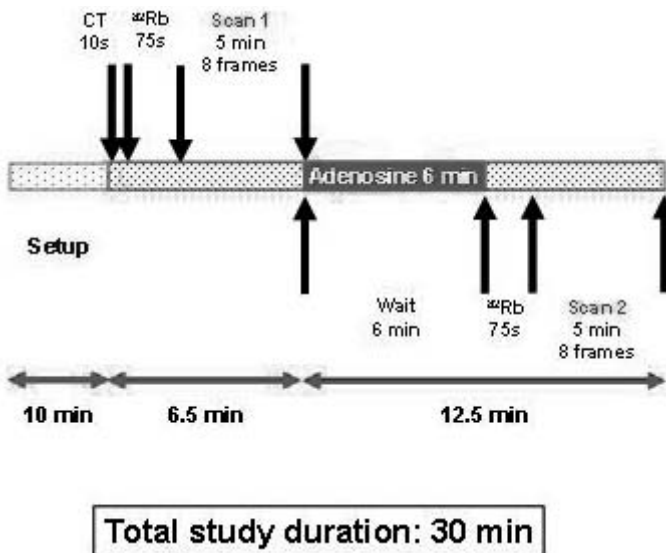


FIG. 4. A typical rest–stress  $^{82}\text{Rb}$  protocol implemented with an infusion system.

## **4. RADIATION EXPOSURE OF PATIENTS UNDERGOING PET/CT EXAMINATIONS**

### **4.1. GENERAL ASPECTS OF PATIENT PROTECTION: JUSTIFICATION AND OPTIMIZATION**

The issue of patient exposure has to be addressed adequately when reviewing the benefits of a new imaging modality. Both the BSS and the International Commission on Radiological Protection (ICRP) [2, 15, 16] adopt a multi-step approach to this. First, a new practice is identified (such as the use of PET/CT in oncology). This must then be justified before it is generally adopted. In the case of PET/CT, a (preliminary) generic justification is provided — at least for cancer patients — by the promising results reported in the literature. However, much more work is required in this regard. For complex diagnostic procedures, including PET/CT, a further step of individual justification that takes into account the objectives of the exposure and the needs of the particular patient is required.

Optimization is a further general principle in the system of radiological protection. It requires that once a practice, or a new examination, is justified the exposure should be kept as low as reasonably achievable for the required image quality, economic and social factors having been taken into account [15]. Optimizations must be undertaken at many levels, ranging from the generic establishment of protocols to the most effective way of employing them in an individual case. It is of particular importance during the early stage of introducing a new diagnostic technology.

In order to provide a rational framework for the justification and optimization of PET/CT examinations, its benefits must be balanced against the radiation risks involved. The latter are usually quantified with reference to radiation dose. The remainder of this section and Section 5 deal with dose and optimization considerations.

### **4.2. DOSIMETRIC QUANTITIES**

#### **4.2.1. Effective dose**

Radiation exposure in PET/CT examinations arises from both internal and external sources. The easily measurable quantities are the amount of administered radioactivity and the entrance exposure (air kerma). The absorbed dose to the organs of patients can be calculated from these measured



quantities. In order to quantify the radiation risk, the effective dose ( $E$ ) is widely used as it takes into account the doses received by all organs weighted for their radiosensitivity as given by the ICRP [16].

The ICRP and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [17] have cautioned against the use of effective dose to estimate detriment (to individual or specific populations). Such estimates suffer from uncertainties arising from potential demographic differences (in terms of health status, age and sex) between a specific population of patients and the general populations for whom the ICRP derived the risk coefficient. It has been suggested, for example, that effective dose could broadly underestimate the detriment from diagnostic exposure of younger patients by a factor of about two and, conversely, could overestimate the detriment from the exposure of older patients by a factor of at least five [17]. Thus, rigorous analysis of radiation risk from diagnostic medical exposure requires detailed knowledge of organ doses and the age and sex of patients.

Despite these limitations, both the ICRP and UNSCEAR have used effective dose as the quantity to represent risk in the absence of a better quantity, but with an understanding of its limitations. In this document, we have decided to follow this approach.

#### **4.2.2. Computed tomography dose index and dose length product**

Calculating patient exposure from CT requires sophisticated quantities and methodology. Special dosimetric quantities are used, such as the computed tomography dose index (CTDI), weighted CTDI ( $CTDI_w$ ) for a single slice, dose length product (DLP) for a complete examination and CTDI ( $CTDI_{vol}$ ) for use with spiral CT. These quantities are described in detail in many sources and are defined briefly in the Appendix [18].

### **4.3. RADIATION EXPOSURE IN PET/CT**

The exposure to the patient from a PET/CT scan is internal and external. Both types of exposure are addressed below.

#### **4.3.1. Internal exposure (PET)**

The effective dose  $E_{int}$  resulting from intravenous administration of an activity  $A$  can be estimated from:

$$E_{int} = \Gamma \cdot A \tag{1}$$

where  $\Gamma$  is a dose coefficient computed for the adult hermaphrodite MIRD phantom. For  $^{18}\text{F}$  labelled FDG and  $^{82}\text{Rb}$ , the dose coefficients are 19 and  $3.4 \mu\text{Sv}/\text{MBq}$ , respectively [19]. These dose coefficients hold for standard patients with a body weight of about 70 kg and are generic rather than patient specific since age, gender of patients and individual pharmacokinetics are not taken into account. In fact, the radiation risk is somewhat higher for females and for younger patients when compared to male and older patients. Age and gender specific dose coefficients can be found in the cited ICRP document.

