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PERSONAL DOSE MONITORING IN HOSPITALS: GLOBAL ASSESSMENT, CRITICAL APPLICATIONS AND FUTURE NEEDS

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It is known that medical applications using ionising radiation are wide spread and still increasing. Physicians, technicians, nurses and others constitute the largest group of workers occupationally exposed to man-made sources of radiation. Many hospital workers are consequently subjected to routine monitoring of professional radiation exposures. in the university hospital, UZ Brussel, 600 out of 4000 staff members are daily monitored for external radiation exposures. The most obvious applications of ionising radiation are diagnostic radiology, diagnostic or therapeutic use of radionuclides in nuclear medicine and external radiation therapy or brachytherapy in radiotherapy departments. Other important applications also include various procedures in interventional radiology (IR), *in vitro* biomedical research and radiopharmaceutical production around cyclotrons. Besides the fact that many of the staff members, involved in these applications, are not measurably exposed, detailed studies were carried out at workplaces where routine dose monitoring encounters difficulties and for some applications where relatively high occupational exposures can be found. most of the studies are concentrated around nuclear medicine applications and IR. They contain assessments of both effective dose and doses at different parts of the body. The results contribute to better characterisation of the different workplaces in a way that critical applications can be identified. Moreover, conclusions point out future needs for practical routine dose monitoring and optimisation of radiation protection.

INTRODUCTION

Ionising radiation is extensively used in medical practices. Most medical radiation procedures use well-established technologies. However, there is always an intension to apply new technologies, in which both patient and occupational exposures need to be reconsidered.

Routine monitoring of occupational exposures is carried out for several reasons. The most obvious reason is to verify and demonstrate compliance with the regulatory dose limits. It can help to identify new exposure pathways or risks and in the framework of the ALARA principle, routine personal dosimetry is also one of the most important tools to achieve or demonstrate an appropriate level of radiation protection.

DOSIMETRIC DATA IN THE MEDICAL FIELD

Characterisation of medical applications in terms of occupational exposures is sometimes done by reporting an average annual individual dose for all exposed and/or measurably exposed workers. In practical radiation protection, this approach is, however, meaningless, as individual doses in the medical field differ substantially. During evaluation of dosimetric data one needs information about the distribution of the yearly doses. It is important to know how many people receive doses lower than X and higher than Y? When individual monitoring is used as a tool in practical radiation protection, it is important to know if the order of magnitude of the individual dose is defined by the nature of the procedure, the individual workload, the level of radiation protection measures or the methodology of the assessment.

Medical applications that use ionising radiation are typically split into three basic domains: radiology, radiotherapy and nuclear medicine. When the medical institute is part of a university, a fourth domain of *in vitro* applications and biomedical research can be considered. Different domains have their own characteristic procedures. In the domain of radiology, we can find conventional radiology, dental radiology, interventional radiology (IR), mammography, bone mineral densitometry and computed tomography (CT). Radiotherapy is usually focused on external beamtherapy and brachytherapy with sealed sources, whereas in nuclear medicine, procedures using single photon emission computed tomography (SPECT) or positron emission tomography (PET) constitute the majority of diagnostic examinations. *In vitro* applications and biomedical research include a wide range of procedures usually

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not on a routine base. Besides the fact that many procedures can be assigned to a particular domain, one can find also applications in the intersection between the basic domains, such as PET–CT, production of radiopharmaceuticals and radionuclide therapy, where exposure pathways can be more complicated. The variety of procedures and the different exposure pathways in the medical field ask for a task-related approach on routine occupational dosimetry. Usually, the highest individual doses can be found in IR and nuclear medicine, where the nature of the procedures, the high individual workload and the difficulties in radiation protection measures justify detailed dosimetry studies.

INTERVENTIONAL RADIOLOGY

Nature of the IR-procedures

Many authors use different definitions for 'IR' but in practical radiation protection, IR includes all treatments or diagnoses using imaging for guidance and where considerable amount of fluoroscopy is used.

These interventional techniques are carried out by clinicians of many specialities. The procedures are consequently not limited to the radiology department but can be found in cardiology, vascular surgery, general surgery, gastroenterology, urology, traumatology etc. Certain types of IR procedures are quite complicated and may involve the use of extended fluoroscopy times together with the use of high dose rates. In contrast to standard radiological investigations, where the operator is protected behind the lead screen of the console, IR procedures require the presence of the medical staff next to the patient in order to perform the medical procedure. For such procedures, it is a standard practice that the medical staff members protects themselves from scattered radiation by wearing a lead apron. The scatter radiation is mainly from the patient and preferentially directed towards the X-ray tube. However, the combination of high dose rates and large workload can result in substantial exposures to unshielded parts of the body.

