Optimization of Radiation Protection as a result of PET/CT Applications

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Abstract. The aim of the study was to quantify the dose received by nuclear medicine technologists and radiotherapeutic technologists as a result of PET/CT applications with ^{18}F-FDG as well as optimization of the procedures and working conditions. Thermo-luminescence dosimeters were used for the determination of the equivalent dose on the hands and for ambient dosimetry. Electronic personal dosimeters as well as the obligatory personal dosimeters provided information concerning the total body effective dose to the workers. The shielding of two shipping containers with different lead thickness for delivery of the FDG to the hospital as well as different dispenser designs for the preparation of the syringes and administration to the patient were evaluated. The effect of the use of a lead shield during supporting and positioning of the patient was also studied. All results were related to a single nuclear medicine technologist (NMT) performing 1000 patients/year, each patient receiving an activity of 370 MBq ^{18}F-FDG. Dispensing the ^{18}F-FDG into syringes, using a specifically designed shielded lead container, the so-called "Koenders" system, resulted in a total equivalent dose on the fingers of 8.4 mSv for the MNT, while the use of the less extensively shielded syringe (the Docking station) resulted in an average finger dose of 71 mSv (p=0.000). Administration of the ^{18}F-FDG to the patient resulted in a finger dose of 4.6 mSv for the "Koenders" system, 6.3 mSv in case of the use of a ready made syringe and 23 mSv (p=0.000) in case of the Docking station. The proper use of the mobile lead shield during administration to the patient and removal of the intravenous access from the patient resulted in a significant decrease of the effective dose. Combined with the use of the thicker walled delivery container and the "Koenders" system, the total effective dose for the NMT was 2.7 mSv, nearly half of the dose before optimization. The positioning of patients for the radiotherapy planning process by RT technologists attributed to an effective dose of 1.9 mSv. The different tasks of the NMT/RT technologists will be discussed. The results of the ambient dosimetry confirmed the effectiveness of the lead shielding present in the walls as well as the classification in supervised (< 6 mSv/yr), controlled (< 20 mSv/yr) and adjacent (< 1 mSv) zones

KEYWORDS: occupational dose, nuclear medicine, TLD-dosimetry,

1.   Introduction

The increasing use of positron emission tomography (PET) in combination with CT-imaging in nuclear medicine departments, concerning the distribution of PET pharmaceuticals and the dose-planning for therapy, could give rise to concerns about the dose exposure to Nuclear Medicine Technologists (NMT) and Radiotherapeutical Technologists (RT). In our institutes two dedicated PET-CT centers are used for these applications. The most widely used radiopharmaceutical for these clinical PET-applications is ^{18}F deoxyglucose, emitting a 511 keV annihilation γ–radiation energy peak, which is far more energetic and penetrating than the conventional non-PET radiopharmaceutical ^{99m}Tc with a γ-energy of 140 keV. The differences are reflected in the kerma-in-air-rate-constant (Γ) and the half-value layer (HVL): the ratio Γ (^{18}F)/ Γ (^{99m}Tc) is about 7.5, the HVL in lead is 4.1 mm for ^{18}F versus 0.27 mm for ^{99m}Tc, in water 6.9 cm versus 4.3 cm. ^{18}F has a half-life of 109.8 min, a β$^+$-abundance of 96.7 %, and a maximum energy of the beta-particle of 0.634 MeV.

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The technologists will receive doses both from working operations related to the manipulations with the radiopharmaceuticals and from escorting and positioning the patients. Relatively high radiation doses received by the workers are reported [1-6], several studies also found acceptable results [7-9]. The results are often difficult to compare because of differences in design and use of the radiation protection means, as well as differences in packaging, supply and transportation of the radiopharmaceutical. Moreover, the results of extremity dosimetry in literature are often different, because they depend strongly on the position of the dosimeter on the limb and thus where the highest dose has been expected. In this study we validated two different commercially available dispenser and delivery systems with regard to the shielding of the ^{18}F-FDG. Also some preliminary results are shown with ready made syringes. The primary goal was to quantify the dose to the exposed workers and the environment, the secondary goal was to inform the technologists about their whole body and finger doses and to optimize their working conditions. A comprehensive study, in which dose to patients were presented, has already been published [10]. The radiation exposure was measured directly by personal monitoring of nuclear medicine technologists and radiotherapy technologists, and indirectly by measuring the ambient dose for determination of the dose to the staff-members and members of the public The study was executed in our medical centre at the department of nuclear medicine and the radiotherapy department.