With  $^{82}\text{Rb}$ , the effective dose for an injection of 2220 MBq is 7.5 mSv. The kidneys are the critical organ and receive an absorbed dose of 19 mGy.

#### 4.3.2. External exposure (CT)

Dose assessment in CT is challenging and depends not only on the body region exposed but also on a variety of scan specific parameters (tube potential (kVp), tube current multiplied by exposure time (mAs), slice collimation, pitch factor) and technical features of the scanner (e.g. beam filtration, beam shaping filter, geometry and acquisition algorithm used) [20, 21]. Thus, values for patient dose vary considerably between centres and machines. Oversimplified approaches have correlated mAs with patient dose, assuming that kVp and other parameters in a particular CT scanner are kept constant. This has also led to the unsatisfactory practice of using mAs as a dose indicator when comparing different scanners.

Various software packages have been developed to address these problems. For example, with whole body CT scans Brix et al. [22] present a simple approach to providing a rough estimate of organ doses and effective dose. The organ dose,  $D_T$ , can roughly be estimated as:

$$D_T = \Gamma_T^{\text{CT}} \times \text{CTDI}_{\text{vol}} \quad (2)$$

where  $\Gamma_T^{\text{CT}}$  is an organ specific dose coefficient that relates the volume CTDI,  $\text{CTDI}_{\text{vol}}$ , to organ dose [22]. The organ doses can be combined with weighting factors in the normal way to give effective dose. For a whole body CT (thyroid to the symphysis), Brix et al. [22] use 1.47 for the combined weighting factors and  $\Gamma$  dose coefficients as a multiplication factor for  $\text{CTDI}_{\text{vol}}$  to give effective dose in mSv.

#### 4.3.3. Combined exposure in PET/CT

The effective dose from a combined PET/CT examination is the sum of the effective doses arising from all scan components and, thus, depends on the

range of acquisition parameters mentioned above. Figure 5 shows an example of an examination protocol, consisting of a topogram for the definition of the scan region, a low dose CT scan (e.g. 130 kVp, 40 mAs), followed by an FDG-PET emission scan and a contrast enhanced diagnostic CT scan (e.g. 130 kVp, 160 mAs). These effective dose ranges for the different scan components as determined in a multi-centre study are also shown in Fig. 5 [19]. The total effective dose for the whole body FDG-PET/CT using the imaging protocol in Fig. 5 averaged 25 mSv [22] and was nearly independent of the selected site. Up to 70% of this was contributed by the CT scan elements, and 85% of the CT contribution (two thirds of the total) arose from the final diagnostic scan. An alternative approach, commonly used, is to perform the PET/CT only from the cerebellum to the mid-thigh. The dose in this case would be approximately in the range of 15–20 mSv.

## 5. PATIENT DOSE MANAGEMENT

Patient dose management in PET is less complex than in CT, provided one has a well designed facility, and one has control of the radioactivity that is administered. Obviously, aspects relating to facility design, shielding and layout are important in this regard. However, they are treated in Sections 6.2–6.5, as they also strongly impinge on staff protection. On the other hand, dose management in CT has continued to be a challenge. CT studies conducted in their own right (without PET) now account for 5 to 25% of all studies in large

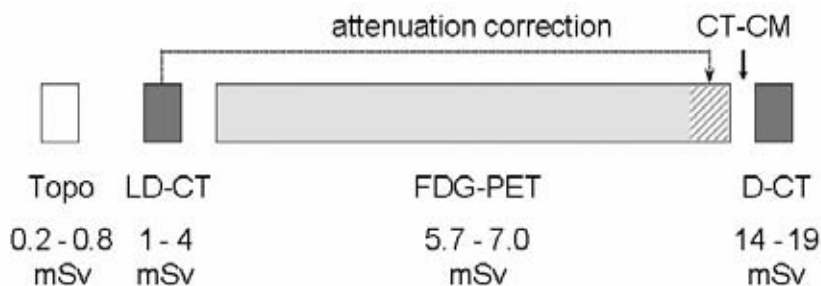


FIG. 5. Typical PET/CT examination consisting of a topogram (Topo), a low dose CT scan (LD-CT) for attenuation correction, an FDG-PET scan and a diagnostic CT scan (D-CT) acquired after the administration of an intravenous CT contrast medium (CT-CM). For each scan component, the range of effective dose values determined in a recent multi-centre study [22] is indicated.

medical centres in the developed world, and contribute half to two thirds of the effective dose received by patients from diagnostic radiology [23, 24].

## 5.1. JUSTIFICATION OF INDIVIDUAL PET/CT EXAMINATIONS

PET with  $^{18}\text{F}$ -FDG has a proven role in the diagnosis and staging of cancer, but is also appealing for assessment of prognosis and treatment. A systematic search of the literature provides good evidence that  $^{18}\text{F}$  FDG uptake on PET has independent prognostic value in newly diagnosed cancers. The number of funded indications will vary depending on the health economy of a particular country as well as on their different health care problems and incidence of disease. Major indications for the role of PET/CT have already been identified and have been included in clinical guidelines endorsed by the main medical societies so that the radiation dose can be justified. Several health technology assessment agencies have run independent systematic evaluations which support clinical applications in selected clinical conditions. Newer indications should be evidence based with leeway to perform a proportion of scans in specific clinical scenarios where the evidence may not be strong but the clinical problem specific for a given patient may be solved [25, 26]. Complete knowledge of the clinical question(s), what recent interventions have been performed (surgery, chemotherapy, radiotherapy, etc.), current medical problems and medication and, most importantly, what other imaging has been performed or is planned will enable the scan to be justified in terms of the radiation exposure and the risk benefit.

