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RADIATION PROTECTION DOSIMETRY IN MEDECINE REPORT OF THE WORKING GROUP N° 9 OF THE EUROPEAN RADIATION DOSIMETRY GROUP (EURADOS) COORDINATED NETWORK FOR RADIATION DOSIMETRY (CONRAD - CONTRACT EC N° FP6 - 12684)

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- Juin 2009 -

RAPPORT CEA-R-6220 –

«Dosimétrie pour la radioprotection en milieu médical – Rapport du groupe de travail n° 9 du European Radiation Dosimetry group (EURADOS) – Coordinated Network for Radiation Dosimetry (CONRAD – contrat CE fp6-12684)»

Résumé - Ce rapport présente les résultats obtenus dans le cadre des travaux du WP7 (dosimétrie en radioprotection du personnel médical) de l'action coordonnée CONRAD (Coordinated Network for Radiation Dosimetry) subventionné par la 6ème FP de la communauté européenne. Ce projet a été coordonné par EURADOS (European RadiationPortection group). EURADOS est une organisation fondée en 1981 pour promouvoir la compréhension scientifique et le développement des techniques de la dosimétrie des rayonnements ionisant dans les domaines de la radioprotection, de la radiobiologie, de la thérapie radiologique et du diagnostic médical ; cela en encourageant la collaboration entre les laboratoires européens. Le WP7 de CONRAD coordonne et favorise la recherche européenne pour l'évaluation des expositions professionnelles du personnel sur les lieux de travail de radiologie thérapeutique et diagnostique. La recherche est organisée en sous-groupes couvrant trois domaines spécifiques : 1. Dosimétrie d'extrémité en radiologie interventionnelle et médecine nucléaire : ce sous-groupe coordonne des investigations dans les domaines spécifiques des hôpitaux et des études de répartition des doses dans différentes parties des mains, des bras, des jambes et des pieds ; 2. Pratique de la double dosimétrie : ce sous-groupe passe en revue et évalue les différents méthodes et algorithmes pour l'usage des dosimètres placés au-dessus et au-dessous des tabliers de plomb pour les expositions importantes intervenant lors des procédures de radiologie interventionnelle, particulièrement afin de déterminer les doses efficaces reçues par les cardiologues pendant la cathéterisation cardiaque ; 3. Utilisation des dosimètres personnels électroniques en radiologie interventionnelle : ce sous-groupe coordonne des investigations dans les laboratoires et les hôpitaux, et des inter comparaisons avec les dosimètres passifs dans le but pour permettre la rédaction de normes.

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RAPPORT CEA-R-6220 –

«Radiation Protection Dosimetry in Medecine – Report of the working group n° 9 of the European Radiation Dosimetry group (EURADOS) – Coordinated Network for Radiation Dosimetry (CONRAD – contract EC N) fp6-12684)»

Abstract - This report present the results achieved within the frame of the work the WP 7 (Radiation Protection Dosimetry of Medical Staff) of the coordination action CONRAD (Coordinated Network for Radiation Dosimetry) funded through the 6th EU Framework Program.Tthis action was coordinated by EURADOS (European Radiation Dosimetry Group). EURADOS is an organization founded in 1981 to advance the scientific understanding and the technical development of the dosimetry of ionising radiation in the fields of radiation protection, radiobiology, radiation therapy and medical diagnosis by promoting collaboration between European laboratories. WP7 coordinates and promotes European research for the assessment of occupational exposures to staff in therapeutic and diagnostic radiology workplaces. Research is coordinated through sub-groups covering three specific areas: 1. Extremity dosimetry in nuclear medicine and interventional radiology: this sub-group coordinates investigations in the specific fields of the hospitals and studies of doses to different parts of the hands, arms, legs and feet; 2. Practice of double dosimetry: this sub-group reviews and evaluates the different methods and algorithms for the use of dosemeters placed above and below lead aprons in large exposure during interventional radiology procedures, especially to determine effective doses to cardiologists during cardiac catheterisation; and 3. Use of electronic personal dosemeters in interventional radiology: this sub-group coordinates investigations in laboratories and hospitals, and intercomparisons with passive dosemeters with the aim to enable the formulation of standards.

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Foreword

EURADOS is an organization founded in 1981 to advance the scientific understanding and the technical development of the dosimetry of ionising radiation in the fields of radiation protection, radiobiology, radiation therapy and medical diagnosis by promoting collaboration between European laboratories. EURADOS operates by setting up Working Groups dealing with particular topics. Among these working groups the number 9 is in charge of radiation protection in medicine. Some of the working groups were funded through the coordination action CONRAD (Coordinated Network for Radiation Dosimetry) of the 6th EU Framework Programme (EC contract n° FP6-12684). The coordination action was split into working packages on Computational Dosimetry, Internal dosimetry, Complex mixed radiation fields at workplaces, and Radiation protection dosimetry of medical staff. The latter working package has number 7 and coordinates and promotes European research for the assessment of occupational exposures to staff in therapeutic and diagnostic radiology workplaces. Research is coordinated sub-groups covering three specific areas: 1. Extremity dosimetry in nuclear medicine and interventional radiology: this sub-group coordinates investigations in the specific fields of the hospitals and studies of doses to different parts of the hands, arms, legs and feet; 2. Practice of double dosimetry: this sub-group reviews and evaluates the different methods and algorithms for the use of dosemeters placed above and below lead aprons in large exposure during interventional radiology procedures, especially to determine effective doses to cardiologists during cardiac catheterisation; and 3. Use of electronic personal dosemeters in interventional radiology: this sub-group coordinates investigations in laboratories and hospitals, and intercomparisons with passive dosemeters with the aim to enable the formulation of standards. This report presents the results achieved by the working package 7 of the CONRAD action.

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REPORT of EURADOS CONRAD WP7/SG 1

Extremity dosimetry in nuclear medicine and interventional radiology

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I. INTRODUCTION

A coordinated network for radiation protection dosimetry, the CONRAD project, was founded in 2005 within the 6th EU Framework Programme. The CONRAD project was aimed at the coordination of the research into measurements and calculations for radiation protection at workplaces. The project was divided in seven work packages. WP7 was focussed on the coordination and promotion of European research in the field of ***Radiation Protection Dosimetry for Medical Staff***. WP7 of the CONRAD project was elaborated by EURADOS Working Group 9 (WG9).

The objective of WP7/WG9 was to promote and co-ordinate research activities for the assessment of occupational exposures to staff at workplaces in therapeutic and diagnostic radiology and nuclear medicine.

For some of these applications the skin of the fingers is the limiting organ from the point of view of the individual monitoring of external radiation. Therefore, subgroup 1 of WG9 dealt with the use of extremity dosemeters in medical radiation fields.

According to the ICRP recommendations the dose limit of 500 mSv for the skin in a calendar year should be applied to the dose averaged over any area of 1 cm^2 regardless of the area exposed. According to the Council Directive 96/29/EURATOM of the European Union, which is based on the recommendations of the ICRP, 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. In practice extremity monitoring is carried out by measuring the personal dose equivalent $H_p(0.07)$, considering it as an estimator of the equivalent dose to the skin.

Some parts of the operator's body, such as the hands, are not protected with shielding equipment and may be close to the source of direct or scattered radiation where there is large dose gradient in the dose rates. Due to this non-uniformity of the radiation field and this high dose gradient, care must be taken on the position of the dosemeters on the body. A dosemeter worn at a certain location will not necessarily be representative of that to the most exposed area, so several dosemeters (extremity dosemeters) worn at various locations might be necessary.

The requirement of finding the area of the skin where the dose is maximum is one of the main problems of extremity monitoring and causes severe practical difficulties. In daily practice when preparing and administering radiopharmaceuticals in nuclear medicine, or participating in a complex radiological intervention in interventional radiology/cardiology, it is not easy to know which part of the hand will receive the highest dose. Moreover, the dose distribution across the hand may vary during a single process as well as when various persons perform the same procedure. Another difficulty is that the dosemeter should not disturb manipulations carried out by the medical staff, it has to be compatible with the wearing of gloves and, if needed, with sterilization protocols. Also, the dosemeter has to be adapted to the encountered radiation fields. For these reasons extremities, and particularly hands, are difficult to be monitored.

Furthermore, a wide variety of radiation fields must be monitored, low and medium energy X-ray beams in interventional radiology and photon, positron and beta emitters in nuclear medicine. Therefore, it is difficult to design a small dosemeter with an accuracy similar to that of a whole-body dosemeter for the whole range of interest.

SG1 focussed on three major tasks: (i) a thorough literature review of dedicated studies (ii) an overview of the use of extremity dosemeters in some European countries and (iii) an intercomparison of relevant extremity dosimetry techniques.

For the literature review, the major relevant papers have been listed, an overview is made of the reported extremity doses, and an analysis of the results is given. The review is divided in 4 parts, covering 4 medical domains: interventional radiology and cardiology, conventional nuclear medicine, positron emission tomography, and therapy. Data related to the use of extremity dosemeters in the medical field were collected from seven countries. They are presented and compared with the doses extracted from the literature review. As expected the use of extremity dosemeters changes a lot from country to country. The reported doses are also lower than could be expected based on the literature review. The collection of such data was not easy, it was found that most international dosimetric networks, such as ESOREX, ISOE or UNSCEAR, do not include information on extremity dosimetry.

There have been very few international intercomparisons for extremity dosemeters and none, to the best of our knowledge, specifically focused on the analysis of performance in typical workplaces both in interventional radiology and nuclear medicine. So it was decided to organise an intercomparison for ring dosemeters. In total 24 services from 16 countries participated, and the ring dosemeters were irradiated in reference gamma and beta fields, and in simulated realistic irradiation set-ups.

II. EXTREMITY EXPOSURE AND DOSIMETRY IN MEDICAL APPLICATIONS: A LITERATURE REVIEW

Some activities of EURADOS Working Group 9 (WG9) are presently financed 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 therapeutic and diagnostic radiology and nuclear medicine. For some of these applications the skin of the fingers is the limiting organ from the point of view of the individual monitoring of external radiation. Therefore, subgroup 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 of measuring a local dose that is representative for the maximum skin dose, usually with one single detector, makes it difficult to perform extremity dosimetry with an accuracy similar to whole-body dosimetry.
Sub-group 1 worked out a thorough literature review. This review is divided in 4 parts, covering 4 medical domains: interventional radiology and cardiology, conventional nuclear medicine, positron emission tomography, and therapy

1. EXTREMITY EXPOSURE IN INTERVENTIONAL PROCEDURES

The increase that has been observed in the use of ionising radiation in medicine, especially in interventional radiology and cardiology, is of concern regarding the radiation protection of the patients as well as of the staff. International Commission on Radiological Protection (ICRP) Publication 85 [1] has given examples of the doses of the monitored workers for various X-ray interventions. The staff that carries out interventional procedures is likely to receive significant radiation doses to their hands, or parts of their body not covered with the protective apron, as they are close to the X-rays tubes.

The doses received by the staff depend on the type of procedure, the equipment used and the protocol that is followed. The training and experience of the staff play a very important role to the radiation protection part. The use of protective devices, such as lead aprons, collars, glasses etc, can reduce the dose received by the staff; however, there are cases where the use of some protective devices can lead as a barrier to the proper and quick operation.

According to the ICRP recommendations [2] the dose limit of 500 mSv for the skin in a calendar year should be applied to the dose averaged over any area of 1 cm^2 regardless of the area exposed. Since some parts of the operator's body (like the hands), that are not protected with shielding equipment, may be close to the source of scattered radiation, there can be a large dose gradient in the dose rates. Due to this non-uniformity of the radiation field and this high dose gradient, care must be taken on the position of the dosemeters on the body. A dosemeter worn at a certain location will not necessarily be representative of that to the most exposed area, so several dosemeters (extremity dosemeters) worn at various locations might be necessary.

Extremity monitoring requires easily applicable techniques. Thermoluminescent dosemeters (TLDs) are widely used to these tasks. They can be worn at different positions with several configurations: TLDs into rings that are worn at the bases of fingers, into sheaths, which enable dosemeters to be worn near finger tips, or into strips worn around the wrists. The TLDs can be packed and placed at the legs, near the eye, on the forehead, at the shoulder, the thyroid etc. However, the extremity monitoring may impede the manipulations carried out by the staff. Moreover, problems of sterilisation, or the wearing of gloves are encountered. It should be stressed out that no suitable dosemeters for knees, feet, or eye lenses are available.

1.1. INTERVENTIONAL PROCEDURES AND DOSE DISTRIBUTION

Interventional Radiology (IR) procedures cover a wide range of procedures that use X-rays for diagnostic purposes (like angiographies) or therapeutic purposes (like percutaneous angioplasties). The IR procedures can be separated in some general categories according to the patient access: *percutaneous* (e.g. biliary procedures), *femoral* (like angioplasties) and through *the internal jugular vein (IJV)*, like the transjugular intrahepatic portosystemic shunts (TIPS). There are also specific interventional procedures that refer to many different parts of the body like: carotid procedures, cerebral ones, vertebroplasties etc.

As far as the interventional cardiology (IC) procedures are concerned, two main categories can be mentioned: the haemodynamic ones, such as the percutaneous transluminal coronary angioplasties (PTCA) and the electrophysiological ones (like the insertion of pace makers, PM).

There are several studies referring to the extremity monitoring for the interventional radiology and cardiology procedures [3-21]. Some of the doses reported are shown in tables 1 and 2. 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 from the patient, etc.

For angioplasty procedures many studies refer to PTCA, where there are reported values from shoulder dosemeters varying from 20 to 100 μSv [3,4] per procedure. Generally, haemodynamic procedures and particularly the PTCAs, involve high DAP values due to the intensive use of image acquisition and therefore the staff doses are higher than in other procedures. For coronary angiographies (CAs) there are doses from shoulder dosemeters varying from 13 – 60 μSv per procedure [3,4]. The lowest doses for CA were found in a hospital centre with very strict radiation protection policy (low fluoroscopy modes, use of spectral filters, low frame rate, proper use of protective screens, protective collar, lead aprons and curtain shields).

Moreover, hand doses of 260 μSv for RF ablations [5] as well as doses from shoulder dosemeters of 8-14 μSv [3] have been reported. Doses from shoulder dosemeters for the insertion of PMs can be as high as 10 μSv [3]. Doses from hand dosemeters of 400 μSv for cardiac procedures [6] have also been reported.

The highest doses for electrophysiological studies or angiographies from dosemeters placed at the shoulders have been reported for ICDs and CAs [3,4]. Especially, for ICDs ankle doses are twice higher than the shoulder ones since in these cases the cardiologist usually works on the left side of the patient, where the protective screen is not available. 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 [7].

The wide range of staff doses at the extremities, even in the same procedure or the same centre, emphasizes the importance of the protective measures, staff experience and the protocols that are followed.

For the IR procedures, and especially for angioplasties, the highest doses are reported for percutaneous procedures [8], doses from hand dosemeters of up to 920 μSv per procedure have been reported. Moreover, for vascular radiology procedures finger doses up to 840 μSv [9] have also been reported. There are also studies for extremity doses for other angiography procedures like femoral angiograms with hand doses up to 50 μSv [8] per procedure. However, without protective devices the hand doses in lower limb angiographies, supraaortic and abdominal ones vary from 120-710 μSv [10]. Hand doses in the range of 50-1250 μSv for femoral angioplasties [6,8,11] have also been reported. As far as the doses at foot are concerned, they can be as high as 320-2640 μSv per procedure depending on the type of procedure if no lead protection is used. These values are higher than the doses recorded to hands for the same type of procedures [11].

Extremity doses for other specific interventional procedures are also mentioned in the literature:

- Biliary procedures: hand dose 800-1500 μSv per procedure [6,11,12]
- TIPS: 500-900 μSv per procedure for hands [6,11]
- Embolisation : 140-1200 μSv per procedure [6,8,11]
- Cerebral procedures: 80 μSv for fingers [13] per procedure.

Ring doses for orthopaedic procedures of 10 μSv per procedure have been reported [14] while 210-450 μSv [15] for ring monitoring are mentioned for vertebroplasty ones, since fluoroscopy imaging time that is required during the latter is higher than the routine orthopaedic procedures.

In the interventional neuroradiology sector the highest DAP values required for cerebral and carotid procedures don't show high extremity doses in fingers or eyes [13].

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 is 2-3 times higher than the doses to the hands. However, if a protective curtain is used the dose to the legs is reduced significantly. During TIPS procedures the doses to legs is also higher than the hand doses [11].

Generally the doses are higher in the complex interventional procedures where there are more than one interventions/insertions of wires in the patient body [9].

Table 1: Reported doses for interventional cardiology procedures (CA: coronary angiography, PTCA: percutaneous transluminal coronary angioplasties, ICD implantation of defibrillators, RF: ablation). The position of the dosemeter is shown at the parenthesis (S: shoulder, A: ankle, F: foot, H: hand, FH: forehead.

Procedure	Extremity dose/procedure (μSv)
CA	13(S) [3] 10(A) [3] 60(S) [4] 70(F) [4]
PTCA	20(S) [3] 20(A) [3] 350(H) [8] 100(S) [4] 200(F) [4]
ICD	30(S) [3] 60(A) [3]
RF	10(S) [3] 5(A) [3] 75(FH) [5] 260(H) [5]

Table 2: Reported doses for interventional radiology procedures (IJV: internal jugular vein, TIPS transjugular intrahepatic portosystemic shunts). The position of the dosemeter is shown at the parenthesis (S: shoulder, A: ankle, F: foot, H: hand, FH: forehead, R: ring.

Procedure	Extremity dose/procedure (μSv)
Percutaneous	920 [1] (H) [8] 820(H)-biliary procedure [6] 620(F)-biliary procedure [11]
JV	630(H) [8] 900(H)-TIPS [6] 2670(F)-TIPS [11]
Angioplasty	210(H) [8] 100(H) [6] 320(F) [11]
Embolisation	140(H) [8] 1200(H) [6] 940(F) [11]
Angiogram	50(H) [8] 100(H) [6]
Vertebroplasty	210-450(R) [15]
Stent	300(H) [6] 690(F) [11]

[1] Dose from the hand nearest to the X-ray tube

1.2 ANNUAL DOSES AND DAP VALUES

In many of the above studies extrapolation of the reported doses to the annual ones has been attempted according to the workload of the hospital. McFadden et al. [5] estimated a mean dose for the hand and the forehead of the cardiologist performing RF ablations of 240 μSv and 50 μSv per procedure respectively that leads to a yearly dose under the relevant dose limits. Trianni et al. [4] extrapolated the shoulder doses to the annual effective dose for cardiologists and they found to be 320 and 360 μSv for CAs and PTCAs respectively, which is lower than the regulatory dose limits. Moreover, the shoulder doses reported by Tsapaki et al. [4] are also not higher than the annual limits. Goldstone et al. [12] found doses to surgeon hands less than 100 μSv per procedure which leads, if it is extrapolated to annual dose, to less than the dose limits. However, Vano et al. [7] reported 3 times higher doses for dosemeters placed at the shoulder which means annual doses higher than the dose limits. Moreover, Damilakis et al. [10] found that operators' doses to hands can approach the relevant dose limit during a high workload.

It should also be mentioned that in most of the studies the mean DAP value is reported in order to find a relationship between the dose to the patient (DAP parameter) with the extremity doses. Comparison between the various facilities can be made using the staff dose normalised to DAP values. This ratio is an indication of practices where high radiation staff doses are received. It is recommended [16] that the DAP value can be used as a significant radiological workload tool. This parameter is important in order to analyze staff doses and practices that result in unnecessarily high doses. Whitby et al. [11] gave a rule of thumb: 100 $Gycm^2$ can lead to 1 mSv to legs if no lead shield is used and 0.02 mSv with protective shield. The correlation between staff doses to legs and DAP values is relatively good since the distance of legs is constant during most of the procedures. Trainni et al. [3] calculated the ratio of effective dose/DAP and it was found to be high for pacemaker implantation, where the operator works very close to the patient. It was also shown that the effective dose per procedure is in good correlation with the DAP value ($r=0.92$, $P<0.01$) for ICD procedures and not for PTCA and CA ones. Moreover, in another study, it was found [17] that there is a good correlation between the finger doses and screening time during percutaneous procedures. The different personal techniques of the operators may well explain the wide range of radiation exposure to fingers. However, Vanhavere et al. [18] found poor correlation between DAP values and doses to legs or hands. Damilakis et al. [10] also reported a bad correlation between dose and fluoroscopy time ($P>0.05$). Tsapaki et al. [4] reported moderate correlation of patients' DAP values with staff shoulder doses; furthermore, correlation between foot dose and DAP value is poor for both PTCA and CA procedures. Therefore, it is not easy to estimate staff doses from DAP values. The bad correlation can be explained by the different parameters that affect the extremity doses like X-ray characteristics, protective devices and different protocols followed by the staff.

1.3. POSITION OF EXTREMITY DOSEMETERS

The high gradient in the dose rates of the radiation field at the interventional radiology procedures causes problems at the monitoring protocol that should be followed. First of all, there are parts of the staff body that are partly or not covered with lead shielding. Secondly, the use of such tools causes higher doses because of the higher time required to perform the procedure. Thirdly, some parts of the staff body are very close to the X-ray beam and these parts are seldom monitored (like legs).

The vast majority of studies for extremity monitoring refer to hands and rings. However, there are studies where other monitoring locations have been used like the eyes [7,13] or the thyroid [15,19], that are areas not protected by the lead apron. In most of the cases the primary operator receives the highest annual dose. Care should be taken to ensure that assistance staff does not receive high doses to their body and also to the lens of the eye or the thyroid. Shoulder dosemeters are also used in many studies [3,4,20,21]; Vehmas et al. [21] reported that shoulder doses are correlated with the hands doses.

Moreover, in many studies the distribution of the dose across the hands is examined in order to find the most suitable position for monitoring [6,8,18]. For most of the IR procedures the bases of the ring and little finger receive the highest dose. However, at the percutaneous procedures the tips of the middle and ring fingers can receive doses 30% higher than the above. Moreover, for dose distributions along the arm, there is a gradual decline in dose up the arm and away from the X-ray tube. In most of the cases the type of the procedure and the manipulations of the staff are factors that affect the distribution of dose in the different parts of the hand. According to Martin et al. [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]. According to Damilakis et al. [10] the hand doses to the operators' hands are higher at the left part since the operator has to stand at the right side of the patient at the abdominal and supraaortic procedures. As it is also indicated in the same study, for procedures regarding the lower extremity procedures the femoral approach makes the right hand doses higher than the left ones. Finally, for radiology procedures high doses to legs can be avoided if lead shields are used.

1.4. CONCLUSIONS

The review emphasizes the fact that there are many parameters that affect the extremity dose of workers in interventional radiology and cardiology departments. The extremity doses can be as high as 1 mSv per procedure for complex procedures (like PTCAs or TIPS) for hand dosemeters. If no proper protective shields are used the doses can be as much as 3 times higher. The doses to the lower limbs of radiologists can also be high if no lead protection is used.

The doses received by the staff depend on, apart from the type of procedure and the workload of the department, parameters directly related to the radiation protection policy like: the protective equipment that are used (collars, apron, shields, eye glasses), the protocol that is followed, the X-ray equipment used, the training of the staff. It makes a big difference for the dose to the staff whether or not they stay next to the table during acquisition in digital subtraction angiography.

However, there are cases where the use of some of the protective devices can lead as a barrier to the proper and quick operation. Among the factors that should be avoided are the following:

- Use of lateral x-ray tubes
- Long fluoroscopy times
- High number of frames
- Use of magnification factors and
- Anything that may interfere with manipulation (e.g. surgical gloves can provide a reduction of 15-20% but may give the operator a false safety impression) or lengthen the procedure.

As far as the annual dose limits there are cases mentioned in the literature where the described practices can approach the dose limits. In these cases either the high workload or the lack of a proper radiation protection policy are responsible for the high doses observed.

Routine monitoring of extremities is difficult, since "the most exposed area" according to the ICRP recommendations [2] cannot easily be found. In most of the cases only finger or hand doses are reported; Doses to the eye lens, legs or thyroid have not been evaluated. In many studies (especially while no protective shielding on the couch is used) leg doses can be even higher than the hand ones. However, even when ring/hand dosimetry is used for extremity monitoring the position of the dosemeter is not clear, since the most exposed area depends on the type of the IR and IC procedures. Finally, it is noted that no proper dosemeter is available for the eye lens, leg or thyroid doses. It should be stressed out that the relevant quantity for the eye dosimetry is still the $H_p(3)$ according to the draft recommendations of the ICRP.

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 that is explained by the variety of parameters that affect the extremity doses. Due to this fact a more structured program of measurements and monitoring may reveal a better correlation of the implicated parameters.

Finally, it should be noted that numerical simulation can play a very important role in evaluating extremity doses in correlation with many different parameters of the procedures in IR and IC.

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2. EXTREMITY DOSIMETRY IN CONVENTIONAL NUCLEAR MEDICINE

2.1. INTRODUCTION

Nuclear medicine is associated to all uses of unsealed radioactive sources for therapy or diagnosis purposes. Therapy and *in vivo* diagnosis are based on the administration to a patient of a radiopharmaceutical which contains a radionuclide and is presented in the form of either a solution (the most frequent case), or powder in pills, or gas. The radionuclide can be either directly used, or associated with a vector (molecule, hormone, antibody, …).

Nuclear medicine is a matter of concern as regards radiation protection of workers since (i) high radionuclide activities are needed, from few tens to several thousands of MBq, (ii) the procedures require the handling of the radiopharmaceuticals at contact with and/or very close to the extremities (hands, fingers) and (iii) pure beta-emitters and mixed photon/beta-emitters are used.

The aim of this paper is to review the literature covering occupational exposure of extremities for conventional nuclear medicine. By conventional nuclear medicine is meant here any diagnosis procedure associated with a scintigraphy carried out with gamma-cameras (bones, heart, lungs, thyroid, …). The large majority of these procedures is dominated by the use of ^{99m}Tc, which represents 80% to 90 %, the rest being mostly associated with iodine and, to a lesser extend, thallium (^{131}I, ^{123}I, ^{201}Tl). For these radionuclides, since in the literature it is often difficult to distinguish between diagnosis and therapy, particularly for procedures involving iodine, this review comprises these latter cases, although their contribution to the dose is marginal. Exclusion is made of PET(–SCAN) procedures, involving mostly ^{18}F beta+-emitter, and all other therapeutic ones with, for example, ^{32}P, ^{90}Y, ^{153}Sm, ^{169}Er, ^{186}Re, ^{188}Re, used for cancer, palliative, anti-inflammatory treatments.

The finger dose from handling syringes containing radionuclides was first noted to be a hazard in 1969 [1,2], soon after the introduction of ^{99m}Tc generators. For example, a dose of around 5 mSv was estimated on the fingertip of a hand handling an unshielded syringe containing 10 mCi (370 MBq) ^{99m}Tc during 5 min [1]. These dose rates, of the order of 1 mSv.min^{-1} at contact, were later confirmed by Hušák [3], Takaku and Kida [4] and Henson [5] by measurements and/or calculations, and also for other radionuclides. Similar values were also obtained by Anderson et al. [6] in more realistic working conditions. These observations motivated some efforts for reducing the doses by improving techniques and using appropriate protection devices, such as 'butterfly' needles and syringe shields, as reported by Bolich [7]. Assessing the efficacy of syringe shields was also the topic of McElroy [8] who showed that dose reduction factors larger than 100 could be reached for ^{99m}Tc. Assessment of the efficacy of various syringe shields were made and possible improvements on their design, replacing lead by tungsten, and adding leaded-glass windows, were investigated (McElroy [8], Schürnbrand et al. [9], Dye et al. [10]), see also Thomson et al. [11] for beta-emitters). Some studies made in medical working conditions were published by Anderson et al. [6], Harbottle et al. [12], and Mussel [13]. For example, a range in dose around 0.3 – 6.9 mSv per 100 injections was observed among different measurement points of the left and right hands [12]: for such short distances between the radioactive source and the hands, geometry effects lead to widely varying differences in doses to various parts of the upper extremities.

2.2. GENERAL DISCUTION

In the following, individual publications from year 1985 are briefly described. Attention is paid on extracting the relevant data relating the extremity doses of staff working in nuclear medicine departments and who have been specifically monitored with this aim.

Koback and Plato [14] measured extremity doses received by three groups of workers, two of them using brachytherapy implants made of ^{192}I and ^{137}Cs, respectively, the third one using liquid radiopharmaceuticals in a nuclear medicine pharmacy. Concerning specifically the nuclear medicine group, seven workers were studied by placing a total of 16 thermoluminescent dosemeters (TLDs), for both arms, at four different positions: the tip and ring position of the third finger, the wrist and the elbow. For each zone a dosemeter was placed at the anterior position (facing the radioactive source) and at the posterior one (on the shaded side). The doses received per procedure were averaged for each zone over the workers. However, information was given neither about the involved radionuclide, though it can be guessed that ^{99m}Tc was the most frequent, nor about the handled activities. Although the use of syringe shields was recommended, some workers were foregoing the shields to speed up the process. They found that the anterior part of tip of the right (dominant hand) third finger received the largest dose: 1.26 mSv per procedure, against 0.52 mSv for the left hand at the same position, and 1 mSv for

the posterior part. Ratios between different positions were determined, among which an observed averaged value of 1.9 between tip and ring positions.

Harding et al. [15] assessed the protective value of syringe shields for ^{99m}Tc by measuring finger doses in a radiopharmacy (i.e. elution of the ^{99}Mo – ^{99m}Tc generator into vials, preparation and labelling of radiopharmaceuticals), a dispensary (i.e. dispensing individual patient syringes from vials) and while giving patient injections. Three, one and three staff, respectively, were equipped with TLDs at the tips of their left and right index fingers, during two periods of one week with and without syringe shield. The study revealed that although theoretical attenuation factors for commercialized syringe shields are high for ^{99m}Tc (of the order of 100 for a tungsten thickness of 3 mm), actual observed dose reductions were of 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 slows-down the process. Furthermore, syringe shields had to be removed for measurements of radioactivity. Their data have the advantage of being normalized per unit handled/injected activity, which is useful for subsequent comparisons. This normalisation can be viewed as a workload unit. For example, an injection workplace represents a typical weekly handled activity of 20 GBq ^{99m}Tc. With shields, the measured doses were, on average, 0.8 mSv.10GBq^{-1}. For radiopharmacy and dispensary locations, the right (dominant) finger received the largest dose. For injections the inverse was observed. During injections, since the left (non dominant) hand is holding the skin taught while introducing the needle inside the vein and injecting. It is then more exposed than the right hand. Extrapolating the highest doses, recorded without shields, to annual doses, radiopharmacy and dispensing led to 330 mSv each and injections to 220 mSv. If all injections would have been carried out by a single person, it was reported that annual doses would have been 430 mSv.

Williams et al. [16] monitored two members of staff while dispensing during one week and two other members of staff while giving injections for one week as well. There was no distinction between radiopharmacy and dispensary, which were merged as dispensary in this paper. TLDs were used and taped at three different locations on each hand: distal phalanx of index, proximal phalanx of middle finger (where ring dosemeters are frequently worn) and palm of the hand. From the different TLD locations, a mean hand dose was estimated for each worker. The maximum doses were observed at the proximal phalanx of index: for dispensary 0.43 and 0.64 mSv.10GBq^{-1}, 0.33 and 0.58 mSv.10GBq^{-1} for injections, for left and right hands, respectively. No significant difference was noticed between left and right hands and a factor of 4 to 5 between ring and fingertips was estimated. From the mean hand doses, annual doses were about 20 mSv for dispensing, and 2.7 mSv for injecting.

In their paper, Harding et al. [17] reviewed the literature dealing with staff radiation doses in nuclear medicine departments. The provided data for extremity doses were those from [15].

Stuardo [18] studied four nuclear medicine technologists during one week performing dose preparation, administration, and imaging. The radioisotopes used were ^{99m}Tc (91%), ^{131}I (9%) and ^{201}Tl (< 0.5%). LiF TLDs were attached to the fingertips of each hand, with a ring TLD worn at the base of the index of the right hand. It was observed that the tip of the index fingers received the largest dose (8.9 and 10.6 mSv for left and right hands, respectively), these positions being associated with a dose factor of 3 larger than the ring dose on average, but ranging from 1.6 to 4.2, depending on the technologist. A maximum annual average dose of 80 mSv (16% of the limit) was extrapolated.

Batchelor et al. [19] investigated the regional distribution of absorbed dose to both hands during dispensing and administration of all radiopharmaceuticals (containing mostly ^{99m}Tc) used in their nuclear medicine department, with a focus on comparing different techniques, i.e. either using or not different butterfly cannula for administration. Special gloves were equipped with nine TLDs and worn during two weeks on both hands by two nurses. Again, without using butterfly cannula, it was observed that the index fingers received the largest doses (1.1 and 0.52 mSv.10GBq^{-1}, for left and right hands, respectively). Here significant differences between left (non dominant) and right (dominant) hands were observed. For all the investigated techniques, it appeared that the base of the second digit gave a good estimation of the mean dose of whole hand. An average factor of 2.5 between the doses recorded at the index and at the ring, and annual mean hand doses of 118 and 59 mSv for left and right hands, respectively, could be estimated.

Jansen et al. [20] reported on the effective doses and doses to the hands received by staff during preparing and injecting ^{99m}Tc-based radiopharmaceuticals, at two hospitals during 8 years (1985–1992). For the monitoring of hand doses TLD dosemeters were worn an the base of the right middle finger. Over the studied period, the mean annual hand doses were 131 ± 56 mSv (hospital A) and 37 ± 11 mSv (hospital B) for radiopharmacy workers, and 50 ± 17 mSv for the nursing sister responsible for injecting at hospital A. The radiopharmacy doses recorded at hospital A could be converted to 10.5 ± 2.8 mSv.10GBq^{-1} for the period 1988–1992. This latter value appears substantially higher than any previously reported, but it is mentioned that during preparation lead vials were used but no syringe shields.

Mackenzie [21] reviewed radiopharmacy methods with the aim of reducing the extremity radiation dose for staff. Three different procedures for the preparation of ^{99m}Tc-methylene diphosphonate (^{99m}Tc-MDP) were

investigated, the so-called standard one being consistent with the manufacturer's instructions. TLDs were placed at the tip of the left and right index fingers of a (left-handed) radiopharmacist. It was observed that the non-dominant (right) index was the most exposed (0.66 and 0.22 mSv.10GBq^{-1} for the non-dominant and dominant hands, respectively). That would lead to mean annual equivalent doses of the order of 28 and 9 mSv, respectively. The two other investigated techniques led to a reduction of the dose by up to a factor 1.7, but for the non-dominant hand only.

Hastings et al. [22] measured, at two separate hospitals, the fingertip doses by means of TLDs worn at the thumb, index and middle fingers of both hands while dispensing and injecting radiopharmaceuticals, containing mostly ^{99m}Tc. Attention was paid on the influence of the technique used for checking the ^{99m}Tc activity drawn up into the syringe before administration to patients. For the conventional technique doses of 0.63 and 0.31 mSv.10GBq^{-1} at the index fingers, and 0.53 and 0.28 mSv.10GBq^{-1} for the average over the monitored fingers were observed, for left and right hands, respectively. It was found that the choice of the technique for checking the activity could lead to dose reductions by more than a factor of two. Whole body doses were simultaneously measured. For the same technique, 5.6 μSv.10GBq^{-1} were recorded. It was mentioned that even in the worst case among those studied, the annual finger dose was still less than 100 mSv.

Dhanse et al. [23] measured the doses to both the fingertip and finger base of the dominant hand of 7 technicians preparing radiopharmaceuticals mostly based on ^{99m}Tc in a radionuclide dispensary. The monitoring period lasted more than 5 years, from 1994 to 1998. TLD tapes were worn on the inside of the distal phalanx (tip) of the index or middle finger and rings on the inside of the proximal phalanx (base) of the index, middle or ring finger. Due to the introduction of additional syringe shields, the doses were reduced through the 1994–1998 period (by 45 % for the fingertip) though there was a 25 % increase in workload. In 1998 the annual doses were 83 ± 11 mSv (0.18 ± 0.02 mSv.10GBq^{-1}) and 61 ± 14 mSv (0.13 ± 0.03 mSv.10GBq^{-1}) at the fingertip and finger base, respectively, the dose at finger base thus representing 70 % of the fingertip one. It has to be mentioned that these authors also constructed static models of hands in order to measure the distribution of dose across the hands while dispensing using an electronic gamma extremity monitoring system (GEMS) [24,25].