2.   Materials and methods

At the time of this study the available PET/CT scanner at the Nuclear medicine department was a Siemens Biograph Sensation 16, used for diagnostic purposes as well as for planning of the radiation therapy patients. Recently, a Siemens Biograph True Point Sensation 40 has been brought into use at the radiotherapy department. All dosimetry was performed under normal working conditions. The rooms of concern were well-shielded with lead (the thickness varied between 3.5 mm and 8.5 mm) The number of patients was registered, as well as the total activity of ^{18}F-FDG that was handled and the total activity administered to the patients.

After being injected, the patient rested for 45 minutes in a shielded room with remote surveillance. After visiting the toilet, the patient was positioned on the scanner bed. First the CT scan was performed, often using iodine-contrast, followed by the PET scan.

2.1   Dosimetry

We used two types of electronic personal dosimeters (EPDs) for occupational dosimetry, the Mini Instruments 6100 Series Dosimeters (Saint-Gobain Crystal & Detectors UK Ltd), and the MK2 (Siemens Environmental Systems Ltd, Dorset, UK). In addition we used TLD100 thermo luminescence dosimeters for finger and ambient dosimetry (TLD 100: LiF, $0.9 \times 3 \times 3 mm^3$, Harshaw, Stratec Services BV, Houten, the Netherlands). The Mini Instrument measured Hp(10), the MK2 both Hp(10) and Hp(0.07), while TLD100 was calibrated in air-kerma.

The EPDs were connected to the chest pocket of the NMT/RT's dress; we will refer to this position as "chest". For ambient dosimetry TLDs were positioned at various locations and left in position for several months. The effective dose (E) to the workers was approximated with the average of the measured Hp(10) on the chest and the estimated exit dose assuming a worker is three half-value layers (21 cm) thick, i.e. E = (9/16)*Hp(10). The TLD's were delivered and read-out by the dosimetry centre of our institute.

2.2   Manipulation of 18F-FDG and protecting devices

For the delivery, dispensing and the positioning of patients four procedures were compared:
1. use of lead containers, holding the ^{18}F-FDG upon delivery to the hospital, with different wall thicknesses (17 mm and 30 mm).
2. dispensing ^{18}F-FDG to syringes with the 'Koenders system' ('Shielding device for PET patient doses', von Gahlen, Didam, The Netherlands) and the 'Docking station' ('Protective vial container for 511 keV with Docking system', Veenstra, Joure, The Netherlands) as well as dose-calibration of the syringes.
3. administration of ^{18}F-FDG by means of the above-mentioned systems as well as the ready made syringes (supplied by GE Health, manufactured by 'Kodde Engineering, Geldrop, The Netherlands)
4. removal of the intravenous line with or without a mobile lead shield (shield: 20 mm Pb-equivalent, Medisystem, Guyancourt, France).