This requires that three major questions be addressed [27]:

- (1) *Is a high quality CT scan for PET/CT needed for diagnosis or therapy management?*

In the case where a separate, diagnostic CT was performed shortly before the PET/CT examination, it may be sufficient to acquire a low dose CT scan as part of the combined PET/CT study. In most cases, the image quality of a low dose CT scan is adequate for anatomical correlation and attenuation correction [28]. With this approach, overall patient exposure is dominated by internal radiation from the emission scan and is, thus, comparable with a conventional PET study.

- (2) *Can previously acquired anatomical data be used for correlative interpretation of the PET?*

If separate high quality CT or magnetic resonance imaging (MRI) scans have been acquired during the clinical work-up, they may possibly be used for retrospective image registration with the PET study [29]. To this

end, anatomical images already available have to be co-registered with low dose CT images acquired with the PET/CT system before they are fused with the attenuation corrected PET data. However, the requirements for clinically acceptable image registration techniques are high. To date, the non-linear fusion approaches, which are required in extra-cerebral applications, have not been successful. While such an approach to image fusion appeals, from a radiation protection point of view, its usefulness is constrained to a limited number of situations, mostly neurological and much further work is required in this area.

- (3) *Can the low dose CT scan be replaced by the contrast enhanced diagnostic CT scan?*

Once the acquisition of a contrast enhanced diagnostic CT has been justified as part of a PET/CT examination, it is necessary to decide whether it can also be used for CT based attenuation correction. The question arises as to whether or not the intravenously administered contrast agent for the CT scan leads to clinically relevant high density artefacts in the attenuation corrected PET images [12]. Most recent studies demonstrate that attenuation correction artefacts rarely cause diagnostic problems in the clinical setting when optimized protocols are used [30]. They do not result in elevated uptake levels that may degrade the diagnostic value of the attenuation-corrected PET images [13]. However, further work is necessary to determine the best approach to practice in this area.

## 5.2. OPTIMIZATION OF PET/CT EXAMINATIONS

Optimization requires that both the PET and the CT elements of the study be individually addressed.

### 5.2.1. PET scan

Radiation exposure to patients resulting from intravenous administration of  $^{18}\text{F}$  labelled FDG is directly proportional to the radioactivity of the glucose analogue injected. As is evident from the literature, the average administered  $^{18}\text{F}$  labelled FDG activities vary from 350 to 550 MBq depending on the detector material (BGO, GSO or LSO) and the count rate behaviour of the PET scanner, and on the acquisition mode used (2D or 3D) and patient size. From a clinical point of view, lower activities eventually result in longer emission scan times, and thus longer overall examination times. However, excessive PET/CT examination times should be avoided as they may result in

patient discomfort and, hence, in motion induced misregistration in the corresponding PET and/or CT images. Administration of greater amounts of radioactivity in order to reduce the scan time is not encouraged. In any case, voiding of the bladder should be forced (provided there are no contraindications), e.g. by oral hydration with water or the administration of a diuretic (e.g. 20 mg furosemide) [31, 32]. This is a very effective measure, because FDG in the bladder, besides being a source of artefacts in PET image reconstruction, is the major source of internal exposure to the bladder itself as well as to neighbouring organs.

### 5.2.2. CT scan

A significant part of the challenge of patient dose management in CT arises from the fact that over-exposure in CT is frequently not detected. In contrast to film based radiography where overexposure results in a dark image, increasing dose in CT and in other digital imaging techniques results in images with less noise (improved visual appearance) and fewer streak artefacts, although not necessarily with greater diagnostic information. It is widely believed that image quality in CT often exceeds the clinical requirements for diagnosis [33]. The ICRP noted that technical and clinical developments in CT have not led, in general, to a reduction in patient dose per examination, and that there was a clear need for optimization of doses [20, 21].

In recent years, many papers have shown that adequate diagnostic information can be obtained with CT studies at lower doses [34–36]. All manufacturers have incorporated automated exposure control (AEC) systems. Basically, three types of control are used to varying degrees:

- Patient size AEC determines the average dose required based on the average size of the patient.
- Longitudinal AEC ( $z$  axis AEC) determines the change in average dose because some parts of the body have higher attenuation than others, e.g. shoulders and hips. It adapts tube current from one slice position to another, based on changes in regional attenuation of the tissues in the cross-sectional volumes at different slice positions.
- Rotation AEC (angle modulated AEC or angular modulation) modulates the dose to account for the difference in attenuation as the tube rotates around the patient, as the anterior–posterior diameter is less than the lateral diameter. Thus, rotation AEC adapts tube current based on the geometry and attenuation of the scan volume at different projection angles within each slice position.

A combined AEC technique, which includes longitudinal and rotational AEC, has recently been introduced. Patient size and longitudinal AEC systems use the scan projection radiographs (SPR) or topograms, which are taken at set-up to estimate patient attenuation. Rotational AEC can also estimate the required modulation from the SPRs with assumptions as to the patient cross-section, or by modulating the dose based upon attenuation in the previous rotation. All manufacturers use some combination of these techniques in their latest multi-row scanners.