Chruscielewski et al. [26] presented the results of measuring the equivalent dose to the hands of sixty workers (physicians, nurses, radiopharmacists and technicians), employed in five nuclear medicine laboratories where ^{99m}Tc, ^{131}I are in common use (included also ^{125}I and ^{59}Fe, but to a much lesser extend with respect to the handled activities). Doses were measured at one month intervals with TLD rings worn as routine extremity monitoring conditions, i.e. at the first phalanx of the middle finger of the dominant hand. Seven months were covered, representing several thousand examinations. Estimated annual doses showed large variability. For example, the radiopharmacists of one of the laboratories were associated with annual hand doses ranging from 3.7 to 200 mSv, with an average of 50 mSv, and all workers of another laboratory revealed hand doses ranging from 0.03 to 0.12 mSv only, with an average of 0.08 mSv.

Jankowski et al. [27] reported a pilot study of the equivalent doses to the skin of the hands of radiopharmacists conducted over 12 months in a nuclear medicine department. TLD rings were worn by the workers at the first phalanx of the third finger of the dominant hand. The results revealed annual hand doses within the range 14.4–87.6 mSv, and an average of 35.2 mSv. These values motivated a more detailed study of the dose distribution on the hands of seven radiopharmacists, carried out by placing TLDs at different positions: wrist, ring, and nails of each finger. In the course of the investigations, the activity ranged from 21 to 76 GBq. The thumb and index fingers were the most exposed (on average 6.4 and 6 mSv), but with an index dose ranging within 1.1–16.6 mSv. Ring and wrist equivalent doses were on average equal to 1.3 and 0.35 mSv, respectively. If an average handled activity of 48.5 GBq was considered, an index equivalent dose of 1.2 mSv.10GBq^{-1}, a ring dose of 0.27 mSv.10GBq^{-1}, and a mean hand dose of 0.68 mSv.10GBq^{-1} could be estimated. This corresponds to an average ratio of 4.6 between index and ring doses. It was also shown that at contact with the vial, the fingertip dose can be 8.7 times larger than the finger nail dose.

Whitby and Martin [28] used an electronic finger dosemeter (AEGIS, see also [29]), worn near to the finger tip, along its side, to investigate options for shielding the hand during the preparation and injection of ^{99m}Tc MDP. This system allowed to analyse the doses received from individual actions, and their evolution with time. It was also used to measure dose distributions around shielded and unshielded vials and syringes. They observed that the tip of the index finger of the dominant hand received the highest dose. Doses received during dispensing were within the range of 10–555 μGy per procedure, while those from individual injections within 1–150 μGy, depending on the way vials and syringes were held, and on the degree of difficulty experienced during the injection. On average, the observed dose per manipulation per unit activity taken into the syringe was 0.3 mGy.10GBq^{-1} in the dispensary, and 4 mGy.10GBq^{-1} for injections. Use of syringe shields during dispensing reduced the finger dose by 75–85 %.

The same authors [30] published a comparison between two groups of hospital workers, namely interventional radiologists/cardiologists and radionuclide staff preparing and injecting ^{99m}Tc radiopharmaceuticals. For nuclear

medicine, again AEGIS was used, and the studies were carried out for three radiopharmacies and three nuclear medicine departments. Using syringe shields, the doses to the index finger ranged within 0.07–0.15 mSv.10GBq^{-1} for dispensing sessions and within 0.1–3.2 mSv.10GBq^{-1} for drawing up and injection. Dose reduction factors, similar to those previously mentioned, were observed when using syringe shields. Depending on the situation, the ratio between the dose to the tip and that to the base of the finger, in the position for monitoring by a ring dosemeter, was in the range 1:1.5 to 1:3 for radiopharmacies, but it could fall down to 1:6 for some nuclear medicine staff. Estimated annual hand doses were 10–200 mSv and 5–40 mSv for radiopharmacy and nuclear medicine staff, respectively.

Whitby et al. [31] studied dispensing methodologies in a number of UK radiopharmacies in order to evaluate the impact of these differences on doses to the hands. Measurements were made again with the AEGIS system. It was concluded that the most important factor determining the level of hand doses for radiopharmacy staff, apart from the skill and experience of the operators, is the use of syringe shield. Among the different results presented in this paper, the authors reported doses, for a selected radiopharmacy, of 0.13 ± 0.07 against 0.08 ± 0.03 mGy.10GBq^{-1} for the tip and base of the dominant hand, respectively.

Sæther et al. [32] estimated annual dose equivalents $H_p(0.07)$ to the hands of X-ray guided surgery and endovascular treatment, nuclear medicine (^{99m}Tc) and research staff (^{32}P), using TLD rings at the base of the middle finger of one hand, generally the closest to the radiation source one. For nuclear medicine, finger doses were measured for 22 persons, doing preparation, dispensing and administration during 2–4 weeks. The extrapolated mean annual finger dose was estimated to be 17.4 mSv, with a maximum of 52.1 mSv. Following the results of Batchelor et al. [19], the authors considered these doses as close to the 'mean hand dose'.

Donadille et al. [33] have published results of measurements carried out during administration by a single operator of ^{99m}Tc-DPD to twenty patients, using syringe shields, for an overall administrated activity close to 13.5 GBq during one week. TLDs were taped at the tips of the thumb, index and middle fingers of the left and right hands, plus ring finger for the right hand. It was observed that for each hand the tips of the index were the most exposed (the dose equivalents $H_p(0.07)$ were 0.77 and 0.38 mSv.10GBq^{-1}, respectively), with the left hand significantly more exposed than the right one (average hand doses of 0.59 and 0.17 mSv.10GBq^{-1}, respectively), and very large variations of the doses as a function of the dosemeter location (almost a decade for the left hand).

In their papers, Vanhavere et al. [34] and Berus et al. [35] have reported on studies intended to map the dose distributions on the hands as function of the manipulation in a nuclear medicine department, for ^{18}F- and ^{99m}Tc-labelled radiopharmaceuticals. Two radiopharmacists, performing preparation and dispensing (not administration to patients), were monitored with TLDs during more than 300 manipulations at 18 different locations on both hands. Taking the results of reference [35], the maximum dose equivalents $H_p(0.07)$, both measured on the right (non-dominant) hand were 1 mSv.10GBq^{-1} (32 mSv.month^{-1}) on the tip of the thumb and 1.3 mSv.10GBq^{-1} (44 mSv.month^{-1}) on the tip of the index, for workers A and B, respectively. Also, large overall differences of the dose distributions, which have complex shapes, were found between these two workers. The major contributions arose from dispensing, task during which the use of a syringe shield was impractical. Without additional radiation protection measures, these values, when added to the doses associated with ^{18}F manipulations, suggested that these staff members would easily exceed the yearly dose limit. An average multiplication factor 'highest dose / ring dose' could be determined for each task: 1.4 (workers A and B) for preparation and 7.0 (worker A) and 2.0 (worker B) for dispensing.

Similar studies were presented by Covens et al. [36] but extended to more than 500 manipulations, for 7 right-handed workers performing kit preparation, dispensing and injections of ^{18}F and ^{99m}Tc (95 % of the overall workload). Highest dose was often located on the left hand, on the tip of the thumb, middle or index finger, depending on the worker. Highest doses were measured in the ranges 0.23–0.26, 0.88–1.16 and 0.37–0.60 mSv.10GBq^{-1} for preparing, dispensing and administrating ^{99m}Tc-labelled radiopharmaceuticals, respectively. Annual doses estimated from the highest dose of each worker were 48–146, 67–484 and 22–48 mSv for the same tasks, respectively. Dose levels close to the annual limit of 500 mSv could then be reached and around 600 mSv was even estimated for two workers when ^{18}F was taken into account. An overall ratio 'highest dose over ring dosemeter' between 2.5 and 3.5 was determined for most workers.

Tandon et al. [37] have published measurements made for 54 Indian institutions, each with 3 to 4 workers having nuclear medicine activities. Each worker wore 4 TLD ring during one month on the dorsal side of the index and ring fingers of both hands. Detailed records of the tasks (from preparation to scintigraphy) and handled activities were kept. Over all the 54 institutions, the recorded ranges of dose equivalents $H_p(0.07)$ were 0.02–3.5 mSv.10GBq^{-1} for elution + radiopharmacy (preparation + dispensing), 0.05–10 mSv.10GBq^{-1} for administration, and 0.04–9.5 mSv.10GBq^{-1} for scintigraphy. The corresponding mean doses received were 75.1, 74.0 and 66.5 mSv.month^{-1}, respectively, or, averaging over the provided doses per unit handled activity, 1.13, 1.76 and 1.49 mSv.10GBq^{-1}, respectively. The reason for these high average finger doses was attributed to the poor work practices and availability of limited handling facilities in the institutions.

Wrzesień et al. [38] performed a series of measurements with 19 TLDs worn per hand, plus one TLD ring on the middle finger, for a group of 13 (right-handed) radiopharmacists (preparation + dispensing) of 5 laboratories wearing 19 TLDs per hand. The most exposed parts were the fingertips of left and right hands, but specifically those of thumb, index and middle fingers. On average, the fingers of the left hand received the highest doses. The values for the tip of the index were 3.6 and 2.4 mSv.10GBq^{-1} for the left and right hands, respectively and 0.5 mSv.10GBq^{-1} for the ring dosemeter and both hands. The doses recorded by the ring dosemeters were on average 5 times smaller than the doses received by the fingertips of the three most exposed fingers; this means if the ring dosemeter recorded about 100 mSv, then the dose for fingertips can exceed the annual skin dose limit of 500 mSv.

On Table 3 the results are summarized per unit workload (mSv.10GBq^{-1}) for the studies which it was possible to extract these data from. Index, ring and mean hand doses are provided for the dominant and non-dominant hands. Most of the index tip doses are within the range 0.1–2 mSv.10GBq^{-1}, except for few cases [28,30,38], particularly in latter reference [38] for which they are substantially larger for the index. It shall be noticed that in reference [37] the estimated mean hand dose are also significantly larger than the other published ones. Ring and mean hand doses are systematically smaller than those measured at the tip of the index. The overall scatter of the results can be explained by variations in techniques and practices between the nuclear medicine departments into which these investigations were performed. Although the non-dominant hand is often observed to be more exposed than the dominant one, the dose levels for both hands are quite similar, not justifying to strongly recommend the wearing of routine rings on a particular hand.

Table 1: Summary of the data collected in the literature, in terms of doses per unit handled activity for the non dominant (ND, generally left) and dominant (D, right) hands. When available, the different steps (preparation, dispensing, injection and scintigraphy) have been distinguished.

Ref.	Task	Index tip dose (mSv.10GBq^{-1})		Ring dose (mSv.10GBq^{-1})		Mean hand dose (mSv.10GBq^{-1})	
		ND	D	ND	D	ND	D
15	Preparation	0.54	0.68			0.50	0.70
	Dispensing	0.67	1.83			0.70	1.80
	Injection	0.67	0.39			0.70	0.40
16	Preparation	0.43	0.64	0.19	0.26	0.24	0.34
	Injection	0.33	0.58	0.12	0.14	0.17	0.26
19	Dispensing + injection	1.06	0.52	0.40	0.22	0.48	0.25
20	Preparation				10.5 ± 2.8		
21	Preparation	0.66	0.22				
22	Dispensing + injection	0.63	0.31			0.53	0.28
23	Preparation		0.18 ± 0.02		0.13 ± 0.03		
27	Preparation		1.24		0.27		0.68
28	Preparation		0,30*				
	Injection		4,00*				
30	Preparation		0,07–0,15				
	Injection		0,10–3,20				
31	Preparation		0.13 ± 0.07*		0.08 ± 0.03*		
33	Injection	0.86	0.45			0.59	0.17
35	Preparation	0.18	0.14	0.09	0.17		
	Dispensing	0.69	0.74	0.20	0.36		
37	Preparation + Dispensing					1.13	
	Injection					1.76	
	Scintigraphy					1.49	
38	Preparation+ Dispensing	3.6 (0.6–8.9)$^{\#}$	2.4 (0.2–8.6)$^{\#}$	0.5 (0.2–2.4)$^{\#}$	0.5 (0.1–2.4)$^{\#}$		

* in mGy.10GBq^{-1}

$^{\#}$ measured minimum and maximum values

2.3. CONCLUSIONS

The published evaluations of extremity doses reviewed in this paper were all carried out experimentally, using almost exclusively TL dosemeters, except in the case of references [28–31] for which an electronic system (AEGIS) was used. TLDs are indeed easy to use. They can either be worn as rings, or taped at different positions on the hands, and they provide accurate results when used with ^{99m}Tc.

For a given study, the dose distributions on the hands are complex. For a given worker the measured dose depends strongly on the position of the dosemeter and also, for successive procedures, of their specific difficulty. For an ensemble of workers, strong variations are also attributed to differences in individual experiences and working habits (see [33–38]).

There is a general consensus about the radiation protection provided by vial and syringe shields (see [15,30]), that should be considered as a must in nuclear medicine.

The tips of the thumb, index and middle fingers receive doses significantly larger that recorded by a ring, generally worn at the base of either the index, middle or ring finger. Reported ratios between the tip of the index and the ring vary from 1.4 to 6, with a tendency to be smaller for preparation activities than for dispensing and injections (see [14,16,18,19,23,27,30,31,35,36,38]).

Extrapolated annual extremity doses can vary from values smaller than 1 mSv [26] up to several hundred millisieverts [15,30,35,36,38], close and even above the 500 mSv limit at the most exposed parts of the hands.

The reviewed published studies for conventional nuclear medicine indicate that extremity doses have to be assessed for each workplace in order to take into account the variability of local and individual practices/habits. The evaluation has to be carried out over a representative period, i.e. covering a significant number of procedures and, idealistically for every operator, using a set of dosemeters located at different positions (at least the tip of the index and the ring). This would allow determining the appropriate corrective factors to be applied to the routine ring dosemeters, to account for the under-estimation of the maximum doses received at the tips of the fingers which should apply to comply with regulatory annual limits.

Finally, if reference extremity doses should be needed for these medical activities a clear evaluation methodology should be defined, coupling a set of measurements at several nuclear medicine departments with numerical simulations of the main hand configurations while performing the different tasks.

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3. EXTREMITY EXPOSURE IN PET EXAMINATIONS

3.1. INTRODUCTION

Positron emission tomography (PET) is considered one of the most relevant diagnostic imaging techniques having the special characteristic of providing functional and quantitative information for the organ of interest, like brain or heart. The use of PET has been increased due to the possibility of annihilation photon imaging by means of new generation coincidence gamma cameras, the new "lower cost" sodium iodide PET cameras and the fact that ^{18}F produced by a single cyclotron can be distributed to several PET centres. ^{18}F-FDG (^{18}F fluorodeoxyglucose) is the most used oncological PET radiotracer and one of the most important tools in diagnostics of brain and heart diseases, especially in oncology.

PET radiopharmaceuticals are positron emitters; their 511 keV annihilation photons are detected by coincidence systems. Specifically, the physical properties of ^{18}F that are important from the radiation safety point of view are: the β+ emission and the 511 keV of the annihilation photons. These features, which are common to clinical positron emitters (carbon-11, nitrogen-13 and oxygen-15), give them specific gamma ray constants Γ, considerably higher than those of conventional isotopes such as ^{99m}Tc. The extremity dosemeters used need to be capable of measuring the emitted positrons, which is not always the case with the present dosemeters.

For radiation protection however, the important aspects are similar to nuclear medicine in general, like shielding, workload, injected activity, time between injection and imaging, metabolic uptake and clearance of the tracer.

At PET workplaces the occupational doses of the respective workers can significantly vary within the departments, workers and practices performed. There are a few studies for the evaluation of the occupational doses for PET facilities that have been reported in the literature [1-7]. Chiesa et al. [5] demonstrated that radiation doses received by PET technologists were higher than those received in nuclear medicine diagnostic departments. However, more recent studies [3,7] showed similar radiation doses for the technicians. A technician whole body dose of 20-30 nSv.MBq^{-1} of ^{18}F is typical of a practice performed in a dedicated PET centre.

3.2. DOSE DISTRIBUTION

Most of the studies refer to the extremity dose of technologists. However, in one study [8] the physician dose, wearing a TLD ring, is also reported. In reference [9] the finger dose of nurses is also mentioned.

The dose surveys were performed in different centers for many PET procedures from 6 months to one year dealing with 4-10 patients per day. Only TLDs were used as finger dosemeters. The radiopharmaceutical used in all of these cases is ^{18}F-FDG. In reference [9] also other pharmaceuticals are mentioned as well: 11C-bicarbonate, ^{15}O-water, ^{13}N-ammonia, ^{11}C-methionine. The activity of the isotopes used varies from 302 MBq (monodose vials of radiopharmaceutical) to 440 MBq. The TLDs were placed on the index finger, the middle finger or the thumb. The measurements were performed usually for both hands.

The lowest dose reported in the literature is 0.19 μSv.MBq^{-1} (for monodose vials) to 0.59 μSv.MBq^{-1} (for multidose vials [10]) for the whole process. The low 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 technologist and the patient. Extrapolation of these results to the annual dose (4 patients per day per technologist) revealed that the annual extrapolated exposure values remained under the authorized limits for classified workers. A dose of 0.19 μSv.MBq^{-1} is also reported by Biran et al. [11] using shielded syringes which reduced the extremity dose by 25% reduction.

Other studies in the literature report doses for different work steps. Doses of 0.16 μSv.MBq^{-1} to 0.19 μSv.MBq^{-1} were reported 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 μSv.MBq^{-1} [12]. Tandon et al. [13] 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 μSv.MBq^{-1}.

Zito et al. [8] reported a dose of 0.7 mSv to 9.9 mSv per month for ring dosemeters for technologists and around 0.2-4.2 mSv per month for physicians taking into account 10 patients per day. This paper suggested that a reduction of the doses could be obtained by distributing the PET work to all the staff of the nuclear medicine department, to get a more uniform distribution of dose among exposed workers. Some practical radiation protection procedures should be further exploited, like interacting with the injected patient only when required and speeding up patient management. As a general consideration some effective reduction of dose to personnel seems to be possible with the introduction of 3D PET scanning with 5-6 fold increase of sensitivity with respect to the 2D one. This allows an important decrease of the activity injected to the patient with consequent reduction

of worker exposure. A possible reduction of dose to the hands of technologists can also be achieved with a fully automatic activity-dose dispenser which prepares the syringe avoiding any kind of manipulation except to pick up the final box containing the syringe for patient administration. The 5 year study of Marti-Climent et al. [9], considering 7032 PET in total, showed that the finger dose at nurses varied from 0.087 to 0.10 μSv.MBq^{-1} and the respective dose at technicians ranged from 0.16 to 0.54 μSv.MBq^{-1}. For both groups (technicians and nurses) a significant correlation was found between doses received and activity manipulated, and there was also a correlation between whole body effective dose and finger dose. The study also revealed that special lead containers and syringe manipulators can be efficient for reducing personnel doses.

3.3. CONCLUSIONS

According to the literature, technologists working in PET facilities usually receive slightly higher doses than those working in nuclear medicine diagnostics departments. However these doses, taking into account a workload of 4 patients per day per monitored worker, are generally below the limits for occupational exposure. Care has to be taken to check if the dosemeters used do not underestimate the contribution of the positrons. As in nuclear medicine diagnostics and therapy, the maximum skin dose can occur on the finger tips, and this can considerably exceed the dose measured by the ring dosemeter.

During the last years progress has been made in order to make the working environment in a PET facility more favourable from the radiation protection point of view. The discrepancies between the various PET centres for the reported doses can be explained on the basis of technological, instrumental and shielding variability. The use of protection means during the manipulation of the pharmaceuticals like shielded syringes, monodose vials and automatic injectors results in dose reductions. The use of the new PET cameras has introduced a lower injected activity and less scanning time that reduce the technologists dose. A further dose reduction in a PET centre can be obtained by better shielded waiting areas.

Monitoring is an ongoing process, especially as the demand for PET facilities is rising and improvements in PET technology is increasing enormously.

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4. EXTREMITY EXPOSURE IN NUCLEAR MEDICINE THERAPY AND IN BRACHYTHERAPY

4.1. INTRODUCTION

There are several reasons for the fact that the use of sealed and unsealed radiation sources for therapy is a matter of concern as regards radiation exposure to staff:

- the high activities needed for therapy purposes, in the range of some ten MBq up to some GBq,
- the use of beta-emitters comprises a considerably higher factor of the dose rate per activity unit than gamma-radionuclides,
- the fact that some procedures require handling of radionuclides close to the skin on the hands and
- the additional risk of contamination when using unsealed nuclides.

Therefore, in situations where safety standards are low, the staff who handles therapy sources may be exposed to high doses which exceed the annual limit of the dose to the extremities and the skin. Thus, adequate safety measures, which include extremity monitoring of personnel, are needed.

Finally, there is limited literature concerning radiation exposure and protection of medical staff in therapy since most of it refers to, interventional) radiology or to personnel involved in nuclear medicine diagnostics.

4.2. 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. Inflammatory joint diseases are treated using radiosynoviorthesis, RSO) by injecting ^{90}Y, ^{186}Re or ^{169}Er-solutions into the joints. Sealed ^{90}Sr/^{90}Y and ^{32}P sources or ^{188}Re liquid-filled balloon catheters are used in intravascular brachytherapy, IVB) to cure patients with so-called in-stent-restenosis [1]. Recently, radioimmuno-therapy, 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) of neuroendocrinic tumours by means of ^{90}Y or ^{177}Lu.

Extremity exposures of staff in diagnostic nuclear medicine was studied by several authors in the 1980's and 1990's,. They found that the dose distribution across the hands of workers who handle radionuclides is more variable than that of radiologists and cardiologists because the hands are closer to the source and individual differences in techniques have a more significant impact. The tip of the index finger of the dominant hand is likely to be the part that receives the maximum dose. Some 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.

The official British HSE actually stated that doses across the hands of staff in nuclear medicine may vary by a factor of four to ten [2].

Except for other nuclides and higher activities, operations at workplaces in nuclear medical therapy do not differ considerably from those in diagnostics. In particular, when using beta sources, the personnel are exposed to rather non-uniform radiation fields. These special exposure conditions raise questions as to individual monitoring.

There are very few studies only on radiation exposure and dosimetry of staff carrying out therapy procedures in nuclear medicine. In this area, where mostly beta-emitters are used, the handling of radionuclides does not essentially differ from those used in diagnostic nuclear medicine. Nevertheless, there is a basic distinction: activities of some GBq are often required to fulfil the therapeutic effect. Moreover, high-energy beta nuclides such as ^{90}Y, Emax=2.28 MeV) are promising candidates in particular, e.g. for the treatment of several types of tumours. Among these therapies, radioimmunotherapy, RIT) and peptide-receptor-guided radionuclide therapy, PRRT) have been investigated in some European countries in clinical studies. RIT is being applied in clinical routines both in the US and several European countries.

The preparation and administration of radiopharmaceuticals in RIT and PRRT require the manipulation of high activities of ^{90}Y. Hence, there is an enhanced risk for the technicians, assistants and doctors to receive high exposures, mainly to the fingers. In cases where radiation protection measures are not properly kept, even non-stochastic radiation damage may occur.

Tosi [3] reported on an accident that occurred in Italy during the preparation of ^{90}Y-labelled peptides. An operator, who did not use shielding or forceps, touched a vial with highly concentrated ^{90}Y-solution directly with

the fingers. The local dose to the finger tips was estimated at 12 Gy, having the consequence that erythema and skin lesions at three fingers occurred. This event evidently underlines the need for extremity dose monitoring when handling high activities of beta-emitters in nuclear medicine.

In a recent paper from the same clinic, comprehensive measuring results of finger doses by means of plastic thimbles with TLD were published [4]. The authors studied extremity exposure during the preparation and application of ^{90}Y-labelled antibodies, Zevalin®) and peptides, DOTA-TOC®). The dose to the fingertips of the staff was estimated for three different tumour treatments for groups of up to 50 patients. The mean ^{90}Y-activity in each of the groups was 0,4, 1,1 and 3 GBq per patient. When using radiation protection means, PMMA-shielding, tongs, X-ray gloves) the mean dose at the finger tips during labelling was found to be between 0.6 and 2.9 mSv per patient. Depending on personal skill and experience the individual exposures comprised a wide range of doses and the maximum was in the order of 30–40 mSv during a single procedure. The authors stated that radiolabelling and administration of ^{90}Y-conjugates can be carried out at an acceptable safety level. They recommended the regular use of TLD for dose monitoring of the finger tips apart from strict protection measures.

The treatment of liver cancer with ^{90}Y-microspheres, Octreother®) and the therapy with ^{90}Y-Zevalin® was the focus of a study in France [5]. Measurements with TLD, type GR 200) performed on the assistants, who carried out the infusion of the radiopharmaceutical, resulted in finger doses up to 20 mSv per patient. Combined finger monitoring and operational dosimetry by means of electronic photon dosemeters, for bremsstrahlung) was considered to be necessary.

In Germany the introduction of the ^{90}Y-Zevalin® therapy into clinical routines was accompanied by extremity dose measurements with TLD [6,7]. Measurements were performed at 6 clinics on 8 radiochemists/assistants and 9 doctors, who were involved in labelling procedures and treatment of 14 patients. A mean activity of 1.5 GBq was used for labelling and 1.2 GBq for injecting. The detectors were fixed with tapes at various points on the fingers aimed at finding out both the maximum skin dose and its localisation. In general, the maximum dose was found on the tip of the left index finger or thumb, for right-handed individuals). However the individual exposure pattern across the hands and the dose range varies. When the personnel worked under an acceptable safety standard the dose range was 1.3-8.1 mSv.GBq^{-1} for the labelling staff and for the doctors it was 0.3-2.2 mSv.GBq^{-1} per patient when performing the i.v. injection. In a few cases fundamental safety measures were neglected and local skin dose up to 600 mSv, labelling) and 27 mSv, injection) were measured. As a consequence, the authors stressed that an adequate radiation protection standard has to be established and strictly applied. Additionally, routine monitoring with ring dosemeters is needed. It is essential to use dosemeters that are appropriate for measuring beta radiation. In general, these dosemeters should be worn close to the tips of the forefinger or thumb of the highly exposed hand.

The benefits of beta-emitting radionuclides have already been used for some decades for the treatment of chronic joint inflammations. The so-called radiosynoviorthesis, (RSO) is applied in Europe. In Germany, for instance, the injection of ^{90}Y, ^{186}Re or ^{169}Er-solutions into joint space is utilised more often than radiotherapy of the thyroid. Over 60,000 therapies are performed annually, of which about 20,000 are knee treatments using ^{90}Y [8]. As to the radiation exposure of the staff, again the ^{90}Y-therapies are most critical. There are some publications, on extremity exposure in this field [9,10,11,12,13].

All these studies revealed that even in RSO the highest dose is to be expected on 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. Very often the tips of these fingers are likely to receive the maximum dose. When safety standards are ignored, up to 200 mSv per day were estimated in single cases [9]. An extended study was carried out to reveal a correlation between the reading of a ring dosemeter and the maximum local skin dose to be limited. The measurements took place in seven nuclear medicine surgeries during the preparation, filling) of ^{90}Y-syringes by the assistants and during the application, injection) by nuclear physicians, respectively. In total, about 20 measuring series during preparation and application by 10 doctors were done, comprising 113 patients, of which an activity of 200 MBq was applied on average. A regular ring dosemeter was worn close to the first joint of the left index finger, of right-handed individuals) simultaneously with TLD, which were fixed with tapes on the finger tips. Moreover, the influence of the usage of various protection means was studied. It was found that a ring dosemeter underestimates the maximum skin dose by a factor of three on average when the therapy is performed at a high safety level. As a result of the study, the implementation of correction factors for ring dosemeters in routine monitoring should be taken into consideration. This factor and the dose to the fingers increase with decreasing radiation protection standard.

Intravascular brachytherapy, (IVB) by means of beta-emitters is another ambitious procedure in nuclear medicine. The use of a balloon catheter with ^{188}Re-solution implies similar problems for radiation protection and dosimetry of the medical staff as already discussed above for the other fields of application. If the method is not properly carried out, very high extremity exposures may also occur. Barth et al [14] reported a case where a

nuclear physician received a finger dose of more than 500 mSv in a single day during the preparation and administration of the radiopharmaceutical for two patients.

IVB and some other applications of ^{188}Re are the focus of an article by Andreeff et al. [15]. They stated that the true radiation dose to the finger tips may greatly exceed the reading of an official ring dosemeter.

4.3. BRACHYTHERAPY

Brachytherapy treatment consists of the direct insertion of radioactive sources, usually sealed sources, into or close to the tissue to be treated. Dose rate ranges from 0,4 Gy/h to more than 10 Gy/h depending on the chosen technique.

Brachytherapy can be split into four main types. In interstitial brachytherapy, sealed gamma sources are implanted into tissue. Nowadays, ^{192}Ir wires are the most common sources, except for permanent implants for early-state prostate treatments, where ^{125}I, ^{123}Pd and very recently ^{131}Cs seeds are used. The effective photon energy of ^{192}Ir is approximately 350 keV, whereas permanent implant radionuclides have an effective photon energy of approximately 20 and 30 keV. ^{192}Ir, because of its high specific activity, is also the chosen radionuclide for very high dose rate, HDR) applications. In intracavitary applications, the radiation sources are inserted into a pre-existing body cavity. The most common treatments of this method are gynaecological or nasopharynx tumours, where ^{192}Ir and ^{137}Cs, 662 keV gamma radiation) are often the preferred radionuclides. Mould brachytherapy is related to the treatment of superficial tumours and requires the placement of sealed sources close to the skin. This type of brachytherapy usually also includes the so-called surface applicator technique with beta sources such as ^{90}Sr and ^{106}Ru/^{106}Rh plates for ophtalmologic applications. Finally, in the 1990's cardiovascular brachytherapy was found to be a very promising technique for the treatment of in-stent restenosis of the coronary arteries. ^{192}Ir and more recently ^{90}Sr/^{90}Y and ^{32}P sources are placed inside the vasculature through a catheter.

In the early days, the radioactive material was handled manually 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, because of a better reproducibility of the sources location.

In manual brachytherapy, generally higher doses are received by the hands of staff during source preparation or source implantation in the patient. However, there are few published data on registered doses. In some works, personnel and even skin dose are estimated from environmental monitoring, which can infer large errors, specially for beta sources where there is a high dose gradient [16]. K. Ennow [17] investigated finger doses for ^{192}Ir and ^{137}Cs manual implants in a radiation therapy department. His results showed an average monthly finger dose of 1.5 mSv within a range of 0 to 43 mSv. He also determined the finger dose/wrist dose ratio, which was of the order of 5 to 9. These results highlight the fact that for most of the staff dose is far below the established limits, but that in some cases high doses can be found. Along the same lines, Huerga et al. [18] also claimed very low finger doses in the handling of ^{125}I seeds, and ^{106}Ru. However, the paper does not describe in detail how the doses were estimated.

Manual brachytherapy cannot allow the removal of the source for nursing or medical visits, thus it requires the use of lead screens to reduce exposures to the staff when they are close to the patient. Unfortunately, the personnel can only be partially shielded and therefore, in this case, there is some difficulty in obtaining a good estimate of staff effective doses. Faulkner et al. [19] analysed the problem of monitoring staff involved in manual ^{192}Ir, ^{137}Cs and ^{226}Ra brachytherapy and points out the importance of measuring the abdomen absorbed dose in pregnant women. The study gives examples of dose overestimation and underestimation depending on dosemeter placement.

The new trends tend to use, whenever possible, remote-controlled high dose rate sources, often ^{192}Ir. The sources are driven along the catheters to the end of a wire by a machine while the patient is isolated in a room. The advantage of this treatment over implanting the sources directly is a lower staff exposure and the source can have a higher activity. If there is no failure of the machine the staff dose should really be very low. However, because of the very high dose produced, an over-dose cannot be disregarded. ICRP-97 [20] is devoted to the prevention of accidents in high dose rate brachytherapy, and unfortunately, many incidents and accidents have been reported. The most common undesired events have been related to sources not moving properly, remaining in the safe position or not being retrieved from the patient. The most severe cases have always affected patients.

Intravascular, also called endovascular, brachytherapy, IVB can involve a higher dose to the medical staff. The procedure requires different phases as regards source handling: deployment, connection of the treatment catheter with the source delivery device and placement of the sources; treatment, irradiation of the stenosis; recovery of the source, storage of the source at the end of the prescribed time. During these three phases the source may on

occasion be free in the air, mainly while it goes from the patient to the treatment device and vice-versa, thus generating high ambient doses. Furthermore, endovascular brachytherapy requires a large team of experts, cardiologists, radiographers, radio-oncologists, physicists, nurses and physicians or surgical assistants, thus making it difficult to ensure appropriate training. This technique showed a rapid increase during the 1990s, but now the situation is very much stabilised, and initial expectations of growth have not been reached.

Balter et al. [21] undertook a survey on personnel exposure during gamma endovascular brachytherapy with ^{192}Ir, 12.4GBq, using a simple hand-operated delivery system. They found that the most exposed individual was the oncologist, who was found to receive between 7 and 95 μSv per procedure to the left arm, with spurious readings of up to 200 μSv. The authors reported on the high variability of measured doses, attributed to the position of the personnel in the room and to the placement of dosemeter. However, data on finger doses were no given. As an example, of the importance of optimising the applied procedure, the authors mentioned that before starting the study, the oncologist doses were 4 times higher because he was located between the patient and the trolley transporting the sources.

Intracoronary beta radiation therapy presents less radiation protection problems for the staff than gamma brachytherapy [22,23], since the most critical phase is during the transition from the shielded container to the patient, and this is performed very quickly, approximately 2 seconds). Nevertheless, it is important that the cardiologist keeps a sufficient distance to the transfer catheter and does not touch it during the source transition.

4.4. INDIVIDUAL DOSIMETRY

Although radiation protection measures have priority over monitoring of radiation exposures, a good monitoring procedure is one of the main instruments to ensure correct radiation protection of the staff.

There is a consensus in the literature regarding the requirement of regular extremity dose monitoring of the staff in nuclear medicine. In nuclear medical therapy and in intravascular brachytherapy, the wearing of extremity dosemeters should be a must for all staff that directly handle radioactive sources or are close to the patient. Nearly all authors point out that generally the skin of the hands of radionuclide workers in nuclear medicine is primarily exposed, with a distinct variation in the dose across the hands. This estimation especially applies to any handling of beta emitters, which has been shown in some recent studies at workplaces.

These specific working and exposure conditions pose problems for extremity monitoring with ring dosemeters. First of all, considering the preferential use of beta emitters, the dosemeters have to be appropriate for beta radiation, taking into account the energy spectra of the nuclides and the spectral dose response of the dosemeter.

Generally, a dosemeter for betas consists of special thin-layer TLD-detectors and a holding-ring with a thin filter to comply with the definition of the quantity $H_p(0.07)$. Such a ‘beta dosemeter’ also reads photons, in most of the cases with an acceptable dose response, even when the dosemeter is calibrated in a beta reference field such as ^{90}Sr/^{90}Y. The level of over- or under-reading of the true value of $H_p(0.07)$ in a real field can be estimated by means of the spectral dose response.

Vice versa, a ring dosemeter designed for photon radiation may not automatically be used in mixed beta/photon fields. Fortunately, many of these dosemeters also indicate $H_p(0.07)$ with a suitable response, at least for high energy beta emitters such as ^{90}Y. Its application in mixed beta/photon fields requires the dosemeters to be carefully calibrated for the particular field.

Even when appropriate dosemeters are available and actually worn by the exposed staff, there is another essential issue to be considered: As a consequence of the definition that the dose limit for the skin has to be applied to ‘the dose averaged over any area of 1 cm² regardless of the area exposed’, it is advisable to measure the local skin dose at the location with presumably the highest exposure. This requirement is the central dilemma of extremity dosimetry and causes severe practical difficulties. In daily practice when preparing and administering radio-pharmaceuticals in nuclear medicine it is not easy to comply with this requirement since it is often not known which part of the hand receives the highest dose. In addition, the dose distribution over the hand may vary during a single process as well as when various persons are performing the same procedure.

