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INVITED PAPER

AN OVERVIEW ON EXTREMITY DOSIMETRY IN MEDICAL APPLICATIONS

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Some activities of EURADOS Working Group 9 (WG9) are presently funded by the European Commission (CONRAD project). The objective of WG9 is to promote and co-ordinate research activities for the assessment of occupational exposures to staff at workplaces in interventional radiology (IR) and nuclear medicine. For some of these applications, the skin of the fingers is the limiting organ for individual monitoring of external radiation. Therefore, sub-group 1 of WG9 deals with the use of extremity dosemeters in medical radiation fields. The wide variety of radiation field characteristics present in a medical environment together with the difficulties in measuring a local dose that is representative for the maximum skin dose, usually with one single detector, makes it difficult to perform accurate extremity dosimetry. Sub-group 1 worked out a thorough literature review on extremity dosimetry issues in diagnostic and therapeutic nuclear medicine and positron emission tomography, interventional radiology and interventional cardiology and brachytherapy. Some studies showed that the annual dose limits could be exceeded if the required protection measures are not taken, especially in nuclear medicine. The continuous progress in new applications and techniques requires an important effort in radiation protection and training.

INTRODUCTION

Monitoring of workers constitutes an integral part of any radiological protection programme. In some medical applications of radiation, there is a high risk of locally high exposures because of direct handling of sources, working close to radiation fields or the use of beta-emitters. However, few measurements of extremity doses have been reported in the literature, especially compared with the large number of workers worldwide who are exposed in the medical field. Medical practices are evolving fast, and new techniques with ionising radiation come into play very regularly, implying the need of radiation protection measures for medical staff and the implementation of new monitoring programmes.

Within the CONRAD project, a working group is co-ordinating the research activities on occupational exposures of medical staff. One of the tasks undertaken was to perform an extensive literature review on extremity dosimetry for radiation-exposed medical staff. This paper describes the main findings of this literature search. The paper is divided in two main parts: one on interventional procedures, and the other on nuclear medicine, and a third shorter paragraph on brachytherapy.

The dose limits to be considered for workers are the same for the extremities and for the skin, i.e. 500 mSv for 12 months averaged over 1 cm^2 regardless of the area exposed. For the eye lens, the limit is 150 mSv per 12 months(1). If the dose to any part of the extremities of a worker is likely to exceed three-tenths of the annual dose limit, an additional dosemeter should be worn on the part of the extremity where the dose is expected to have its highest value(1). However, the extremity monitoring may impede the manipulations carried out by the staff. Moreover, problems with the sterilisation and the wearing of gloves are encountered. It should be stressed out that no suitable dosemeters for knees, feet or eye lenses are available at the present time.

USE OF EXTREMITY DOSEMETERS IN INTERVENTIONAL PROCEDURES

In interventional radiology/cardiology (IR/IC), X-rays are used to image catheters and guide wires into position within the patient. These comprise both diagnostic and lengthier interventional procedures, where a number of conditions are treated using stents or embolisation media. IR and IC procedures require the operator and assisting personnel to remain close to the patient, and thus to the primary radiation beam. While the body area can be individually

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*Corresponding author: filip.vanhavere@sckcen.be shielded by protective lead aprons, the hands, legs and the eye lenses remain practically unshielded. The unsuitable use of protective tools or bad practice (e.g. placing the hands in the direct X-ray beam) could lead to high doses at unexpected positions.

The International Commission on Radiological Protection (ICRP) Publication 85(2) has given examples of the doses of the monitored workers for various X-ray interventions. The dose ranges for the same kind of procedures vary a lot, since there are many factors affecting the extremity doses like the protective devices, the X-ray geometry and spectra, the irradiated area of the patient, etc.