Difficulties in personal dosimetry

Because of the specific nature of the application, personal dosimetry encounters a dual problem during IR procedures.

The first problem is the correct assessment of E. Effective dose to workers is estimated by the personal dose equivalent (Hp(d)). The Hp(10) is a good estimate for effective dose when the worker is uniformly exposed over the whole body in anterior–posterior direction to photons with energies above 1 MeV. However, these conditions are clearly not met in IR, where the scattered radiation is not distributed uniformly and photon energies are around 80 keV. The body is furthermore partially shielded by a lead apron and possibly other protective measures. This implies not only that Hp(10) will be a poor estimate for E, but also that Hp(10) will depend strongly on the location on the body where the measurement is carried out. For lead apron workers, a dosemeter placed above the apron will severely overestimate E, whereas a dosemeter placed underneath the apron will underestimate E.

Various authors[1–6], as well as the ICRP[7] and the NCRP[8], have recommended the use of two dosemeter readings for monitoring the dose of lead apron workers. Until today there is no consensus about a suitable algorithm for the assessment of *E* concerning the number of dosemeters, the location of dosemeters, the applied operational quantities and the correction factors.

A second problem in personal dosimetry is the assessment of the dose to the extremities and the eyes. The wide range of interventional procedures and the different applied techniques for the same procedures make routine monitoring of extremity doses in IR difficult. Solutions for routine monitoring at legs and eyes are mostly inconvenient while routine monitoring of the hands is often refused due to sterility problems.

In UZ Brussel, exposures in IR have been monitored during >10 y by means of two or three dosemeters:

- Under-apron dosemeter worn at chest level for the assessment of Hp(10),ch,u
- Over-apron dosemeter worn at chest level for the assessment of Hp(10),ch,o
- Wrist dosemeter for assessment of shallow dose Hp(0.07),wrist

Measured Hp(10),ch,o-values have reached up to 140 $\mathrm{mSv\,y^{-1}}$ for some workers with high workload, whereas for Hp(0.07),wrist doses up to 100 $\mathrm{mSv\,y^{-1}}$ are recorded on a routine base.

All workers, whose exposures are measured by means of double dosimetry, are obliged to wear a lead collar. Consequently, only one algorithm is applied for the assessment of E:

$$E = \mathrm{Hp}(10),\mathrm{ch,u} + 0.05 \times \mathrm{Hp}(10),\mathrm{ch,o}^{(9)}$$

Belgian multi-centre study

Personal dosimetry is mandatory in Belgium for all exposed workers but very few medical centres monitor their workers with more than one dosemeter during IR procedures. Because of the possible high exposures to patients and staff in IR, the Federal Agency of Nuclear Control (FANC) took the initiative by organising a multi-centre study in Belgium. Besides the magnitude of patient doses, the different partners of this project (FANC, KU Leuven, UZ Brussel, SCK•CEN, CHU-Liège, CH-Jolimont) also focused on staff dosimetry. The task of staff dose subproject was dual.

- Find an algorithm for the assessment of E that is suitable for various exposure geometries and workloads. This algorithm should use the operational quantity Hp(10) and the use of two dosemeters, resulting in the smallest possible overestimation and a maximum of 10% underestimation for a specific geometry.
- Assess the dose to the extremities and eyes of workers during a large number of procedures and various exposure geometries that are used in several centres. Try to find a possible relation to the workload, e.g. number of procedures, Dose Area Product Value (DAP).

A suitable algorithm for E

The unique approach that was followed in the multi-centre study can be summarised as follows: a Monte-Carlo simulation environment was set up to calculate both the effective dose in the staff following the (theoretical) exposure of a patient and the dose that would be measured with a dosemeter at different positions (Hp(10)chest, under apron, Hp(10)neck, etc.). The simulations were performed for different exposure geometries (tube over couch, under couch and for different viewing angles) and for typical positions of the staff during interventional work. It was then searched for the best prediction of the effective dose based on selected measurable doses and this for a mix of typical conditions.

The simulations resulted in different double dosemeter algorithms for several exposure geometries (Table 1).