Figure 1: Presentation of different dispenser and injection systems: (A) Docking dispenser station, (B) Docking station ready for use for dispersion, (C) Koenders dispenser system, (D) Koenders system syringe put in the dose calibrator, (E) Ready made Kodde Engineering injection system (GE-system).
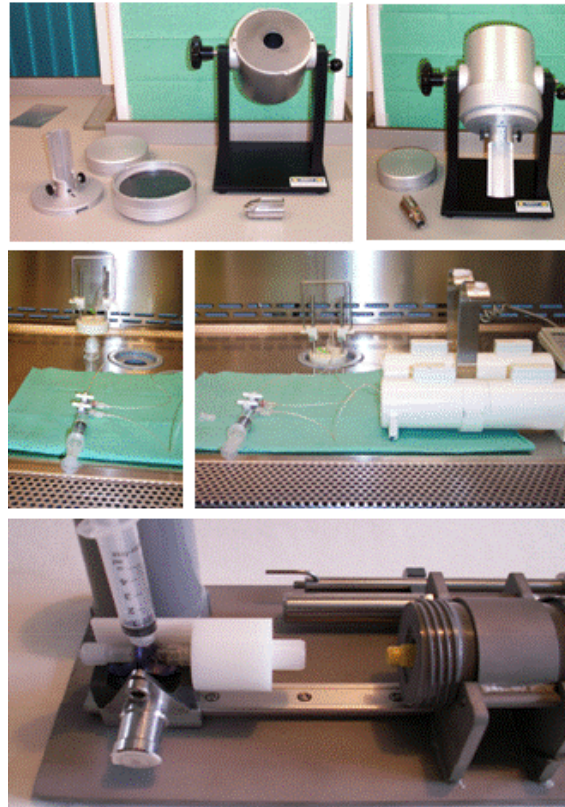
Dispensing of ^{18}F activity is performed in a lead-shielded laminar flow cabinet. When the Koenders system is used, the vial with the stock ^{18}F-FDG remains in the dose calibrator and activity is withdrawn through thin tubing into a syringe in a well shielded container [12] This container can also be used during injection. The activity in the syringe is given by the difference in reading of the dose calibrator before and after withdrawal of activity. The bulk of activity is always shielded, only the activity in the thin tube is not, but only as long as the line is not flushed with saline.

The Docking station consists of a heavily shielded container for the ^{18}F-FDG vial. Activity is withdrawn into a syringe protected by a conventional syringe shield with a lead-glass window. This is facilitated by placing the syringe with shield in a docking system that is connected to the container with vial. For measurement of the activity, the syringe has to be taken out of the syringe shield. For the ready made syringe from GE, the calibration of the activity has been done by the supplier (for a schematic presentation of the used devices see Figs. 1A-1E).

In the normal routine the following steps were distinguished (*italic* are the alternatives studied):
1. Daily quality control using the 6 litre ^{68}Ge/68Ga barrel phantom (15 – 40 MBq),
2. Unpacking of container *(17 or 30 mm wall)* with ^{18}F-FDG and transport to hotlab,
3. Filling syringes with ^{18}F-FDG *(using either Koenders system or Docking station),*
4. Measuring the activity in a dose-calibrator
5. Placing the shielded syringes with ^{18}F-FDG into a mobile lead container for transport,
6. Transport of the ^{18}F-FDG to the room where the patient will be injected,
7. Injection of the ^{18}F-FDG via an already established intravenous line *(w or w/o shield),*
8. Sending the patient to the toilet after a 45 min wait,
9. Taking the patient to the scanner,
10. Positioning of the patient in the scanner,
11. Connecting the line for iodine contrast for optional diagnostic CT *(w or w/o shield),*
12. Removal of the intravenous line *(w or w/o shield),*
13. Patient off table and leaving the department.

Steps 1-4 have been skipped in case of the use of the ready made syringes of GE.
Note that during the CT-scan no worker is present in the room. After each step the reading of the EPD was registered. All occupational dosimetry results were normalized to 1000 patient studies and 370 MBq ^{18}F-FDG administered to the patient. Thousand patients approximately correspond to the workload of 1 year in our departments.

3 Results

3.1 Extremity dose

Ambient dosimetry showed that the limits in the supervised (6 mSv/y), controlled (20 mSv/y) and adjacent (1 mSv/y) zones were nowhere exceeded. The measured results also confirmed the calculated data of the shielded walls in the different rooms [11].
Occupational dosimetry was performed during approximately 750 patient studies. There was a large difference in finger dose (air kerma) associated with the use of the two dispenser systems (Fig. 2). The Koenders system provided a much better protection of the fingers than the Docking station. A similar large difference was observed while injecting the activity into the patient. Preliminary results of the GE-system, that show a good shielding capacity, have also been included.