Generally haemodynamic procedures, particularly the percutane transluminal coronary angioplasty (PTCA), involve high dose area product (DAP) values due to intensive use of image acquisition and therefore, the staff doses are higher than for other procedures. The lowest doses for coronary angiographies (CAs) were found in a hospital centre(3) with very strict radiation protection policy (low exposure rate fluoroscopy modes, use of spectral filters, low frame rate, proper use of protective screens, protective collar, lead aprons and curtain shields). The use of a protective barrier can reduce staff doses by a factor of 2, whereas the use of a ceiling mounted screen by a factor of 3(4).

For vascular radiology procedures, finger doses up to 840 μSv per procedure(4) have been reported. Without protective devices, the hand doses in angiographies vary from 120 to 710 μSv per procedure. For other interventional procedures (embolisation, stent placements and vertebroplasty), following range of hand doses are reported(6–9): 50–630 μSv per procedure. If lead protection is not used, the dose to the feet may range from 320 to 2640 μSv per procedure, which exceeds the hand exposure during the same procedure(8). Studies(3,4,7,10) on IC procedures (CA, PTCA and ablations) report shoulder doses between 10 and 100 μSv per procedure, feet doses between 10 and 200 μSv per procedure and hand doses between 260 and 350 μSv per procedure.

The doses to the legs in most of the biliary procedures are lower than the hand doses whether a lead protection curtain is used or not. During stenting, embolisation and angioplasty procedures, if no shielding is used, the doses to the legs of the staff are two to three times higher than the doses to the hands. However, if a protective curtain is used, the dose to the legs is reduced significantly. The wide range of staff doses at the extremities, even for the same procedure or the same centre, emphasises the importance of protective measures, staff experience and protocols that are followed.

In many of the above studies, extrapolations of the reported doses to the annual ones have been attempted. Most studies estimate that the annual extremity doses for hand, forehead and shoulders stay below the limit. However, Vano *et al.*(4) reported that the doses measured at the shoulder would be higher than the limits. Damilakis *et al.*(5) also found that operator hand-doses can approach the dose limit during high workload.

The DAP value can be used as a radiological workload tool, so it is often checked whether a relationship between the DAP (as a measure for the dose to the patient) and the staff extremity dose exists. Although some studies found some good correlation between staff doses and DAP values(3,8,11), generally a wide range of radiation exposure relative to patient dose is found(5,10,12). The bad correlation can be explained by different parameters that affect the extremity doses such as protective devices and especially different protocols followed by the staff. For instance, moving away from the table during acquisition decreases the staff doses significantly while the DAP is unaffected. Therefore, it is not easy to estimate staff doses from DAP values.

For interventional procedures, there are some studies on the dose distribution across the hands in order to find the most suitable position for monitoring(6,7,12). For most of the IR procedures, the bases of the ring and little finger receive the highest dose, and the type of procedure and the manipulations of the staff affect the dose distribution. According to Martin and Whitby(6), a finger dosemeter placed at the little finger of each hand is appropriate for extremity monitoring. However, during percutaneous procedures, the tips of ring and middle fingers may receive 20–30% higher doses(3).

EXTREMITY DOSIMETRY IN NUCLEAR MEDICINE

Nuclear medicine is associated to all uses of unsealed radioactive sources for therapy or diagnosis purposes. Nuclear medicine is a matter of concern as regards radiation protection of workers since, first, high radionuclide activities are needed, from few tens to several thousands of megabecquerel, secondly, the procedures require the handling of radiopharmaceuticals at contact and/or very close to the extremities (hands, fingers) and, thirdly, often pure beta-emitters and mixed photon/beta-emitters are used.

Conventional diagnostic nuclear medicine

By conventional diagnostic nuclear medicine is meant, any diagnosis procedure associated with a scintigraphy carried out with gamma-cameras (bones, heart, lungs, thyroid, etc.). The large majority of these procedures use ^{99m}Tc, which represents 80–90%, the rest being mostly associated with iodine, and to a lesser extend thallium (^{131}I, ^{123}I and ^{201}Tl).