The double dosimetry algorithms developed in this study were designed for over-apron readings at the neck and under-apron readings at the centre of the chest. Any deviations from these positions will influence the quality of the dose estimates due to the high degree of inhomogeneity of the dose distribution in close proximity to the patient. Dosemeters should be positioned as close to the referenced positions as possible. The use of an additional collar is less pronounced for under-table geometry since it generally influences the results in high organ dose reductions for all organs at risk in the neck region and for organs exposed to secondary scattering by the neck and shoulder holes of the apron.

Other simulations in this study show also that error margins for dose estimates based on single dosemeter readings are very large. Therefore, the use of only a single dosemeter for routine dose monitoring is not recommended. Moreover, a dosemeter worn above the apron at neck level can be used to estimate the dose to the eye since the simulation point out a very strong correlation Hp(0.07), neck, o—eye dose (Figure 1).

The implementation of six different algorithms is not practicable in routine dosimetry and provisionally the study proposes general algorithms (third and fourth in Table 1) to be used in function of the presence of a lead collar.

However, application of this general algorithm results in significant possible overestimation for high exposures that are likely to occur in close proximity to the patient (Figure 2). Following the ICRP[7] philosophy of the required higher accuracy at higher doses, one could consider to apply Algorithms 5 and 6 as general algorithm even when this results in higher possible underestimation when the distance worker–patient increases.

If we consider the wide range of applications in IR together with the variations in primary beam energy, filtration, tube position, scatter media and exposure rates, it should be obvious to use only one algorithm in practical radiation protection, which is furthermore easy to use. If the assessment of E in IR is based on double dosimetry, e.g. $E = a \times X_{\text{under-apron}} + b \times Y_{\text{over-apron}}$, it would be more sustainable to set $a = 1$ and X = Hp(10) chest and 'sell' the under-apron dosemeter as the basic dosemeter and the over-apron dosemeter as the tool that should be used in case high exposures are expected.

Table 1. Different calculated algorithms for double dosimetry in Belgian multi-centre study.

	Algorithm	Lead collar	Max overestimation of E (%)
Over table tube, mixed worker position	2.83 × Hp(10) chest, u + 0.04 × Hp(10) neck, o	No	43
	2.74 × Hp(10) chest, u + 0.01 × Hp(10) neck, o	Yes	52
Under table tube, mixed worker position	2.25 × Hp(10) chest, u + 0.12 × Hp(10) neck, o	No	146
	2.25 × Hp(10) chest, u + 0.10 × Hp(10) neck, o	Yes	235
Under table tube, position close to patient	1.64 × Hp(10) chest, u + 0.08 × Hp(10) neck, o	No	60
	1.64 × Hp(10) chest, u + 0.06 × Hp(10) neck, o	Yes	105

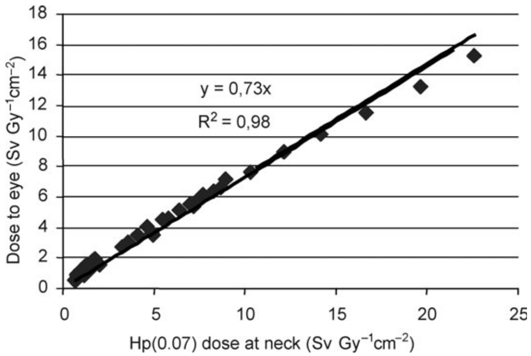

Figure 1. Estimated Hp(0.07) at neck in function of estimated eye dose.

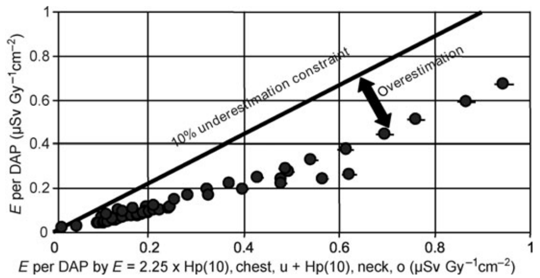

Figure 2. Possible overestimation when using general algorithm for *E*.

This brings us to the question whether double dosimetry should be applied for all lead-apron workers or that it should be related to the workload (#procedures, DAP,...)? In addition, the importance of a collar is undeniable in high exposure conditions and consequently one should think making double dosimetry and lead collar a *conditio sine qua non*.

Extremity and eyes dose during IR procedures

The aim of the multi-centre study was to measure extremity doses to the medical staff in various Belgian centres where various types of IR procedures were carried out. These were both angiography (radiology) and vascular surgery centres. Individual extremity doses were monitored per procedure at five positions: the forehead, both hands and both legs.