Figure 2: Nuclear Medicine Technician finger dose (air kerma) incurred during 1000 studies of 370 MBq using two different dispenser systems (Koenders system and Docking station). Left graph: filling syringes. Right graph: patient injection.
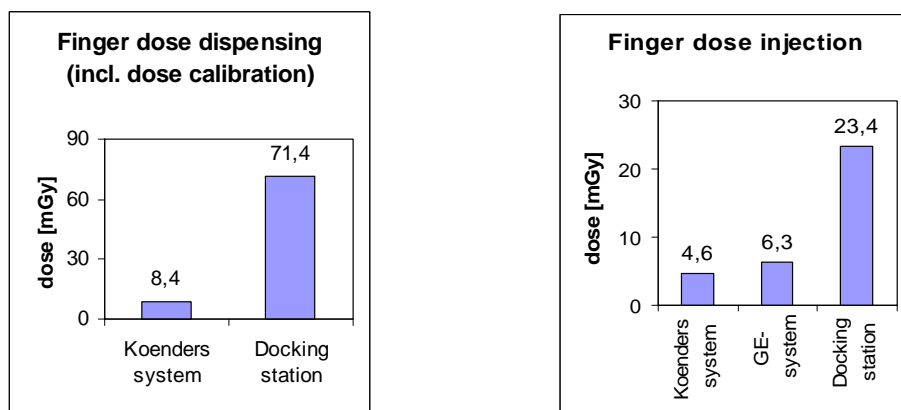
When the syringe with ^{18}F-FDG is handled without shielding, the skin of the hands is also exposed to beta radiation. Using the MK2 it was found that the β^+-radiation accounts roughly for 50% of Hp (0.07). Most of these betas were stopped by the cap of the finger ring that holds the TLD. In the rare case that a technologist holds an unshielded ^{18}F-FDG filled syringe in his bare hands, the finger dose derived from TLD measurements may have to be doubled. In this study however, all manipulations were performed using shielding materials.

3.2 Whole body dose

The difference in Hp(10) at the chest as measured with the EPD for the various alternatives we studied are shown in Figures 3-5. Fig. 3 shows the advantage of using a 30mm walled lead container for ^{18}F-FDG delivery to the hospital instead of one with a 17mm thick wall.

In Fig. 4 the chest dose is shown when using the two different dispenser systems for filling the syringes and injecting the patient, the latter with the mobile lead shield in place. Again, the Koenders system helps best to keep the dose to the NMT low.
In Fig.5 the benefit of the lead shield while injecting the activity and removing the intravenous line is illustrated.

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Figure 3: Dose (Hp(10)) at the chest of the MNT for 2 different shipping containers used for delivery of ^{18}F-FDG to the hospital for 1000 studies of 370 MBq ^{18}F-FDG.

Unpacking, to hotlab

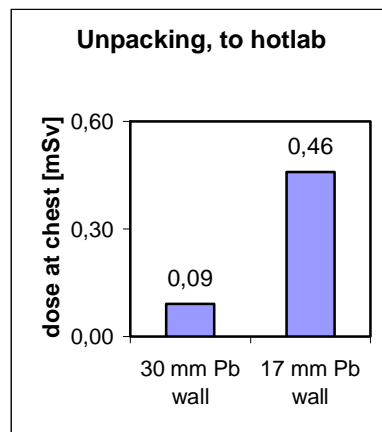| dose at chest [mSv]	
30 mm Pb wall	0,09
17 mm Pb wall	0,46