The degree to which the dose is modified depends upon the criteria used. The criteria can be:

- A target noise value in the image;
- A reference image;
- An average mAs value.

Further sophistication can be introduced to obviate the very high doses that such approaches would require for large patients. These techniques have demonstrated dose reductions of typically 15–65% using AEC [34–36]. Although the design and operation of AEC systems differ between different manufacturers, in general they all require the user to define acceptable noise levels or exposure settings for a standard patient. Therefore, patient dose may not be minimized if inappropriate values are used for these settings. Image noise is affected by mA, scan time, kVp, patient size, pitch, thickness of reconstructed slices, reconstruction algorithm, and the window/level used to view the images. Of these, the first four affect both image noise and patient dose; the last three affect only noise. There has also been some work on image noise and patient size. Regardless of the approach used, it is essential that the end user is fully trained in how best to use the particular approach employed [20, 21].

A recent CRP run by the IAEA in six countries in different parts of the world demonstrated dose reduction in abdominal CT from 25 to 62% and from 12 to 79% for chest CT [37]. This project was based on identifying acceptable values of target noise for patients of different weight, without sacrificing the diagnostic confidence level in the image. For all the countries involved, average patient doses were lower than published reference values for CT [18, 38–40]. Despite this, the image noise was low for several countries, and it was still possible to further reduce the patient dose. This indicates the need for population specific diagnostic reference dose values.

Care should be taken when planning the PET/CT acquisition that, whenever clinically justifiable, the scans should spare the gonads and eyes at either extremity of a typical range. There are, of course, situations where it is necessary to include organs proximal to either or both. Typical examples

include melanoma and cancers of unknown primary origin. In these cases, however, the resulting increase of the radiation exposure (from the CT) is motivated, or even mandated, by a clinical need.

The CT scan must cover the same axial extent in order to provide attenuation correction factors and localization for the PET images. This technical limitation may be overcome in the future through the implementation of continuous bed motion acquisition for PET data. In general, non-congruent imaging ranges of PET and CT scans, as well as multiple spirals with different CT parameters should become available with clinical PET/CT acquisition software. This flexibility would open up the possibility, for example, of acquiring high quality CT scans for part of the body, and to image the remaining axial imaging ranges with a low dose CT. Hopefully, these possibilities will be realized in the near future.

### 5.3. PET/CT AND THE PREGNANT OR BREAST FEEDING/ LACTATING PATIENT

In the very rare situation where a PET/CT is prescribed for a pregnant patient, special attention must be given to the justification of the procedure, and the risks and benefits that apply to both the mother and the foetus. This issue is discussed in the BSS, many safety reports, textbooks as well as in a recent European Union report [2, 3, 41, 42]. At a practical level, the protocols for both PET and CT must be modified and optimized, taking account of the presence of the foetus, with a view to minimizing its exposure, and the concerns of the mother after due counselling. It is essential to use as low an activity of FDG as possible without losing the necessary image quality. Typical uterine doses from FDG are  $21 \mu\text{Gy}/\text{MBq}$  [19] and this amounts to 7.5 mGy for a 370 MBq dose. Optimization of the protocol for CT includes limiting mAs and other parameters to minimize CTDI without compromising image quality, and limiting the extent of region scanned to that essential for diagnosis. Whenever imaging of the region involving the foetus is required, it should be performed with a minimal number of slices. Essentially, practice in this situation should follow good practice for both CT and nuclear medicine.

When a PET/CT is prescribed for a breast feeding or lactating patient, special attention must be given to the justification of the procedure, and the risks and benefits that apply. The mother should be adequately counselled and her wishes should be determined. FDG is concentrated in the breast but little is secreted in the breast milk ( $5.5\text{--}19.3 \text{ Bq}\cdot\text{mL}^{-1}\cdot\text{MBq}^{-1}$  injected) [43]. The infant would, in practice, receive more radiation from contact with the mother than from the breast milk. It is reasonable to advise no contact between the child



and mother within 4 h of the activity injection. The mother should also preferably express breast milk prior to the injection and this should be used for the first feed after the scan. The mother should express one feed 2 h after the scan and this should be discarded.

## **6. RADIATION PROTECTION OF THE STAFF IN A PET/CT FACILITY**

### **6.1. SOURCES OF RADIATION EXPOSURE**

The main sources of radiation exposure for staff in the PET facility include:

- Unshielded radiopharmaceuticals (present during preparation and dispensing);
- Patients injected with PET radiopharmaceuticals;
- The patient toilet;
- Sealed calibration sources, QA phantoms;
- The CT scanner.

### **6.2. WORK PRACTICE CONSIDERATIONS**

Factors affecting the staff radiation exposure include the number of patients imaged, type and amount of radiopharmaceutical administered per patient, length of time spent by the patient in each area of the PET/CT facility, and its physical layout. The highest staff exposures occur while performing the following tasks:

- Assaying the amount of radiopharmaceutical;
- Administering the radiopharmaceutical;
- Performing tasks near the patient (post-injection) during the radiopharmaceutical uptake period;
- Escorting the patient to and from the scanner;
- Positioning the patient on the scanner bed;
- Calibration and QC of the PET scanner using sealed sources.