The dosemeter at the forehead was attached to the skin between the eyes, for both hands the detectors were attached to the dorsum of the base of the index finger. This location is chosen as it is observed that this is the area of the hand that receives the highest dose for the majority of IR procedures[10]. For both legs, the detectors were attached to the trousers, anterior on the tibia, 5 cm below the lead-apron border in order to exclude any shielding from the apron. For each procedure, a monitoring of up to three people was foreseen. First of all always for the physician who carries out the procedure. He is standing at the shortest distance to the patient or scatter source. If present, the assistant or nurse who stands directly next to the physician and hands out equipment. If present, a third person (nurse) who is also in the room at greater distance usually does not remain stationary but walks around the room to control medical equipment.

Following parameters were recorded:

- identification of X-ray unit
- patient exposure data (DAP, kVp, exposure geometry, ...)
- position of the staff members in relation to the tube/patient location during the procedure
- exposed patient region (head, thorax, trunk or legs)
- availability of personal protection (lead-apron, thyroid collar, gloves, ...)
- presence of additional protection by mobile lead screen or lead curtain

Data were collected from a total of 280 procedures from 17 centres. The results are presented in Figure 3 as median Hp(0.07) values for the head and the hand and leg that receives the highest dose.

Large differences in dose are observed due to the large variety of procedure types (diagnostic and interventional) and procedure protocols or working methods (type of equipment, number of frames, etc) that are used in the different centres. Also, some centres applied specific radiation protection measures (marked as ‘ + RP’) such as the use of a mobile lead screen or by increasing the distance to the patient during image acquisition, not during fluoroscopy. All these factors have a substantial influence on the measured doses.

A non-parametric Spearman ρ method shows a moderate to strong correlation between DAP and personnel dose only in situations where the physician carries out the procedure and in case no additional radiation protection measures are used. The correlation between the procedure DAP and the dose of the physician at the level of the head, hand and leg yields coefficients of, respectively, 0.60, 0.71 and 0.91. The correlation becomes weaker when the distance to the scatter source increases, when radiation absorbers are applied or when the position of the personnel is not fixed.

Large differences in procedure types and protocols will strongly influence the cumulated DAP value of a procedure. In order to evaluate personnel doses more independently from procedure type or amount of patient exposure, they can be normalised to cumulated procedure DAP. In general, the DAP normalised personnel doses that were observed during

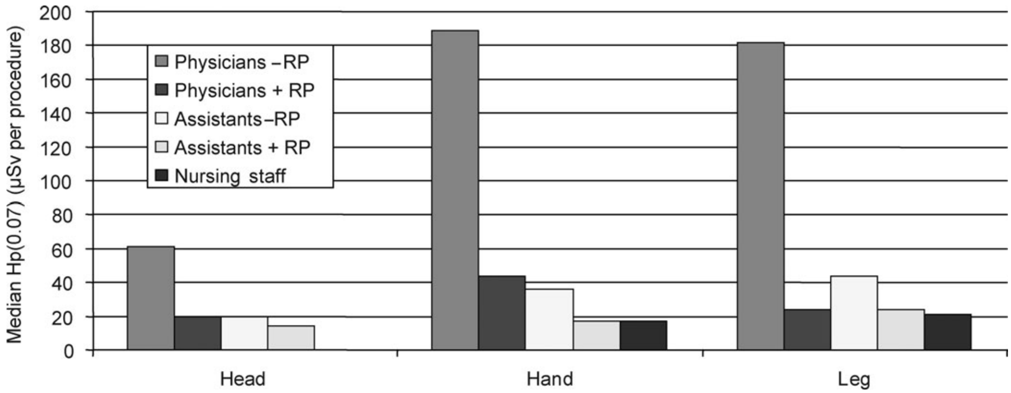

Figure 3. Observed median Hp(0.07) per procedure at the level of the head, hand and leg.

Table 2. Observed DAP normalised Hp(0.07) to the physician for angiography and vascular surgery centres.

	Angiography centres	Vascular surgery centres
Median procedure DAP (cGy cm^2)	5428	923
Median Hp(0.07) (µSv cGy^{-1} cm^{-2})		
Head	0.013	0.038
Hand	0.045	0.058
Leg	0.058	0.116

In both cases the physician stands next to the patient.

procedures carried out in the vascular surgery centres were higher than those observed in the angiography centres to all monitored positions on the body (Table 2).