Furthermore, for most staff different procedures are practised during a monitoring period of a month. Thus, rather different exposure situations may occur with regard to radiation energy, beta and gamma field, X-rays) and the radiation incidence, whole body/extremity exposure, field homogeneity, angle of incidence). Hence, it is hardly possible to estimate the quantity $H_p(0.07)$ according to the rules with a single ring dosemeter worn on a finger. Consequently, doubts should be raised about whether the monitoring of the dose limit for the skin is possible at some workplaces in a similar manner as it is usual in supervising whole body exposures.

4.5. CONCLUSIONS

The main objective of most radiation therapy procedures is to provide effective patient care using minimally invasive techniques. The development of technology and radioisotope production together with a better knowledge of radiobiology causes continuous new isotopes and new applications of sealed and unsealed sources for radiation therapy [24,25,26]. This continuous progress requires an important effort in both training and understanding of the new techniques. Staff radiation protection is an important issue that cannot be ignored. This review has shown that in spite of the high doses handled in radiation therapy, there are few data available regarding staff doses, in particular about extremity doses associated with this type of radiation practice. Most authors point out the wide range of measured doses depending on individuals and procedures.

Some of the techniques involve the use of mixed beta and photon fields, but the monitoring is not always performed with the appropriate dosemeter. The position of the dosemeter can also be of major importance in order to have a good estimate of the skin dose or the effective dose. However, there are no generally accepted recommendations. Recently an intercomparison between most of the ring extremity dosemeters used in Europe has been undertaken, within the framework of EURADOS and the results of the study should give good hints regarding the performance of extremity dosimetry in radiation fields of interest for medical staff [27].

Many of the referenced papers show the need to be aware of the basic radiation protection parameters to reduce external dose: shielding, time and distance. They also stress the need for good training and awareness of beam directions to establish the optimised position of the personnel when they must be close to the patient. International recommendations to improve radiation protection of staff in the most common techniques could improve protection of the individuals involved in these applications.

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III. AN OVERVIEW OF THE USE OF EXTREMITY DOSIMETRY IN MEDICAL APPLICATIONS IN SOME EUROPEAN COUNTRIES

1. INTRODUCTION

The CONRAD project is aimed at the coordination of research on radiation protection at the workplace. One of the working groups in the network has been involved with the coordination and promotion of European research in the field of ***Radiation Protection Dosimetry for Medical Staff***. One of the main attention points are the extremity doses for medical staff, and a thorough review of the literature was performed to find out the state of the art of the subject and also to identify areas where improvements are still needed.

From this literature review, it is clear that there are several medical applications where radiation protection is an important issue and where recorded doses can be very high. Some studies have highlighted the need to establish regular monitoring of the extremities of exposed workers, mainly in nuclear medicine, interventional radiology and some radiotherapy applications. The analysis also showed a wide range of reported doses for similar situations together with an important lack of data for some identified critical working conditions. For example, it was found that most international dosimetric networks, such as ESOREX, ISOE or UNSCEAR, do not include information on extremity dosimetry.

Although research studies indicate the position of extremity dosemeters can be very important to ensure a correct estimate of the maximum skin dose, there are no international recommendations available.

The aim of this report is to gather as much information as possible on the status of extremity dosimetry in medical applications in some chosen European countries. The interpretation of the data is not easy because of the wide range of procedures involved and also because of the different criteria followed by the different countries. However, the overview can highlight fields where there is a greater need for harmonization and improvements.

Another point that must be kept in mind when comparing dosimetric data is that there are very few data on the performance of extremity dosemeters in realistic medical fields. The wide variety of radiation fields in medical applications, together with the difficulties of designing an appropriate ring dosemeter, make it difficult to perform extremity dosimetry to an accuracy similar to that of a whole-body dosemeter [1]. The intercomparison organised within the CONRAD project showed significant underestimates or overestimates for some types of dosemeters. Among the consulted countries, only Germany has a well-established periodic national intercomparison for extremity dosimetry [2].

Data related to the use of extremity dosemeters in the medical field have been collected within 7 European countries: Switzerland (CH), Germany (D), Spain (E), France (F), Greece (GR), Ireland (IE) and Poland (PL) and are presented in this document. The data have been provided by the central register of each country, except for France and Poland. The data for France have been obtained from different dosimetric services, nevertheless representing all monitored workers. For Poland, the data come from one dosimetric service, representing the majority of the monitored workers.

2. REGULATION AND PROCEDURES

The 96/29 European Union directive [3], which is based on the recommendations of ICRP 60 [4], establishes the general requirements to ensure appropriate radiation protection of exposed workers. Individual monitoring constitutes an integral part of the radiological protection programme. According to the 96/29 EU Directive, "*individual monitoring shall be systematic for category A workers,"* which means for those workers liable to receive an effective dose greater than 6 mSv per year or an equivalent dose for the skin greater than three tenths of the annual dose limit on the equivalent skin dose. The limit on equivalent skin dose should be 500 mSv a year. This limit should apply to the dose averaged over any area of 1 cm², regardless of the area exposed. The operational quantity of interest for extremity dosimetry is Hp(0.07).

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. This requirement is one of the main dilemmas of extremity dosimetry and causes severe practical difficulties. In daily practice when preparing and administrating radiopharmaceuticals in nuclear medicine, or when participating in a complex radiological intervention, it is not easy to know which part of the hand will receive the highest dose. Moreover, the dose distribution across the hand may vary during a single process as well as when various persons perform the same procedure.

Another practical difficulty associated with the design of an extremity dosimetry programme, is that the dosemeter should not disturb manipulations carried out by the medical staff, it has to be compatible with the wearing of gloves and, if needed, with sterilisation procedures.

The development of extremity dosimetry has been substantially different in the 7 chosen countries. This paragraph highlights some of the different approaches. As regards the position and type of dosemeter, Spain and France perform extremity dosimetry both with a wrist or a ring dosemeter, depending on the dosimetry service. Switzerland, Germany, Ireland and Poland only use ring dosemeters, whereas in Greece, ring dosemeters have been introduced since 2007. The monitoring period is 1 month for all 7 countries. According to regulations, the dosemeter should be placed where the highest value is expected. However, in practice this is not done. In general, the wrist dosemeter is worn at wrist level on one of the two arms, but there is no recommendation or information about which of the two arms is monitored. Differences in position are even larger in the case of ring dosemeters, since each user decides on which finger the dosemeter is worn on and what the orientation is.

Another parameter on which there is no consensus is the reporting level. In Switzerland, Germany, Greece and Poland the reporting level is 1 mSv, whereas in Ireland and Spain it is 0.1 mSv, or between 0.1 and 0.3 mSv for France, depending on the dosimetry service. This difference influences the numerical value of the reported mean dose for exposed workers.

There is a lack of criteria for the unification of activities within the medical field. This makes the classification of the different activities very difficult. In addition, there are very few data bases providing this kind of information.

The above-mentioned examples confirm that there is a need for harmonization of dosimetric practices in extremity monitoring across Europe [5].

3. EXTREMITY DOSIMETRY IN THE MEDICAL FIELD

Most exposed workers in the medical field wear a whole body dosemeter. However, only a minority, between 2 % and 9 %, also wear an extremity dosemeter. Table 1 shows the number of monitored[1] workers in the medical field in the 7 chosen European countries, together with the fraction that uses extremity dosimetry, detailing the type of dosemeter used. As mentioned in the previous paragraph, Switzerland, Germany, Ireland and Poland always use a ring dosemeter, Greece only uses a wrist dosemeter, Spain and France use both, but mainly the wrist type.

Table 1. Summary of individual monitoring in the medical field for 7 European countries in 2005: France (F), Germany (D), Greece (GR), Ireland (IE), Poland (PL) Spain (E) and Switzerland (CH).

Country	Number of whole body monitored workers	Percentage of workers wearing an extremity dosimeter	Percentage of workers wearing	
			ring dosemeter	wrist dosemeter
F	159000 (*)	5%	19%	81%
D	240000	5%	100%	0%
GR	9200	2%	0%	100%
IE	6900	5%	100%	0%
PL	29200	2%	100%	0%
E	43000	9%	5%	95%
CH	50800	2%	100%	0%

(*) including veterinary activities which represent 6.7% of the total.

[1] Monitored workers are those workers wearing an extremity dosemeter independently of the dose received.

4. RECORDED EXTREMITY DOSES

The following paragraphs present the registered mean extremity doses classified by field of medical application and type of dosemeters together with their evolution in the last 5 years. Three medical applications are considered: interventional radiology, nuclear medicine and radiation therapy. In general, the group of interventional radiology includes any use of X-rays in diagnostics, with and without fluoroscopy. Similarly, the group of nuclear medicine includes installations of conventional diagnostic nuclear medicine, PET, therapy with unsealed pharmaceuticals and radiopharmaceutical units. Radiation therapy involves workers in brachytherapy and therapy.

In all cases, the reported mean dose has been calculated for extremity monitored workers. Of course, this value would have been higher if it had been given for exposed[2] workers and, in both cases; it is influenced by the reporting level value. In Germany, the exposed workers represent about 25 % of the monitored workers for interventional radiology and 50 % of nuclear medicine workers. In Spain, the exposed workers are 60 % of those monitored for interventional radiology and 85 % for nuclear medicine.

4.1. INTERVENTIONAL RADIOLOGY

Table 2 presents the mean annual dose to the extremities in interventional radiology for the 7 European countries considered in this study for two different kinds of extremity dosemeters, ring and wrist, for the year 2005. Mean doses range from 2.5 mSv to 19 mSv. In the countries where both ring and wrist dosimetry are used, mean annual doses measured with a ring dosemeter are always higher than those obtained with a wrist dosemeter, differences range from a factor of 2 to a factor of 7. The second part of the table indicates the number of workers with a mean annual dose higher than 5 mSv and those with a dose higher than 50 mSv for each country, the percentage of monitored workers that represent each category are shown beside. It can be seen that the annual extremity dose is found to be above 50 mSv in very few cases.

Table 2. Mean annual doses in extremities in interventional radiology and number of workers with annual doses above 5 mSv and 50 mSv for the year 2005.

Type of extremity dosimeter	Country	Number of workers wearing extremity dosimeters	Reporting level [mSv]	Mean annual doses [mSv]	Number of annual doses > 5 mSv		Number of annual doses > 50 mSv	
RING	F	1279	0.1 to 0.3	10.9	--	--	--	--
	D	7155	1	2.5	--	--	--	--
	IE	188	0.1	2.3	0	0%	0	0%
	PL	585	1	8.2	--	--	0	0%
	E	50	0.1	19.2	25	50%	10	20%
	CH	407	1	3.6	39	10%	9	2%
WRIST	F	5302	0.1 to 0.2	1.5	--	--	--	--
	GR*	133	1	17.9	7	5%	2	2%
	E	2799	0.1	8.9	654	23%	144	5%

** For Greece the mean annual dose is reduced to 1.85 mSv when two cases of bad-practices are not considered.*
-- indicates no data available

For Switzerland, Germany, Spain, Greece, Ireland and Poland, we have information on the evolution of the use of extremity dosemeters since 2001 and of the recorded mean doses during this period. Figure 1 shows the mean annual dose in interventional radiology for each country from 2001 till 2005. In general, the number of monitored workers has increased in the evaluated period but in some countries the number is still too low to draw general conclusions.

The mean extremity doses for ring dosemeters were stable for Germany and Switzerland and below 5 mSv. For Ireland, annual doses were approximately 10 mSv during years 2001 and 2002, but they have decreased below 5 mSv in 2005. Poland started to use extremity dosimetry in 2002 and reported a mean annual dose of

[2] Exposed workers are those workers wearing an extremity dosemeter with doses larger than zero.

approximately 30 mSv, while in the following years the annual dose decreased below 10 mSv. This decrease was interpreted by the dosimetric service as an improvement of the practice.
Concerning wrist dosemeters in Greece, the mean annual doses were below 5 mSv from 2001 to 2004, but they increased to 18 mSv in 2005. This change is attributed to two cases recorded cases of bad-practice in a specific hospital. Ignoring these two cases, the mean extremity dose for 2005 is 1.85 mSv. In the case of Spain, mean annual dose from wrist dosemeters was stable in the 5 monitored years and below 10 mSv (results from more than 2700 workers). However, the mean annual doses estimated from the ring dosemeters are higher and range from 20 mSv to 35 mSv. Ring dosemeters started to be used in Spain for interventional radiology in 2003, but they still represent a minority of workers, less than 50.

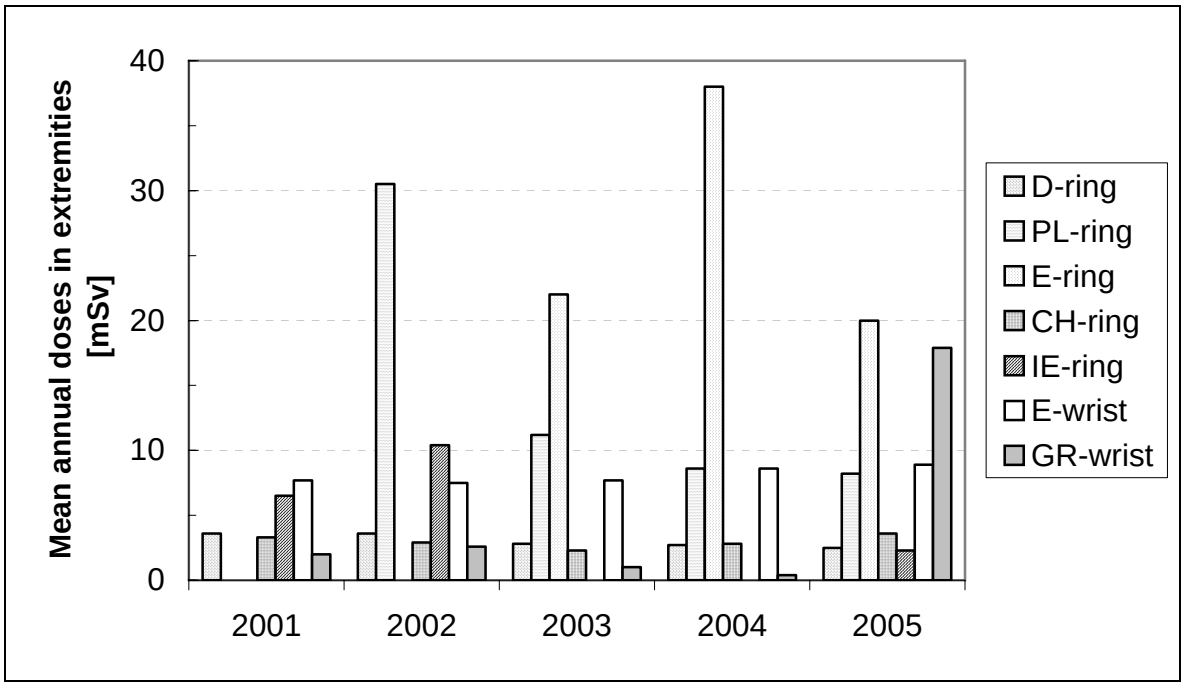

Figure 1. Evolution of the mean annual extremity doses in interventional radiology for 6 European countries. Dotted bars refer to ring dosemeters, plane bars to wrist dosemeters

4.2. NUCLEAR MEDICINE

Table 3 and 4 give a summary of the radioisotopes most commonly used in nuclear medicine, respectively, for diagnosis and for therapy and their percentages of use for 4 different countries. Doses will depend upon the procedure and radioisotope used. Tc-99m is the radioisotope most commonly used in diagnosis and I-131 in therapy. However, in Germany, radiosynoviorthesis is a very common therapy practice using radioisotopes such as Er-169, Re-186 and Y-90. The frequency of these treatments is very high, almost at the same level as those using I-131.

Table 3. List and distribution of most commonly used radiopharmaceuticals in nuclear medicine diagnosis.

Radioisotope	% of use in D (1997)	% of use in CH* (2006)	% of use in B* (2005)
Tc-99m	86,8	49.3	83,3
Tl-201	4,4	23.9	0,05
I-123	2,9	3.5	0,6
F-18	2,3	14.0	7.6
In-111	0,7	0.2	0.41
Cr-51	0,2	6.7	3
Others	2,7	2.3	5.17

(*) data from only one university hospital

Table 4. List and distribtion of most commonly used radiopharmaceuticals in nuclear medicine therapy

Radioisotope	% of use in GR (2004)	% of use in CH (2006)	% of use in B (2002)	% of use in D (2005)
I-131	34.5	89.7	95.7	42.8
Er-169		0.7		40.1
Re-186	14.8	5.5		
Y-90	17.4	2.8	1	16
In-111	22.8			
Y-90 (zevalin)		0.7		0.2
Sr-89	6.2		2.7	0.9
Sm-153	4.3	0.7	0.2	
P-32			0.2	
I-125			0.2	

Table 5 gives the mean annual extremity doses in nuclear medicine for Switzerland, Germany, Spain, France, Greece, Ireland and Poland for the two different kinds of extremity dosemeters, ring and wrist, for the year 2005. Likewise in Table 2, the number of workers receiving doses higher than 5 mSv and 50 mSv are shown. Again, the number of workers with annual doses above 50 mSv is very low.

Table 5. Mean annual doses for extremities in nuclear medicine and number of workers with annual doses above 5 mSv and 50 mSv for the year 2005.

Type of extremity dosimeter	Country	Number of workers wearing extremity dosimeters	Reporting level [mSv]	Mean annual doses [mSv]	Number of annual doses > 5 mSv		Number of annual doses > 50 mSv	
RING	F	314	0.1 to 0.3	12.2	--	--	--	--
	D*	3104	1	7.1	78	3%	46	1%
	IE	111	0.1	5.7	34	31%	0	0%
	PL	143	1	7.6	--	--	0	0%
	E	129	0.1	29.1	75	58%	23	18%
	CH	404	1	9	119	29%	19	5%
WRIST	F	862	0.1 to 0.2	3.1	--	--	--	--
	GR	45	1	1.9	3	7%	0	0%
	E	698	0.1	6.5	206	30%	11	2%

** For Germany, the number of workers with doses larger than 5 mSv (50 mSv), actually corresponds to number of workers with doses larger than 1 mSv (10 mSv).*

-- indicates no data available

The reported mean annual doses in nuclear medicine range from 2 mSv to 29 mSv. In the countries in which both ring and wrist are used, mean annual doses measured with a ring dosemeters are about four times larger than those obtained with the wrist ones.

When comparing the values of mean doses for nuclear medicine with those of interventional radiology for the same country, it can be observed that mean doses for ring dosemeters are higher for nuclear medicine than for interventional radiology.

The evolution of extremity annual doses in nuclear medicine from 2001 to 2005 is shown in Figure 2. As in the case of interventional radiology, in general, the number of monitored workers has increased in the evaluated period. For most countries, the annual doses during this period are below 15 mSv. In the case of Spain, an increase from 10 mSv to 24 mSv was observed in 2003 for ring readings, and from then on the mean dose measured with ring dosemeters kept increasing slightly. This behaviour could be explained because of an increase in the number of monitored workers in 2003. In addition, the reported dose, which is higher than for the other countries, could be due to the fact that in Spain ring dosemeters in nuclear medicine are mainly worn by workers in charge of preparing PET radiopharmaceuticals.

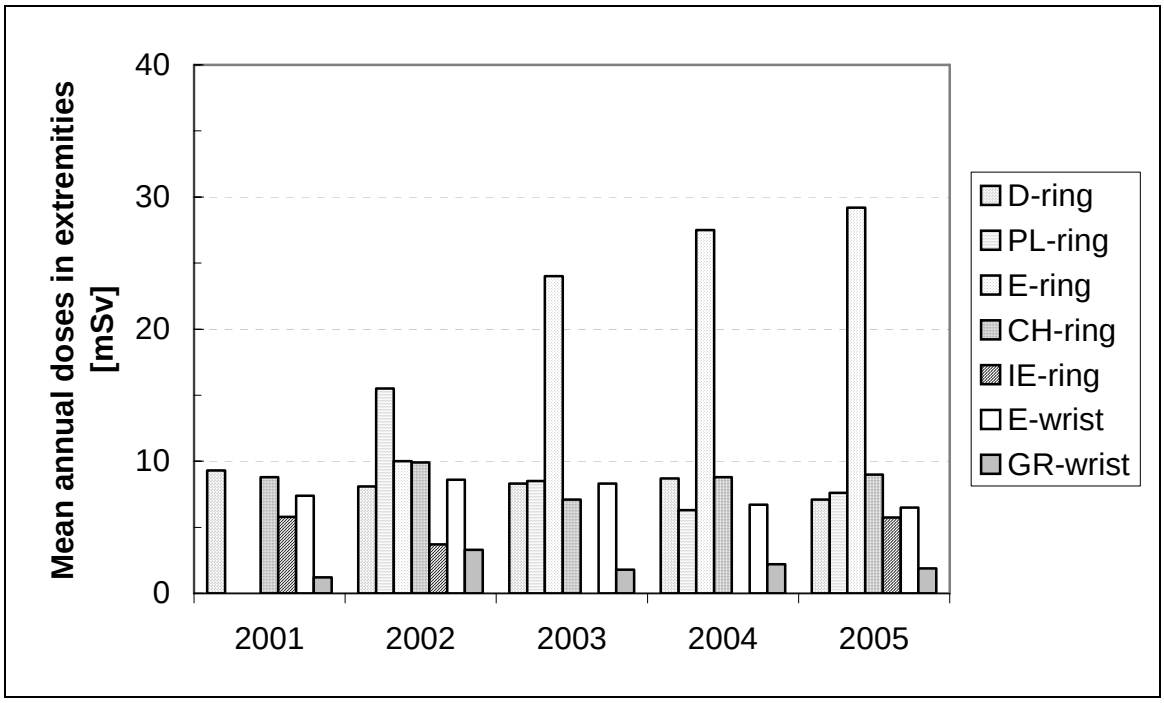

Figure 2. Evolution of the mean annual dose in extremities in nuclear medicine for 6 European countries. Dotted bars refer to ring dosemeters, plane bars to wrist dosemeters

4.3. RADIATION THERAPY

There are very few data available for extremity doses due to radiation therapy. Table 6 presents the mean annual extremity doses in radiation therapy for Germany, Ireland and France for the year 2005, together with the number of workers receiving doses higher than 5 mSv and 50 mSv in this medical field. Reported mean annual doses are between 2 and 8 mSv for ring dosemeters and 1.4 mSv for wrist dosemeters. In France, where, both, ring and wrist are used, mean annual doses measured with a ring dosemeter are about six times larger than those obtained with a wrist dosemeter.

Table 6. Mean annual doses in extremities in radiation therapy and number of workers with annual doses above 5 mSv and 50 mSv for the year 2005.

Type of extremity dosimeter	Country	Number of workers wearing extremity dosimeters	Reporting level [mSv]	Mean annual doses [mSv]	Number of annual doses > 5 mSv		Number of annual doses > 50 mSv	
RING	F	24	0.1 to 0.3	8	--	--	--	--
	D*	544	1	2	5	1%	2	0.4%
	IE	63	0.1	4.6	28	44%	0	0%
WRIST	F	590	0.1 to 0.2	1.4	--	--	--	--

** For Germany, the number of workers with doses larger than 5 mSv (50 mSv), actually corresponds to number of workers with doses larger than 1 mSv (10 mSv).*

-- indicates no data available

5. CONCLUSIONS

The increasing use of ionising radiation in medicine requires the development of new radiation protection programmes. The annual doses reported in national dosimetric data bases and presented here are much lower than the measured doses found in pilot research studies and reported in the literature [6]. This shows that the present dose extremity routine monitoring underestimates the real radiological risk of exposed medical staff and that no particular effort on the identification of the most exposed area is done. Nevertheless the mean values recorded with ring dosemeters indicate that this kind of extremity dosemeters are better estimators of the maximum dose to the extremity than wrist dosemeters.

In spite of the difficulties involved in the routine monitoring of extremities, the development of a systematic study which could identify "the most exposed area" for typical or more common activities could enable agreement on general requirements that could be followed by most of the users, and thus ensure adequate harmonization within the EU member states.

Finally, it should be pointed out that it would be very desirable to complete general international individual monitoring data bases, such as ESOREX, UNSCEAR or ISOE, with extremity doses.

ACKNOWLEDGMENTS

The authors acknowledge the representatives of regulatory bodies and dosimetric services for sharing the information used in this report.

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IV. INTERCOMPARISON ON MEASUREMENTS OF THE QUANTITY PERSONAL DOSE EQUIVALENT $H_P(0.07)$ BY EXTREMITY DOSEMETERS IN MEDICAL FIELDS

1. INTRODUCTION

EURADOS Working Group 9 (WG9) coordinated research activities on the assessment of occupational exposures at workplaces in therapeutic and diagnostic radiology as well as in nuclear medicine (funded by the European Commission, CONRAD project). The rapidly evolving medical practices and the introduction of new techniques make the implementation of special monitoring programs more than necessary. For some of these applications the skin of the fingers is the limiting organ for the individual monitoring of external radiation. Sub-group 1 of WG9 dealt with the use of extremity dosemeters in medical practices. A recent literature review showed that extremity doses especially in nuclear medicine can be quite high (Vanhavere et al., 2007).

One of the tasks of sub-group 1 was to perform an intercomparison exercise for ring dosemeters presently used in medical fields and to assess the capabilities of the extremity dosemeters that are in use in Europe. The wide variety of radiation fields in medical applications together with the difficulties of designing an appropriate extremity dosemeter, makes it difficult to perform extremity dosimetry with accuracy similar to that of a whole-body dosemeter (Bordy et al., 2000). Moreover, there is a growing need for harmonization of dosimetric practices in extremity monitoring across Europe with the aim of mutual recognition of extremity dose results (Kamenopoulou et al., 2006).

The objective of the intercomparison was to verify the performance of extremity dosimetry systems in order to measure the quantity $H_p(0.07)$ in photon and beta reference fields, and in in realistic fields in interventional radiology (IR) and nuclear medicine (NM). The intercomparison has been limited to ring dosemeters only. The participants have been selected in order to guarantee a good representation of different EU countries and of various types of dosimetric systems used in medical fields. Data relevant to the characteristics of the dosemeters, the uncertainties of the measurements and the participating dosimetric services were collected.

Not many extremity dosemeter intercomparisons have been reported. An intercomparison was organized 7 years ago by the PTB for extremity dosemeters in beta and/or photon radiation fields (Helmstädter et al., 2001). The study was more oriented towards the testing of the extremity dosemeters for the German requirements. Another intercomparison was organised by EURADOS in 2000 as part of a performance test of services for dose assessment (Bordy et al.,2000).

In this paper the results of the present intercomparison are presented in detail and are correlated with the dosimetric characteristics of the detectors and dosemeters.

An analysis has been performed based on dosimetric requirements established by ICRP (ICRP, 1997) and represented by the so-called “trumpet curves” described in the Technical Recommendations Report EUR 73 (Christensen et al., 1994).

2. PROGRAMME OF THE IRRADIATION EXERCISES

To accomplish the objectives of the intercomparison, an irradiation program has been designed in order to investigate dosemeters’ performance in standard reference photon and beta fields and under realistic conditions. The following irradiation fields were selected:

- Photon fields at ^{137}Cs sources at 0°, 60° and 180°,
- Realistic interventional radiology fields; two positions were used: in the emission cone of the primary beam and outside the primary cone beam in the scattered field at the edge of the patient phantom. A typical spectrum was chosen: 70 kVp, with the filtration of 4.5 mm Al and 0.2 mm Cu, produced by a medical X-ray generator MPH65 (GEMS) was used.
- Beta fields using $^{90}Sr/^{90}Y$, ^{85}Kr and ^{147}Pm sources at 0° and 60° and
- Realistic nuclear medicine fields using a syringe, without shield, with ^{99m}Tc and ^{18}F.

The delivered doses varied from 1 mSv to about 11 mSv. The irradiations were performed using the ISO rod phantom, which is a PMMA cylinder of 19 mm diameter and 300 mm length (ISO, 1999 and ISO, 2006a). The

relevant ISO standards have been used for the reference irradiations, ISO 4037 and 6980 series (ISO, 1996 and ISO 2006b).

The irradiation program was performed in four laboratories: IRSN, CEA-LIST-LNHB (France), BfS (Germany) and AZ-VUB (Belgium) in collaboration with the SCK-CEN (Belgium).

The ^{137}Cs source of IRSN (France) was used in the horizontal beam configuration as part of the photon irradiation programme (figure 1). The second part of the photon irradiation program was performed at CEA-LIST-LNHB (France) using a diagnostic X-ray facility in order to simulate irradiation at interventional radiology fields.The setup is shown in figure 3. The beta irradiations were performed at the BfS (Germany) (figure 2). Finally, the realistic nuclear medicine irradiation set-up was performed at AZ-VUB (Belgium) using the set-up shown in figure 4. The syringe with the radiopharmaceutical was placed at the centre of the configuration while the dosemeters were placed on the rod phantoms at 14.05 cm distance from the source.

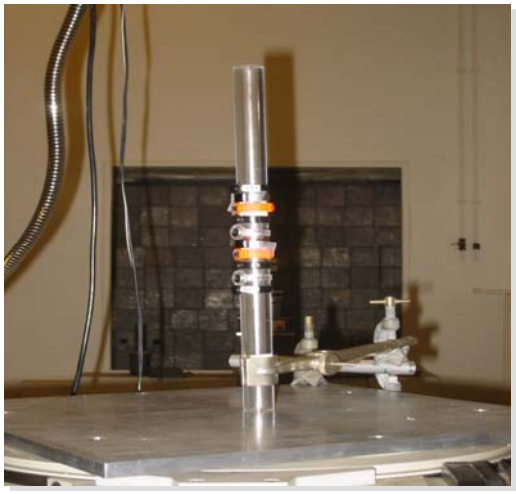

Figure 1: Irradiation setup for the Cs137 source.

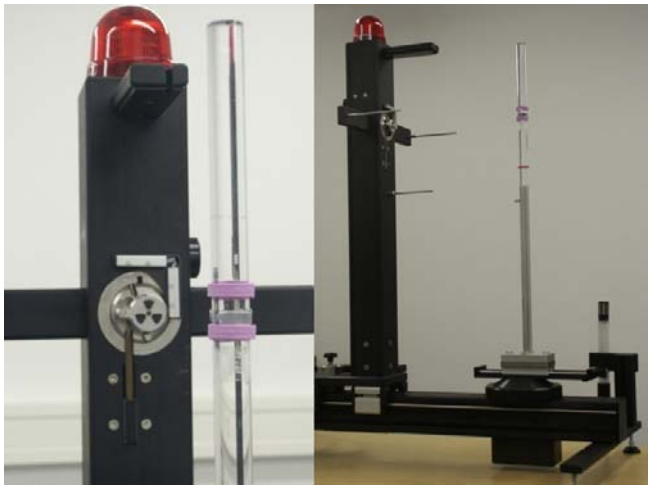

Figure 2: Irradiation setup for the beta sources.

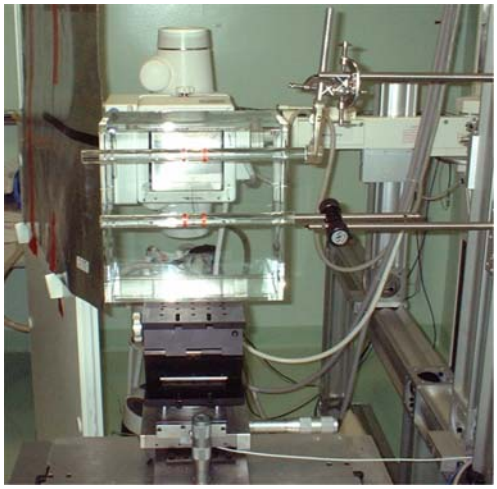

Figure 3: Realistic interventional radiology setup. The slab phantom the irradiation field represents the patient and the ring phantoms were used for the irradiation of the dosemeters, in and outside the primary beam.

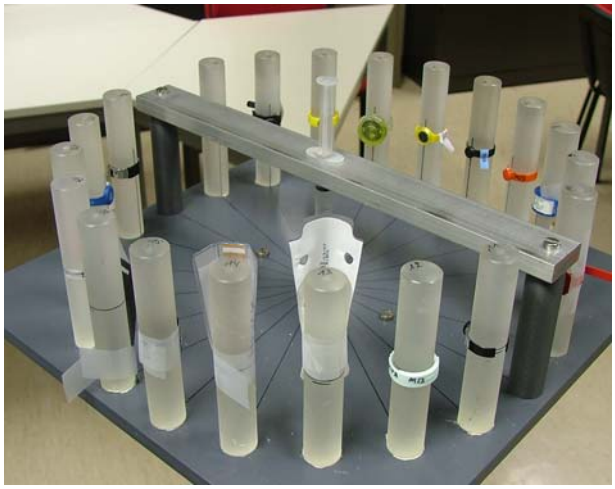

Figure 4: Realistic nuclear medicine setup. The dosemeters are placed on the phantoms and the syringe with the radiopharmaceutical is inside the circle.

3. DETERMINATION OF THE REFERENCE $H_p(0.07)$ VALUES

The reference values of $H_p(0.07)$ were determined according to the irradiation configuration. In particular:

° For the ^{137}Cs irradiation fields the $H_p(0.07)$ was determined according to the equation

$H_p(0.07) = h_p(0.07, \alpha) \times K_{air}$,

where $h_p(0.07, \alpha)$ is the conversion coefficient from kerma free in air to $H_p(0.07)$ for an irradiation angle α provided by Grosswendt (Grosswendt, 1995). The K_{air} value was measured at IRSN using a secondary standard ionization chamber. Reference values ranged between 4 and 6 mSv. . For Cs^{137} irradiation fields different type of uncertainties were considered, i.e. on the conventional true value of the reference $H_p(0.07)$, the source – dosemeter(s) distance, the irradiation time and the angles. This led to an overall uncertainty equal to 4.8% (k=2), the main contribution being due to the conversion coefficients (taken as 4%, k=2) (ISO,1999).

° For the interventional radiology fields the $H_p(0.07)$ was determined using the same equation; The K_{air} value was measured at CEA using an ionization chamber traceable to primary standards. The photon spectra in terms of fluence were calculated with the MCNPX Monte Carlo Code (MCNPX2.5.0, 2005, Struelens et al., 2007) at the two points of tests. The average conversion coefficients from air kerma free in air to personal dose equivalent, $h_{p,K}(0.07, \alpha)$, for the IR beams, were then derived from the calculated spectra (taking both angle and energy into account) folded with the individual conversion coefficients taken from ICRU 57 (ICRU, 1998). The reference personal dose equivalent values were equal to 2.6 mSv for the direct beam and to 0.61 mSv for the scattered field. The uncertainty for the IR fields come partly from the uncertainty on the air kerma measurement (5%, k=2) and partly from the calculated spectra (0.1%, k=2). The uncertainty on the air kerma measurement includes the statistical uncertainty on the measurement and the correction for air density (temperature, pressure). But these were small compared to the uncertainty on the positioning of the dosemeter and the calibration of the ionisation chamber. The calculated spectra led to the calculation of the conversion factors K_a to $H_p(0.07)$ giving an uncertainty of 4%. The total uncertainty on the reference value is thus 6.5% (k=2). Extra calculations have been done to evaluate the influence of multiple scattering between patient and worker phantom, but the influence of this is less than 0.1%.

° For the beta fields the reference values of $H_p(0.07)$ were provided directly by a BSS-2 secondary standard chamber, traceable to the primary laboratory at the PTB, according to equation $H_p(0.07) = h_{p,D}(0.07, \alpha) \cdot D_t(0.07)$, where $h_{p,D}(0.07, \alpha)$ is the conversion coefficient from absorbed dose in 0.07 mm of ICRU tissue, $D_t(0.07)$, to personal dose equivalent, for an irradiation angle α. It was assumed that the conversion coefficient $h_{p,D}(0.07, 0^o)$ is equal to 1 Sv/Gy. For the irradiation at 60º, $h_{p,D}(0.07, 60^o)$, the ISO 6980-3 (ISO, 2006) was used. Reference values ranged from 6 to 11 mSv and the uncertainty was equal to 2.3% for $^{90}Sr/^{90}Y$ and ^{85}Kr, and 3% - 3.7% for ^{147}Pm (k=2). It includes uncertainties of the source activity and its decay, for the correction factors for the air density and attenuation (temperature, humidity and pressure) and the irradiation time span. Moreover, for estimating the total uncertainties of the reference doses in the intercomparison, the geometrical uncertainty was considered additionally, which originates from the inverse square law when irradiating not only one but several detectors on the rod phantom simultaneously. By convention, no uncertainty was assigned to the conversion coefficient in this case.