In all cases, these exposures can be minimized through good design, good practice, patient instruction/cooperation and attention to the importance of the basic approaches including distance, time and shielding. Radiochemists and radiopharmacists also receive significant exposure in facilities that manufacture and prepare their own radiopharmaceuticals. However, this aspect is beyond the scope of this report.

### 6.3. GENERAL ENVIRONMENT AND LAYOUT OF A PET/CT FACILITY

Building a new PET/CT facility de novo or setting one up in an existing nuclear medicine or radiology department requires a good planning team. This should include an architect, a designated project manager, a medical physicist with facility design experience, a radiation protection officer, a construction or site engineer, an administrator, a PET/CT technologist or radiographer, a nuclear medicine physician/radiologist and other physicians as appropriate. It is imperative that the installation be planned in a way that takes due account of operational considerations, workflow and shielding requirements; architectural drawings must be evaluated against these [44].

Access to the department for both ambulatory and trolley (gurney) patients will be required. Some areas will be designated as controlled areas, with access restricted to PET/CT staff. Other areas may be designated as supervised with access controlled by signage and warning lights. Access to staff only areas should be possible without passing through high activity areas. Patients should be able to enter and leave the department without passing through staff only areas. The layout should be such that it facilitates patient movement through the various steps involved. The exit route for patients post scanning should be planned so that, where possible, they leave the hospital promptly without passing through other departments or busy public areas. If the PET/CT scanner is to be located in or close to nuclear medicine, care must be taken to avoid interference from injected patients with other imaging equipment. Likewise, care must be taken that interference with sensitive equipment, including gamma cameras, does not arise as patients leave.

A well designed facility includes a separate hot laboratory for radiopharmaceutical storage, calibration and dispensing, an appropriately shielded waste storage area/container(s), and separate patient injection and holding areas. Careful attention should be paid to the location of the dispensing and patient injection areas, the post injection holding rooms and the patient toilet in relation to areas used by the general public and staff. The distances from

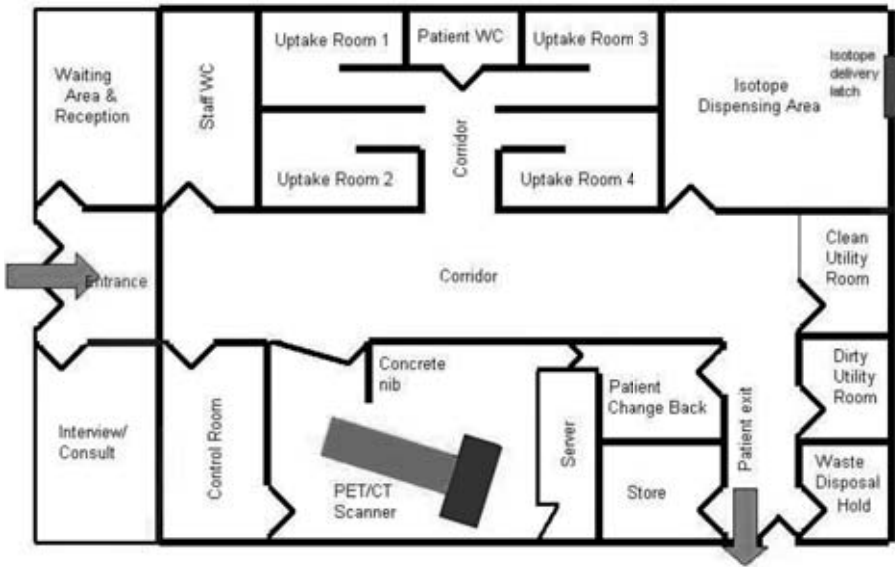


FIG. 6. An example of a possible layout for a diagnostic PET/CT facility.

injected patients and/or sources to shielded walls should be maximized to limit the amount and cost of shielding required.

Figure 6 shows a possible design that takes advantage of room layout to separate staff and detectors from the high exposure patient uptake area. The patient toilet is easily accessible and close to where it will be needed in practice. Impractically heavy doors on the uptake room are avoided by use of a nib at the entry to each uptake area. The resulting high exposure in this short corridor can be justified since it has low occupancy, and is limited to staff accompanying patients. Shielding needs in the radiopharmacy walls may be more modest since the radiopharmaceuticals are only removed from their shielded containers briefly for calibration purposes. Even with a typical 4.3 m floor to floor spacing and normal density concrete, it is unlikely that one could locate a high use room (such as an office) directly above or below the patient uptake rooms without significant additional shielding. Some of the other rooms are briefly discussed in Sections 6.4 and 6.5.

## 6.4. PATIENT FACILITIES

The following patient facilities contribute to both optimization of the scan (see Section 5) and to staff protection [44].

### 6.4.1. Interview room/consultation room/office

Thorough patient screening and preparation is an important element of successful PET imaging. An interview room or office where this can be done prior to attendance for scanning is desirable. This should be located so that patients attending should not have to pass through high activity areas. This room might also double as a nurse/technologist office.

### 6.4.2. Waiting room

The waiting area requirements for a PET/CT scanner are relatively modest because of the pattern of workflow. The waiting area is for patients and any accompanying persons prior to administration of the radiopharmaceutical and no special shielding is required. Access to a patient toilet should be available.

### 6.4.3. Uptake rooms

As many as four injection/uptake rooms may be required per scanner, depending on local work patterns. These allow the patient to be isolated in a quiet and darkened area to avoid stimulation, which could result in regional increases of brain or muscle uptake of FDG that might complicate the interpretation of the study. These areas will require high levels of shielding. Each room should accommodate a reclining patient chair, instrument trolley and shielded waste/sharps bins. The patient may also change into a hospital gown in this area. At least one of the uptake rooms should be able to accommodate a patient trolley.