The reason of the higher normalised dose in the vascular surgery centres is probably the fact that the physician is located at a shorter distance to the patient when compared to the distance during angiography procedures. The reason for this shorter distance is unclear but can be possible attributed to the demands of the clinical procedure or a lack of radiation protection management. The absolute dose values in the vascular surgery centres remain however rather limited due to the strongly reduced DAP that is used when compared to the DAP values from the angiography room procedures.

Additional radiation protection efforts are either the use of mobile radiation absorbers such as a lead curtain or a lead screen, or the use of increased distance to the patient during image acquisition. The latter measure results in median dose per DAP that are a factor of 10 lower than those that were observed when the physician remains next to the patient.

A conservative estimation of annual doses to the extremities and eyes of the physician can be made by using the third-quartile values of the observed DAP normalised doses for angiography and vascular surgery centres in function of patient exposed area (head, thorax-neck, trunk and trunk-legs). These values can be multiplied by the corresponding annual cumulated DAP-value for each monitored physician. The results of this exercise in Figure 4 illustrate that two physicians in this study are likely to exceed the annual dose limits.

Both these physicians have a very heavy workload compared to those in other centres. Physician 5 performed fewer procedures than Physician 1 but may still exceed the dose limits at the hand and eyes due to the fact that doses observed in vascular surgery centres are generally higher. The annual estimated doses to the angiography physicians that removed themselves from the patient during acquisition were limited.

The above performed calculations result in an estimation of the annual extremity doses. Nevertheless, the large differences in DAP- and procedure-normalised doses emphasise that the assessment of extremity doses in IR should occur by means of routine monitoring.

Challenges and future needs

The multi-centre study demonstrates the difficulties in personal dose monitoring during IR procedures. The results represent some useful findings that can be implemented for practical routine monitoring. Validation of the results in this study is however needed and should be a subject in future studies. Besides this validation, these studies should also consider situations where biplanar systems are used. The complex radiation fields resulting from this technique will certainly influence algorithms for E and

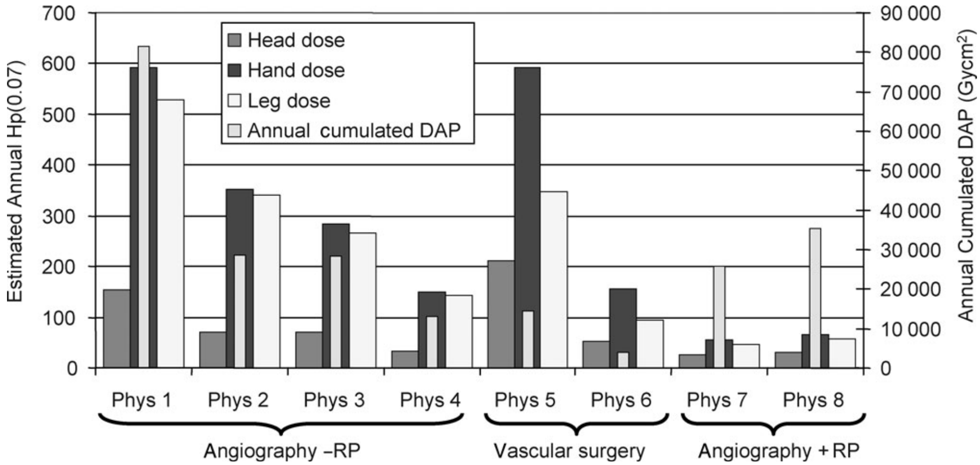

Figure 4. Estimated annual Hp(0.07) at the level of the head, hand and leg.

increase the DAP-normalised doses for the head and hands. Attention should also be given to CT-fluoroscopy where an increasing number of procedures are registered, particularly for biopsies. During such procedures, doses up to 700 and 200 μSv per procedure for, respectively, hand and eyes were recorded in UZ Brussel[11]. The varying radiation protection measures that were observed during the Belgian multi-centre study indicate that radiation protection training should be continuously encouraged. Initiatives in training are taken on European level[12], but a lack of radiation protection is still present in many cases. Besides training and education, new radiation protection devices can provide a substantially reduction in staff exposure[13].

NUCLEAR MEDICINE

Nature of the nuclear medicine procedures

Besides some therapeutic procedures, a nuclear medicine department can be generally characterised by various diagnostic examinations involving intravenous administration of radiopharmaceuticals. These pharmaceuticals are usually labelled with ^{99m}Tc and among the more common are also ^{18}F, ^{201}Tl, ^{123}I, ^{51}Cr and ^{67}Ga. Current trends in clinical nuclear medicine include an emphasis on radioimmunodiagnosis, SPECT and PET that mainly involves the use of ^{18}F-labelled fluorodeoxyglucose (^{18}FDG).