° For the mixed nuclear medicine fields, the reference values of $H_p(0.07)$ were calculated using the MCNPX code (MCNPX2.5.0, 2005) normalized by the measured activity of the radioactive solution. A simplified set-up was defined in the simulation model compared to the experimental geometry shown in Figure 4. The radiopharmaceutical was simulated as a cylindrical water source limited by a 0.75 mm thick, 0.93 g cm^{-3} polyethylene syringe wall. The whole geometry was surrounded by dry-air of 1.205 g cm^{-3}. For each solution (^{99m}Tc and ^{18}F), decay data were taken from Brown and Firestone (Brown and Firestone, 1986) and Stabin and da Luz (Stabin and da Luz, 2002). For the ^{18}F problem, 511 keV annihilation gamma-rays were taken into account as created where each positron (beta-ray) came to rest. The dose equivalent $H_p(0.07)$ was estimated as the dose deposited in a 0.5 cm height water cylindrical cell at 7±1 mg cm^{-2} depth within the phantom (2 mg cm^{-2} thick). The rod phantom was simulated as a 10 cm high, 1.9 cm thick water cylinder, with the front wall located at 14.05 cm from the centre of the source cell. Photons and electrons were transported in the calculations, following the method recommended by Schaart et al. (Schaart, 2002). For ^{18}F it was observed that 57% of the total $H_p(0.07)$ value is due to direct exposure to positrons and 43% due to annihilation gamma-rays. Calculated deposited doses were expressed in terms of Sv per ^{99m}Tc or ^{18}F disintegration, as appropriate. Subsequently, they were normalized by the measured total number of disintegrations during the irradiation. The latter parameters were obtained from measurements of the initial activities of radioactive solutions in a radioisotope calibrator and the irradiation

times. The reference values ranged from 4 to 6 mSv for ^{99m}Tc and from 10 to 15 mSv for ^{18}F, with an uncertainty (k=2) of 10.5% and 8%, respectively. This uncertainty includes the component due to activity measurement (4.5% for k=2) and the simulation. The latter is calculated as the square root of the variance of the statistical uncertainty (2% for k=2) plus the variance associated with the simulated model (9.2% for ^{99m}Tc and 6% for ^{18}F, for k=2), which was estimated by comparing the influence of a different set-up and of different Monte Carlo codes in the results.

The reference values of the $H_p(0.07)$ are shown in table 1.

Table 1: Reference values of the $H_p(0.07)$ for the various fields with the relevant uncertainty

Field	Description	$H_p(0.07)$ mSv	Uncertainty (%), k=2
^{137}Cs	0°	4-6	4.8
^{137}Cs	60°	4-6	4.8
^{137}Cs	180°	4-6	4.8
IR	70 kVp, 4.5 mm Al, 0.2 mm Cu, in beam	2.60	6.5
IR	70 kVp, 4.5 mm Al, 0.2 mm Cu, out beam	0.61	6.5
^{90}Sr/^{90}Y	0°	8.22	2.3
^{90}Sr/^{90}Y	60°	9.01	2.3
^{85}Kr	0°	10.29	2.3
^{85}Kr	60°	10.99	2.3
^{147}Pm	0°	5.84	3.0
^{147}Pm	60°	8.25	3.7
^{99m} Tc	Unshielded syringe	4-6	10.5
^{18}F	Unshielded syringe	10-15	8.0

4. PERFORMANCE CRITERIA

The performance requirements of passive extremity dosemeters are described in ISO 12794 (ISO, 2000). This standard specifies the recommended type tests and dosimetric requirements for extremity individual monitoring purposes. The scope of the standard includes measurements of photon beams with energies from 15 keV to 3 MeV and beta radiation with a maximum energy ranging from 0.5 MeV to 3 MeV. As regards the performance criteria, the standard requires that the energy response of the dosemeter for reference qualities defined in ISO 4037-1 (ISO, 1996) and ISO 6980-1 (ISO, 2006), within the energy range of the scope, shall not vary by more than ± 50%. The standard defines performance criteria for the angular response of 60 keV photon beams but it does not describe detailed requirements for angular beta response.

The main aim of the intercomparison was not to verify if the services fulfilled the ISO 12794, but to analyse the dosemeter performance in radiation fields of interest in some medical applications. Therefore, it only included some of the ISO type-tests and it was completed with additional simulated work-place fields.

In the overall analysis of the results, the general dosimetric requirements established by ICRP (ICRP 1992, 1997) and represented by the so-called “trumpet curves” (Christensen 1994) were applied.

5. DOSIMETRIC SERVICES

24 services from 16 countries participated in the intercomparison. The dosemeters represented in this study are used to monitor over 33 000 workers. Table 2 shows the main characteristics of the dosemeters. The intercomparison includes extremity dosemeters manufactured by Rados, TLD Poland, Panasonic and Harshaw (Thermo Electron Corporation) type. Home made dosemeters were also included. The detectors were of many

different types: TLD-100, TLD-100H, TLD-700H, MCP-N, MCP-Ns, MTS-N, MCP-7, $Li_2B_4O_7$, CaF_2:Mn and $Li_2B_4O_7$:Cu. Most of the dosemeters (21/24) used LiF phosphors as detectors with different types of dopants, isotopic concentration of Li and thicknesses. The filter material, in most of the cases, was plastic of thickness 3-30 mg/cm^2. The overall thickness of the detectors and filters ranged between 12 and 300 mg/cm^2. Most of the dosemeters are calibrated to Cs^{137} sources, while five services also use X-rays from the ISO 4037 (ISO. 1996) series to calibrate their dosemeters.

Each participating service was asked to prepare two dosemeters per irradiation field, meaning 26 dosemeters for the irradiations and four sets of at least 2 detectors for background correction. The dosemeters were labelled differently for photon (^{137}Cs and IR) and mixed fields (beta and NM). This is because some services may provide different dosemeters for different applications in their routine. However, in the end, none of the participating services chose to send different dosemeters for different fields. Four services chose not to participate in the mixed field tests. Some dosemeters, specifically labelled, were also used for the background subtraction. The services were also asked if they were accredited. Eight services have ISO 17025 accreditation, four are approved by a national authority, and 12 are not accredited for the extremity measurements.

The participants were informed for the results of their own dosemeters. However, since the results are used for scientific publications, the names of the participating services were not mentioned, but they are presented using the numbers 1 to 24 to preserve their anonymity.

Table 2: Main characteristics of the extremity dosemeters used in the intercomparison

	Dosemeter name	Detector Type	Filter material	Filter thickness (mg/cm^2)
1	Rados ring dosemeter	TLD-100	PE	30
2	Rados ring dosemeter	MCP-Ns TLD-100	PET	30
3	TLD Poland ring	MTS-N	Plastic	30
4	TLD Poland ring, TD60	MTS-N	Plastic	30
5	Home made	MCP-7	PE	30-35
6	Home made	TLD-100	PVC	7
7	Panasonic UD-807	$Li_2B_4O_7$	Plastic	65
8	Rados ring dosemeter	TLD-100	PE	30
9	Plastic bags	Li^7F - 15 %	Plastic	30
10	Harshaw EXT-RAD	TLD-700H	AL/PET	4
11	Harshaw EXT-RAD	TLD-100	AL/PET	3
12	Home made type	MCP-Ns	Mylar	23 μm
13	Harshaw DXTRAD-707H DXT-100/DXT 707H	TLD-100H	Mylar	42 3.3
14	Harshaw EXT-RAD	MCP-Ns	PET	12
15	Home made	CaF_2:Mn	Cu+Sn	26
16	Rados ring dosemeter	MCP-N	Plastic	30
17	Harshaw DXT-707H	TLD-700H	Plastic	3.3
18	Landauer Inc. TLD Ring	TLD-100	Polystyrene	40
19	DXT-107H	TLD-100H	Mylar	3.3
20	Rados ring dosemeter	MTS-N	Plastic	30
21	Panasonic UD807	$Li_2B_4O_7$:Cu	Plastic	65
22	Harshaw EXT-RAD	TLD-100H	Plastic	7
23	Holders DTU-01	DTG-4 (LiF:Mg,Ti)	Plastic	20
24	Harshaw DXT-RAD DXT-100	TLD-100	Plastic	42

6. UNCERTAINTIES ON THE REPORTED VALUES

The participants were also asked to report the uncertainties of their results. From the 24 services, 3 reported that they had not evaluated their uncertainties yet. Four others reported their 'total' uncertainty, but they did not give any specification on how it was calculated. All the others gave information on the uncertainty budget, and as it was expected the description on how it was calculated varied significantly.

From the Technical Recommendations EUR 73(Christensen, 1994) for monitoring individuals occupationally exposed to external radiation the following sources of uncertainties can be considered of importance for TL detectors:

- energy dependence
- directional dependence
- non-linearity of the response
- fading, dependency on ambient temperature and humidity
- effects from exposure to types of ionising radiations that are not intended to be measured
- calibration errors
- variation in local natural background
- uncertainty on individual calibration factors
- random uncertainties from detector sensitivity and zero dose
- fluctuations in reading parameters

Only three services reported that they took all these parameters into account, thus including type test results.

The main source of uncertainty is expected to be the energy dependence. In total 13 services took the energy dependency into account. From these 13, one took an overall uncertainty from an intercomparison. The rest have performed energy dependence tests. The magnitude of the uncertainties depends on the range of energies tested. Especially, when beta energies are taken into account, the uncertainty is much bigger for most services.

Another major uncertainty source is the directional dependence which is reported to be considered only by 4 services.

Another source of uncertainty that was mentioned quite often was the uncertainty on the calibration (10 times) and the intrinsic random uncertainty on the TL signal (10 times, too). The reader stability was mentioned 5 times, the uncertainty on the individual correction factor 4 times. Fading, linearity and environmental factors were mentioned only 3 times.

The uncertainty on the background correction was considered by 14 of the 21 services.

It was surprising to see that from the 14 accredited/approved services, only 9 have reported to take the energy uncertainty into account. One service with national approval reports no uncertainties at all. Two services have ISO 17025 accreditation but do not include energy dependence in their uncertainty. Only three from the accredited services take the angular dependence into account.

7. RESULTS OF THE INTERCOMPARISON

In each field, two dosemeters from each service were irradiated. Services were requested to read the dosemeters and to evaluate $H_p(0.07)$ and its uncertainty for each dosemeter. The services had no information about irradiation conditions except for the fact that the dosemeters irradiated with ^{137}Cs and X-rays were labelled as photon fields and the rest were identified as mixed beta/gamma fields.

For each tested field, *i*, the response of the services, R_i, was calculated as:

$$R_i = \frac{(L_{i,1} + L_{i,2})/2 - Bk_i}{H_p(0.07)_{ref,i}}$$

Where:

L_{i1} and L_{i2} are the two readings of irradiation field i,

Bk_i is the measured background of irradiation field i, calculated as the mean value of the background dosemeter readings.

$H_p(0.07)_{ref,i}$ is the reference personal dose equivalent in i.

Table 3 shows the response of the participants, for each irradiation field**.** Values outside the trumpet curve limits are indicated in italic-bold case. Table 4 provides a general overview of the performance of the participants and summarises the main results: mean response, response range and number of services that failed to fulfil trumpet curve criteria. The results that were sent to the participants are presented in Annex 1.

Table 3: Participant response for each tested radiation quality. Responses outside the trumpet curve limits are highlighted in bold-italic case. (Each service is identified by an anonymous number from 1 to 24).

ID	Beta reference fields						NM workplace		Gamma reference fields ^{137}Cs			IR workplace	
	^{90}Sr-^{90}Y		^{85}Kr		^{147}Pm								
	0°	60°	0°	60°	0°	60°	^{18}F	^{99m}Tc	0°	60°	180º	in beam	outside beam
1	0.84	***0.46***	0.74	***0.31***	***0***	***0***	***0.45***	1.14	1.03	0.68	0.9	1.38	1.81
2	1.33	0.78	0.7	***0.39***	***0.01***	***0.01***	0.69	1.01	0.81	0.81	0.8	1.25	1.36
3									***2.3***	***2.2***	***2.4***	***3.5***	***2.6***
4									1.02	1.03	1.04	1.67	1.57
5	***0.42***	***0.36***	***0.06***	***0.04***	***0***	***0***	***0.26***	0.56	0.63	***0.43***	***0.42***	***0.46***	0.51
6	1.15	0.63	***0.2***	***0.11***	***0.01***	***0.01***	***0.51***	1.27	1.08	1.07	1	1.5	1.4
7	1.09	***0.44***	***0.1***	***0.03***	***0***	***0***	***0.43***	0.85	1.05	0.96	0.99	0.89	0.94
8	0.7	***0.44***	***0.13***	***0.03***	***0.01***	***0.01***	***0.43***	1.19	1.03	1.06	1.1	1.56	***2***
9	1.05	0.76	***0.48***	***0.33***	***0.09***	***0.05***	***0.47***	1.04	0.79	0.78	0.82	1.41	1.58
10	1.02	0.93	0.89	0.79	0.49	0.69	0.75	0.81	0.6	0.73	0.75	1.12	1.2
11	0.94	0.67	0.88	0.72	0.81	0.51	0.73	1.14	0.59	0.79	0.8	1.36	1.11
12	1.39	1.28	1.24	0.94	1.18	0.63	1.06	1.11	0.78	0.79	1.12	1.42	1.55
13	1.27	0.89	1	0.65	0.87	0.88	0.92	0.95	0.89	0.95	0.9	1.51	1.42
14	1.17	1.06	0.88	***0.5***	***0.08***	***0.04***	0.73	0.93	0.78	0.77	0.83	1.27	1
15	0.94	***0.47***	***0.11***	***0.07***	***0.01***	***0.01***	***0.4***	***2.3***	0.87	0.87	0.9	***12***	***11***
16	1.14	0.55	***0.15***	***0.06***	***0***	***0***	***0.5***	1.03	1.07	1.09	1.05	1.28	1.43
17									0.65	0.61	0.67	1.1	1.06
18	0.82	***0.43***	***0.1***	***0.02***	***0***	***-0.01***	***0.42***	1.06	0.88	0.85	0.97	1.5	1.23
19									0.7	0.81	0.88	0.76	0.64
20	0.94	***0.48***	***0.07***	***0.07***	***0***	***0.01***	***0.48***	1.17	1	0.96	0.95	1.42	1.52
21	1	***0.46***	***0.13***	***0.04***	***0***	***0***	***0.37***	0.73	0.77	0.76	0.75	0.71	0.68
22	1.22	1.05	0.99	0.66	0.42	***0.25***	0.84	0.89	0.77	0.85	1.22	1.83	1.45
23	0.59	***0.1***	***0***	***0***	***0***	***0***	***0.26***	1.29	0.99	0.97	0.95	1.57	1.53
24	1.03	***0.43***	***0.17***	***0.04***	***0***	***0.01***	***0.42***	1.11	0.92	0.92	0.89	1.46	1.43

Results show that, for ^{137}Cs, at all tested angles, with two exceptions, all reported doses are very close to 1. The average relative response is 0.93. For ^{90}Sr/^{90}Y, normal incidence, the results are also satisfactory except in one case, the average relative response is 1.00. The performance is slightly worse at 60º, with an average relative response of 0.63 and half of the services are below the trumpet curve lower limit. For ^{85}Kr and ^{147}Pm, normal incidence, $H_p(0.07)$ is underestimated, the average relative responses are 0.45 and 0.25, respectively. Only dosemeters with thin filters and thin detectors provided appropriate results, 8 out of 20 for ^{85}Kr and 5 out of 20 for ^{147}Pm. Responses were even lower for the 60º angle of incidence.

In realistic interventional fields, both within and outside the beam, two services reported very high doses and one underestimated the given dose. The rest of services were within the limits. The average relative response was 1.86, taking into account the 24 participants but it was reduced to 1.29 if the two services with a large overestimation (id: 3 and 8) were excluded. It was shown that, generally, there was an overestimation of 30% of the reported doses by the services that use LiF detectors and an underestimation of 15% for those that use $Li_2B_4O_7$.

Table 4: Summary of the intercomparison results for each tested radiation quality:

mean response, response range and number of services outside the trumpet curve

$H_p(0.07)$ (mSv)	Radiation quality	Mean response	Response range	Number services outside the trumpet curve
8.2	^{90}Sr-^{90}Y, 0°	1.00	0.38 – 1.42	1/20
9.0	^{90}Sr-^{90}Y, 60°	0.63	0.03 – 1.30	10/20
10.3	^{85}Kr, 0°	0.45	0 – 1.31	12/20
11.0	^{85}Kr, 60°	0.29	0 – 0.95	15/20
5.8	^{147}Pm, 0°	0.25	0 – 1.34	15/20
8.3	^{147}Pm, 60°	0.16	0 – 0.95	16/20
10.1	^{18}F	0.55	0.02 – 1.08	13/20
4.2	^{99m}Tc	1.08	0.48 – 2.36	1/20
4.5	^{137}Cs, 0°	0.92	0.35 – 2.35	1/24
4.8	^{137}Cs, 60°	0.91	0.38 – 2.37	2/24
5.2	^{137}Cs, 180°	0.96	0.37 – 2.52	2/24
2.6	IR in beam	1.86	0.27 – 12.5	3/24
0.7	IR outside beam	1.86	0.21 – 11.7	3/24

The results obtained for the ^{99m}Tc irradiation were satisfactory in 19 out of 20 cases and the average relative response was 1.08. On the other hand, in the case of ^{18}F irradiation, there was a general underestimation of the dose. The average relative response was found to be 0.55 and only 7 services were within the trumpet curve for this field. It is important to notice that the services that had a good relative response to betas also presented a good response for ^{18}F dose.

The uncertainties assigned by the services to their results varied substantially among them. In order to compare the responses and the uncertainties of the services with the reference doses we divided the participants in two groups: group I, those that included energy dependence in their uncertainty budget (13), and group II, those who did not include it (8). The uncertainties (k=2) ranged from 12 to 50% in the first group and, from 5 to 21% for the second group. These values do not necessarily have the same meaning, and are just given as an indication of order of magnitude. For lower reference doses, these uncertainties are higher.

In figures 5 to 13 the responses, R_i, of the services of class I (energy uncertainty) and class 2 (no energy uncertainty) for the all tested configurations are shown. All uncertainties are indicated with k=2. The reference uncertainty is included as the dashed line.

For the irradiations at ^{137}Cs sources at 0^o, in class I, 10 out of the 26 data points with the error bars show no overlap with the reported results and the uncertainty on the reference. This means that in these cases the reported uncertainty (supposedly the total uncertainty) is underestimated if ^{137}Cs is included in the energy range for the dosemeter. We should stress here that for some services other influence factors (like fading or background) could have lead to deviations that are not included in the uncertainty. In class II this is 5 out of 16 services with their results and the respective uncertainties being out of the reference values, but here this can be caused by the energy dependence.

If we do the same evaluation for the 180° irradiation at ^{137}Cs, 5 out of 26 do not overlap for class I, and 3 out of 16 for class II. So actually the situation is not worse than at 0°, although hardly any services have included angular dependence. For beta radiation, where there is larger energy dependence, this can be completely different.

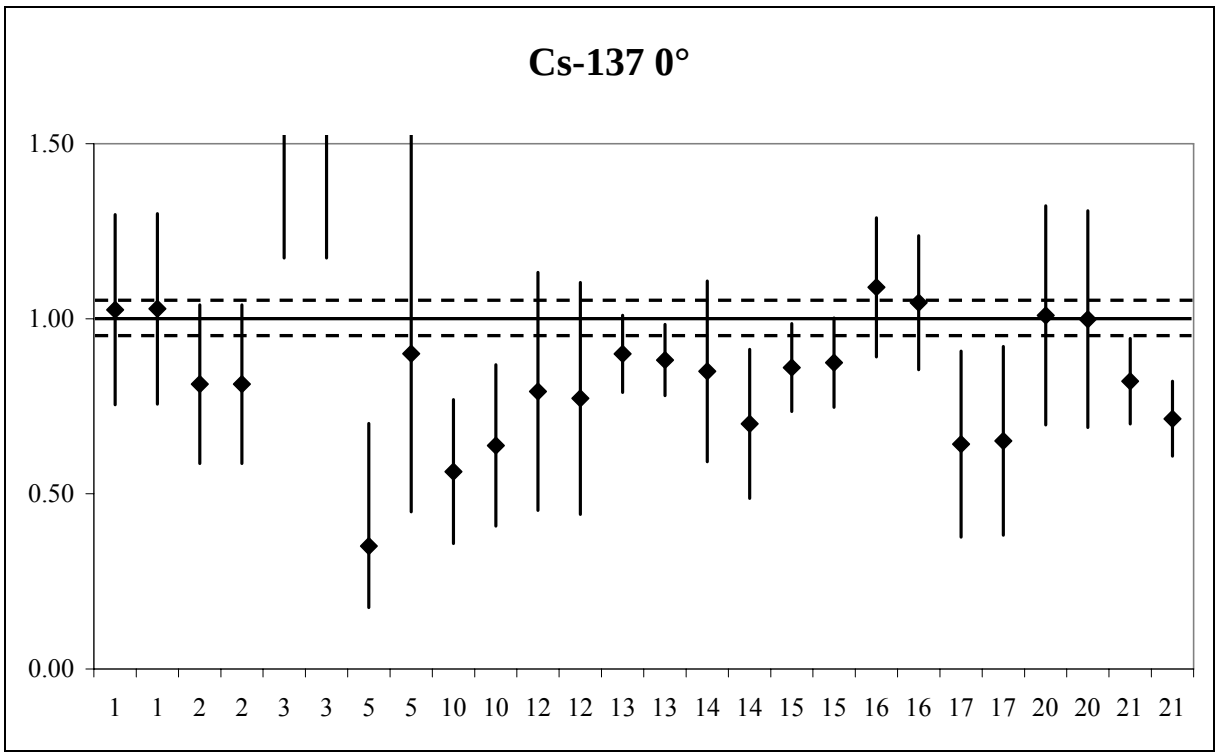

Figure 5: Responses for ^{137}Cs at 0° with the uncertainties indicated for class I (energy uncertainty included)

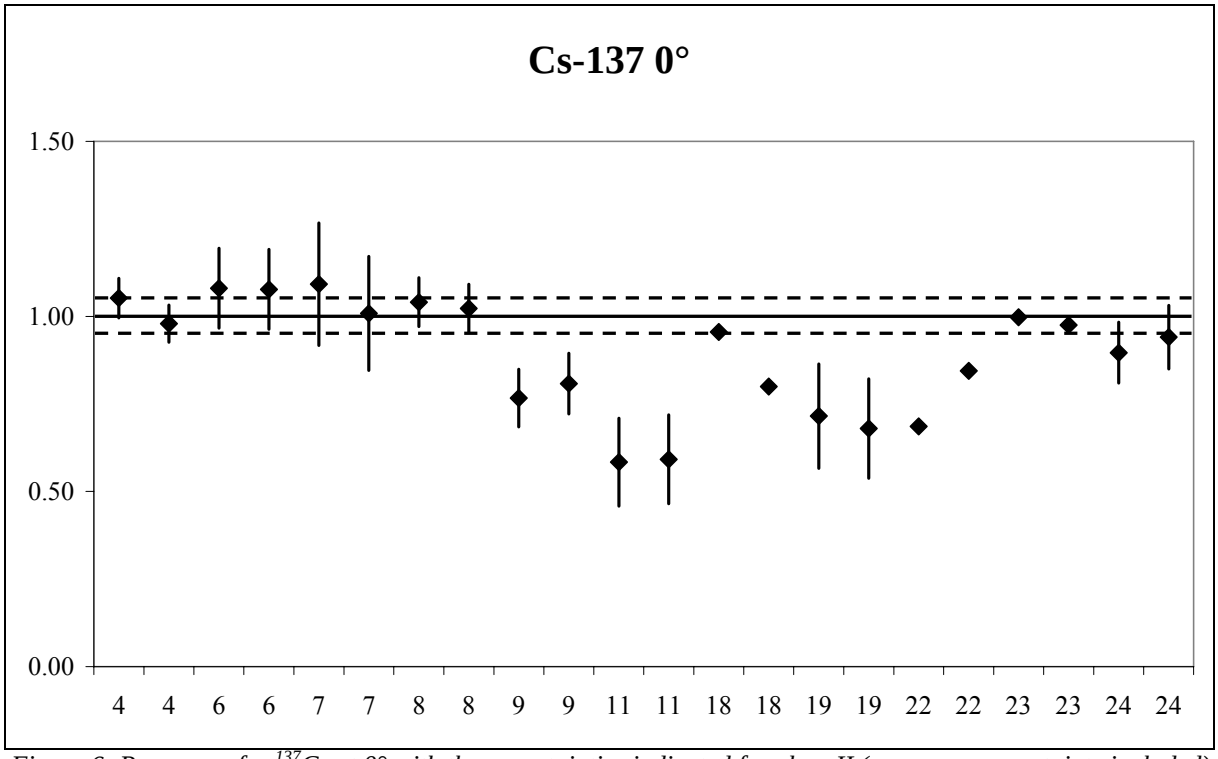

Figure 6: Responses for ^{137}Cs at 0° with the uncertainties indicated for class II (no energy uncertainty included)

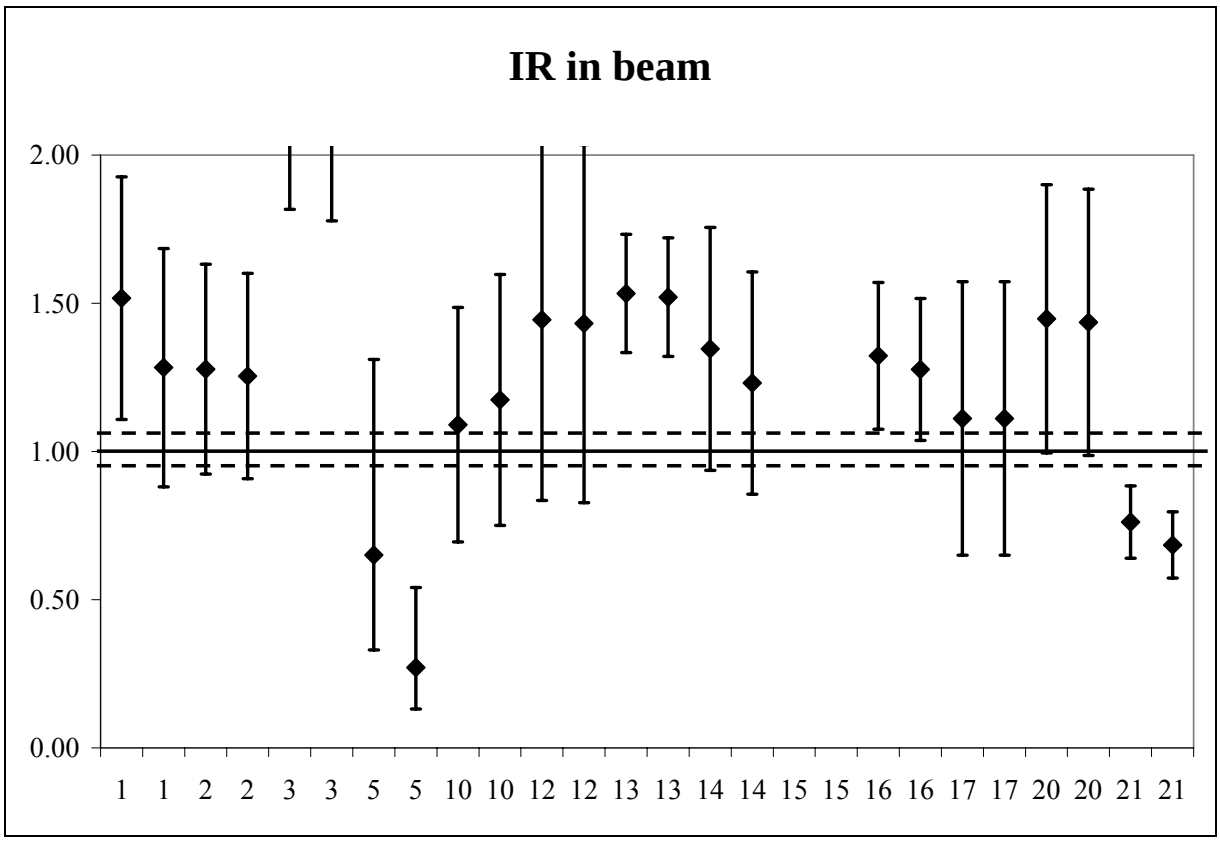

Figure 7: Responses for IR in beam with the uncertainties indicated for class I (energy uncertainty included)

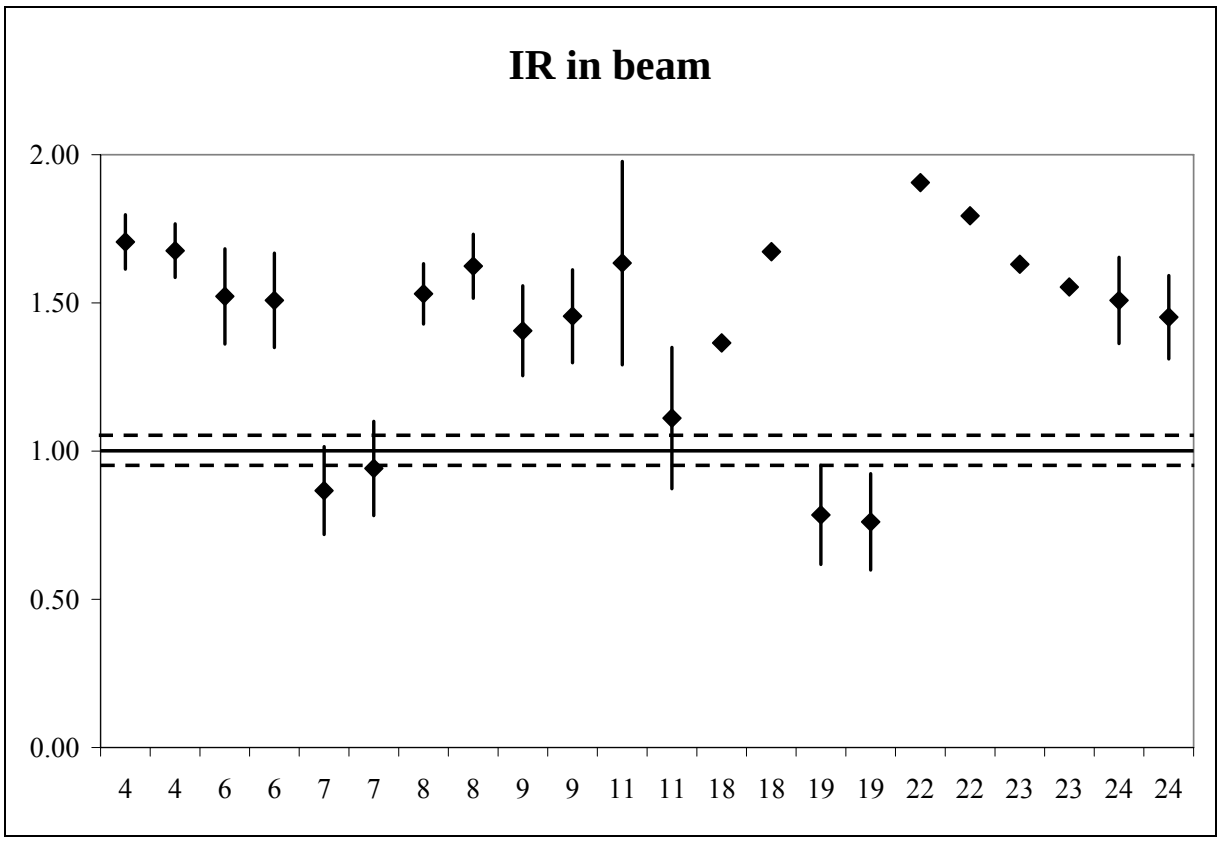

Figure 8: Responses for IR in beam with the uncertainties indicated for class II (no energy uncertainty included)

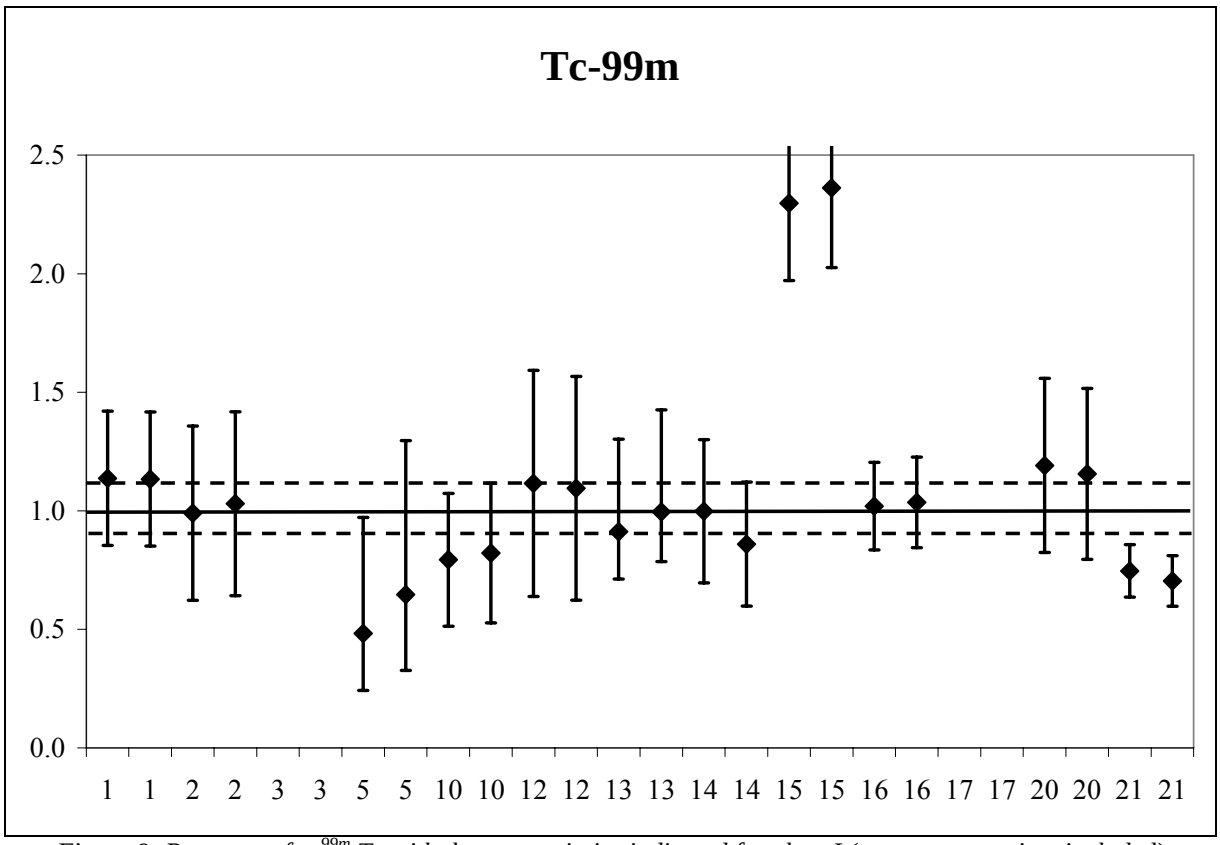

Figure 9: Responses for ^{99m}Tc with the uncertainties indicated for class I (energy uncertainty included)