A basin for washing hands with non-contact taps should be provided. Surfaces should be non-porous and easily cleaned and decontaminated. Privacy curtains, subdued lighting and noise control should be provided [45]. Reliable climate control is desirable, both for patient comfort and to ensure optimal conditions for uptake. CCTV may be required for remote patient monitoring and will facilitate reduction of staff doses.

A toilet dedicated for patients is provided nearby so that the patient can empty his/her bladder prior to scanning, without having to walk through the department.

#### **6.4.4. Scanning rooms**

The minimum requirements for space in the scan rooms should be obtained from the site planning documentation provided by the vendor [45]. Typical dimensions are of the order of 30–35 m<sup>2</sup> with an additional 10–15 m<sup>2</sup> for the control room/console area. Extra space provided within the scanning room will reduce the shielding required to reduce the exposure at the boundaries. The scanner should be oriented with the bore at the end of the scan room furthest from the operator's console, and separated from the scanning room by lead-glass windows. Means of observing the patient and maintaining aural communication with them must be provided. Provision for an automatic CT contrast injector may be required. There are strict requirements for environmental control in scan rooms because of the sensitivity of the PET scanner to temperature.

The control/console room should provide direct access to the scanner room, and be close to the dispensing and uptake rooms. The shielding of the control/console room must be specified depending on whether the dose constraint to be applied is that for the public or designated radiation workers. Achieving the 0.3 mSv/a required for public exposure, in some countries, is in practice very difficult given the requirement for patient observation. This should be considered when designing the layout of the facility. This is particularly important if the control/console area has general purpose consultation and teaching functions, or if it is shared with a non-ionizing radiation imaging modality, such as MRI.

#### **6.4.5. Post-scan patient changing room**

If the patient will be scanned in a hospital gown, changing facilities pre-scanning can be incorporated into the uptake rooms. However, after scanning, it is convenient to have a changing area elsewhere so that maximum usage of the uptake rooms can be achieved. A single changing room should be adequate, as only one patient at a time will require it. This should be sited close to the scanning room in order to minimize movement of the patient through the facility.

### **6.5. SHIELDING CONSIDERATIONS**

The purpose of the shielding is to limit the amount of radiation reaching patients, workers, visitors and nearby sensitive radiation detectors, such as gamma cameras or unexposed film. A useful framework for shielding

calculations is provided by the recent National Council on Radiation Protection and Measurements (NCRP) document, taking due allowance of the remarks on design guidelines and dose constraints below, and in Section 6.4.4 [46]. All areas surrounding a PET facility must be evaluated for shielding, including those beside, above and below patient injection, holding and scanning rooms. Shielding calculations for a PET and/or PET/CT centre have added complexity due to the contributions from multiple source locations adjacent to each occupied area. Shielding materials generally include lead, iron and low or normal density concrete (1.84 and 2.35 g/cm<sup>3</sup>, respectively).<sup>1</sup> Generally, where concrete is used, the higher density should be specified. If the lower density must be used, allowance must be made for this in the shielding calculations. Because of scatter buildup factors, the sometimes quoted 4.1 mm half value layer for 511 keV photons in lead may not be valid for shielding calculations. The attenuation of 511 keV annihilation photons in these materials under broad beam/thick absorber geometries is complex, but excellent useful practical advice, data and techniques are available in Ref. [47].

It would not be unusual for a small uptake room to require 2 cm of lead to shield it adequately. This might take the form of interlocking lead blocks sandwiched between layers of plywood for structural support. Due to cost and weight considerations, it is worth exploring the possibility of varying the thickness of the shielding material in each boundary. Other than patient holding and the radiopharmaceutical preparation/handling areas, rooms may only need 3 mm of lead to satisfy the NCRP recommended facility design guidelines of 5 mSv in one year for controlled areas and 1 mSv for uncontrolled areas. However, not all countries accept the NCRP guidelines. Several countries, with a view to optimization, set more demanding goals. For example, 1 and 0.3 mSv are used in some countries as the design goals for areas occupied by workers and the general public, respectively [46, 48].

In practical terms, with FDG use, the uptake area will generally require more shielding than the scan room, which is used for only 20 min, after the <sup>18</sup>F has already significantly decayed. By comparison, the scanning room becomes the primary focus for shielding with the very short-lived <sup>82</sup>Rb, which must be injected with the patient already in the scanner bore and undergoes almost total decay before the patient leaves the room. Despite its very short half-life, it may not result in significantly lower scan room shielding requirements than the

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<sup>1</sup> Construction contractors prefer to use low density concrete because the thermal insulation resulting from the encapsulated air bubbles improves its fire rating properties. This helps to avoid applying fire retardant materials under the floor that are difficult to handle and make future sub-floor utility alterations unpleasant.

substantially decayed FDG activity. This is partly accounted for by the three to six times higher  $^{82}\text{Rb}$  activity used in cardiac studies for each of the resting and stress scans.