Internal radiation exposures

Internal exposure of workers can occur after inhalation, ingestion or skin contamination with radionuclides. The described exposure pathways should be avoided by procedures where the need for hygienic measures represents the basis principle. Individual monitoring for intakes of radionuclides is usually more difficult than external monitoring. It can be achieved by body activity measurements, excreta monitoring or air sampling. The fact that 95% of the applied radionuclidess have relatively short half-lives represents a major problem in routine internal dosimetry. Furthermore, the initial worker hesitation to report contaminations increases the lack of traceability. Besides some incidents where considerable amounts of activity are spilled, doses arising from internal exposure during routine work are much less than external exposures.

Whole body external radiation exposures

During many procedures, nuclear medicine technologists have to be close to patient when giving injections or when positioning the patient on camera for scintigraphy. Dose rates from patients are usually in the order of 10 μSv h^{-1} at 1 m distance resulting in measured Hp(10) values of ~5 mSv y^{-1} for a technologist with a typical workload. Many studies[14–18] have tried to measure whole body occupational exposures to technologists per procedure. These normalised exposures can, however, vary an order of magnitude due to factors such as administered activity, imaging time, patient condition, camera-console distance, presence of local shielding, etc… Last decades, many nuclear medicine departments have extended the procedures to PET from which an increase in occupational exposures was expected. In many cases, the influence of these PET-procedures on the whole body dose is hardly observable as the procedures represent only 10% of the total workload, the applied activities per study are lower and the introduction of '511 keV' photons increased the awareness in radiation protection.

Assessment of extremity doses

Extremity dose assessments are usually carried out using thermoluminescent dosemeters (TLDs) because of their convenient size. For accurate measurement of Hp(0.07), the dosemeter must be physically thin to avoid significant attenuation of the radiation. The dosemeter also needs to be robust because it may be placed on the hands carrying out manual work.

The position on the hand at which a dosemeter is worn and the choice of hand on which it is placed both have a large influence on the value of the assessed dose, especially when working with localised sources. Since the skin dose limit is applied to the dose averaged over any area of 1 cm^2 [13], it is necessary to identify, as accurately as possible, the location of the highest dose. Extremity dose monitoring in a nuclear medicine department can be carried out by TLD-tapes or finger stalls, which enables to measure doses at the tip of the finger. However, these dosemeters are often inconvenient during manipulations, which can result in longer exposure time. Ringdosemeters are usually worn at the base of the middle finger and are quite convenient during manipulations but give an underestimation of the highest dose. A wristdosemeter does not hamper most manipulations but results in a significant underestimation of the dose due to the distance between the wrist and the possible highest dose location. Ideally, a dosemeter should be used to monitor the part of the extremity receiving the highest dose. If this is impractical, it may be necessary to monitor a different part in which case a factor may be employed to ensure dose limits are not being exceeded.

Before imaging the patient with SPECT or PET, the radiopharmaceutical causes radiation exposure during a number of manipulations. Generally, one can consider three basic manipulations:

- During kit preparation multidose kit vials of different radiopharmaceuticals are prepared. The preparation of ^{18}FDG occurs generally by fully automated modules in heavy shielded 'hot cells' and is not considered as a significant source of exposure to the extremities. This is, however, not the case during ^{99m}Tc labelling where the manipulation starts with the elution of the ^{99}Mo–^{99m}Tc generator into an elution vial and ends up with the injection of a typical activity into a multidose kit vial.
- These kit vials have to be dispensed into syringes after which the individual patient activity is checked in the dose (activity) calibrator and the syringe is transferred with a shielded transport box to the administration room.
- The third manipulation is the administration to the patient. The insertion of a butterfly cannula into a vein, prior to the radiopharmaceutical administration, is prevalent in many hospitals in terms of dose reduction to the staff members performing this task.

Study on extremity doses in UZ Brussel

In the nuclear medicine department of UZ Brussel, extremity doses have been monitored during several years by means of wristdosemeters and ringdosemeters. The significant results of this monitoring urged the need for a detailed dosimetry study[18] on the distribution of extremity doses at 18 locations of each hand (Figure 5). The internal organisation of the above mentioned basic tasks can differ from department to department. In UZ Brussel, only two radiopharmacy workers continuously carry out kit preparation and dispensing, whereas other technologists are responsible for administration. Since ^{99m}Tc and ^{18}F cover 95% of the workload, only manipulations with these radionuclides were considered. Over a 1-y period, more then 500 manipulations were measured, divided over five different manipulation types.