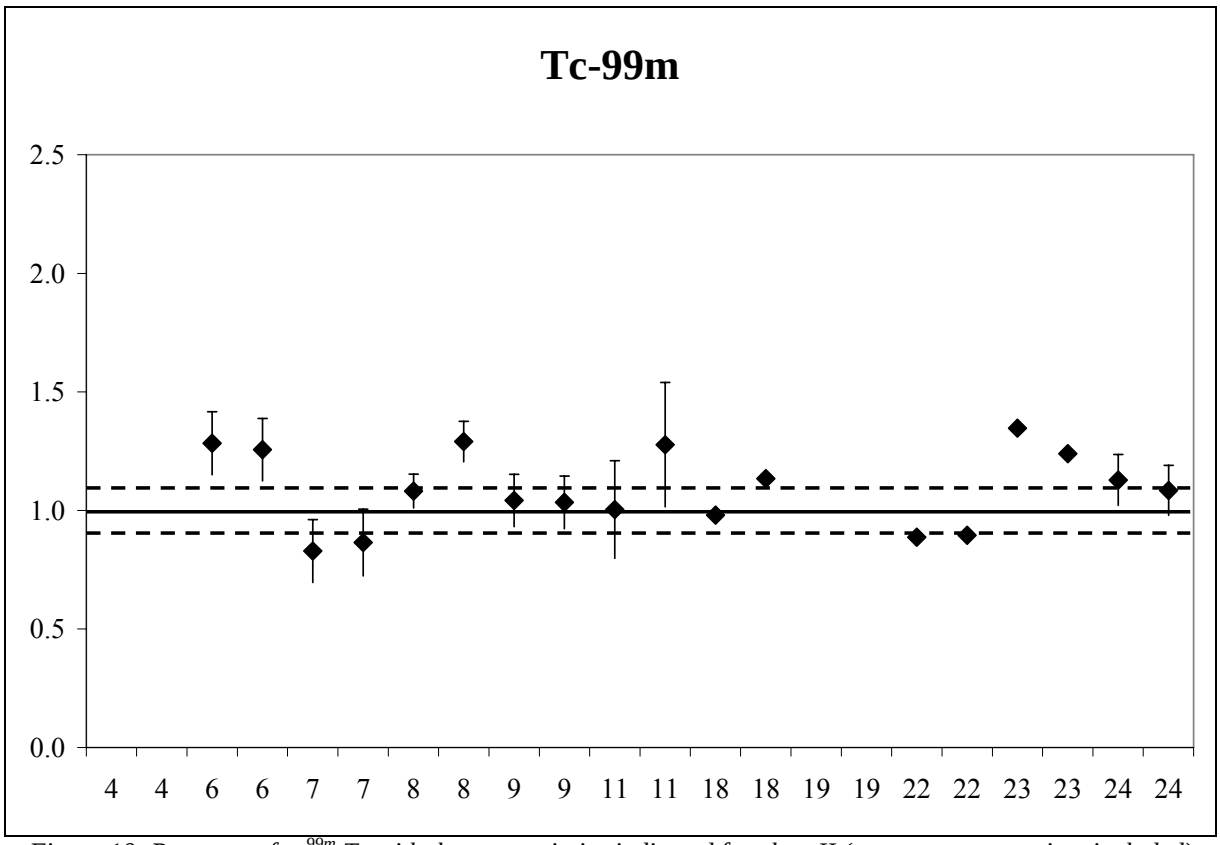

Figure 10: Responses for ^{99m}Tc with the uncertainties indicated for class II (no energy uncertainty included)

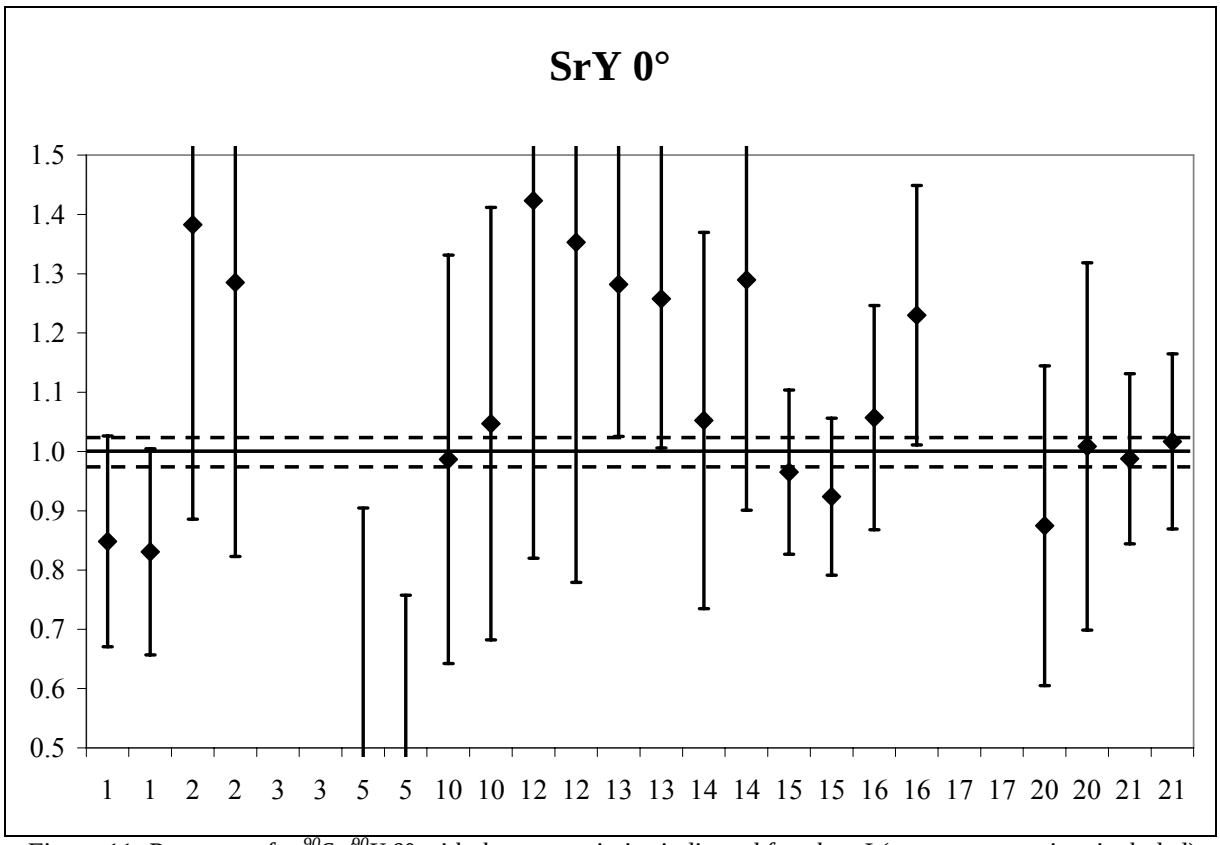

Figure 11: Responses for $^{90}Sr/^{90}Y$ 0° with the uncertainties indicated for class I (energy uncertainty included)

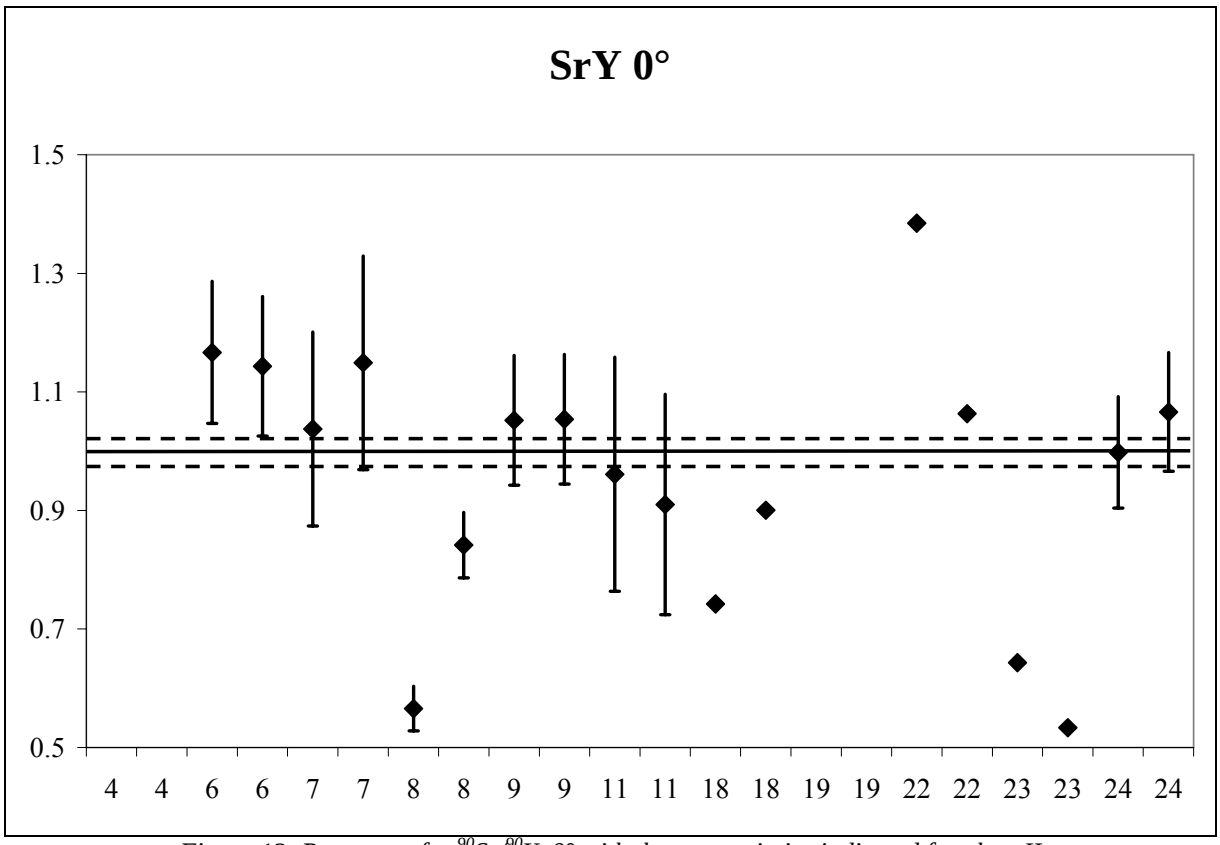

Figure 12: Responses for $^{90}Sr/^{90}Y$ 0° with the uncertainties indicated for class II (no energy uncertainty included)

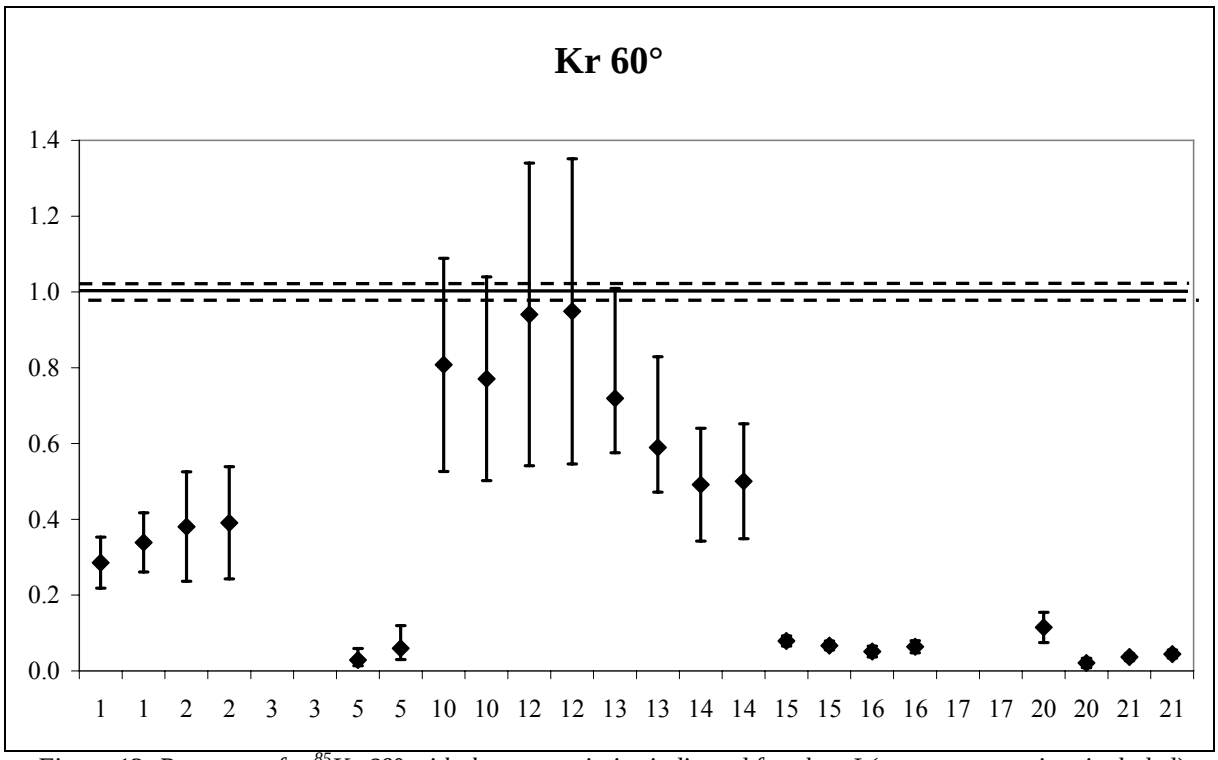

Figure 13: Responses for ^{85}Kr 60° with the uncertainties indicated for class I (energy uncertainty included)

In the case of IR fields (figures 7 and 8) it is clear that the reported uncertainties for class II are too small. Only 5 out of the 16 data points overlap within the uncertainties (95% interval) with the reference values. For class I, most services have estimated the uncertainties big enough, 17 out of 26 fall within the limits.

The realistic NM field of ^{99m}Tc and the 0° of ^{90}Sr/^{90}Y show similar results, as it can be seen in figures 9, 10, 11 and 12 (there were some services that didn't participate to this irradiation exercise).

Most services underestimated the lower energy betas and the betas at higher angles. In figure 13 it is clearly seen that the energy uncertainty is not taking into account in this underestimation.

8. CONCLUSIONS

Analysis of the intercomparison fulfilled the expected objectives since it provides a large overview of the capabilities and the difficulties of extremity dosemeters in measuring the quantity $H_p(0.07)$ in photon and beta reference fields and in realistic workplace fields characteristic from interventional radiology and nuclear medicine. In particular, the following conclusions can be drawn after the evaluation of the present intercomparison:

- There are services that use ^{137}Cs sources for calibration and still present a serious deviation from the conventional true value of $H_p(0.07)$,
- The general overestimation in the IR fields might be explained by the energy response of LiF that is the material mostly used by the participating services,
- The two services that use $Li_2B_4O_7$ detectors present a flat response, as it concerns the ^{137}Cs and IR irradiations, due to the lower effective atomic number of the detector material,
- CaF_2:Mn should not be considered as a proper detector in medical fields, without any energy corrections,
- The under-response of detectors to the ^{18}F is due to the positron contribution that can give a significant amount of the dose for unshielded syringes,
- There is a clear correlation between filter and detector thickness and response to beta particles,
- A few dosemeters show good results for all radiation qualities, especially the ones with thin detectors and filters.
- The collected data show a large variation of the reported uncertainties, which ranged between 5% and 50% (k=2). These differences were due to the different components of uncertainty considered by the services, thus indicating that there is a need for harmonization in this field. Results also highlight the

fact that the contribution of energy response dependence on the measurement uncertainty cannot be neglected and should be estimated for all fields of interest.

Finally, it should be noted that some dosemeters have been tested for fields for which they are not indented to be used. Among them there are dosemeters with very good response to photons without being appropriate for beta particles; however, if they are not supposed to be used in mixed fields they can still be considered adequate for use in photon fields.

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V. **CONCLUSIONS**

The coordinated network for radiation protection dosimetry, the CONRAD project, was funded in 2005 within the 6th EU Framework Programme. Working group (WG9) dealt with the coordination and promotion of European research in the field of ***radiation protection dosimetry for medical staff***. The progress of technology and the research on the production of radioisotopes together with a better knowledge of their radiobiological effects lead to the continuous development of new medical applications: radiodiagnosis and radiotherapy with sealed and unsealed sources, increased number of interventional radiology and cardiology procedures. This continuous progress in the use of ionizing radiation in medical applications requires an important effort in both training and understanding of the new techniques.

The possibility of non-uniform exposure of the body to ionizing radiation has been acknowledged for a long time by ICRP and was reflected through adoption of the effective dose, as one of the main protection-related quantities. It was also recognized that different types of radiation effects may occur in the same person, when exposures are non-uniform. For this reason, the dose limits for occupational exposure have been defined for stochastic effects (in terms of the effective dose) and separately for deterministic effects on the skin and the eye (in terms of the absorbed dose or dose equivalent). In numerical terms the two categories of the annual dose limits are grossly different: 20 mSv for effective dose and 500 mSv for skin (e.g. hands and feet) averaged over 1 cm^2 of the most exposed part. It has also been recognized for decades that typical monitoring of occupational exposure in terms of personal dose equivalent for different source–object distances, by means of a single dosimeter, will not provide information on the dose to hands when radiation sources are handled manually.

WG9 carried out a thorough literature review and state-of-the-art analysis of extremity dosimetry which has been presented at several scientific meetings and reports. The main conclusions of the study are highlighted herein.

In nuclear medicine and interventional radiology, the extremities (hands and fingers) are often in contact or very close to the radiation beam or the radiopharmaceuticals. Thus, extremity doses can be high and even exceed occupational limits. In addition, several studies report a wide range of measured doses depending on individuals and procedures. Both the experience of the physician and radiation protection measures have been proven to be important factors in reducing the dose.

Routine monitoring of extremities is, in general, difficult because some of the techniques involve the use of mixed beta and photon fields. Thus, monitoring is not always performed with the appropriate dosemeter for such a large range of types of radiation. Another difficulty is the selection of the position where the dosemeter is worn to ensure a good estimate of the skin dose or the effective dose. So far, there are no generally accepted recommendations on the best monitoring procedure.

The staff that carry out interventional procedures are likely to receive significant radiation doses to their hands, or parts of their body not covered with a protective apron, as they are close to X-ray tubes. In interventional radiology and cardiology, finger or hand dosimetry is sometimes performed on a regular basis. However, the dose to the eye lens and feet is, in general, not known, although, in some cases, they can be even higher than finger doses. An increased prevalence of radiation-related lens opacities in interventional radiologists has been reported in recent years. However, the eye lens doses are never measured in routine applications since there is no easy dosemeter available for eye lens dosimetry. A large variation in dose ranges for the same kind of procedures has been reported, thus highlighting the fact that many factors, such as protective devices, X-ray geometry and spectra and scattered radiation from the patient, can influence the actual extremity doses.

The literature concerning radiation exposure and protection of nuclear medicine staff mostly refers to conventional diagnostic nuclear medicine (nuclear medicine based on the use of photon emitter radiopharmaceuticals for diagnostics, mainly ^{99m}Tc) and is much more limited for PET and radiation therapy applications. Although ring dosemeters are used more frequently in nuclear medicine than in interventional radiology, this is still not a generalised practice. An additional difficulty in nuclear medicine is the large dose variation across the hands. Because the definition of the dose limit for the skin implies the measurement of 'the dose averaged over any area of 1 cm² regardless of the area exposed', it is necessary to measure the local skin dose at the location with presumably the highest exposure. This requirement is one of the main problems of extremity dosimetry since it causes severe practical difficulties. In daily practice when preparing and administering radio-pharmaceuticals in nuclear medicine it is not easy to comply with this requirement since it is often not known which part of the hand receives the highest dose. Moreover, the dose distribution over the hand may vary during a single process as well as when various people perform the same procedure.

Positron emitters for positron emission tomography and beta or mixed beta/gamma unsealed sources for radiation therapy are being increasingly used in nuclear medicine. In these situations, the dosemeters must be appropriate for beta radiation measurement, both the energy spectra of the nuclides and the spectral dose response of the dosemeter have to be taken into account. Because of the specificities of the radionuclides handled (high activity, emission characteristics), in PET and, in particular, in nuclear medicine therapy, staff may be exposed to higher doses than in conventional nuclear medicine. Thus, adequate safety measures including monitoring of personnel are highly recommended.

The influence of the type of dosemeter and of the dosimetric procedure (ring or wrist dosemeter, position on the hand) is especially critical in nuclear medicine because of the wide range of radiation fields and of the large dose gradients across the hands. According to several studies, the highest doses are found at the finger tips.

Furthermore, the literature review highlights the fact that the dose estimates obtained in research studies are much higher than registered values in routine dosimetry, thus indicating that the present dose assessment is clearly underestimating the real radiological risk of nuclear medicine staff.

To complete the general overview on extremity dosimetry obtained from the literature, an intercomparison was organised within the framework of CONRAD. The main aim was to verify the performance of different extremity dosemeters in use in Europe, focussing on the response in typical workplaces corresponding both to interventional radiology and nuclear medicine. Twenty four dosimetric services from sixteen countries participated in the intercomparison. The analysis of the intercomparison fulfilled the expected objectives since it provided an extensive overview of the capabilities and the difficulties of extremity dosemeters to measure the quantity $H_p(0.07)$ in photon and beta reference fields and in realistic workplace fields. It was shown that, in general, there is a satisfactory response for photon fields: ^{137}Cs, direct and scattered X-ray fields and ^{99m}Tc. Major difficulties were encountered for the measurement of beta radiation. This limitation is of concern not only when handling beta emitters, but also when handling positron emitters. The importance of the dosemeter design, particularly, the thickness of the filter and the detector is shown.

The conclusions from the CONRAD project have highlighted high extremity doses and a lack of systematic data analysis on exposures to the staff in interventional radiology (IR) and nuclear medicine (NM). To optimize the working procedures in the medical field with respect to radiation protection, a new consortium was founded in April 2007 in order to undertake a new project, ORAMED, focussed on improving the knowledge on extremity and eye lens exposures. The project was launched in February 2008, within the framework of the 7th EU Framework Programme. It addresses five main topics:

a) Measurement and calculation of extremity and eye lens doses in interventional radiology:
The aim of this topic is to obtain a set of standardized data on doses for staff in interventional radiology and cardiology and to design recommended radiation protection measures and procedures to both guarantee and optimize staff protection. Systematic measurement campaigns in European hospitals, together with simulation of fields of interest will be performed to determine the main parameters that influence extremity and eye lens doses and the effectiveness of different radiation protection measures.

b) Development of practical eye lens dosimetry in interventional radiology:
The objective of the project is to fill the "dosimetry gap" for the eye lens by developing a formalism to measure eye lens doses and by designing a specific dosimetric system that could be worn comfortably.

c) Improvements in extremity dosimetry in nuclear medicine, with special emphasis for PET applications and nuclear medicine therapy:
An experimental campaign together with a series of simulations of typical procedures used in nuclear medicine is foreseen to systematically map the hand doses received in nuclear medicine. The distribution of the dose across the hand of the technicians will be measured to validate the simulations and to provide an overview of the doses that are received in the different techniques and procedures in nuclear medicine. Efforts in nuclear medicine will concentrate on those areas where radiation exposure of staff is more critical and less information is available at the present time. This is the case of the use of unsealed sources for therapy applications and, in general, the handling of positron emitters.

d) Optimization of the use of active personal dosemeters in interventional radiology:
Active personal dosemeters (APD) have been found to be very efficient tools to reduce occupational doses in many applications of ionizing radiation. Interventional radiology operators belong to a specific worker category, which would benefit from a real time, accurate assessment of
their dose. For adequate dosimetry of these scattered photons, APDs should be able to respond to

low-energy [10-100 keV] and pulsed radiation with high instantaneous dose rates. Unfortunately, these are situations in which current APD technology is not always adequate. The objective of this part of the project is to optimize the use of active personal dosemeters (APDs) in interventional radiology and to design a new prototype to improve the response of the presently available devices.

e) Training and dissemination

The final objective of the project is to design and develop an accurate teaching and knowledge dissemination program to make sure that the conclusions and recommendations of the
project are transmitted to the stake-holders, mainly medical staff and radiation protection officers.

In summary, the CONRAD project has led to an enlarged partner consortium, which includes research institutes, metrology laboratories, regulator bodies, hospitals and manufacturers, which is the ideal group to develop the objectives to optimize radiation protection of medical staff exposed to radiation in both a rigorous and realistic way. The development of CONRAD has helped us to identify the area where more research is needed and has promoted networking between the different members of the WG. It has been essential to establish the objectives of the new project.

REPORT of EURADOS CONRAD WP7/SG 2

Double Dosimetry with Recommendations

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I. Introduction

Interventional radiology as a rapidly developing branch of minimally invasive medicine has brought large social dimension connected with lower morbidity, shorter reconvalescence time and lower costs for the treatment of patients. The consequence of the high health and economic benefits from the application of modern interventional technologies is the rapidly growing number of fluoroscopy-guided procedures reaching 500-1000 examinations typically performed for million inhabitants, mainly in developed countries. Increasing number of dedicated X-ray systems increases also the number of professionals (radiologists, technicians, nurses). Interventional procedures involve extended use of low dose rate fluoroscopy, as well as high dose rates in image aquisition mode, hence the patient and staff can potentially receive high radiation doses. While the skin doses to the patient can reach several Gy, scattered radiation around the patient can reach dose rates in the range 2-200 mGy/h. As the operator works very close to the patient, considerable occupational doses are observed, influenced mainly by long fluoro times, high number of radiographic frames and by the level of trainig in radiation protection and the experience of the operator.

The complexity of the interventional procedures and variability of radiation fields involved require extensive investigations and growing concern of the safety of staff involved in interventional procedures. Adequate monitoring has to be established for estimation and optimization of the radiation exposure of professional staff.

To respect the annual effective dose limits for radiation workers according to the EURATOM Council Directive 96/29 and the International Atomic Energy Agency (IAEA) Basic Safety Standards the effective dose has to be determined (EURATOM, 1996; IAEA, 1996). Therefore the radiation dose measured from a dosemeter has to be converted to an estimate of effective dose (E). In practice, the assessment of the occupational radiation exposure is based on the evaluation of the readings of legal personal dosemeters and, for a typical dose range and working conditions frequently existing, the dose measured in front of the body is assumed to be a conservative estimate of the effective dose. This official statement, confirmed by the ICRP and the ICRU recommendations, is based on the asumption that personnel are exposed to a nearly homogeneous radiation field. This statement is not well applicable to the staff in interventional radiology, where the irradiation is not homogeneous in space and energy due to the complexity of the procedures, thus making the accurate staff dose measurement a difficult task.

The effective dose is usually determined from a single dosemeter reading. The effective dose can then be underestimated, because the high dose to unprotected body areas is not taken into account and the ratio of effective dose and the reading of personal dosemeter varies considerably with the type of the protective clothing (wrap-around style lead apron and thyroid lead shield, various lead equivalence of apron) and with the energy spectrum of the emerging radiation. The conversion factors given by various authors for calculation of effective dose from a single dosemeter reading can lead to an underestimation of the true effective dose by a factor of up to 5. It has been shown by many authors in the past decade that wearing an additional dosemeter at collar level above the lead thyroid shield, the so called „double dosimetry system“, makes possible to combine the two dosemeter readings to provide an improved estimate of the effective dose.

Taking into account that effective dose is a useful and convenient quantity to estimate the stochastic risk of radiation exposure, allowing comparison of alternative protocols applicable to the same interventional examination, the importance of improving the accuracy of effective dose calculation has been emphasised by radiation protection experts. In the framework of the Working Group (WG9) of the CONRAD project coordinated by EURADOS, the occupational dosimetry practices in interventional radiology, the available double dosimetry algorithms, and the accuracy of using either a single dosemeter or double dosemeters for effective dose estimation have been reviewed.

The relevant literature published for double dosimetry has been reviewed, and the accuracy of the 14 different algorithms prepared by various authors for various configurations and lead apron thicknesses have been tested. The purpose has been to find out whether any firm consensus on the most suitable algorithm could be obtained in order to harmonize the regulations for double dosimetry. Testing was carried out by intercomparison of algorithms in a few critical configurations frequently used in interventional radiology, by using Monte Carlo calculations and experimental measurements with phantoms.

II. Concepts of personnel dosimetry in interventional radiology

1. CHALLENGING RADIATION ENVIRONMENT IN INTERVENTIONAL RADIOLOGY

It is typical that the radiation dose to the personnel performing interventional procedures is non-uniform, with relatively high dose to the head, neck, and extremities; and much lower doses to the trunk and other regions protected by shielding. There is high variability of the angle of incidence of scattered radiation, the energy of the scattered radiation and the types of shielding used. The size of the individual also affects the geometry and thus the dose to be received.

Personnel in a fluoroscopic procedure room are required to wear lead aprons during the fluoroscopic examination. In addition to lead aprons, shielding used in medical fluoroscopy includes thyroid shields, movable transparent lead shields, and lead drapes. These protective devices shield various organs in the trunk region but leave some radiosensitive organs in the head and neck region unshielded. The use of these shielding devices is variable and depends both on the type of procedure and individual preference.

All these variables make the personnel dosimetry in interventional radiology a challenging task.

2. APPROACHES TO PERSONNEL DOSIMETRY

There has been a continuing scientific debate about the personnel monitoring arrangements in interventional radiology. It is the aim that the maximum dose at any location on the body will be measured. In the uniform exposure situation this corresponds to wearing a dosimeter on the front of the torso between neck and waist. For the non-uniform exposure of IR, the dosemeter should either be located at the position of the highest dose or multiple dosemeters should be applied.

Although the need for multiple dosimeters in personnel dosimetry has been recognized, the dosimeter value with the highest measured dose typically has been recorded as the whole body dose. Individuals are still most generally issued a single dosimeter to wear, the reading of which is taken to indicate whole-body dose. This may result in a large overestimation of effective dose.

The above practices can lead to a number of false overexposure incidents, i.e. there is a possibility that an individual may appear to exceed the annual effective dose limits when the individual, in fact, has not. The situation can cause potential worry for the individual monitored and avoidable problems for the personnel monitoring services concerned. It can also be that workers unnecessarily could be stopped from doing the job, which has consequencies for health care efficiency and economy. The credibility of personnel monitoring and radiation protection procedures in general can decrease within the medical environment.

An accurate estimate of effective dose is of value because it allows an accurate estimation of risk. Models based on extremely conservative assumptions are of little value if individuals cannot estimate risk or if risk estimates are inflated by overestimating effective dose.

2.1. Effective dose

From the viewpoint of radiological protection the quantity of interest is effective dose (E), which is the weighted sum of several organ doses as defined by the International Commission on radiological Protection (ICRP):

$$E = \Sigma_T \, w_T \, H_T \qquad (1)$$

where w_T is the tissue weighting factor and H_T is the equivalent dose to tissue $_T$ defined by:

$$H_T = \Sigma_R \, w_R \, D_{TR} \qquad (2)$$

Here w_R is the weighting factor for radiation $_R$ (w_R = 1 for x-rays) and D_{TR} is the absorbed dose averaged over tissue $_T$ due to radiation $_R$.

It is assumed that the effective dose is proportional to the risk of the late effects of ionizing radiation, like tumour induction and harm to off-springs (hereditary effects).

The most direct but purely theoretical method is to calculate tissue and organ dose and apply the tissue weighting factors to calculate effective dose. This method is not practical because of the many variables of the IR conditions.

2.2. Personal dose equivalent

As organ doses cannot be measured and effective dose determined in practice, two practical operational quantities have been defined by the International Commission on Radiation Units and Measurements (ICRU): the personal dose equivalents, $H_p(10)$ and $H_p(0,07)$. These are doses at at depth d (in mm) below a specified point on the body (d=10 mm and 0,07 mm for deep and shallow penetrating radiation, respectively). A personal dosemeter is supposed to yield $H_p(d)$ either directly as indicated reading or indirectly after application of a correction factor. $H_p(10)$ is assumed to be a conservative estimate of E while $H_p(0,07)$ yields an estimate of the equivalent dose to skin.

Both dose quantities, E and $H_p(d)$ vary in a complicated way with radiation type and quality, energy spectrum, fluence rate and direction of incidence. Hence their equivalence cannot be quaranteed and $H_p(d)$ might not properly reflect E in all conditions.

2.3 Single dosimetry (SD)

The most common approach in personnel dosimetry relies on the use of a single dosemeter. A single dosemeter may be worn in over-apron or under-apron position. The reading ($H_p(d)$) in this report will be indicated by H_o and H_u for over-apron and under-apron measurements, respectively. However, as shown in Section 3, there is no consistent practice how the dosemeter should be worn.

In the single dosimetry approach, effective dose is determined by applying a correction factor to the dosemeter reading. The correction factor can be called either a devider (D) in over-apron case or multiplier (M) in under apron case. The divider is the number by which over-apron reading should be divided to yield effective dose. The multiplier is the number by which under-apron reading should be multiplied to yield effective dose.

The value of the correction factors should generally be determined in an optimum way so that the underestimation of E is minimized and as close estimate of E as possible is obtained under conditions most frequently encountered in clinical practice. In is therefore generally required that

$$E \leq H_0 / D \qquad (3)$$

or

$$E \leq M\, H_u \qquad (4)$$

The methods based on the use of correction factors for a single dosimeter can result in significant errors, because a single correction factor cannot account for the range of imaging conditions typically encountered in fluoroscopy. For most irradiation conditions, the dosimeter worn above the lead apron will significantly (up to a factor of at least 60) overestimate effective dose. A dosemeter worn under the apron at either waist or chest level, will yield a closer estimate of effective dose, but can usually underestimate effective dose, typically within a factor of 7 for the most common lead apron thicknesses and irradiation conditions.

When the correction factor is applied to the over-collar dose, and estimation of the lead apron attenuation must be made. Apron attenuation is a function of x-ray energy, lead apron thickness, and imaging geometry (under-table/over-table, beam direction). It is difficult to estimate all the three factors. Large errors may also result from a correction factor applied to an under-apron dose because head, neck and extremity dose must also be estimated.

2.4. Double dosimetry (DD)

Where underestimations of effective dose become unacceptable, two dosemeters (double dosimetry) should be used, one over and one under the protective appron. The use of two dosimeters allows the dose to be measured both on the protected region and unprotected regions of the body, thus having the potential to provide a more accurate estimation of effective dose under a variety of conditions. The double dosimetry algorithm provides an estimate of effective dose which is independent on the lead apron thickness. It can also be designed to take into account the use of the thyroid shield which may reduce the effective dose by one half. The double dosimetry algorithm is generally written as follows:

$$E = \alpha H_u + \beta H_0 \qquad (5)$$

where H_u is the personnel dose equivalent measured under the apron, usually $H_p(10)$ (deep dose), and H_o is the personnel dose equivalent measured over the apron, usually $H_p(0,07)$ (shallow dose). The under apron personnel dose equivalent is typically only a few per cent of the over apron value.

In principle, the place of the dosimeter should comply with the position of the dose measurement as specified in the algorithms. For H_u, the place of the dosimeter is not very critical; it is usually either chest or waist. For H_o, the place of the dosimeter is generally chosen on neck level (usually neck but sometimes also shoulder), because the dosimeter is expected to yield information also on the dose to the eye.

Several algorithms of the type of Eq.(5) have been developed (see Section 4). The earliest DD algorithms were based on estimating effective dose equivalent (EDE) instead of the effective dose. The major difference between these quantities is the tissues included and the values of the tissue weighting factors. These algorithms will result in substantial errors in the estimation of effective dose because of the different weighting factors associated with EDE and because the use of the thyroid shield was not considered in the early algorithms. The change of tissue weighting factors and dose quantities has resulted in a large contribution from organs or tissues in the trunk which are shielded by a lead apron during fluoroscopy procedures.

2.5. Extremity dosimetry

For deterministic effects, equivalent dose to certain risk organs should be known. In IR the conditions often require the operator (radiologist) to have the hands or eyes close to the radiation field. The shallow dose $H_p(0,07)$ to the skin, or $H_p(3)$ for eyes, may become of interest for the control of dose limits and for deterministic effects. Usually it is the dose to the eye which may sometimes become of interest in IR.

When this is the case, the most effective is to use particular extremity dosemeters, e.g. ring or finger dosemeters for hands. These dosemeters are not discussed in this report. When the second dosimeter in the DD approach is positioned on the neck level this allows an estimation to be made of the eye dose.

III. Status of double dosimetry in the participating countries

1. EARLIER PERSONNEL DOSIMETRY SURVEYS

EURADOS has taken a lot of efforts in the last decade to collect data on the individual monitoring for external radiation in Europe. The aim of this long-term work has been to achieve harmonisation in the implementation of standards (Fantuzzi et al., 2004) and in the quality of individual monitoring using personal dosimeters (Bartlett et al., 2001). The term ”harmonisation” does not mean that the dosimetric procedures, standards and work of dosimetric services have to be exactly the same, but “they should aim to meet the same general requirements and their results should be comparable”. For this reason EURADOS working group prepared a catalogue of dosimetry services in EU and Switzerland (van Dijk et al., 2000) which was updated in 2004 and extended to include some other countries in Europe (Lopez-Ponte et al., 2004).