Figure 4: Dose (Hp(10) at the chest of the MNT due to 1000 studies of 370 MBq for two different dispenser systems (Koenders system and Docking Station). Left graph: filling syringes. Right graph: patient injection (with the additional mobile shield in place).
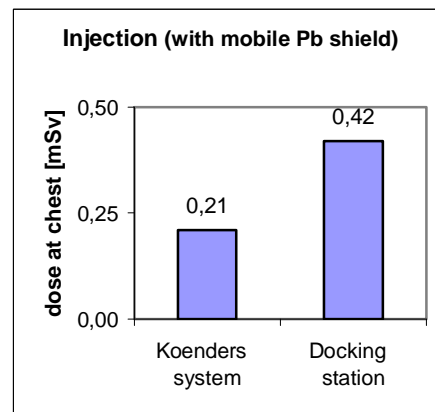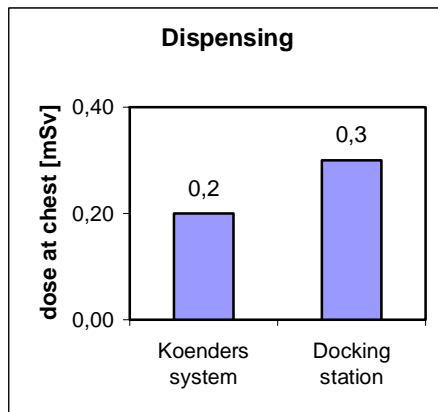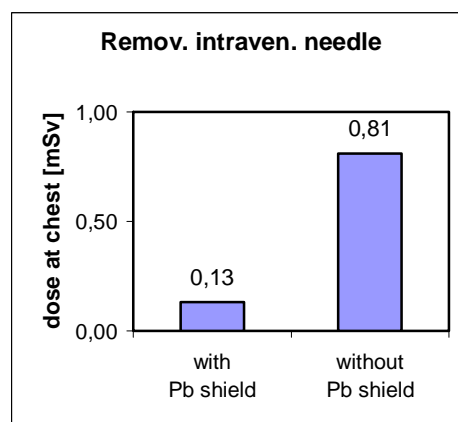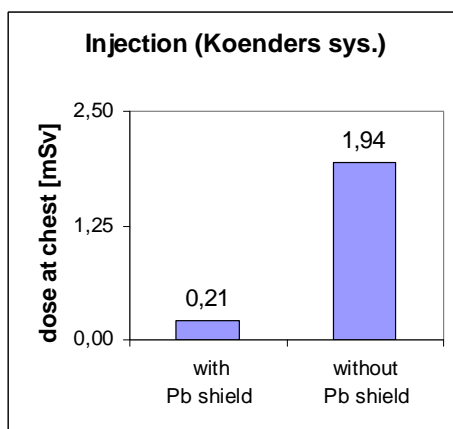
Dispensing

dose at chest [mSv]	
Koenders system	0,2
Docking station	0,3

Injection (with mobile Pb shield)

| dose at chest [mSv]	
Koenders system	0,21
Docking station	0,42

Figure 5: Dose (Hp(10) at the chest of the MNT with and without using the mobile lead shield for 1000 studies of 370 MBq. Left graph: injection of the patient. Right graph: removal of the intravenous access.

Injection (Koenders sys.)

dose at chest [mSv]	
with Pb shield	0,21
without Pb shield	1,94

Remov. intraven. needle

dose at chest [mSv]	
with Pb shield	0,13
without Pb shield	0,81

Upon completion of this study, the standard procedure was chosen to include the use of the 30 mm walled lead container, the Koenders dispenser/injection system, and the mobile lead shield. The contributions to Hp(10) at the chest from the various steps in the investigation of patients using this protocol are shown in Fig. 6; the total dose is 4.96 mSv. The corresponding effective dose to a NMT performing 1000 patient studies of 370 MBq is estimated at 2.7 mSv (4.4 mSv before optimization).