Doses to hands and fingers are generally reported per gigabecquerel of activity handled. On the fingertip, doses between 0.007 and 0.18 mSv GBq^{-1} were measured. With ring dosemeters, values between 0.01 and 0.04 mSv GBq^{-1} were found, and mean hand doses between 0.017 and 0.18 mSv GBq^{-1} are given(12–19).

Harding *et al.*(13) assessed the protective value of syringe shields for ^{99m}Tc. The study revealed that although theoretical attenuation factors for commercialised syringe shields are in the order of 100 for ^{99m}Tc, actual observed dose reductions were in the order of 2 on average. This was attributed to the design of the shields that does not protect in all directions and to the fact that using these devices slow down the process. Whitby and Martin(14) found a 75–85% dose reduction by using a syringe shield.

Hastings *et al.*(15) found that the choice of the technique for checking the activity could lead to dose reductions by more than a factor of 2. The extremity doses can also differ largely between two technicians according to their individual techniques and expertise(12).

Martin and Whitby(6,14) found that the tip of the index finger of the dominant hand is likely to be the part that receives the maximum dose. The authors also stated that this rule is not universally applicable and depends on various individual circumstances, e.g. on the way the syringe and vial are held. If a ring dosemeter, for practical reasons, is worn at the base of the finger, the dosemeter reading could be five or six times smaller than the dose at the finger tip. Vanhavere *et al.*(12) found values between 1.4 and 7.0 between the dose at the ring dosemeter position and the maximum dose location. Jankowski *et al.*(16) showed that the fingertip dose can be nine times larger than the finger nail dose. Stuardo(17) studied four nuclear medicine technicians during 1 week performing dose preparation, administration and imaging. At the tip of the index finger, a dose of a factor 3 larger than the ring dose was found.

Different authors extrapolated the measured doses to annual doses. Harding *et al.*(13) found that radiopharmacy and dispensing led to 330 mSv each, and injections to 220 mSv annual doses. Chruscielewski *et al.*(19) presented the results of measuring the equivalent dose to the hands of 60 workers (physicians, nurses, radiopharmacists and technicians) during 7 months, representing several thousand examinations. They estimated large variability in annual doses. For example, the radiopharmacists of one of the laboratories were associated with annual hand doses ranging from 3.7 to 200 mSv, and all workers of another laboratory revealed hand doses ranging from 0.03 to 0.12 mSv only. Jankowski *et al.*(16) reported a annual hand dose of 14.4–87.6 mSv. Whitby and Martin(14) estimated annual hand doses of 10–200 mSv and 5–40 mSv for radiopharmacy and nuclear medicine staff, respectively.

Positron emission tomography examinations

Positron emission tomography (PET) is considered one of the most relevant diagnostic imaging techniques to provide functional and quantitative information for the organ of interest. The radiopharmaceutical used in most of the cases is ^{18}F-FDG. The use of PET is increasing in most countries. PET radiopharmaceuticals are positron emitters. One of its features from a radiation protection point of view, compared with ^{99m}Tc labelled radiopharmaceuticals, is that they have higher specific gamma ray constants, and larger half value layer (HVL).

Just as in conventional diagnostic nuclear medicine, the occupational exposure of PET staff can vary significantly for different departments, workers and practices. In the literature, there are few studies dealing with the evaluation of occupational doses for PET facilities(20–25). Chiesa *et al.*(26) reported on radiation doses for PET technicians that were higher than those received in conventional diagnostic nuclear medicine departments. However, some more recent studies(20,21) showed radiation doses for the technicians similar to the doses received in conventional diagnostic nuclear medicine departments. These lower extremity doses may be explained by the use of a homemade syringe drawing device, a semiautomatic injector and patient video tracking, allowing a shorter duration of contact between the technician and the patient. Shielded syringes, according to Biran *et al.*(22), can produce a 25% reduction in the extremity dose. Doses of 0.16–0.19 mSv GBq^{-1} were reported(23) for the index and the middle finger during the manipulation, while the respective doses for the preparation of the radiopharmaceuticals are higher varying from 0.92 to 0.39 mSv GBq^{-1}. Tandon *et al.*(24) evaluated doses at the fingers during the dispensing, injection and scintigraphy. The respective numbers for the above phases are: 0.098, 0.324 and 0.56 mSv GBq^{-1}. The 5-y study of Marti-Climent and Peñuelas(25), in a total of 7032 PET studies, showed finger doses for nurses varying from 0.087 to 0.10 mSv GBq^{-1}, and for technicians ranging from 0.16 to 0.54 mSv GBq^{-1}. The study also revealed that special lead containers and syringe manipulators can be efficient for reducing personal doses.