The estimated total number of individual monitoring services in Europe is about 200, and 91 of the services have participated in the EURADOS survey. While the data in the first survey (van Dijk et al., 2000) indicate that in 2000 approximately 50% of radiation workers in Europe were monitored in terms of personal dose equivalent $H_p(10)$, in 2004 the services almost exclusively apply $H_p(10)$ for individual monitoring (Lopez-Ponte et al., 2004; Lopez et al., 2007). The calibrations of dosemeters were carried out mostly in terms of air kerma. Comparing the 2000 and 2004 surveys (Ranogajec-Komor, 2007) it can be concluded that 104 services from 29 countries in Europe monitored more than 700000 radiation workers regularly.

69 of the individual monitoring services used thermoluminescence (TLD) dosimeters, 30 of them film and 5 of them various other methods such as optically stimulated luminescence (OSL), radiophotoluminescent (RPL) glass and electronic dosimeters. In spite of the large number of TLD services, 443000 radiation workers were controlled with film dosimeters, because several large national services applied film. However, the situation in personnel dosimetry is permanently changing indicating the need for updating the data. For example from 2006, because of introducing RPL dosimetry in France, the number of film controlled workers in Europe was reduced about 50%.

2. PRESENT PERSONNEL DOSIMETRY SURVEY

In order to overview the double dosimetry practices in Europe, the working group of the EURADOS CONRAD project carried out a new personnel dosimetry survey within the the countries which have representatives in the working group. For this purpose a questionnaire was prepared and distributed to selected dosimetry services in these countries, in total to 13 services (Table 1). The first part of the questionnaire requested information about general dosimetry subjects, such as the type and calibration of the personnel dosemeters. The second part was focused on double dosimetry. The general dosimetric data were compared to the former data collected by EURADOS (van Dijk et al., 2000, Lopez-Ponte et al., 2004).

Table 1. List of country coordinators and the dosimetry services participating in the survey

Country	Coordinator	Dosimetry service, City
Belgium	Filip Vanhavere	SCK.CEN, Mol
Croatia	Maria Ranogajec-Komor	Ruđer Bošković Institute, Zagreb
Finland	Hannu Järvinen	Doseco Ltd., Jyväskylä
France	Isabella Clairand	IRSN/DRPH, Fontenay-aux-Roses
Germany	Arndt Rimpler	GSF-National Research Centre for Environment and Health, Neuherberg
Greece	Eleftheria Carinou	Greek Atomic Energy Commission. Agia Paraskevi
Hungary	Andor Kerekes	National Personal Dosimetry Service, Budapest
Italy	Elena Fantuzzi	ENEA Radation Protection Institute, Bologna
Netherlands	Janwillem Van Dijk	Personal Dosimetry Service NRG-RE, Arnhem
Poland	Jerzy Jankowski	Nofer institute of Occupational Medicine, Lodz
Schwitzerland	Marta Sans Merce	IRA, Lausanne
Slovakia	Denisa Nikodemová	Slovak Legal Metrology, Bratislava
Spain	Eliseo Vaňo	National center of personal Dosimety,Valencia

There is no harmonisation between the national recommendations for use of double dosimetry. According to the national recommendations, in five countries the dosimeter is worn over the apron, in seven countries under the apron, and in one country above and under the apron. The place of the dosimeter is mostly the chest, but arms and thyroid was also indicated as a position for the dosimeters. Only in two countries it was foreseen by legislation or regulatory guide to wear one dosimeter above and one underneath the lead apron in some cases in interventional radiology. In three countries the need of a second dosimeter could be determined by an expert of the authority or by the medical staff, but only one regulation defines that in case of the second dosimeter it should be worn over the apron and should be different from that used under the apron. The remaining eight countries had no national recommendations for double dosimetry, however several pilot studies or occasionally also routine measurements were carried out. For example, Vekić et al. (2007) reported on the results of recorded double dosimetry measurements performed during the period of ten year.

According to the Croatian radiation protection regulations for the effective dose estimation it is mandatory to use one dosimeter placed at the left side of the chest under the protective apron. From the dosimeter reading (dosimeter is calibrated in term of $H_p(10)$) the effective dose is estimated. The results of the additional dosimeters worn on the apron at the neck or shoulder position has to be recorded, but are not used for effective dose estimations.

The dosimetry services involved in the double dosimetry survey used mostly TLD. Four of them applied film dosimeters, but in 2006 one of them introduced RPL instead of film. There were differences in calibration procedures also: nine dosimetry services used ^{60}Co or ^{137}Cs for calibration. while five of them applied various photon energies in the range from 16 keV to 1.3 MeV. One service applied 250 keV X-ray irradiation for calibration of TLDs, while another service with film dosimeters applied also X-radiation for calibration in the range of 10 keV-150 keV. Two services did not indicate the calibration procedure.

Numerous algorithms have been described in the literature for estimation of E from the measured personal dose values (see Section 4). The result of the recent survey showed that in most dosimetry services personal doses are recorded and reported as $H_p(10)$, especially if one dosimeter is used. Effective dose is not evaluated and reported routinely but case-specifically when needed, taking into account radiation environment and personal protective devices. In the most services the recorded and reported $H_p(10)$ is accepted as effective dose: $E = H_p(10)$, and this is regarded as conservative estimation of effective dose. In one service, the effect of the lead apron is taken into account by dividing $H_p(10)$ by various factors depending on the case. In two dosimetry services, $H_p(10)$ is the measured value and qualified expert is responsible for calculation of E. In one of these services the assessment of E is done by the radiation protection officers of the hospitals according to the NCRP Report 122 (NCRP, 1995). The radiation protection officers report the result to the personnel dosimetry department.

Only three of the services reported on the algorithm for double dosimetry. Two of them calculate the effective dose as follows:

$$H_{total}(10) = H_{under}(10) + a * H_{over}(10)$$

where $a=0.1$ if the protection for thyroid is not used and a=0.05 when the protection for the thyroid is used. $H_{total}(10)$ is accepted as E (Baechler et al., 2006).

The third service using double dosimetry applied the method described by Niklason et al. (1994). This method provides a reasonable estimate of effective dose that is independent of lead apron thickness and accounts for the use of a thyroid shield.

The differences in the application of protective devices (apron, thyroid collar, glasses, gloves and other devices) were also significant. In the most cases the dosimetry services did not have information or control about the use of these devices. In the most countries typically lead apron (0.25 mm/0.35 mm/0.5 mm equivalent lead thickness) was used as wrap around the body at least by the cardiologist. Tilted plate (0.35 mm thick) thyroid collar in addition to the apron was used in three countries. Two countries had no national recommendation and the dosimetry service had no information about the protective devices. They differed from hospital to hospital in these two countries. In two countries only wrap around type of apron was used for protection, while in two other countries all devices were indicated for use. In four countries other devices were used case by case, in addition to the obligatory apron.

The results of the present survey indicated that there is no harmonisation between the European countries in respect of double dosimetry. The double dosimetry practices of the services do not meet the same general requirements and therefore, the results of personnel monitoring are not fully comparable. This statement is valid also for estimation of effective dose, especially if double dosimetry is used.

IV. DEVELOPMENT OF SINGLE DOSIMETRY AND DOUBLE DOSIMETRY ALGORITHMS

The literature review for double dosimetry covered altogether about 140 publications, giving rise to the total of 14 different algorithms The 11 most recent ones are summarized in Table 2. A summary of this review have been published elsewhere (Järvinen et al., 2008a).

1. EARLY ALGORITHMS WITHOUT CONSIDERATIONS FOR THYROID SHIELD

The early double dosimetry algorithms given by Gill et al. (1980) , Webster (1989) and Balter et al. (1993) were based on the determination of "effective dose equivalent" (*EDE*) as defined in ICRP Publication 26 (ICRP 1977) . The effect of thyroid shield was not considered. In 1991, ICRP Publication 60 (ICRP 1991) issued a new set of weighting factors and in addition, the name "effective dose equivalent" was replaced by the term "effective dose" (*E*).

Faulkner and Marshall (1993) used the new weighting factors in their intensive study of the staff exposure. They did not give an algorithm but their work was the valuable source of data for other authors. They studied the exposure during fluoroscopic procedures for different irradiation conditions (overcouch X-ray tube/undercoach image intensifier and undercouch X-ray tube/overcouch intensifier geometries, primary radiation in the range of 70 kVp – 110 kVp, different lead apron thicknesses etc.). A Rando phantom with the film badge dosemeters attached to the skin surface at seven commonly used monitoring sites and loaded with lithium fluoride thermoluminescent dosemeters was irradiated when a lead apron was not present. Absorbed doses to the tissues when a lead apron was present were estimated from the absorbed doses without a lead apron, as modified by transmission data for the appropriate X-ray tube potential and lead thickness. The main results can be summarised as follow: For most irradiation conditions studied, a dosemeter worn above the lead apron will significantly overestimate effective dose by a factor between 2 and 60, depending on the irradiation conditions. A dosemeter worn under the apron at either waist or chest level will generally yield a closer although usually an underestimate of effective dose, typically within a factor of 7 (the range is between 1.2 and 7) for the most common lead apron thicknesses and irradiation conditions. They concluded that *no single dosemeter can accurately monitor effective dose* for all irradiation conditions in fluoroscopy. The data presented in the paper can be used as a basis for the assessing above-apron corrections factors. On the other hand, a single dosemeter worn under the apron will yield a closer estimation of effective dose but with the underestimation of E in many circumstances.

Wambersie and Delhove (1993) recommended the following: when a lead apron is used due to the important resulting dose heterogeneity *two dosemeters have to be worn*, the first one permanently at the level of the chest (behind the lead apron), the second one at the level of the non-protected parts of the body (e.g. neck, shoulders). The effective dose is then calculated by adding the dose received by the first dosemeter and the dose received by second dosemeter (not shielded by the lead apron) divided by a weighting factor of 10. This evaluation of the effective dose is fully conservative. Their algorithm is the first one shown in Table 2.

Rosenstein and Webster (1994) used the experimental data from Faulkner and Marshall (1993) for their new algorithm. The method was based on iteration the values of the weighting multipliers for H_u and H_o by trial and error until a desired approximation of E for radiation protection purposes was achieved for the clinical range of X-ray tube voltages, the two X-ray tube locations, and for both 0.5 mm and 0.3 mm thicknesses of lead aprons. Their criteria for a desired formula were: a) to minimise the underestimates of E, even at the expense of larger overestimates of E for some conditions, and b) to obtain a close estimate of E at the combination most frequently encountered in clinical practice (90 kVp, 0.5 mm lead apron and under-table X-ray tube). The resulting formula is shown in Table 2.

Based on the analysis of the papers published until 1993, NCRP Report No. 122 (NCRP 1995) recommended divider D=21 for a single personal dosemeter worn at neck above apron, and for double dosimetry the formula given by Rosenstein and Webster (1994).

Huyskens et al. (1994) in their extensive study defined two correction factors, divider (D) and multiplier (M). The divider is the number by which the over-apron reading should be divided to yield effective dose and the multiplier is the number by which the under-apron reading should be multiplied to yield effective dose (Section 2.1.3). The values for D and M were calculated for a variety of exposure situations which were modelled to simulate the actual exposure conditions of staff in interventional radiology. For fluoroscopic interventional practice they recommended D=5 and M=3 (Table 2). They also emphasized that *single badge monitoring is often not sufficient* when occupational doses may reach recommended dose limits.

2. ALGORITHM TO COVER ALSO THYROID SHIELDS

Niklason et al. (1994) concluded that the algorithms by Gill et al. (1980) and Webster (1989) would result in substantial errors because of *different weighting factors associated with EDE* and because the *use of thyroid shields were not considered*. Further, they noted the possibility of large errors when using a single dosemeter (Faulkner and Marshall, 1993; Faulkner and Harrison, 1988). They proposed a new algorithm which was *independent of lead apron thickness and also accounted for the use of a thyroid shield. E* was calculated using an over-apron collar dose and an under-apron waist dose. The proposed model was based on: (1) the under-apron dose was assumed to be whole body dose; (2) the head and neck effective dose were calculated using organ dose tables, depth dose tables and collar dosemeter measurements, and (3) the extremity effective dose was estimated from depth dose tables and the collar dosimetry. The proposed equations are shown in Table 2. For the over-collar dose the shallow dose (H_{os}) was used rather than the deep dose since the shallow dose was considered more appropriate when organ dose tables and depth dose tables were used for dose calculation (these tables are based on skin entrance dose rather than the dose at a depth of 1 cm). Their algorithm requires the use of two dosemeters, but is suitable also when a single dosemeter is worn over the apron at the neck level, provided that the apron attenuation is of the order of 98-99% (Padovani et al., 2001).

The accuracy of the Rosenstein-Webster and Niklason algorithms was checked experimentally by Mateya and Claycamp (1997) and by Monte Carlo (MC) calculations by Kicken et al.(1999). Their results did not support the Rosenstein-Webster algorithm but found a better agreement with Niklason et al. (1994). Padovani et al. (2001) concluded that both two-monitor algorithms discussed show evidence of some limitations when compared with experimental data and that Niklason algorithm has the advantage over the Rosenstein-Webster algorithm that it accounts for the use of a thyroid shield and seems to yield estimates in better agreement with the results of the most recent survey (Kicken et al., 1999) of radiologists' doses until then. From their analysis it was the Niklason algorithm that in the estimation of E in interventional radiology performs within the recommended uncertainty range given in NCRP Report 122 (NCRP 1995). NCRP Report 122 accepts an overestimation of the value of *E* by a factor of 3 when a single dosemeter is worn at the neck over the apron and a factor of 2 when two personal monitors are used.

3. FURTHER DEVELOPMENT

Swiss ordinance on personal dosimetry (1999) requires the use of double dosimetry for work involving high dose and introduces an algorithm for effective dose calculation.

McEwan (2000) derived algorithms for two dosemeters worn at collar and trunk (under apron) and also for a single dosemeter. He assumed that thyroid shielding is not being used and that the H_{collar} is a good measure of thyroid dose.

Franken and Huyskens (2002) focused on two main issues: (1) how much protection does a lead apron provide, and what are the main factors that determine the protection efficiency, and (2) how can measured badge dose be translated into a realistic estimate of the effective dose, and how does this depend on dosemeter placement. They developed a model that calculates equivalent doses in function of scattered X-ray spectrum, shielding parameters and exposure geometry. The model assumes broad parallel beams, simulating orientation and movement of a person in a radiation field by a combination of exposures geometries. For each exposure scenario they calculated effective dose according to ICRP Publication 60 (ICRP, 1991). They performed model calculations for a variety of practical situations, with and without a lead apron, and for many apron models, fits and lead thickness. They concluded that *apron model and fit are often more important than lead thickness*. Their simple expressions in Table 2 were constructed in such a way that effective dose is estimated as accurately as possible, but never underestimated. The expressions may overestimate effective dose by up to 50% in exposure conditions that occur in interventional radiology and they are valid for aprons of at least 0.25 lead thickness.

Sherbini and DeCicco (2002) used MC dose calculations in an anthropomorphic mathematical phantom to estimate *EDE*, *E* and $H_p(10)$ under a variety of irradiation conditions. The photon energies used included several standard X-ray spectra as well as mono-energetic photons with energies extended from 0.03 to 1.0 MeV. The results of this study showed that the adjusted Webster (1989) and Rosenstein-Webster (1994) algorithms gave estimate that was consistently within the acceptable range over entire energy range considered. The adjusted algorithm is shown in Table 2.

Von Boetticher at al. (2003) and Lachmund (2005) based their algorithm on measurements of the occupational radiation exposures at the relevant places in diagnostic radiography. To determine effective dose values, TLD measurements were performed with one Alderson phantom used as a source of scattered radiation and a second

one replaced the medical specialist. Various types of personal radiation protection garment and fixed shields were considered. Based on these measurements the method for a simple determination of the effective dose was derived and shown in Table 2. A mathematical model was derived which verifies the empirically determined coefficients. Also, their measurements show that the relevance of thyroid protection as a part of protecting garment is underestimated: if the additional thyroid protection is worn the effective dose can be reduced approximately to a third.

Schultz and Zoetelief (2006) carried out an example of dose calculations by MC method in mathematical phantoms for cardiologist and patient (baby boy), for cardiac catheterization procedure, and applied the results to various published algorithms. Almost all algorithms overestimate their effective doses. In that particular example the NCRP recommendations (NCRP 1995) including Rosenstein-Webster algorithm (1994) for double dosimetry seem to yield the closest approximations to the effective dose. But as they concluded, with only one example the results cannot be generalized. Furthermore, the comparison was not completely fair, "because for double dosimetry the chest values were used as the neck over-apron and waist under-apron values must be less reliable in that simulation." Also, in Niklason's algorithm instead of $H_p(0.07)$, $H_p(10)$ was used for over apron dosemeter. Findings in this work hold no indications that double dosimetry yields more accurate estimates of E than single dosemeter. Both methods require correction factors that should be best determined for selected procedures in medical radiology. MC simulation can be a convenient tool for doing this.

Siiskonen et al. (2007) carried out similar type of MC simulations for eight cardiac and two cerebral exposure conditions. The effective dose was calculated for conditions with and without lead apron. They also presented data for estimating the radiologist's effective dose from the dosemeter reading (the personal dose equivalent), when dosemeter is worn above and under the protective clothing and from DAP data. In actual practice, the accurate information on the exposure conditions is rarely available and the effective dose cannot be calculated accurately. Therefore, particular emphasis was placed on the sensitivity of the results with respect to variations in simulation parameters: geometrical factors, X-ray beam filtration, tube voltage and field size. Simulations were done with the MCNPX Monte Carlo code version 2.5f. Mathematical MIRD-type hermaphrodite phantoms of the patient and the radiologist were used. In the MC model the phantom representing the radiologist and the model of the lead apron were not optimal. Especially, the calculation of the dose to the thyroid was not realistic. One of the reasons is that the thyroid position is not realistic in the MIRD-type phantom. Furthermore, they did not use the neck location for the external dosemeter because of the unrealistic shape of the MIRD-type phantom at the shoulder region. Some of the conclusions of this comprehensive study are summarized as follows: the results from the MC simulations reveal that the effective dose to the radiologist and the protection provided by the lead apron vary significantly with changing irradiation conditions. Moreover, the location of the personal dosemeter has a major impact on the simulated as well as measured H_o value. The thyroid shield often reduces the effective dose by a factor of two. The exposure conditions in this and earlier studies are not exactly comparable. Their results indicate that the often used conversion coefficient from H_o to E when thyroid shield is not used around 1/30, somewhat overestimates the effective dose. Since the conversion coefficient varies greatly from one exposure condition to another, a generally applicable accurate relationship between the dosemeter reading(s) and E of the radiologist can not be established based on the presented data. However, the rough estimates of the conversion coefficients H_o to E were recommended.

Clerinx et al. (2007) also performed MC simulations for typical geometries of interventional radiology procedures. The simulation model consisted of an X-ray source and an image intensifier, a patient phantom and a voxelized staff member phantom with a lead apron. The effective staff dose and dosemeter readings for several positions and orientations of the worker relative to the patient, while imaging in PA, AP, lateral and 45° oblique directions, were simulated. Simulated organ doses were experimentally verified for a single geometry with a Rando-Alderson anthropomorphic phantom placed in a scatter field. The results showed that dosemeter reading at the neck level and under apron at thorax level give the best correlation with the calculated effective dose. Their recommended algorithm for the E to a physician, positioned in close proximity to the primary beam is shown in Table 2. Furthermore, they showed that the using of some of single dosemeter algorithms from the literature in some exposure geometries could result in unacceptable underestimation of E.

Table 2. Algorithms for the calculations of effective dose (E)

	Authors	Algorithm	Place of dosemeters	Remarks
1	Wambersie and Delhove (1993)	$E = H_u + 0.1\ H_o$	H_u: chest H_o: neck or shoulders	
2	Rosenstein and Webster (1994)	$E = 0.5\ H_u + 0.025\ H_o$	H_u: waist H_o: neck	Based on Faulkner and Marshall (1993)
3	NCRP Report No. 122 (NCRP 1995)	single: $E = H_o/21$ double: same as No. 2	H_o: neck	Based on data published until (including) 1993.
4	Huyskens et al. (1994)	single: $E = H_o/D$ or $E = H_u \cdot M$		D=5 and M=3 for fluoroscopic interventional practice
5	Niklason et al (1994)	(a) without TS, double: $E = 0.06(H_{os} - H_u) + H_u$ single*: $E = 0.07\ H_{os}$ (b) with TS, double: $E = 0.02(H_{os} - H_u) + H_u$ single*: $E = 0.03\ H_{os}$	H_u: waist H_{os}: collar	*Recommended by Padovani et al. (2001); assuming $H_u \sim 0.01\ H_{os}$ Tested by Mateya and Claycamp (1997) and Kicken et al. (1999)
6.	Swiss ordinance (1999)	$H_p(10) = H_u + \alpha H_o$ $\alpha = 0.1$ without TS $\alpha = 0.05$ with TS $H_p(0.07) = H_u + H_o$	Not defined	Without TS same as No.4.
7.	McEwan (2000)	double: $E = 0.71\ H_u + 0.05\ H_o$ single: (a) $E = 0.08\ H_o$ (b) $E = 2 \cdot H_u$	H_u: trunk H_o: collar	Without thyroid shield. Based on $E/H_p(10)$ ratios for AP exposures published by NRPB (1993)
8	Franken and Huyskens (2002)	single: $E \leq H_o/5$ (a) double without TS: $E \leq H_u + H_o/10$ (b) double with TS: $E \leq H_u + H_o/30$	H_o: mid front (1) H_u: mid front (2) H_o: mid front (3) See→	Lead apron: at least 0.25 mm lead (1) at collar or chest level (2) at waist level (3) at collar level
9.	Sherbini and DeCicco (2002)	$E = 1.0\ H_u + 0.07\ H_o$	H_u: waist H_o: neck	
10	von Boetticher at al. (2003) and Lachmund (2005)	(a) double without TS: $E = 0.65\ H_u + 0.074\ H_o$ (b) double with TS: $E = 0.65\ H_u + 0.017\ H_o$	H_u: anterior thorax H_o: neck	
11.	Clerinx et al. (2007)	$E = 1.64\ H_u + 0.075\ H_o$	H_u: thorax H_o: neck	Estimation within a 10 % under-estimation margin

Symbols: H_u: under apron dose, H_o: over apron dose, E: effective dose[13], H_{os}: over-collar shallow dose i.e. $H_p(0.07)$, TS: thyroid shield

V. TESTING AND COMPARISON OF THE ALGORITHMS

1. INTRODUCTION

There is no international consensus on what is the best double dosimetry algorithm, and the extensive literature review of the published double dosimetry algorithms (Section 4) did not indicate convincing data for the preference of any of the algorithms. In this work, preliminary testing and comparison of the algorithms have been carried out by using data from published Monte Carlo calculations (Section 5.3). Due to the high uncertainties in applying the published data for the testing of the algorithms (mainly caused by the differences in dosemeter positions), further testing of the algorithms have been carried out by experiments and calculations in typical IR conditions (Section 5.4). The details of these studies have been published elsewhere (Järvinen et al. 2008a; 2008b) while the following gives a brief summary of these studies.

2. METHODS OF TESTING

The accuracy of the algorithm for a given IR geometry can be tested by determining H_u, H_o, and E (see Section 2.1.4) either experimentally or by Monte Carlo calculation. For double dosimetry, the values of H_u and H_o obtained are inserted in Eq. (5) and the effective dose E_1 is calculated. For single dosimetry, the value of H_o is inserted in Eq. (5) with α=0, and the effective dose E_1 is calculated. The result is then compared with the value of effective dose E_2 directly obtained by measurement or calculation.

3. TESTING AND COMPARISON OF ALGORITHMS BASED ON PUBLISHED MONTE CARLO CALCULATIONS

Some of the published algorithms (Table 2) have been tested based on published measurements and/or Monte Carlo calculations of the relevant dose quantities. In this work, results from Schultz and Zoetelief (2006) were adopted, and further calculations were carried out based on the data from Siiskonen et al. (2007). The effective dose E_1 was calculated by the algorithms using MC calculated dosemeter readings (H_u and H_o), and the result was compared with the MC calculated effective dose E_2 for the similar irradiation conditions. If $E_1 > E_2$, then the ratio E_1/E_2 is reported as the factor of overestimation. If $E_1 < E_2$, then the ratio E_2/E_1 is reported as the factor of underestimation.

For the irradiation geometries used by Siiskonen et al. (2007) (cardiac and cerebral fluoroscopy procedures), the results of calculations indicate overestimation of E by all single and double dosimetry algorithms tested (Figures 1 to 2).

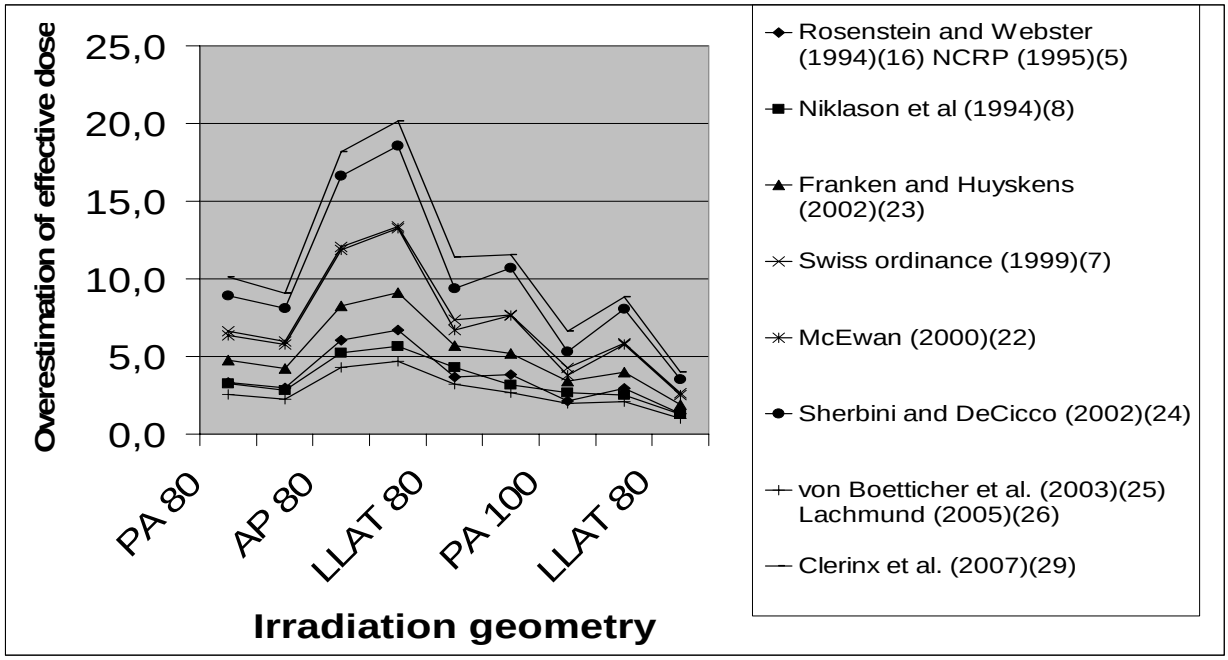

Figure 1. Overestimation of E by the various double dosimetry algorithms in the clinical cases considered and calculated by Siiskonen et al. (2007).

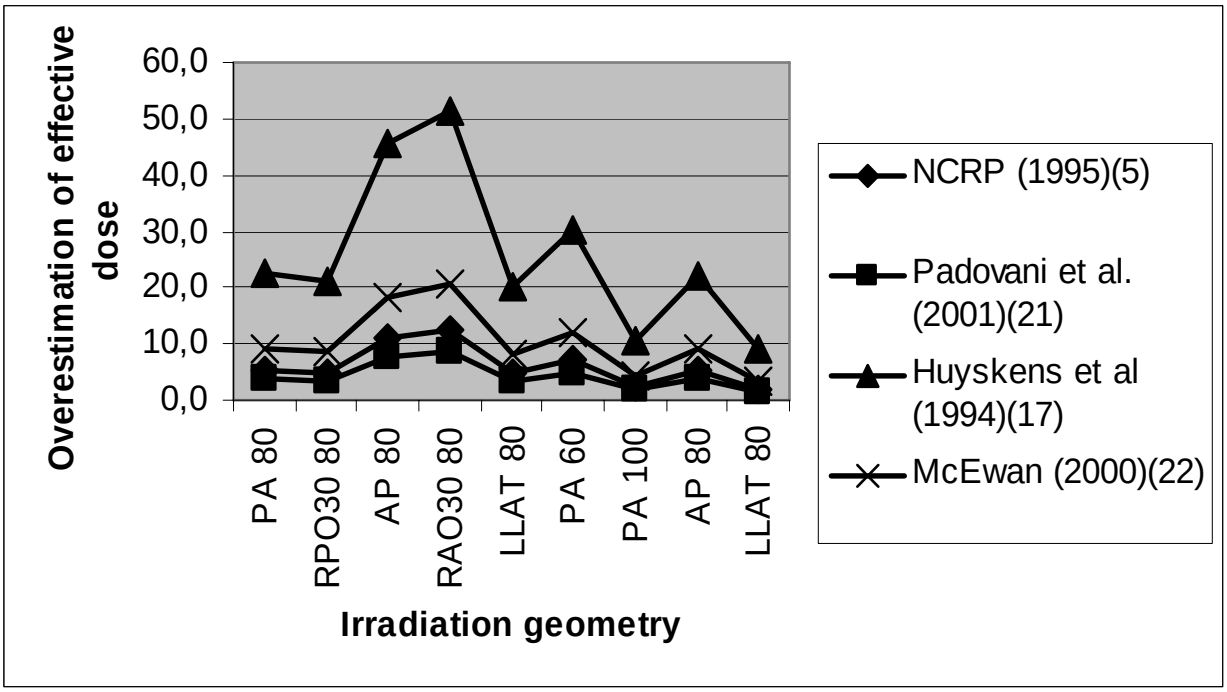

Figure 2. Overestimation of E by the various single dosimetry algorithms in the clinical cases considered and calculated by Siiskonen et al. (2007).

Figure 1 shows that the overestimation depends highly on the irradiation geometry and there are significant differences in the overestimation by different algorithms (maximum overestimations by a factor of 6 to 20). For the single dosimetry algorithms (Figure 2), the overestimations are of the same order of magnitude (by a factor of about 1,5 to 20) except for the algorithm by Huyskens et al. (1994), when it is up to a factor of about 50.

The overestimations reported earlier are somewhat lower than shown in Figures 1 and 2 (Järvinen et al. 2008a). Furthermore, there can also be significant underestimations of E for certain cases, in particular for the single dosimetry algorithms. The results from the cases considered by Schultz and Zoetelief (2006) and Siiskonen et al. (2007) cannot be generalized, because they deal with only a few typical geometries and irradiation conditions.

4. TESTING AND COMPARISON OF ALGORITHMS BY NEW EXPERIMENTS AND MONTE CARLO CALCULATIONS

As the next step in this study, both experiments and calculations were carried out to obtain parameters H_u, H_o, and E. Parameter H_u and H_o were determined for both the chest and the waist positions, while H_o was determined also for a neck position. The irradiation geometry was selected to be representative of typical IR conditions. A cardiological undercoach set-up (PA geometry) was chosen and is schematically shown in Fig. 3 (Järvinen et al., 2008b). The patient was simulated by a rectangular block of PMMA slabs, with dimensions 30 cm x 30 cm x 15 cm. The cardiologist was simulated by a Rando-Alderson (RA) phantom in the experiment and by a voxel phantom (MAX) in the Monte Carlo calculation. The cardiologist was provided with a wrap-around type lead apron of 0,35 mm thickness, with a separate collar, for both the experiment and the calculation.

For the estimation of organ doses and the calculation of the effective dose, the RA phantom was filled with 195 thermoluminescent dosemeters (TLD) of the type TLD-100H (LiF:Mg,Cu,P; cylindrical shape, 4,5 mm diameter and 0,9 mm thickness). The calculation of effective dose from the measured doses was carried out using 16 organs of a male patient (as specified by the ICRP Report 60, excluding breast and skin; six organs for the remainder). Skin was not included due to practical difficulties of measurement (large number of TL dosemeters needed for accurate measurements). For personnel dose determination, TLDs of the type TLD-100 (LiF:Mg,Ti), GR-200A (LiF:Mg,Cu,P) and TLD-100H (LiF:Mg,Cu,P) were used, calibrated at ^{137}Cs source in terms of $H_p(10)$.

For the Monte Carlo calculation of dosemeter readings and effective doses, a Monte Carlo code MCNPX2.5.0 was used. Besides the results of this calculation, the results of other MC calculations obtained by two different institutes in the same irradiation geometry and set-up as used in this work were applied for the testing of the algorithms; for more details, see Järvinen et al. (2008b).

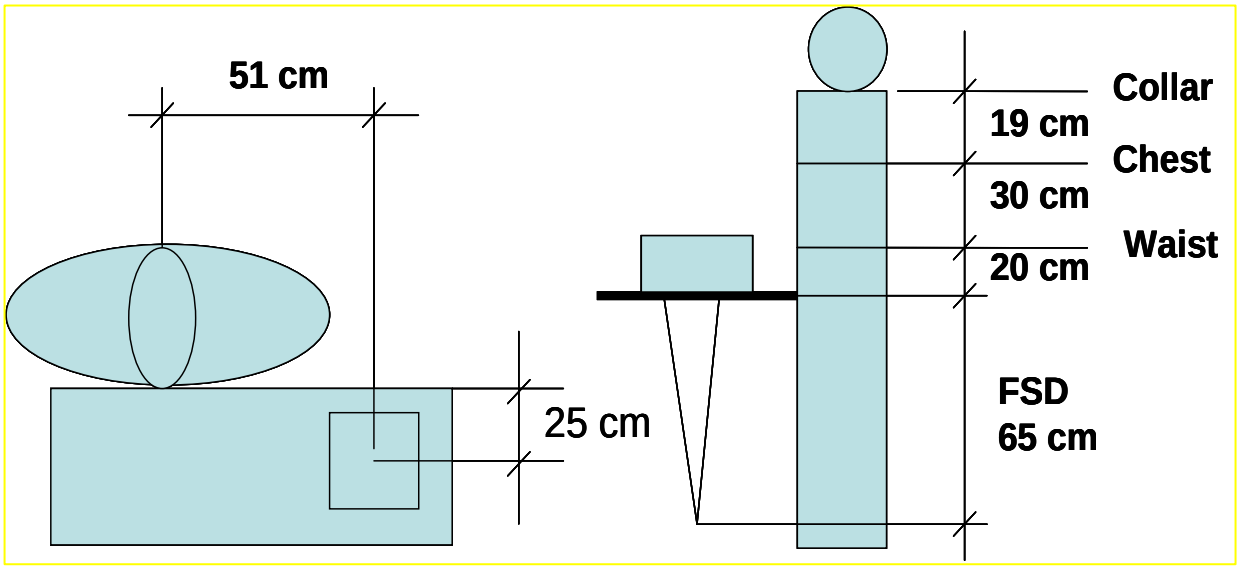

Figure 3. Irradiation geometry for the measurements and calculations, for the testing of the algorithms to calculate effective dose.

The algorithms tested in this work can be found in Table 2. The criteria to assess the performance of the algorithm were considered as follows: Underestimation of effective dose shall be avoided, while the overestimation of effective dose should be kept to a minimum, and a close estimation of effective dose should be obtained at the conditions most frequently encountered in local clinical practices.