Figure 6: Dose (Hp(10) at the chest of the MNT due to the various tasks in the complete optimized patient investigation (1000 studies of 370 MBq). Note that some steps mentioned in Materials and Methods were combined.
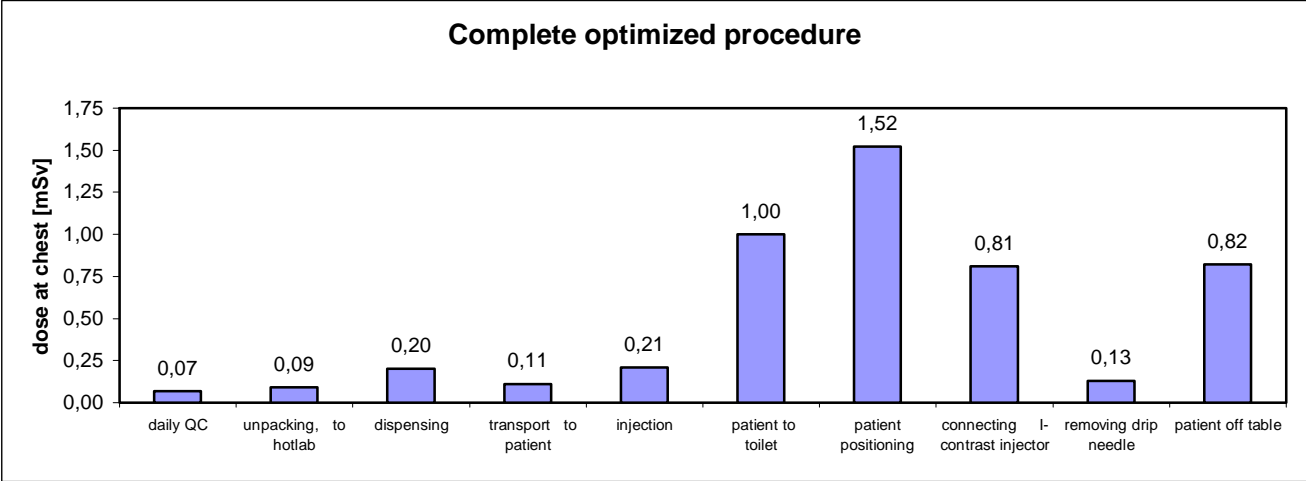
Radiotherapy technicians, who are only involved in positioning the patient, receive a considerable effective dose when compared to NMTs who are involved in all steps of the studies: 2.0 mSv per 1000 studies of 370 MBq. Although a normal PET/CT procedure is performed, patient positioning requires extra care because the images have to be used in radiotherapy planning.

Preliminary results of a recent study on the Siemens Biograph 40, where only RT-workers have been included and ready made syringes (Ge-system, Kodde engeneering) have been used exclusively, confirm the lower dose of the RTs compared to the dose of the NMT-workers. Fig. 7 shows the results of the chest dose, corresponding to an effective dose of about 1.7 mSv.

Figure 7: Comparison of the total dose (Hp(10) at the chest of the MNT en the RT-worker
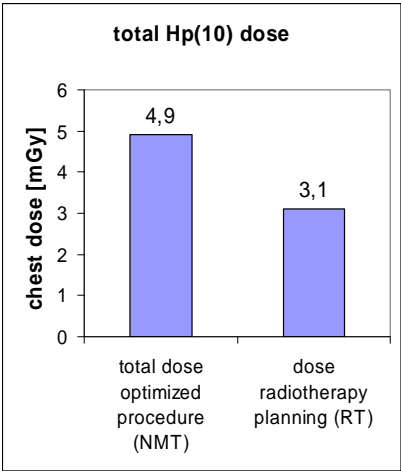

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Figure 8: Overview of the results from different researchers concerning PET/CT studies with comparable working conditions.