The results generally give a good reproducibility ($\pm$30%) for the individual worker, despite the general bad reproducibility during manipulations of localised sources. Particular personal habits in handling the radiopharmaceuticals determine the location and the order of magnitude of the highest skin dose. Figure 6 shows the order of magnitude of the highest skin dose together with the highest dose location on the hand. All monitored workers are right-handed but highest skin dose is often located on the left hand, since the syringes and needles are

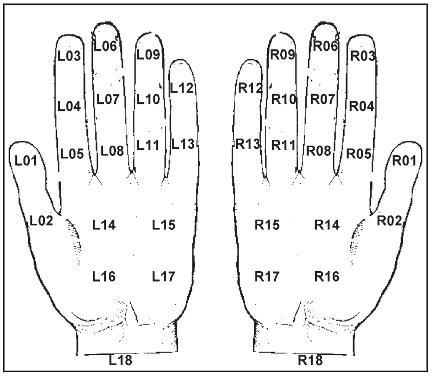

Figure 5. Eighteen dose locations on the palm of each hand. Position R08 corresponds with the position of routine ringdosemeter.

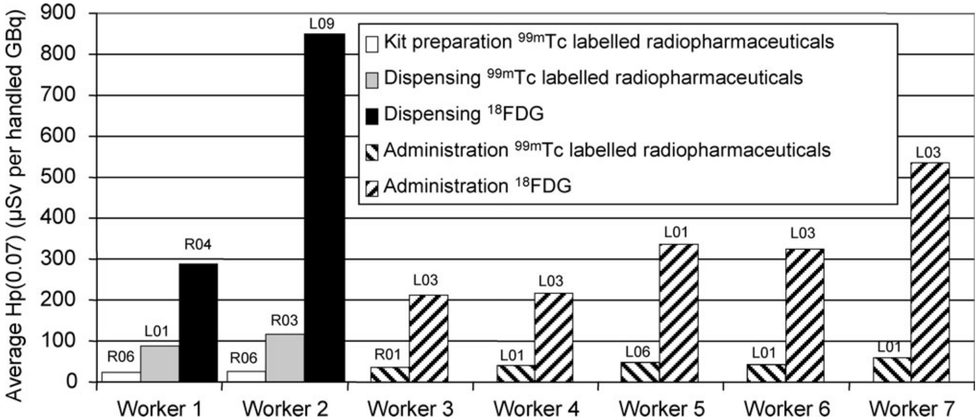

Figure 6. Observed average highest Hp(0.07) per handled GBq during five different manipulations.

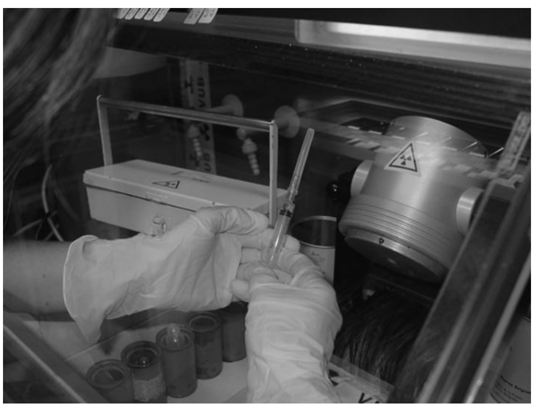

Figure 7. Supporting the syringe for removal of air bubbles during dispensing.

Figure 8. Supporting the needle during administration.

often supported here during several manipulations (Figures 7 and 8). The highest skin doses range from 20 to 60 μSv per handled GBq during manipulations with ^{99m}Tc, but can reach values up to 850 μSv per handled GBq when ^{18}F is manipulated!

Routine extremity dose assessments cannot be carried out at 36 locations. The use of a ringdosemeter is convenient during routine operations. The results of this study indicate, however, the location and the order of magnitude of the highest skin dose, which is manipulation related. In the future, the values of the routine measurements (location R08) can be multiplied by a factor to obtain the value of the highest dose. For certain manipulations, like the removal of air bubbles during dispensing or the support of the needle during ^{18}FDG administration, this ratio can mount to a factor of 9! Applying the average or the highest ratio as the future factor for routine monitoring would be incorrect since the contribution of the different manipulations to the annual skin dose is not equal. The annual skin dose at 36 positions of the hand can be predicted by using the individual annual workload per worker and per manipulation. The results of this calculation are shown in Figure 9 and point out a limited overall ratio 'highest dose/ringdosemeter dose' between 2.5 and 3.5 for most workers. For all monitored workers, the highest dose location is situated on the non-dominant hand and without radiation protection measures, radiopharmacy workers 1 and 2 will easily exceed the annual dose limit of 500 mSv at this location.