Some practical radiation protection measures should be further analysed to reduce personal doses, like interacting with the injected patient only when required, and speeding up patient management. Even the introduction of 3D PET scanning with 5- to 6-fold increase of sensitivity compared with the 2D, may reduce the dose to the personnel considerably. This allows an important decrease of the activity injected to the patient with the consequent reduction of workers' exposure. A possible reduction of dose to the hands of technicians can also be achieved with a full automatic activity-dose dispenser.

Nuclear medicine therapy

Unsealed radiation sources are being increasingly used in nuclear medicine for radiation therapy, in particular, nuclides that emit beta or mixed beta/gamma radiation. Joint diseases are treated using radiosynoviorthesis (RSO) by injecting ^{90}Y, ^{186}Re or ^{169}Er solutions into the joints. Recently, radioimmunotherapy (RIT), using ^{90}Y-labelled antibodies for treating malign lymphoma, has been introduced in clinical routines. Another promising method is the peptide–receptor-guided radiotherapy (PRRT) for neuroendocrinic tumours by means of ^{90}Y or ^{177}Lu.

Although the handling of radionuclides does not essentially differ from diagnostic nuclear medicine, in therapy, activities are much higher and very often beta-emitters such as ^{90}Y ($E_{\max} = 2.28$ MeV) are used, thus producing a considerably higher dose/-dose rate per activity unit than gamma-radionuclides.

The preparation and administration of radiopharmaceuticals in RIT and PRRT requires the manipulation of high activities of ^{90}Y. In cases where radiation protection measures are not properly kept, even non-stochastic radiation damage may occur as it was reported by Tosi(27).

In a recent paper(28), the authors studied extremity exposure during the preparation and application of ^{90}Y-labelled antibodies (Zevalin®) and peptides (DOTA-TOC®). When using radiation protection means (polymethylmethacrylate-shielding (PMMA)-shielding, tongs, X-ray gloves), a mean dose at the finger tips during labelling of 0.6–2.9 mSv per patient was found. Depending on personal skill and experience, the individual exposures comprised a wide range of doses with a maximum of 30–40 mSv during a single procedure. In France, finger doses up to 20 mSv per patient were reported(29). In Germany, the introduction of ^{90}Y-Zevalin® therapy into clinical routines was accompanied by extremity dose measurements with thermoluminescent detectors (TLD)(30,31). When the personnel worked under an acceptable safety standard, the dose range was 1.3–8.1 mSv GBq^{-1} for the staff in charge of labelling, and 0.3–2.2 mSv GBq^{-1} for the doctors. In a few cases, fundamental safety measures were neglected, and local skin doses up to 600 mSv (labelling) and 27 mSv (injection) were measured. The authors stress the need of an adequate radiation protection standard. As far as shielding is concerned, it was also observed that tungsten syringe shields provide a better protection for ^{90}Y than PMMA ones(29,32,33), in contradiction to the recommendation made in ref.(34). Additionally, routine monitoring with ring dosemeters is needed. It is essential to use dosemeters that are appropriate for measuring beta radiation. In theory, these dosemeters should be worn close to the tips of the forefinger or thumb of the highly exposed hand.