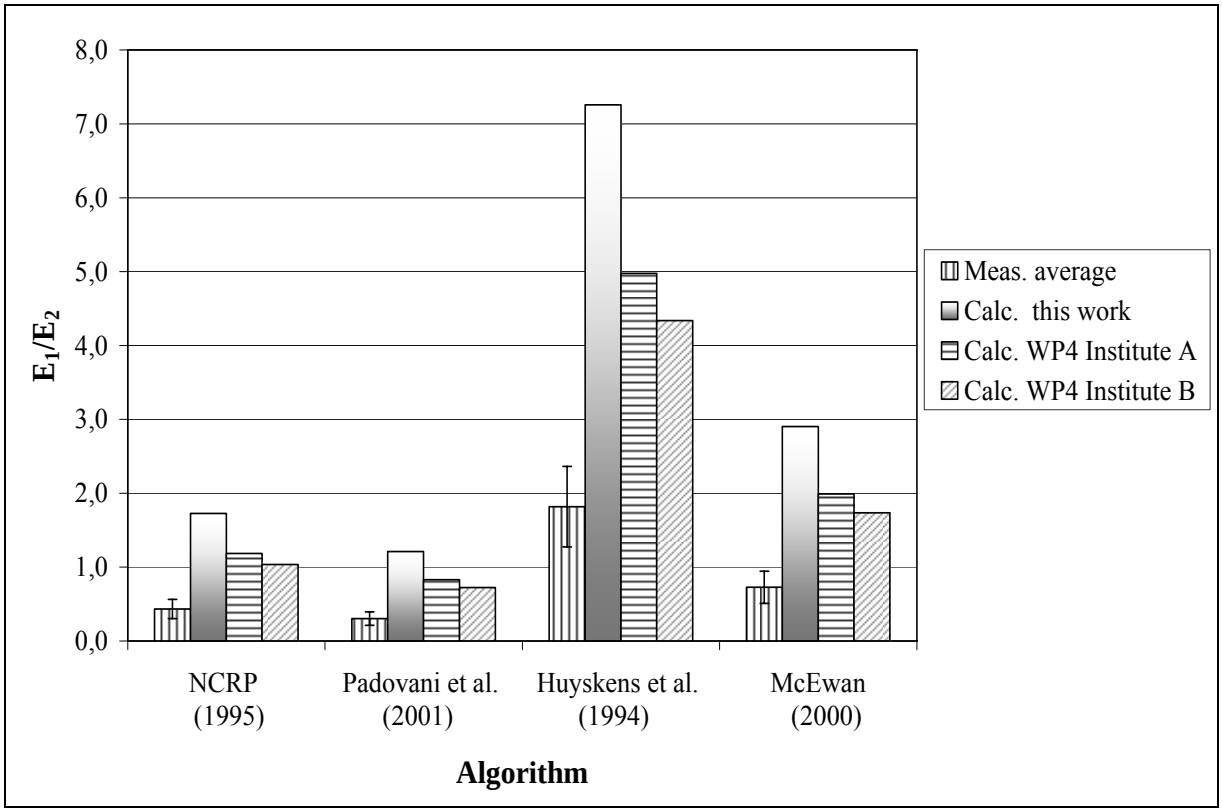

Figure 4. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from either measurement in RA phantom or from the MC calculations, for the various single dosimetry algorithms in the PA geometry of Fig. 3. The error bars in the measured values indicate the estimated average uncertainty of the ratio E_1/E_2 as one standard deviation.

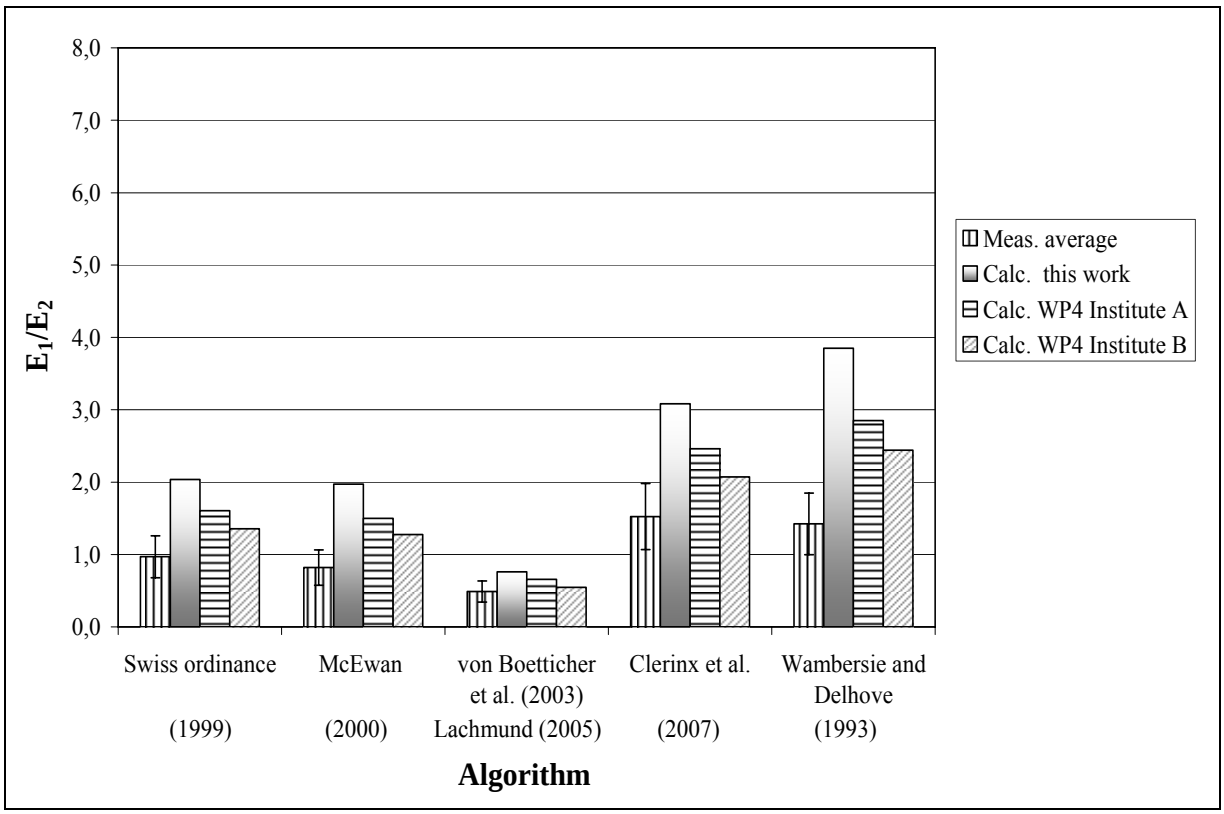

Figure5. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from either measurement in RA phantom or from the MC calculations, for the various double dosimetry algorithms in the PA geometry of Fig. 3. The value of H_u in the algorithms corresponds to dosemeter position on the chest. The error bars in the measured values indicate the estimated average uncertainty of the ratio E_1/E_2 as one standard deviation.

As an example of the results, the results for the dosemeter in the chest position are shown in Figures 4 and 5 (for the complete results, see Järvinen et al., 2008b). The reading of H_u in this case corresponds to dosemeter position on chest, while H_o is always specified on the neck in all the algorithms tested.

For the irradiation geometry studied, with the *single* dosimetry algorithms by NCRP (NCRP 1995) and Padovani et al. (2001) there is a risk to underestimate effective dose. The single dosimetry algorithm by Huyskens et al. (1994) is overly conservative and seems to overestimate effective dose by a factor of 2 to 7.

From the *double dosimetry* algorithms, that presented by von Boetticher et al. (2003) and Lachmund (2005) seems to underestimate effective dose in the irradiation geometry studied. The algorithms given by Wambersie and Delhove (1993) and Clerinx et al. (2007) seem to be on a rather conservative side and overestimate effective dose by a factor of about 2 to 3. From the double dosimetry algorithms tested, the algorithms given in the Swiss ordinance (1999) by McEwan (2000) seem to best meet the specified criteria.

From Figures 4 and 5 it can be seen that the uncertainties of the ratio E_1/E_2 can be rather high, mainly due to the high uncertainties of the measured values of H_u and E_2. Therefore, the above conclusions on the performance of the algorithms must be considered with caution. Further, as shown in Section 5.2 (for more details, see also Järvinen et al., 2008a), the ratio E_1/E_2 can depend highly on the irradiation geometry, so the results cannot be generalized to all irradiation conditions. For example, the algorithm by von Boetticher et al. (2003) and Lachmund (2005) has been reported to overestimate effective dose by a factor 1,1 to 1,82 instead of the underestimation obtained in this study (von Boeticher et al., 2007).

The amount of overestimation by the double and single dosimetry algorithms and the conclusion on its dependence on the irradiation geometry are roughly consistent with an earlier study by Schulz and Zoetelief (2006). For double dosimetry algorithms in a PA geometry, this study has suggested typically an overestimation by a factor of 2 to 5 for many of the algorithms.

5. CONCLUSIONS

There might not be just one double dosimetry algorithm which would be the optimum for all possible IR conditions. However, the selection of different algorithms for different conditions is not possible in practical personnel dosimetry and compromises must be made.

The algorithms to calculate effective dose from double dosemeter readings seem most generally to overestimate the effective dose. In some typical irradiation conditions of interventional radiology, however, there is also a risk of underestimating the effective dose by the least conservative algorithms. Two of the algorithms tested in this work seem to comply closely with the chosen criteria of performance, i.e. no underestimation, minimum overestimation and the close estimation of effective dose in the typical IR conditions. However, it might not be justified to generalize the results. It is recommended that whenever the personnel doses approach or exceed the dose limit, the IR conditions should be further investigated and the possibility of over- or underestimation of effective dose by the algorithm used should be considered e.g. by comparing the calculation with a few other algorithms.

VI. Recommendations for occupational dosimetry in interventional radiology

Based on all the findings and the conclusion from this study, the following recommendations for occupational dosimetry in interventional radiology are proposed.

1. GENERAL

- Personnel dosimetry, instead of group or site dosimetry, should be used for occupationally exposed workers.
- Personnel dosimeters should be used on a regular basis and in the recommended positions, consistent with the algorithms used for the calculation of effective dose.
- Use of lead apron and other personal protective devices like thyroid shields is essential for meaningful personal dosimetry.
- Whenever the dosemeter reading is higher than 1/3 of the dose limit, or significantly higher than values usually obtained in the local practices, the reasons for the doses should be investigated. The investigations should include individual interviews of workers exposed.

2. DD VERSUS SD

- Double dosimetry (DD) is generally recommended, because no single dosimeter can monitor effective dose accurately for all interventional radiology conditions. Single dosimetry (SD) algorithms are more prone than DD algorithms to underestimate effective dose in certain interventional radiology conditions.

3. DD ALGORITHM

- *General design/selection criteria of an algorithm:* Underestimation of effective dose shall be avoided, while the overestimation of effective dose should be kept to a minimum, and a close estimation of effective dose should be obtained at the combination most frequently encountered in local clinical practices.
- No algorithm can be optimum for *all* interventional radiology procedures. The assessment of effective dose by the algorithm is affected by:
    - Image parameters (x-ray tube voltage etc)
    - Geometry
    - Protection devices, in particular lead apron thickness and type, use of thyroid shield
    - Dosimeter type
    - The gender and size of the radiologist and the patient
- *The selection of a precise algorithm*, based on the selected imaging parameters, geometry and shielding used, for each exposed worker *is impractical*, in particular as these can vary in the course of the interventional radiology procedures. Therefore, compromises need to be made.
- For accurate personnel dosimetry, the accuracy of the selected algorithm *should be tested for typical local interventional radiology condition.* Detailed description of the technique and clear definition of all associated parameters need to be made. The methods used in this study (Section 5) can be applied. If the local procedures are limited to a certain type, then an optimum algorithm may be selected.
- The raw data of dosimeters should be retained for possible later re-estimation of effective doses and of doses to unprotected parts of the body.

4. POSITION OF THE DOSEMETER

- The dosimeter above the apron should be on a collar. The over apron dose should be used to assess the risk of lens injuries. There is a linear relationship between the $H_p(10)$ measured on a collar and the eye dose.
- The dosimeter under the apron can be on the chest or waist level, but *the position of the dosimeters must be consistent with the algorithm used.*

- When using a single dosimeter, *over apron* measurements are recommended. For under apron measurements, the errors of effective dose assessments tend to be larger because of the low signal, and the under apron measurement gives no indication on the eye dose.

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EURADOS CONRAD WP7/SG 3-4

The Evaluation of Active Personal Dosemeters in Interventional Radiology

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I. INTRODUCTION

The evaluation of active personal dosemeters (APDs) in interventional radiology was performed by work package 7 (Radiation protection dosimetry of medical staff) of the CONRAD project, which is a Coordination Action supported by the European Commission within its 6th Framework Program. The subgroup 3 of this work package was in charge of the APD intercomparison on reference facilities and the subgroup 4 of calculations related to this work.

APDs are used for the monitoring of occupational doses in many applications of ionising radiation. In interventional radiology, the possibility to assess the dose in real time is particularly interesting since operators can receive relatively high doses while standing close to the primary radiation field and being exposed to radiation scattered by the patient. For the adequate dosimetry of these scattered photons, APDs should be able to respond to low-energy (10-100 keV) and pulsed radiation with relatively high instantaneous dose rates. Unfortunately, the current APDs are not always adequate. This problem was clearly highlighted during an international intercomparison organised by EURADOS and IAEA (IAEA, 2007).

An evaluation of the behaviour of six APD models deemed suitable for application in interventional radiology was performed through an intercomparison. This intercomparison used pulsed and continuous X-ray beams produced by reference facilities. The reference dose equivalent $H_p(10)$ was derived from air kerma measurements and from measured and calculated energy distributions of the scattered radiation field. Additional Monte Carlo calculations were performed notably to determine the energy spectra of the different facilities.

The aim of the intercomparison was the identification of the APDs which provide a correct response when used in the specific low-energy spectra and dose rates of pulsed X-rays encountered in interventional radiology. The detailed outcomes of these investigations are presented hereafter, including the characteristics of the six selected APDs, a description of the irradiation facilities, the reference dose measurements and calculations. The discussion highlights notably the difficulties encountered in the determination of the calculated conversion coefficients $H_p(10)/K_a$.

II. MATERIAL AND METHODS

1. DESCRIPTION OF TESTED APDS

Selection of APD models was based on the results from a previous intercomparison organized in 2005 by EURADOS and IAEA (IAEA, 2007), and on the available data from different European countries. A pre-requisite for consideration was that each unit should respond to photon energies down to 20 keV. Six APDs were finally selected for the study (figure 1): DMC 2000XB (MGPi), EPD Mk2.3 (Siemens), EDM III (Dosilab), PM1621A (Polimaster), DIS1 (Rados) and DIS100 (Rados). These last two APDs are based on the same detector, the main difference lies in the fact that DIS100 has an integrated reader.

Data provided by the manufacturers on the energy response of these APDs are reported in table 1. Each dosemeter was controlled against a reference ^{137}Cs-beam for a few hundred of µSv (table 2). Responses were around unity within 4%, except for RADOS DIS-100 which under-responded by 7%. All dosemeters fulfil the IEC 61526:2 (IEC, 2005) requirement that all ^{137}Cs responses should be around unity within 10%. Two dosemeters of each type were tested, except for the DIS-100 of which we had only one unit.

Figure 1. Tested APDs.

Table 1. Photon energy response characteristics of tested APDs as provided by the manufacturers; E_{min} and E_{max} refer to minimum and maximum energy limits.

APD type and manufacturer	Energy range		Deviation (%)
	E_{min} (keV)	E_{max} (keV)	
DMC 2000XB – MGPi	20	6000	30
EPD Mk2.3 – Siemens	15	7000	20
EDM III – Dosilab	20	1500	10
PM1621A - Polimaster	10	20000	15
DIS1 – Rados	15	9000	30
DIS100 – Rados	15	9000	30

Table 2. Responses of all APDs against a reference ^{137}Cs beam

Type	Number	Response
EPD Mk 2.3	70389	1.018
	70386	1.018
COMET EDM III	2710977	1.030
	2710416	1.012
MGP DMC 2000XB	374740	1.032
	374703	1.036
PM1621 A	62002	0.980
	61983	0.982
RADOS DIS 100	220016	0.924
RADOS DIS 1	20408613	0.920
	20408532	0.920

2. DESIGN OF A REALISTIC CALIBRATION FIELD FOR DIAGNOSTIC RADIOLOGY

The concept of realistic radiation fields was extrapolated from previous studies on neutron fields (Chartier et al., 1995; Thomas et al., 1997; ISO, 2007a) to photon fields to reproduce the exposure conditions of medical staff during interventional procedures. This work was done in close collaboration with the WP4 of CONRAD (WG6 of EURADOS) dealing with computational dosimetry to share the calculations required for studying such a new calibration facility.

In interventional radiology the X-ray tube is most of the time located under the patient and the cardiologist stands at his side, often at the level of the hip. Thus, the surgeon is exposed to the radiation scattered by the patient. Sometimes, collective protection equipments (e.g. suspended screens, curtains) are available and can be used to protect the surgeons from the radiation scattered by the medical equipment. The image intensifier is located symmetrically to the X-ray generator with respect to the patient (figure 2).

The X-ray generator delivers pulsed radiation through a square collimator. For the intercomparison, the following parameters for the radiation characteristics were chosen: peak tube voltage = 70 kVp, tube current = 640 mA, pulse duration 100 ms, filtration = 4.5 mm Al + 0.2 mm Cu and size of the field = 17x17 cm² at the entrance of the image intensifier. The distances between the different equipment and the persons were taken from information gathered from the practitioners.

The idea was to propose an irradiation assembly which could be set up easily in any primary or secondary calibration laboratory. From a real workplace situation few simplifications were introduced. First, since it was found that the image intensifier and the patient table do not contribute significantly to the scattered radiation field at the surgeon level, they were not included; however the attenuation of the table was included in the total filtration considered. Secondly, the patient was replaced by an ISO water slab phantom (ISO, 1999). Other material as lung tissue equivalent material could also have been used (Bordy et al., 2008). The surgeon was represented by an ISO slab phantom on which the dosemeters were calibrated. Figure 3 shows a scheme of the facility. It can be seen that the surgeon-phantom was shifted from the level of the hip of the patient to the side face of the patient-phantom. Calculations showed that the energy distributions at both locations are similar (figure 4) but the total fluence is multiplied by a factor of 36 when moving the calibration point (Bordy et al., 2008). Figure 4 also shows that using a Rando Alderson phantom (Alderson Research Laboratories, Stanford, CT, USA) for the patient instead of an ISO water slab phantom does not change significantly the shape of the scattered spectrum.

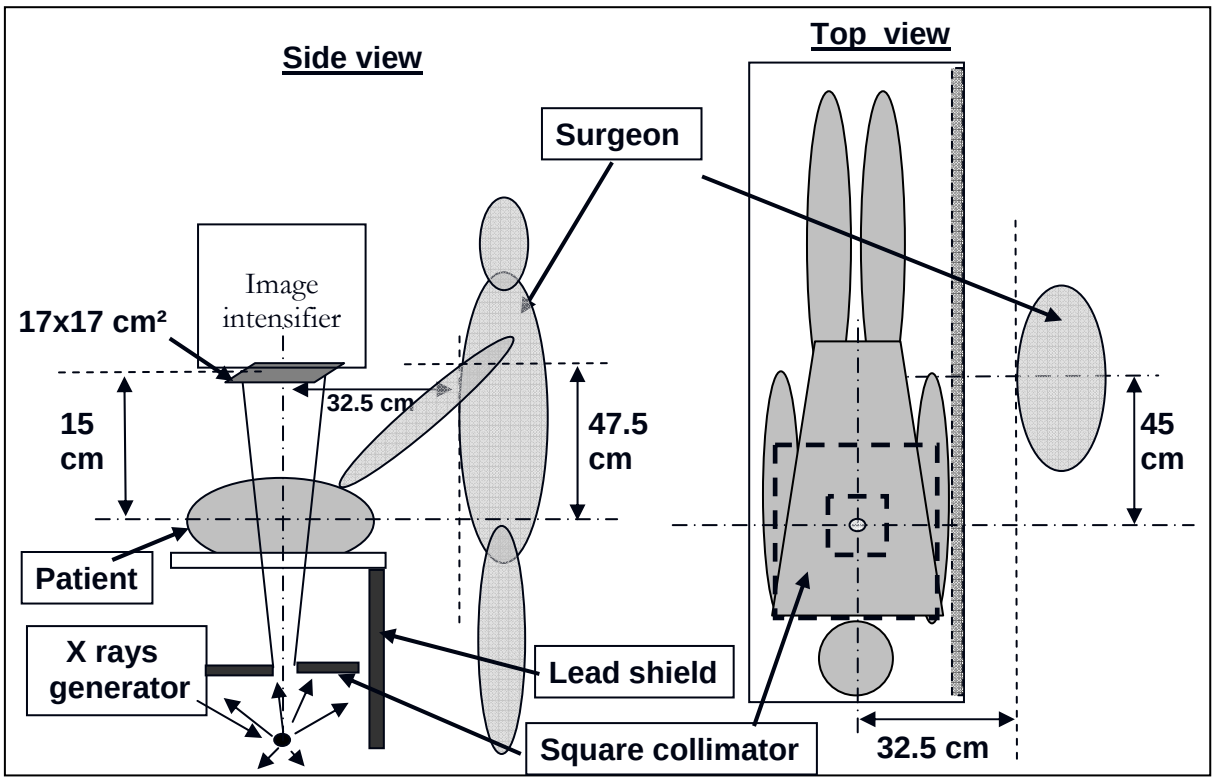

Figure 2. Side and top views of the workplace configuration.

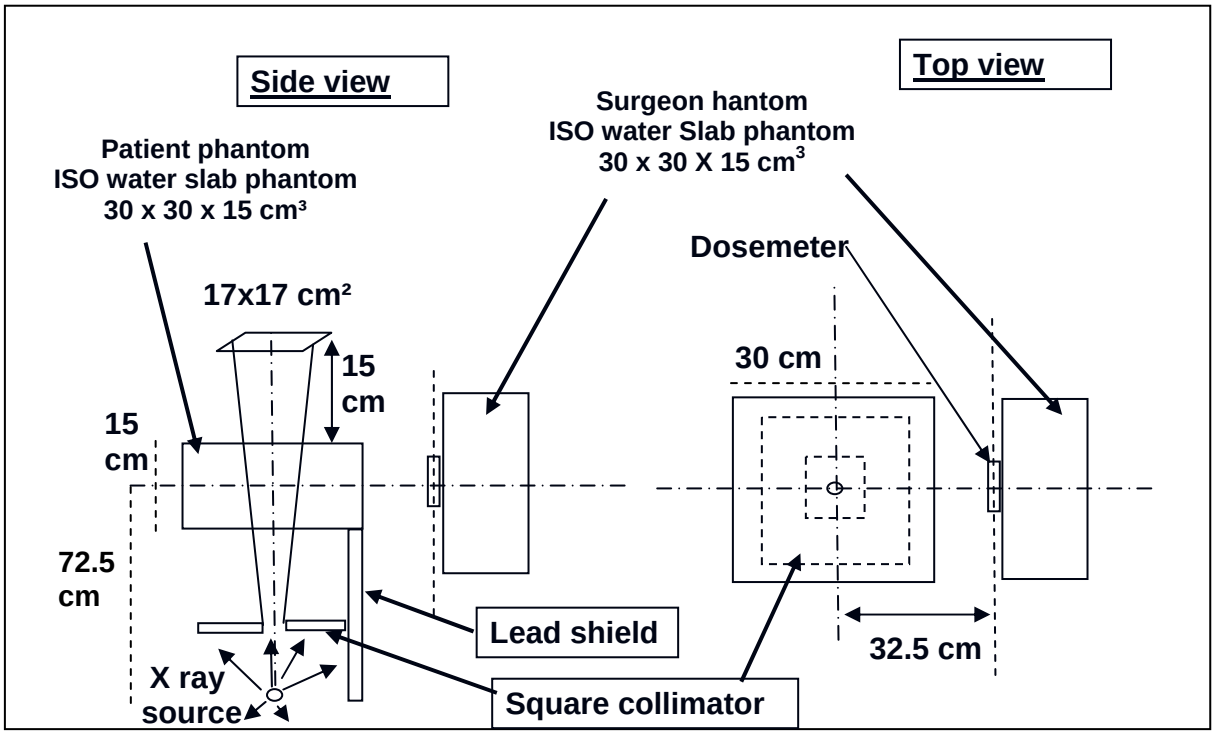

Figure 3. Top and side view of the simplified configuration for calibration purposes.

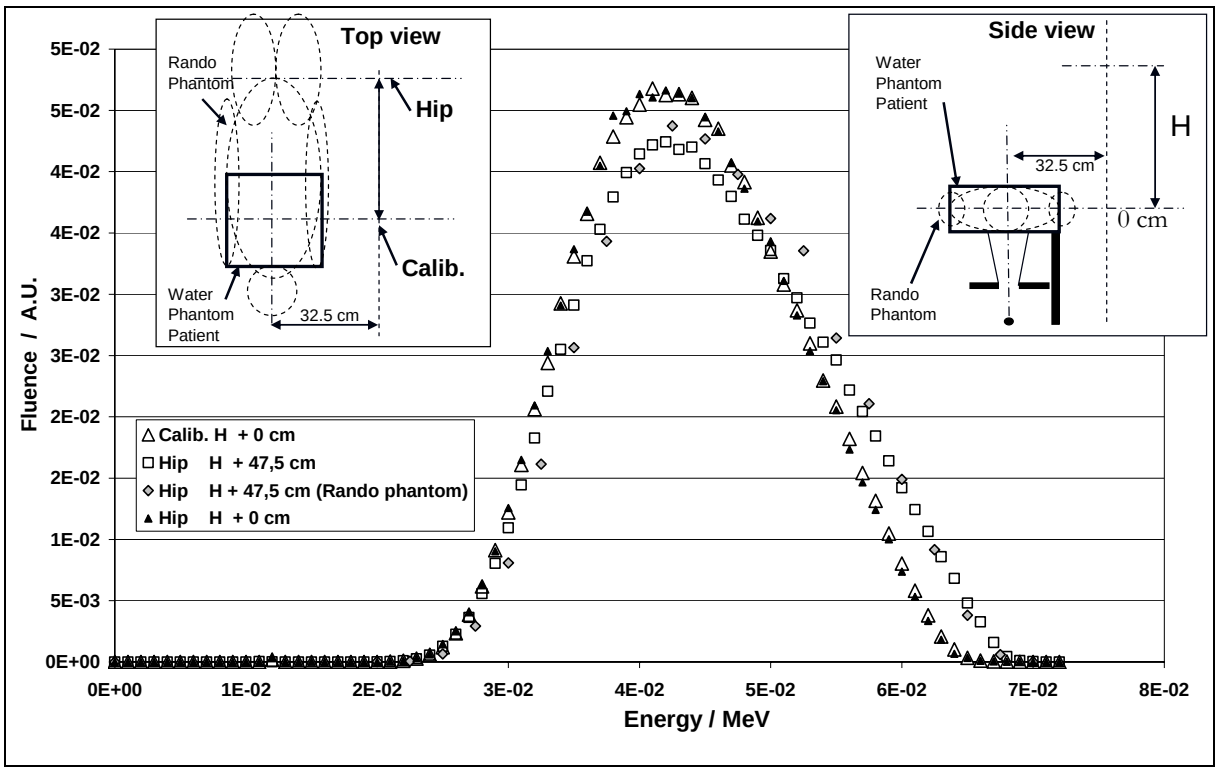

Figure 4. Comparison of the spectra calculated at different locations around the patient phantom (ISO water slab or Rando Alderson phantom)

As pointed out in ISO standard 12789-2 (ISO, 2007b) for realistic neutron radiation fields, the surgeon-phantom shall not induce disturbance of the radiation field during calibration. In our case, such an effect is liable to arise from multiple photon scattering between the patient and surgeon phantoms; the closer the phantoms, the higher multiple scattering. Despite the small distance (17.5 cm) between the phantom faces in the configuration studied for this new calibration facility, the multiple scattering was found negligible (increase of the photon fluence of 0.03% at the calibration point).

3. DESCRIPTION OF THE FACILITIES AND INTERCOMPARISON CONFIGURATION

The intercomparison used pulsed and continuous X-ray beams, available respectively at the Laboratoire National Henri Becquerel (LNHB) at CEA-LIST, the French National Metrology Laboratory for ionizing radiation in Saclay, and at a metrology laboratory of the Institute of Radiological Protection and Nuclear Safety (IRSN) in Fontenay-aux-Roses. Both laboratories are accredited according to the ISO standard 17025 (ISO, 2005).

The diagnostic pulsed X-ray beam was generated with a MPH65 (GEMS) medical X-ray unit designed to generate only one pulse at a time. The continuous X-ray beam was generated with a 100 kV (Philips) X-ray unit.

A configuration close to clinical practice was considered. In table 3, all beam parameters are summarized. Same tube voltage (70 kV) and total filtration (4.5 mm Al + 0.2 mm Cu) were used. Because collimation devices did not have the same geometry (circular and square for continuous and pulsed facilities, respectively), the collimator openings were chosen such as the areas of both (non-scattered) beam cross sections were the same (around 290 cm² at 95 cm from the source). For the pulsed facility, the minimum possible pulse width of 100 ms was used. Tube currents were chosen such as, given the reference dose at the detection point, irradiations lasted a reasonable amount of time (less than one hour for each dosemeter). It should be noticed that 640 mA used for the pulsed installation corresponded to the maximum current sustainable by its tube. For the continuous beam, a tube current of 20 mA was used. Both installations have different anode angles; the influence of this angle on the X-ray spectrum is very small, as shown in figure 5.

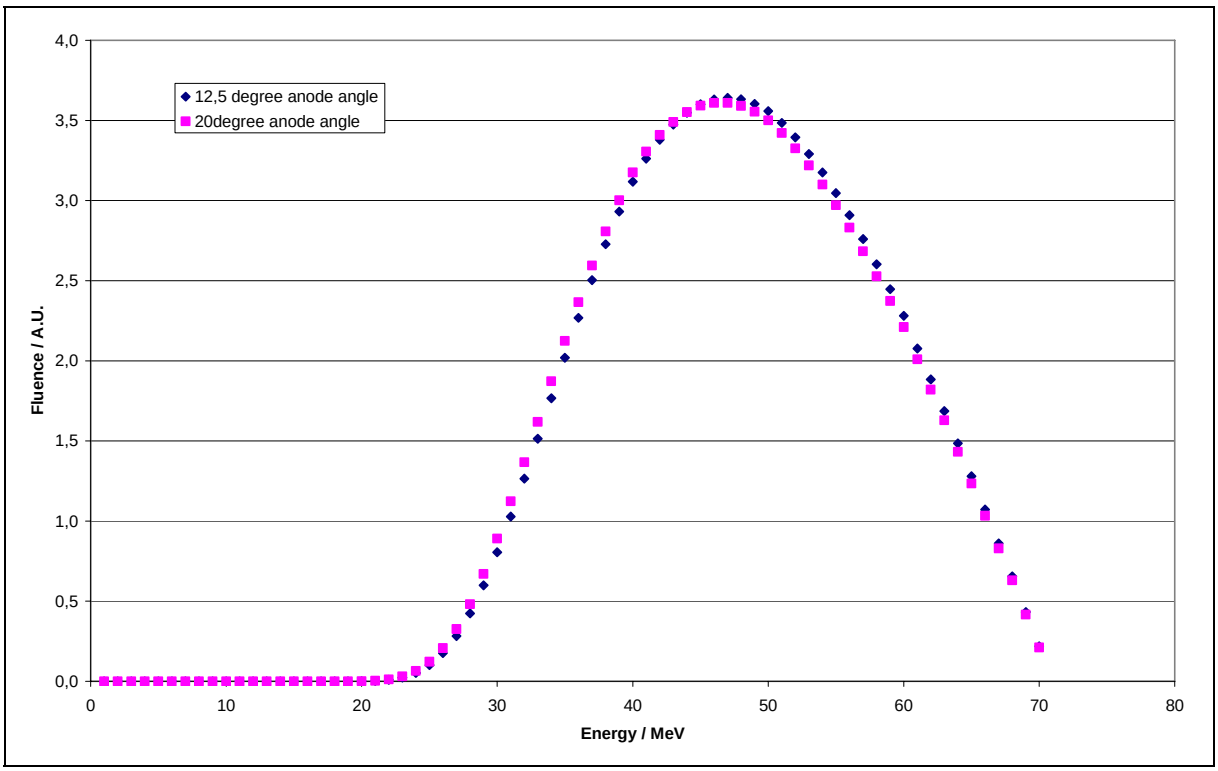

Figure 5. Calculated energy spectra for 12.5° and 20° anode angles corresponding to pulsed and continuous X-ray tubes, respectively.

The ISO water slab phantom with PMMA walls (30×30×15 cm^3; front PMMA wall 2.5 mm thick, other walls 10 mm thick), as defined in ISO standard 4037-3 (ISO, 1999), was used to simulate photon scattering by the patient (a cross section of the geometry is shown in Figure 3). An ISO water slab phantom was also used for the calibration of the dosemeters. The patient phantom's front wall was positioned at 65 cm from the source. APDs were irradiated one by one at the centre of the radiologist phantom's front wall. The centre of the radiologist phantom was positioned at the same level as the centre of the patient phantom (72.5 cm from the source). The centre of the tested APD was shifted by 32.5 cm in the normal direction with respect to the beam axis. A lead shield was used to remove X-ray components produced through scattering in the tube housing and irradiating the radiologist phantom and the dosemeter. Without the shield, this scatter component appeared to increase the dose rate by more than 30% at the dosemeter position and it was shown (see later on in this report) that it was due to scattering in the filters.

For practical reasons, irradiations were carried out with the beam axis oriented in the horizontal plane (figure 6).

Table 3. Beam parameters used for the intercomparison.

	Continuous field	Pulsed field
Tube voltage (kVp)	70	
Total filtration	4.5 mm Al + 0.2 mm Cu	
Tube current (mA)	20	640
Pulse width (ms)	-	100
Field shape	circular	square
Field size at 95 cm from source (cm)	diameter = 19.3	edge = 17
Angle of tungsten anode (°)	20	12.5

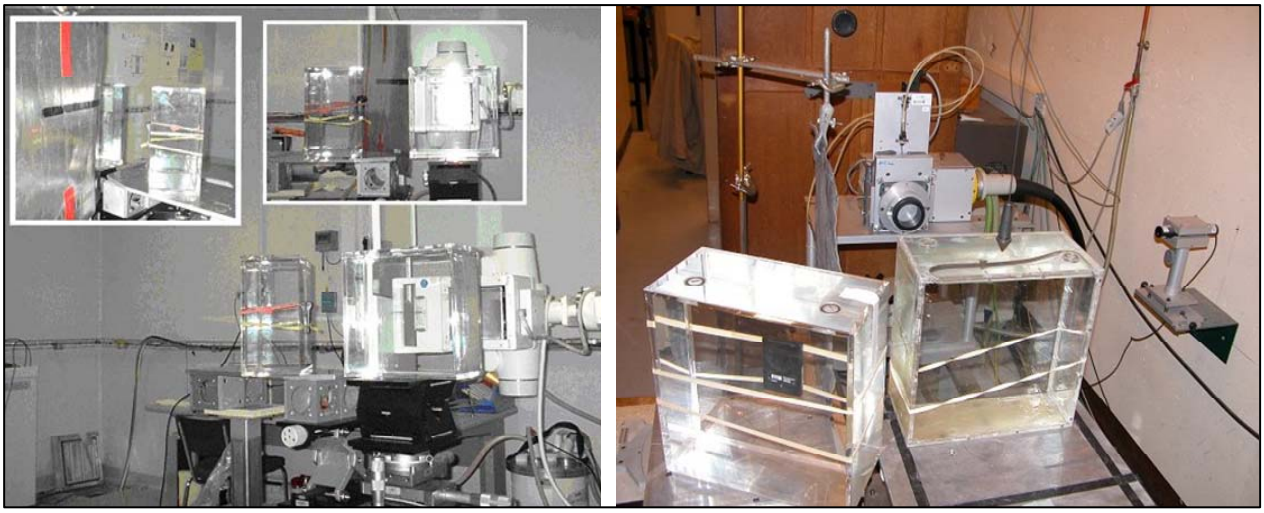

Figure 6. Experimental set up using the pulsed X-ray facility (left)
and the continuous X-ray facility (right).