Former studies[20–23] indicate the highest dose location on the dominant hand (fingertip index finger). Some of these studies also calculated the ratio between doses at the fingertip and doses at the base of middle finger during dispensing of ^{99m}Tc-labelled radiopharmaceuticals and found ratios

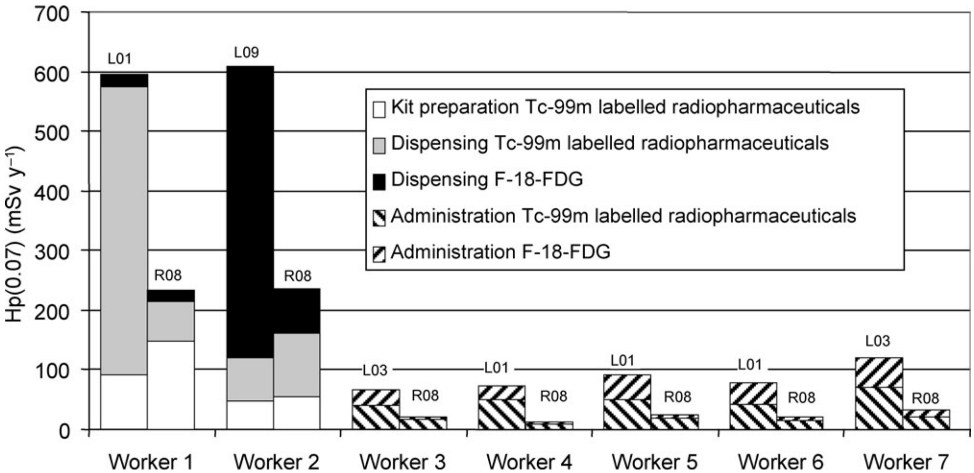

Figure 9. Estimated annual Hp(0.07) at the highest dose location and the ringdosemeter location.

ranging from 4 to 5 between the doses at these two locations.

One could recommend a convenient location for routine monitoring on the hand were the highest dose is found. However, these locations do not always represent higher doses compared with a convenient location on the other hand. Moreover, deviation from a standard location for each individual worker in a department can create confusion and limits the sustainability of routine extremity dose monitoring.

Challenges and future needs

Although new SPECT radiopharmaceuticals are continuously being developed, there is a major trend to extend PET procedures to PET–CT procedures. Today, ^{18}FDG is the most useful PET tracer but the research on other ^{18}F-labelled molecules has resulted in several new radiopharmaceuticals. Furthermore, the search for new radionuclides introduced $^{60/61/62}$Cu, ^{68}Ga, ^{86}Y, ^{94}Tc and ^{124}I. Many of these radionuclides emit positrons with relatively high energies combined with high-energy gamma emission. The future number of procedures and the nature of these radionuclides can consequently increase whole body exposures as well as exposures to the extremities.

Besides the diagnostic procedures, there is a continuous growth in the use of therapeutic modalities. Many medical centres gained experience in staff dosimetry around radionuclide therapy with ^{131}I. Other non-conventional applications like specific therapeutic targeting with labelled peptides and radiosynoviorthesis (RSO) use, however, β-emitting radionuclides and are accompanied with high exposures to the extremities that can mount up to 700 mSv d^{-1} [(24)]. Due to the application of these procedures and the introduction of new PET tracers, future studies should pay attention on the β-response of personal extremity dosemeters.

CONCLUSION

During personal dose monitoring in hospitals some pitfalls can occur. The nature of the procedures and the sometimes complex and mixed radiation fields in hospitals induce technical and accuracy problems. In addition, the differences in methodology of assessment and the lack of consensus in the interpretation of results make the evaluation of dosimetric data complicated.

During the critical applications like IR and nuclear medicine relatively high exposures can be found. The individual workload is mostly the origin of the high individual exposure but education, training and new radiation protection devices are often missing despite the fact that they are easily available.

Detailed characterisation of workplaces should be carried out on routine base and can help in the optimisation process since the increasing diversity of departments and the introduction of new techniques and procedures often change the exposure pathways.

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