In Germany, over 60 000 RSO therapies are performed annually(35,36). All these studies revealed that even with RSO, the highest dose is to be expected on the top of the left forefinger or thumb. This happens when using these fingers to maintain the position of the needle of a syringe during withdrawal, dispensing or injection of the radionuclide solution. When safety standards are ignored, up to 200 mSv per day were estimated in single cases. It was found that a ring dosemeter underestimates the maximum skin dose by a factor of 3 on average when the therapy is performed at a high level of safety.

BRACHYTHERAPY

Brachytherapy treatment consists of the direct insertion of radioactive sources, usually sealed sources, into the target tissue. In the early days, the handling of radioactive material was manual, thus implying a potential high risk for the hand dose. However, nowadays, most of the procedures are performed using manual or remote afterloading machines, thus reducing the personnel dose. The use of remote afterloading devices is highly recommended to reduce radiation exposure of medical staff and to improve patient treatment.

In manual brachytherapy, the hands of staff receive the higher doses during source preparation or source implant in the patient. However, there are very few published data. Ennow(37) investigated finger doses for ^{192}Ir and ^{137}Cs manual implants. His results showed an average monthly finger dose of 1.5 mSv within a range of 0–43 mSv. For most of the staff, the received dose is below the limits, but in some cases high doses can be found. Along the same lines, Huerga *et al.*(38) also claimed very low finger doses in the handling of ^{125}I seeds and ^{106}Ru.

CONCLUSIONS

It is very difficult to compare extremity doses in IR unless comparable protective measures, procedures and characteristics of X-ray equipment are used. Even so, the differences from one operator to another, and from one patient to another, can be substantial. When good practice is used and protective measures are present, the occupational limits should not be reached. However, it is very difficult to completely avoid accidental exposures such as being exposed to the direct radiation beam. Besides, the increase in complexity and the duration of the procedures give rise to higher patient and staff doses. Depending on the set-up and the shielding protections, the limiting organs may very well be the eye lens, the feet or the legs. Training and experience of the staff play as well a very important role to radiation protection issues. The use of protective devices, such as lead aprons, collars, glasses, etc. can reduce the dose to the staff. However, there are cases where their use can impede a proper and quick operation. Factors that should be avoided are the use of lateral X-ray beams, the use of magnification factors or anything that may interfere or lengthen the medical procedure. Poor or even bad correlation has been found between the extremity doses and the DAP values in most of the cases mentioned in the literature review. It would be advisable to organise a systematic programme of measurements and monitoring that could reveal in a better way the effect of the implicated protection measures.

There is a consensus in the literature regarding the requirement of regular extremity dose monitoring of the staff in nuclear medicine. The wearing of appropriate extremity dosemeters should be a must for all staff who directly handle radioactive sources or are close to the patients. Nearly all authors point out that generally the skin of the hands of workers in nuclear medicine is primarily exposed, with a distinct variation in the dose across the hands.

Some studies showed that the annual dose limit of 500 mSv could be exceeded if the required optimisation is not applied.

According to the literature, technicians working in PET facilities usually receive slightly higher doses than those working in conventional diagnostic nuclear medicine departments. However, these doses are generally below the limits if adequate radiation protection measures are taken. It is important to keep in mind that the maximum skin dose can occur on the finger tips, and this can be considerably higher than the dose measured with a ring dosemeter. However, since dosemeters worn on the finger tips can alter the touch sensation and in general are not easily accepted by exposed workers, the ring dosemeter value must be multiplied with a correction factor to ensure that the dose limit for the skin is not exceeded.

The discrepancies between the reported doses in various centres could be explained on the basis of technological, instrumental and shielding variability. The use of some radiation protection measures, such as shielded syringes, monodose vials or automatic injectors, can result in significant dose reductions. Still, during dispensing of the radiopharmaceuticals, the use of a shield can be impractical and hampers when an accurate volume and corresponding activity has to be drawn. The continuous progress in new applications and techniques requires an important effort in both training and understanding of the new techniques. Staff radiation protection is an important issue that cannot be ignored. Many of the referenced papers show the need to be aware of the basic radiation protection parameters to reduce external dose: shielding, distance and time.

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