References/ type of dosemeter	Syringes	Dispenser/ injection	Manipulation at the patient during PET	Average dose/ 370MBq/ 1000 patients
				Extremity dose
Marti-Climent, ring TLD's			taking bloodsamples after injection	32.1
Biran, ring TLD's			All manipulations	69.3
This study, ring TLD's	shielded	dispenser (docking station)		71.4
This study, ring TLD's	shielded	dispenser (Koenders system)		8.4
				Effective dose
Benatar, EPD	shielded		All manipulations (incl. other PET-nuclides)	7.4
This study, EPD	shielded		All manipulations	2.7
				Whole-body (chest/entrance) dose
This study, EPD			All manipulations (optimized)	4.9
Biran, EPD	shielded		All manipulations	7.2
Chiesa, EPD			All manipulations	4.4
This study, EPD	shielded		All manipulations (not optimized)	8.1
This study, EPD	shielded	Kodde system	optimized	3.1

4 Discussion

Quantitative assessment of radiation exposure due to PET/CT requires some effort, but the benefits are considerable. These advantages include the possibility of optimisation of procedures, of comparison of quantitative information with guidelines and legal rules, and of making workers aware about their own influence on their exposure.

It was found that the finger dose can be kept low by carefully shielding the activity. The Koenders system performs very well in this respect. Only when the activity is passing through the thin tubing between stock vial and patient syringe it is unshielded. However, since the plunger of the syringe is moved with long tweezers, the distance between the hand and activity is large. The Docking station uses a syringe in a conventional syringe shield, and although considerably heavier than for ^{99m}Tc, it provides less protection than the still heavier container of the Koenders system that surrounds the syringe more fully. Moreover, for the Docking station the syringe has to be taken out for measurement of the activity.For the radiotherapy planning we now use ready made syringes. Perliminary results showed an effective dose of the RT worker of 1.67 mSv, which confirmed the calculated data on the technical sheets delivered with the syringes of Kodde engineering (1.72 mSv).

With the shielding of ^{18}F-FDG activity optimized, the dose to the NMT is mainly caused by patient contact. Even if the patient has been instructed well, some coaching and body contact may be necessary, especially in the case of sick patients. Close patient contact is also responsible for the relatively high exposure of the radiotherapy technicians. Their dose is only slightly lower than that of the NMTs who perform complete patient studies.

The overview in fig. 8 shows that the results of the different researchers are in good agreement, dependent of the working conditions and whether the procedures are optimized or not. Also the dose-measurements of the separate manipulations are comparable within the different results of the authors.

After optimizing the working procedure, the occupational exposure we realized is in the low range of what other investigators have reported [7 -9]. Also, in an absolute sense, an effective dose of 2.8 mSv per year in our study, assuming a workload of 1000 patients each receiving 370 MBq ^{18}F-FDG, seems

quite acceptable. In this study the dose is calculated or measured for one NMT/RT worker. In the practical situation however, the dose is divided over at least ten employees and will therefore be much lower per worker. In fact, no statistically significant increase in readings of the legally obligatory personal dosimeters was observed after the introduction of PET/CT.

At this moment the department is working with a next generation PET/CT, the Philips Gemini TF, a system that uses time of flight detection. On this system, the activity administered to the patient has been reduced from nominally 370 MBq to 180 or 220 MBq, depending on the body mass index of the patient. In addition to this, the activity required for the daily PET quality control is lower now: a 3.7 MBq ^{22}Na point source instead of the bucket phantom with 15 – 40 MBq of ^{68}Ge/^{68}Ga. Therefore, the exposure might now even be somewhat lower than observed during the initial optimization as described here.

Finally one should consider exposure of persons outside the nuclear medicine department by a patient injected with ^{18}F-FDG, who, as we have seen, is a non-negligible source of radiation. In a comprehensive study Cronin et al [13] investigated the exposure during travel, at the patient's work place, at home (partner and children in different age groups) and nursing staff: "The only possible area of concern is in an oncology ward, where patients may be regularly referred for PET investigations and other high activity radionuclide studies and are partially helpless. Even in this area, however, it is unlikely that a nurse would receive a daily dose of more than 24 µSv. We conclude that there is no need for restrictive advice for patients undergoing ^{18}F-FDG PET studies given the current administered activities." Cronin et al set a dose limit of 1 mSv/y for all persons, except for the nurses, for whom they applied 6 mSv/y. Using Table 6 from the article by Cronin et al an estimate of the exposure of nurses in a local situation can be made.

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