### 6.5.1. Data for shielding calculations

The average number of patients per week, type of procedures performed and radiopharmaceutical activity used per patient must be realistically estimated. The following data set is typical of what might prevail with FDG scanning:

- Dose rate constant =  $0.147 \mu\text{Sv}/\text{MBq}\cdot\text{h}$  at 1 m.
- The body of the patient absorbs some of the annihilation photons; thus, the external dose rate is reduced by approximately 36% [46].
- Typical activity injected: 555 MBq.
- Patient voiding will reduce activity by about 15–20% in the first two hours [47].
- Uptake time: 45–90 min.
- Workload:  $10 \text{ patients}/\text{d} \times 5 \text{ d}/\text{week} = 50 \text{ patients}/\text{week}$ .<sup>2</sup>

Shielding for the CT component of the PET/CT systems is essentially the same as that of an independent CT system, though the CT workload is generally lower than for a dedicated CT unit. Since the half-value layer (HVL) for CT techniques is much lower than that of the positron annihilation photons, additional shielding for the CT component is often minimal. Finally, the CT shielding applies to the scanning room only.

## 6.6. DOSE REDUCTION STRATEGIES FOR STAFF

PET imaging personnel receive relatively large annual radiation doses compared to their counterparts in general nuclear medicine and diagnostic radiology, so much so that they are becoming one of the subgroups with highest exposure, along with radiological and cardiological interventionalists. The main contribution to the radiation dose for the technologist comes from patient handling. A general nuclear medicine technologist typically receives an annual

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<sup>2</sup> It is important to count only patients scanned during the busiest work shift in a week. This is now the standard approach used to calculate workload in an environment using multiple shifts or weekend work.

whole body radiation dose of about 0.3–0.4 mSv and an extremity dose (hand) of approximately 15 mSv. At the other extreme, a PET technologist, involved in both dispensing and administering patient doses, may receive as much as 8 mSv whole body and 65 mSv to the hand [49]. The actual doses received by a particular technologist will obviously depend on the range of duties actually undertaken.

PET radiopharmacists, at facilities performing radiopharmaceutical synthesis and unit dose preparations, can receive significant hand and body doses, even where heavily shielded ‘hot cells’ are available to moderate dose. However, QC procedures performed outside the hot cells may still result in significant exposure. In some countries, those without access to hot cells install commercially available lead L-block shields to protect the body, though reaching around the shield to manipulate radiopharmaceuticals will give significant hand doses. In addition, it must be remembered that such facilities may not meet all local radiopharmaceutical preparation requirements for cleanliness, asepsis and infection control.

## 6.7. GOOD RADIATION PROTECTION PROGRAMME

PET/CT should be conducted within the framework of a well established radiation protection programme. This includes the usual assignment and delineation of responsibilities within the host institution, appointment of radiation safety committee, appointment of the person(s) responsible for radiation protection and safety, and preparation of a set of local rules, protocols and practices [3]. The radiation protection officer must institute an adequate personnel radiation safety programme. This will involve a number of staff members, including a radiopharmacist, technologists, nursing and other supporting staff who will be exposed as part of their routine activities. Arrangements must be made for personnel monitoring for all radiation workers, and, where necessary, whole body or beta sensitive extremity monitoring must be established. Work should take place in a framework that takes account of good practice in both CT and nuclear medicine.

A few points are worthy of special mention. Radiopharmaceuticals should be stored and transported in lead or tungsten containers specifically designed to limit external radiation levels from higher energy PET nuclides. An additional Lucite shield inside a lead or tungsten syringe shield will absorb positrons before striking the tungsten, minimizing unwanted production of bremsstrahlung radiation. The use of tongs to handle unshielded radiopharmaceutical vials markedly reduces hand doses. It is generally helpful to have radiopharmaceuticals that must be hand injected delivered to the facility in



ready to inject unit dose syringes. More recently, automatic systems have been made available which allow safe and quick radiopharmaceuticals dispensing into vials, thus minimizing operators' actions. The use of  $^{82}\text{Rb}$  does not, in practice, share many of these problems since the very short half-life requires an automated injection system that transfers the eluate directly from the shielded generator to the patient without the presence of a technologist.

In addition to the above, staff should use normal protective clothing, such as surgical gloves and hospital gowns/aprons to avoid skin contamination. However, these sometimes fail and attention should be given to monitoring for skin contamination and decontamination when it occurs. Each facility should have a monitor to check staff hands and feet on a frequent basis. Continuous radiation monitoring devices in the hot lab and injection room should be used to alert personnel to contamination or spills in these areas. Staff should institute procedures to minimize the time spent with radioactive patients, including use of remote video cameras and audio communication. This should be facilitated, as pointed out above, by the facility design, including appropriate use of remote video and audio monitoring. Finally, the facility design should carefully attend to the differences in design dose constraints for radiation workers and other hospital staff/students/public; it must ensure that the latter are not exposed to the dose levels appropriate to radiation workers, particularly in the control room, but also in adjoining areas.

## **7. TRAINING**

The basic training requirements and guidelines set by each country for each category of staff (nuclear medicine physicians, radiologists, medical physicists and technologists or radiographers as appropriate) should be followed for PET/CT. Its interdisciplinary nature will, in many instances, be best met through a collaboration and consensus among professional bodies on training requirements, and judicious use of continuing education programmes. If PET/CT is housed in a nuclear medicine facility, the physicians may need to gain the knowledge and skills required to interpret CT, and the nuclear medicine technologists may need to be able to perform CT examinations. On the other hand, if it is housed in a radiology department, the radiologists and radiological technologists may need to acquire knowledge and skills in nuclear medicine. Either way, the physicians, radiologists and technologists involved must be well educated and trained in PET/CT imaging procedures and

radiation protection principles. Some preliminary guidelines on training and education are available in Refs [50–53].

## 8. SUMMARY OF GUIDANCE

The guidance is summarized below:

- Careful attention is required to good practice with regard to justification of PET/CT, which may draw on experience in both nuclear medicine and CT. In addition, it is worth noting that:
  - Low dose CT is sufficient for anatomical correlation and attenuation correction in most cases;
  - It may not be necessary to acquire a high quality contrast enhanced CT as part of the combined PET/CT examination;
  - When a contrast enhanced diagnostic CT is justified for clinical reasons, it should, where possible, also be used to avoid an additional low dose scan.
- Attention is required to establish good practices for optimization/dose reduction drawing on current experience in both CT and nuclear medicine. In particular it is worth noting that:
  - Patient protection and image quality are enhanced when, after FDG injection, the patient is placed at rest in a quiet dimly lit room for 45–90 min to avoid brain and muscle stimulation;
  - After uptake and prior to scanning, patients are asked to void to minimize scan interference from the bladder contents and reduce bladder irradiation;
  - Where relevant, start from the pelvis, moving toward the head, to avoid high bladder activity during the scan;
  - Optimize CT technical factors for the patient, following up to date best CT practice;
  - Professional societies should develop guidelines on examination protocols;
  - Attention should be given to establishing local, national and international reference/guidance levels, and their use in practice.

- When PET/CT is used to monitor therapy, dose reduction may be achieved using a low dose diagnostic CT;
- Special attention should be given to the justification and optimization of PET/CT examinations in the case of women of childbearing age;
- Equipment suppliers should implement new designs with a view to realizing the potential for decreasing individual doses. Areas of current concern include:
  - Software development, for fusion of pre-existing MR/CT images, acquired during the patient's work-up;
  - Resolving the problems arising from the non-congruent imaging ranges of the PET and CT components, which result in unnecessary irradiation (Section 5.2.2);
  - Design modifications to the CT component, which could lead to considerable dose reduction (Section 5.2.2).
- Special attention should be given to the design and shielding of facilities to ensure that the doses to the public, hospital staff who are not radiation workers, and those in adjoining buildings are in keeping with regulations for dose constraints or limits.

## Appendix

### QUANTITIES USED IN CALCULATING PATIENT EXPOSURE FROM CT

Patient exposure is quite different in CT compared with conventional X ray examinations, with the X ray tube rotating around the patient producing images of thin slices of the irradiated body region. Dose calculation requires the introduction of special dosimetric quantities such as the computed tomography dose index (CTDI) and the weighted CTDI ( $CTDI_w$ ) for a single slice and the dose length product (DLP) for a complete examination. These quantities are described in detail in the European Guidelines and in many other sources [18]. With the launch of spiral CT scanners, volumetric CTDI ( $CTDI_{vol}$ ) was introduced in order to determine the dose in one rotation.

CTDI is defined by the following equation:

$$CTDI = \frac{1}{T} \int_{-\infty}^{+\infty} D(z) dz \quad (3)$$

where  $T$  is the nominal slice thickness and  $D(z)$  is the dose profile along a line parallel to the  $z$  axis (tube rotation axis). CTDI integrates the radiation dose imparted within and beyond a single slice. It is measured using a specially designed pencil ionization chamber with an active length of 100 mm both in free air at the centre of rotation ( $CTDI_{air}$ ) and within cylindrical polymethylacrylate (PMMA) phantoms 16 and 32 cm in diameter, simulating the head and body of a patient, respectively.  $CTDI_c$  and  $CTDI_p$  are defined, respectively, as the CTDI values measured with a pencil chamber dosimeter positioned within the centre and in the periphery of the PMMA phantom.  $CTDI_p$  can, thus, be considered to be a good approximation of the entrance surface dose (ESD).

$CTDI_w$  is used for approximating the average dose over a single slice in order to account for variations in dose values between the centre and the periphery of the slice. It is defined by the following equation:

$$CTDI_w = 1/3 CTDI_c + 2/3 CTDI_p \quad (4)$$

where  $CTDI_p$  is the average of the four  $CTDI_p$  values measured in the periphery of the phantom (at 3, 6, 9 and 12 o'clock).

$CTDI_{vol}$  is introduced to determine the radiation dose in one tube rotation using spiral scanners and allows for variations in exposure in the  $z$  direction when the pitch,  $p$  (pitch is the ratio of table feed in one rotation to

slice collimation) is not equal to one ( $CTDI_{vol} = CTDI_w/p$ ). For a pitch of  $p = 1$ ,  $CTDI_{vol}$  is equal to  $CTDI_w$ . DLP is used to estimate the total dose to a patient. It is defined as:

$$DLP = CTDI_{vol} \cdot L \quad (5)$$

where  $L$  is the length of the scan region. Certain manufacturers display the DLP value in each patient examination.



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Hybrid imaging systems, such as the combination of computed tomography (CT) and positron emission tomography (PET), are examples of a technique that has only been introduced in the last decade. PET/CT has established a valuable place for itself in medical research and diagnosis. However, it is an application that can result in high patient and staff doses. This report reviews current PET/CT technology and the radiation protection issues arising from its use. Associated radiation dose implications for both patients and staff are discussed and guidelines offered on dose management and optimization. The report also includes some recommendations.

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