4. REFERENCE QUANTITIES

It was necessary to determine a reference value in terms of $H_p(10)$ in the scattered beam at the position of the APD. The different steps for achieving this goal are

1. measurement of K_a in the primary beam using a free air chamber;
2. calibration of a transfer cavity ionization chamber at the same position;
3. measurement of K_a with the calibrated cavity chamber at the point of test in the scattered beam;
4. determination of the conversion coefficient from K_a to $H_p(10)$;
5. determination of the reference $H_p(10)$ at the point of test multiplying the measured K_a by the conversion coefficient.

Steps 1 to 3 are K_a measurements therefore all phantoms are removed for steps 1 and 2, only the patient phantom is kept for step 3.

4.1. DETERMINATION OF K_A IN THE PRIMARY BEAM.

For these measurements, the free air ionization chamber MD03 was used at CEA-LIST (LNHB) (Denozière and Peudon, 2004) and SDOS 98 at IRSN (Itié and Debroas, 2007). K_a was measured at 65 cm from the source (defined as point 0), where for the intercomparison the entrance of the patient phantom was positioned (figure 7).

For the MD03 chamber, the standard uncertainty associated to this measurement was 0.45 %.

For the SDOS 98 chamber, the statistical uncertainty associated with this measurement was due to the series of measurements (0.3 %), its calibration coefficient (0.8 %), the positioning and the environmental conditions (temperature, pressure). This led to an overall uncertainty of 0.9 % (k = 1) on K_a.

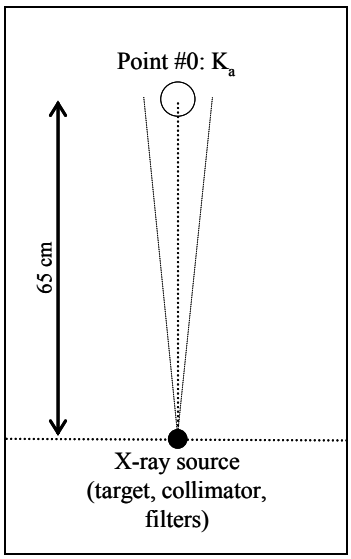

Figure 7. Geometry used for the calibration of the ionization chambers in terms of K_a in the primary beam

4.2. DETERMINATION OF THE CALIBRATION OF THE CAVITY IONIZATION CHAMBER

The cavity ionization chamber used was a 30 cm^3 PTW Type 23361. This chamber has been calibrated in the primary beam by direct comparison with the free air ionization chamber (see 4.1). This resulted in a calibration factor for this specific radiation quality.

With the tube parameters listed in table 3, the K_a rates at point 0 were 2.16 $Gy.h^{-1}$ and 1.51 $mGy.pulse^{-1}$ for the continuous and pulsed fields, respectively. The uncertainties on these values, estimated for the transfer ionization chamber in a similar way than in paragraph 4.1, were 0.95 % and 1.2 % (k = 1) for the continuous and pulsed fields, respectively. Taking into account the uncertainty on the positioning, the temperature, the pressure, etc. the standard uncertainty on the calibration coefficient was found equal to 1.39 %.

4.3. MEASUREMENT OF K_A AND CALCULATION OF ENERGY DISTRIBUTION AT THE POINT OF TEST

The K_a value was measured at the position chosen to test the APDs (point 3, figure 8). At this point, the K_a rates were found equal to 3.03 $mGy.h^{-1}$ and 3.20 $\mu Gy.pulse^{-1}$ for the continuous and pulsed installations, respectively.

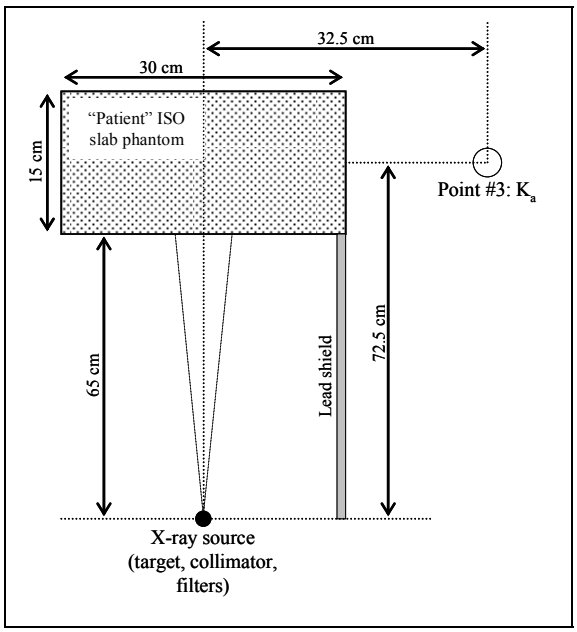

Figure 8. Geometry used for the measurements of K_a at point 3.

The energy distributions in the scattered field at point 3 were calculated. The initial photon spectrum of the X-ray generator was calculated using the software XCOMP5 (Nowotny and Hofer, 1985). The validation of the Monte Carlo calculations was done by measuring and calculating the energy distribution with a CdTe spectrometer. Figure 9 shows the results for the pulsed configuration. It can be observed that a good agreement between measurements and calculations is achieved when the spectrometer and its collimator are included in the calculations. Indeed, the low energy tail is due to photon escape from the spectrometer. A similar agreement was observed for the continuous installation.

The relative response of the ionization chamber within the energy range considered was measured in the pulsed radiation fields for RQR (Radiation qualities in radiation beams, IEC, 2005a) qualities 4, 7 and 9, the results are given in table 4. The radiation qualities at the point of calibration and in the direct beam are between RQR 4 and 7. So, assuming a flat density probability distribution of the response RQR 4 and RQR 7 cases, a $1.3\%/2\sqrt{3} = 0.38\ \%$ (k = 1) uncertainty was added to the uncertainty budget for the pulsed installation, and a similar additional contribution was assumed in the continuous case.

Table 4. Relative response of the 30cc PTW cavity ion chamber in the direct radiation field.

	kV	Relative response (normalised to RQR 9)	Standard uncertainty (%) (k=1)
RQR 4	60	1.021	1.2
RQR 7	90	1.008	1.2
RQR 9	120	1.000	1.2

The overall uncertainties on the K_a, were thus estimated to 1.2 % and 1.0 % (k = 1) for the continuous and pulsed installations, respectively.

Table 5 summarizes the K_a values and uncertainties used for the experiments at points 0 and 3.

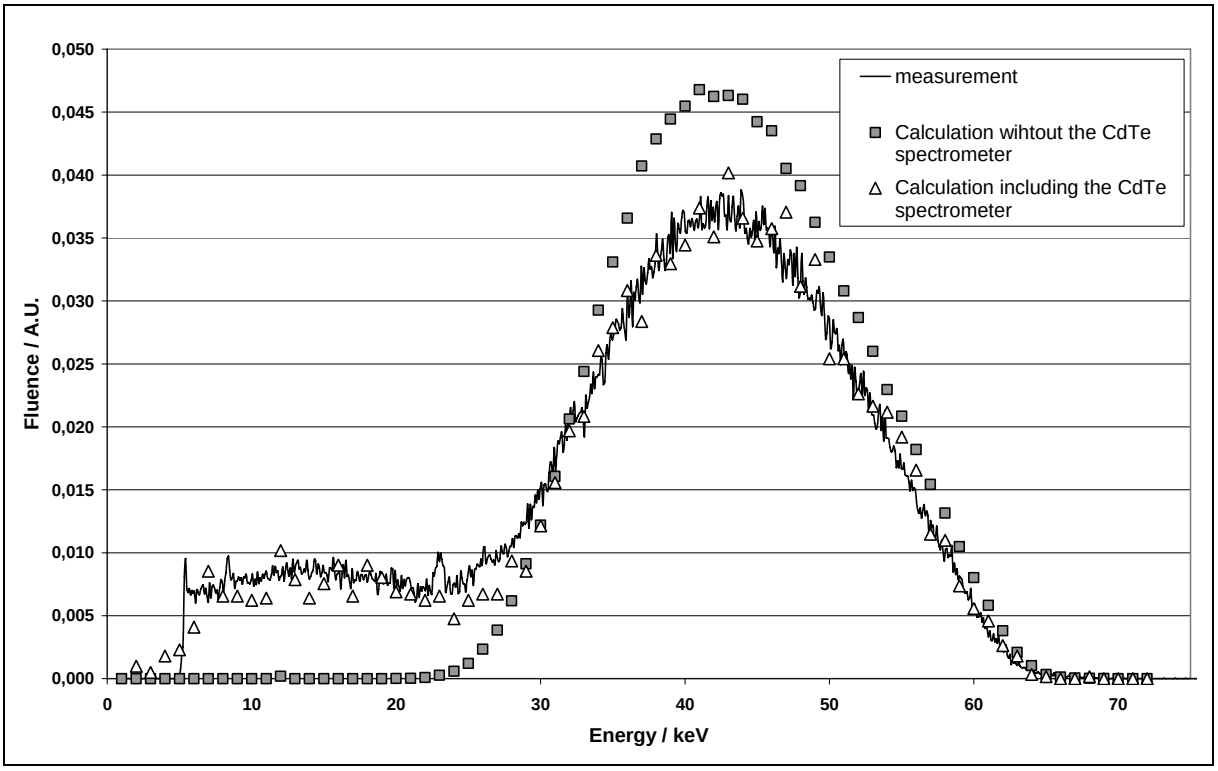

Figure 9. Measurement and calculation of the energy pulse height distribution in the scattered field at the point of test.

Table 5. Reference K_a rates at points 0 and 3 used for the experiments and integrated K_a at point 3 (for irradiations corresponding to 178 s and 25 pulses for the continuous and pulsed installations, respectively).

Facility	Point 0 (Figure 7)		Point 3 (Figure 8)			
	K_a rate	Uncertainty (%) (k=1)	K_a rate	K_a	Irradiation duration	Uncertainty (%) (k=1)
Continuous	2.16 Gy.h^{-1}	1.0	3.03 mGy.h^{-1}	150 µGy	178 s	1.2
Pulsed(*)	1.51 mGy.pulse^{-1}	0.7	3.20 µGy.pulse^{-1}	80 µGy	25 pulses	1.6

(*) Pulse duration: 100 ms

4.4. DETERMINATION OF THE CONVERSION COEFFICIENT FROM K_A TO $H_P(10)$

The published conversion coefficients from K_a to $H_p(10)$ (ICRU, 1998) are defined for parallel, expanded radiation fields, which is not representative for the considered energy and angular distributions in the scattered field used for this intercomparison. Thus, Monte Carlo calculations were performed for the determination of $H_p(10)/K_a$ for the specific scattered beam spectrum. Different codes were used: MCNP4C (Breismeister, 2000), MCNP5 (MCNP, 2003, revised 2004), MCNPX (MCNPX, 2005) and Penelope 2006 (Salvat et al., 2006).

First K_a was calculated in a 1 cm radius sphere filled with air centered at point 3 (figure 8) where the APDs were irradiated, in the absence of the radiologist phantom. Secondly, $H_p(10)$ was calculated at point 3 as the dose scored in a cell centered at this point and part of the 30x30x15 cm³ ICRU slab phantom (figure 10). Both scoring cell and ICRU slab phantom were made of 1 g.cm^{-3} ICRU soft tissue (ICRU, 1989) i.e. defined, in fraction by weight as H:10.1%; C:11.1%; N:2.6% and O:76.2%. The lead shield was introduced as well in the model, with 65 cm height and covering the whole patient phantom width (30 cm). It was defined as either a 2 mm thick lead cell or a photon killer cell (perfect shield i.e. with null importance for photons entering the shield). No significant effect on the results was observed between these two cases. The whole geometry was surrounded by 1.205 g.cm^{-3} dry air defined, in fraction by weight, as N:75.5%; O:23.2% and Ar:1.3% (ICRU, 1989).

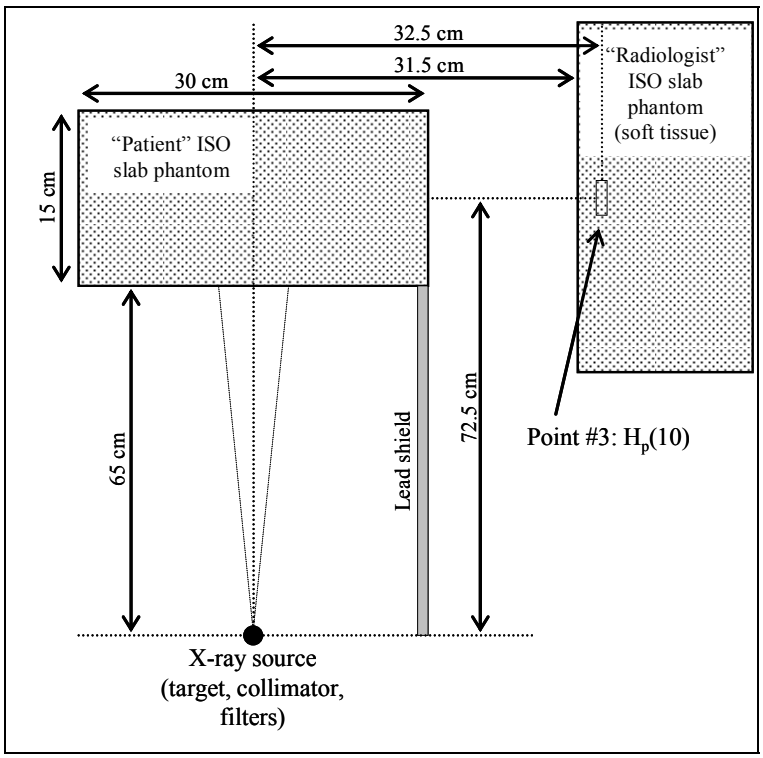

Figure10. Geometry used for the calculation of $H_p(10)$

The source filtered 70 kVp X-ray spectrum used in the Monte Carlo simulations was calculated with the deterministic software XCOMP-5 (Nowotny and Hofer, 1985), taking into account the filtration (4.5 mm Al + 0.2 mm Cu) and the different tungsten anode angles (20° and 12.5°). This means that filters were not explicitly introduced in the simulations. However, the XCOMP-5 filtered spectrum was checked against an MCNPX calculation (figure 11) in which the source unfiltered spectrum (calculated by XCOMP-5) was filtered by 4.5 mm Al and 0.2 mm Cu. It can be seen that the agreement is very good and that the source spectrum ranges from around 25 keV up to 70 keV. From this comparison it was also observed that less than 10% of the collimated source flux is transmitted through the filters.

From the source, considered as a point-like isotropic X-ray emitter, collimation was taken into account by restricting the emission angles to a cone with appropriate opening angle. In the instance of the pulsed installation, for which the collimator was a square, an additional perfect square collimator (null importance for photons) was defined.

All tricks previously mentioned (not explicitly defining filters and collimators), although strongly simplifying reality (see discussion later on in the text), allowed to greatly speed-up calculations.

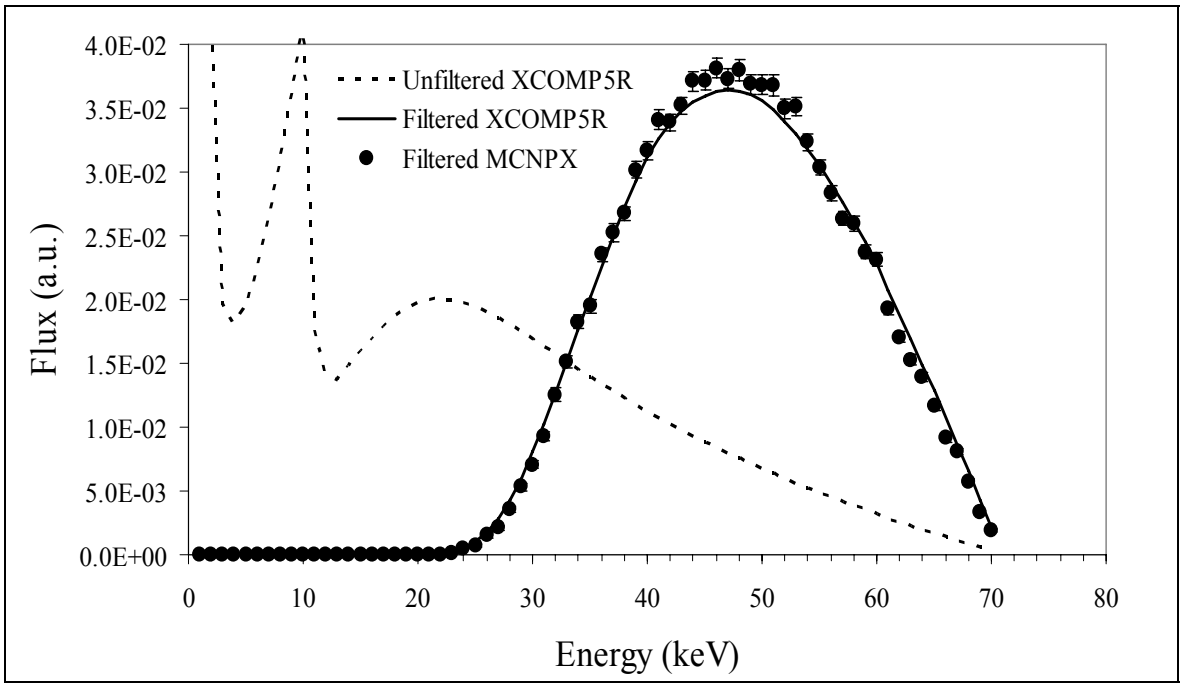

Figure 11. Unfiltered and filtered by 4.5 mm Al and 0.2 mm Cu 70 kVp X-ray spectra, on an arbitrary unit, calculated with XCOMP-5 (Nowotny and Hofer, 1985) for a tungsten anode with angle 20°; the filtered spectrum is compared to an MCNPX calculation with an unfiltered source spectrum, filtered by 4.5 mm Al and 0.2 mm Cu filters.

To describe photon transport, different libraries distributed with MCNP(X) were used: either MCPLIB02 (Hughes, 1996) or the most recent evaluations MCPLIB04 (White, 2002). Only photons were transported (kerma approximation: secondary electrons generated by photon interaction depose their energy locally), detailed photon physics treatment, as defined in MCNP4C manual, was considered and all photon physical processes taking place at these energies, i.e. fluorescence emission, photoelectric absorption, incoherent (Compton) and coherent (Thomson) scattering, were taken into account.

Dose was scored by different means, either by fluence tallies (F2, F4, F5 in MCNP) multiplied by appropriate ICRU conversion coefficients, or dose tally (F6 in MCNP), or energy deposition tally (*F8 in MCNP). For the fluence tallies, the dosimetric quantities (either K_a or $H_p(10)$, as appropriate) were calculated by folding the fluence with the conversion coefficient taken from ICRU report 57 (ICRU, 1998) according to the following equations:

$$K_{air} = \int_E \phi_E \left[\frac{K_{air}}{\phi} \right](E)\, dE \qquad H_{p,slab}(10,0) = \int_E \phi_E \left[\frac{H_{p,slab}(10)}{\phi} \right](E)\, dE$$

where the ratios K_a/ϕ and $H_{p,slab}(10)/\phi$ are the appropriate conversion coefficients.

4.5. DETERMINATION OF THE REFERENCE VALUE IN TERMS OF $H_P(10)$

To determine the reference $H_p(10)_{ref}$ value, $H_p(10)/K_a$ calculated as previously explained was multiplied by the reference value in terms of $K_{a,ref}$, measured as explained in 2.4.3, i.e.:

$$H_p(10)_{ref} = {H_p(10)}/{K_{air}} \times K_{air,ref}$$

For the continuous beam, the reference K_a at point 3 was 150 µGy after 178 s of irradiation and for the pulsed beam, the reference K_a at point 3 was 80 µGy after 25 pulses (table 5).

III. RESULTS

1. CALCULATED CONVERSION COEFFICIENTS FOR THE DETERMINATION OF THE REFERENCE QUANTITY

Three different laboratories performed calculations to define the appropriate conversion coefficient from K_a to $H_p(10)$ for the considered energy spectrum in the scattered field: CEA-LIST (LNHB), IRSN and SCK•CEN. In table 6, all calculation results are summarized.

Table 6. Summary of all calculation results of $H_p(10)/K_a$ for CEA-LIST, IRSN and SCK•CEN

X 10^{-6} (pGy/history or pSv/history)		K_a			$H_p(10)$			$H_p(10)/K_a$		
		F5	F6	*F8	F5	F6	*F8	F5	F6	*F8
CEA-LIST	MCNP4C - lib02p square field	4.64 (0.2%)	4.40 (0.3%)	4.42 (1.2%)	6.97 (0.2%)	6.31 (0.6%)	6.33 (3.0%)	1.50	1.43	1.43
	MCNP5 - lib04p square field	4.29 (0.2%)	4.38 (0.2%)	4.35 (0.7%)	6.44 (0.2%)	6.23 (0.4%)	6.16 (1.9%)	1.50	1.42	1.42
	Penelope2006 square field		4.87 (2.6%)			6.77 (0.5%)			1.39	
IRSN	MCNPx2.5f - lib04p circular field		4.83 (0.7%)			6.75 (0.5%)			1.40	
	MCNPx2.5f - lib04p square field		4.85 (0.7%)			6.80 (0.6%)			1.40	
SCK•CEN	MCNPx2.5.0 – lib04p square field	4.67 (0.04%)	4.93 (0.7%)	4.93 (1.0%)	7.06 (0.03%)	6.96 (0.6%)	6.91 (0.9%)	1.51	1.41	1.40

Note: conversion coefficients calculated with a tissue equivalent lung phantom for the patient are similar to those reported here (Bordy et al., 2008).

The conversion coefficient used in the APD intercomparison was obtained by averaging all results, excluding those obtained with the F5 tally. The value of 1.40 $Sv.Gy^{-1}$ was taken.

A study on the angular dependence of the scattered radiation was performed, calculating the spectra for different angles with respect to the normal axis of the radiologist-phantom and considering the $H_p(10, \alpha)/H_p(10, 0°)$ coefficients in ICRU Report 57 (ICRU, 1998). We could conclude, however, that this study changed the conversion coefficient $H_p(10)/K_a$ by less than 2%.

Taking into account both Monte Carlo statistical (type A) errors and scattering of the different results around the mean value, that accounts for type B errors, the uncertainty on the $H_p(10)/K_a$ conversion coefficient could be estimated to 1.2 % (k = 1). However, since all calculation results were obtained with similar and simplified models for the radiation source and the geometry, an additional type B uncertainty on the conversion coefficient was assumed, leading to a total relative uncertainty estimated to 3 % (k = 1).
Thus, the conversion coefficient was taken as:

$$\frac{H_p(10)}{K_{air}} = 1.40\ Sv.Gy^{-1} \pm 3\%$$

2. RESULTS OF THE APD INTERCOMPARISON

The responses of the APDs at 0° are presented in tables 7 and 8. Five dosemeters out of six were sensitive to the single pulse radiation used for this comparison. The PM1621A model did not respond to pulsed radiation at 0° and thus was not tested for 30° and 60°.

For photons, IEC 61526 standard (IEC, 2005b) requires a variation of the relative response in the range [0.71 – 1.67] for energies from 20 to 150 keV or from 80 keV to 1.5 MeV and for the angles 0° to 60°. As compared with the responses for ^{137}Cs presented in table 2 which were all measured close to unity within ± 7 %, from table 7 it can be observed that the DIS100 dosemeter did not fulfil this requirement at 0° (0.59 and 0.63 for continuous and pulsed radiation fields, respectively) and that the DIS1 was just below the inferior limit for the continuous beam (0.70). It shall be noticed that the relative response is analysed here for an energy range (from 45 keV on average to the ^{137}Cs energy of 662 keV) larger than that required by IEC (20 – 150 keV or 80 keV – 1.5 MeV). However, the manufacturers provide energy ranges for the tested APDs that cover the whole IEC range (table 1). Except for model PM1621A, a systematically larger response is observed for the pulsed field compared with the continuous one (13 % on average). Still for the pulsed radiation the DMC 2000XB response (1.25) is larger than that measured during the joint IAEA-EURADOS intercomparison (1.14; IAEA, 2007). It shall be mentioned that different radiation qualities were used in both comparisons: RQR4 (60 kVp) for the joint IAEA-EURADOS and 70 kV with 4.5 mm Al + 0.2 mm Cu for this one. The response of the EPD Mk2.3 still remains very close: 0.85 in this study compared to 0.82 in the IAEA comparison (2007).

Angular responses at 30° and 60° are given and compared in table 8 to those given in ISO 4037-3 (ISO, 1999) for the W-60 radiation quality. For 30° all responses are close to the expected W-60 value within ± 20 %. The same behaviour is seen for 60° except for model PM1621A. Surprisingly, which did not fulfilled the requirement of IEC 61526 at 0°, fulfils them for both angles 30° and 60°.
The observed standard deviations were in between 0.3 and 1.5% for a single APD (repeated irradiations) and less than or equal to 5% for two APDs of the same type, but one has to keep in mind that only two dosemeters of the same type were tested.

Table 7. Response of APDs in terms of $H_p(10, 0°)$

Mode	Reference $H_p(10)$	DMC 2000XB	EPD Mk2.3	EDMIII	PM1621A	DIS1	DIS100
Continuous	210 µSv	1.14	0.79	0.95	1.09	0.70	0.59
Pulsed	112 µSv	1.25	0.85	1.17	0.01	0.80	0.63

Table 8. Angular response of APDs in terms of $H_p(10, \ ) / H_p(10, 0°)$

Angle	W-60 (ISO 4037)(*)	Mode	DMC 2000XB	EPD Mk2.3	EDMIII	PM 1621A	DIS1	DIS100
30°	0.96	Continuous	1.00	0.98	1.10	0.93	0.92	1.00
		Pulsed	0.96	0.96	1.05	–	0.92	0.97
60°	0.76	Continuous	0.81	0.84	0.83	0.53	0.80	0.86
		Pulsed	0.65	0.71	0.66	–	0.76	0.74

(*) These values were taken from ISO 4037-3 (ISO, 1999) for quality W-60 which is similar to the spectra used for this study

IV. DISCUSSION

1. DIFFICULTIES IN DETERMINATION OF THE $H_P(10)/K_A$ CONVERSION COEFFICIENTS

The $H_p(10)/K_a$ conversion coefficient that we used for this intercomparison was 1.40 $Sv.Gy^{-1}$, i.e. a mean value between the estimates from the different codes using dose (Tally F6 in MCNP) or energy deposition (Tally *F8 in MCNP) tallies. It is interesting to notice that if K_a and $H_p(10)$ were calculated at point 3 through fluence spectrum (Tallies F2, F4 or F5 in MCNP) folded with the energy-dependent ICRU report 57 (ICRU, 1998) conversion coefficients at 0°, a value around 1.5 $Sv.Gy^{-1}$ was obtained, i.e. 7 % larger than 1.40 $Sv.Gy^{-1}$. This is due to the fact that ICRU hypotheses were not fulfilled for the investigated configuration, i.e. (1) the scattered X-ray beam incident on the radiologist-phantom was not parallel, though angular effects were shown to be small and (2) the radiologist-phantom was not homogeneously (and not completely) irradiated, thus leading to a reduced contribution of back-scattered photons. The latter point provides the principal explanation of the different conversion coefficients between the two calculation methods. Therefore, ICRU report 57 conversion coefficients should not be used in combination with the fluence spectra calculated for this study.

2. COMPARISON BETWEEN EXPERIMENTS AND CALCULATIONS

Next to calculations performed for the determination of the reference quantity $H_p(10)/K_a$ for the APD intercomparison, Monte Carlo calculations were also done in the framework of the CONRAD-WP4 working group on 'uncertainty assessment in computational dosimetry'. Different problems were defined and distributed to interested institutes. The medical staff dosimetry problem was divided into 2 parts. The first part represented the simplified geometry as used for the APD intercomparison and is described in part 2.3. In the second part of the problem a more representative clinical situation was selected for simulation. The purpose of this part was to derive uncertainties in the calculated effective dose to the cardiologist due to different laboratories translating a clinical practice into a numerical simulation. For the work of subgroup 3, we were interested in the results of the first part. The results of the second part were of concern for subgroup 2 (double dosimetry) of WP7 and is discussed in the final report of this subgroup. The results can also be found in the proceedings of the workshop organized by WP4 in Bologna in October 2007 (Bordy et al., 2008; Schultz et al., 2008; Struelens et al., 2008).

For the first part on the simplified geometry, five institutes sent in their solutions. The codes used for the calculations were MCNP4C (MCNP, 2000) for institutes B and C, MCNPX (MCNPX, 2005) for institutes A and D and Penelope 2006 (Salvat et al., 2006 for institute E. All calculation results were compared and differences were analyzed (Struelens et al., 2008). It was concluded that the differences in calculation results are mainly due to the use of different libraries. Fluence tallies (F2, F4 and F5 in MCNP(X) calculations) are sensitive to angular distributions of secondary particles. Each update to the photon libraries includes, not only adjustments to cross section values, but also angular distributions of secondary particles. Also the choice of fluence-to-air kerma conversion coefficients caused differences in calculated results. For uncharged ionizing radiation of energy E, the relationship between particle fluence ϕ and kerma K may be written as

$$K = \int \phi[E.(\mu_{tr}/\rho)]dE$$

with:
μ_{tr}/ρ the mass energy transfer coefficient
μ_{tr}/ρ equals μ_{en}/ρ for low-energy photons where μ_{en}/ρ is the mass energy absorption coefficient.
A comparison was also performed between the calculated results and the measurements carried out for the APD intercomparison. The scattered energy spectra at point 3 in air were measured in both installations (continuous and pulsed) with a CdTe XR-100T spectrometer (calibrated at CEA-LIST). These measured pulse height distributions could be compared to the calculated ones by some of the participating institutes in Figure 12. It can be observed that the spectra agree fairly well except for the experimental low energy tail due, as mentioned previously (see paragraph 4.3), to photon escape from the CdTe XR-100T spectrometer not taken into account in calculations presented in figure 12.

Rather than trying to compare the absolute results at point 3, because they depend on the absolute normalizations in each laboratory, it is more appropriate to compare the ratios of K_a at point 0 and point 3. Point 0 is located on the central beam axis at 65 cm from the source, without patient phantom (figure 7). In table 9, the results of the calculations are compared to the experimental data reported from table 5. The calculation results using a fluence tally in combination with the older library mcplib.02p are excluded.

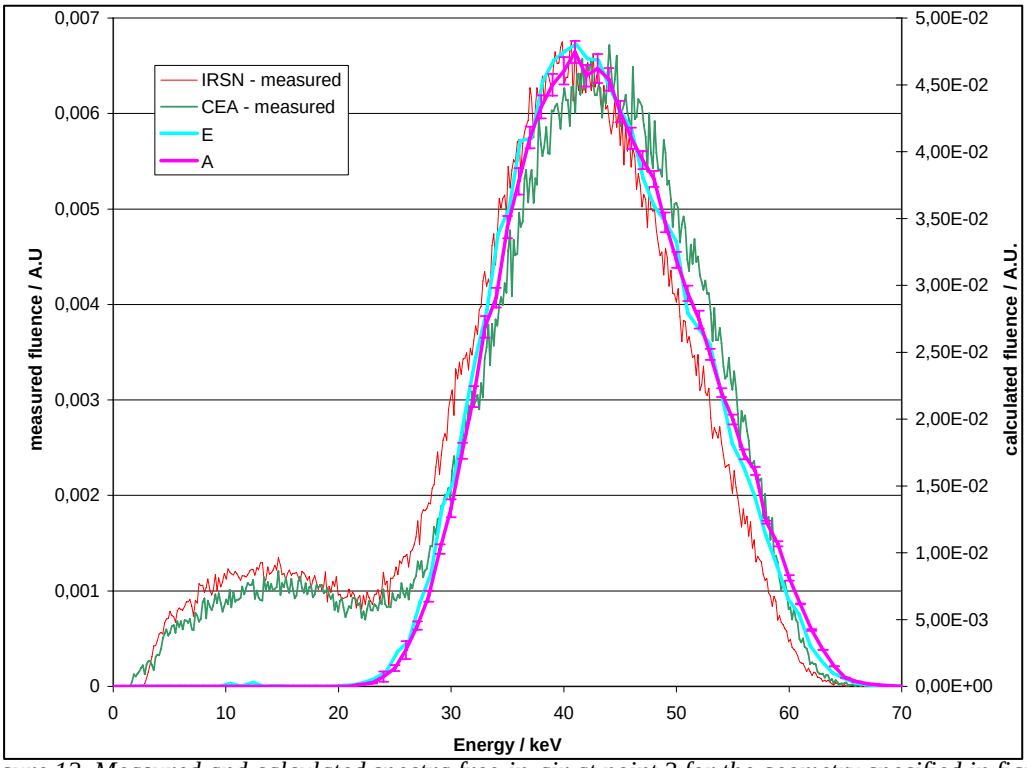

Figure 12. Measured and calculated spectra free-in-air at point 3 for the geometry specified in figure 8.

Table 9. Comparison of ratio of K_a at point 0 and point 3 between calculations and experiments.

	Institute	Code/Tally MCNP	point 0		point 3		ratio points 0/3	
			K_a (Gy.NPS^{-1})$^{(*)}$	rel. err. (%) (k=1)	K_a (Gy.NPS^{-1})$^{(*)}$	rel. err. (%) (k=1)	value	rel. err. (%) (k=1)
Calculations	A	F5	2.81E-15	0.001	4.75E-18	0.8	592	0.8
		F6			4.61E-18	1.9	609	1.9
		*F8			4.65E-18	2.4	604	2.4
	B	F6	2.85E-15	0.004	4.71E-18	2.1	605	2.1
		*F8			4.78E-18	3.5	597	3.5
	D	F2	2.67E-15	0.01	5.10E-18	3.3	524	3.3
		F4			5.14E-18	2.5	520	2.5
		F5			5.03E-18	1.5	531	1.5
	E	PENELOPE	4.57E-15		7.50E-18	2.7	609	2.7
	average		3.23E-15	0.003	5.14E-18	0.8	577	0.8
Experiments			point 0		point 3		ratio points 0/3	
			K_a (Gy.NPS^{-1})$^{(*)}$	rel. err. (%) (k=1)	K_a (Gy.NPS^{-1})$^{(*)}$	rel. err. (%) (k=1)	value	rel. err. (%) (k=1)
	Pulsed		1.51E-03	0.7	3.20E-06	1.0	472	1.2
	Continuous		2.16E+00	1.0	3.03E-03	1.2	713	1.6

(*) NPS = number of source particles

We can conclude that an overestimation of the ratios of 22 % and an underestimation of 19 % are observed for the calculations compared with pulsed and continuous data, respectively.

Another difference was observed between experiments and calculations. As mentioned before, in the experiments an additional lead shield was used to attenuate most of the scattered radiation produced in the filters. These filters are inserted after the collimation system. When calculations are performed with and without this lead shield, the K_a ratio without/with at point 3 is close to unity (1.06). However, when K_a at point 3 was measured with and without lead shield, a without/with ratio of 1.30 and 1.94 measured at the pulsed and continuous installations, respectively.

All these differences between both experimental facilities (collimator shape, position of the lead shield) and between measurements and calculations led us assume that some of the experimental conditions are not well reproduced in the calculation models.

When the filtration is explicitly taken into account in the calculation model, starting from an unfiltered spectrum, filtered in the model by 4.5 mm Al + 0.2 mm Cu (see figure 11), a K_a ratio without/with lead shield at point 3 is found to be 2.45 (for the continuous installation), which is closer to the measurements.

It was also observed that there was a difference in position of the lead shield between both installations, but it was investigated that this factor could not have an impact larger than 5 % on the resulted measurements.

To complete the investigation of the differences between both experimental installations and between experiments and calculations, the sensitivity of the results with respect to the knowledge we have about the X-ray tube have been investigated. First, the distance between source and beam collimator was changed. According to the collimator geometry (thickness = 0.6 cm), the opening angle of the continuous beam is 5.8° (field diameter = 19.3 cm at z = 95 cm). If the collimator would be 0.6 cm closer or further away from the source, the opening angle would then be 6.4° (diameter = 21.3 cm at z = 95 cm) or 5.3° (17.6 cm at 95 cm), respectively. This results in a change of the K_a ratio between point 0 and point 3 varying from 398 to 636, respectively.

Secondly, the influence of the position of the source with respect to the beam-axis was investigated. Changing the source by 0.1 cm and 0.2 cm off-beam axis in the direction of point 3, resulted in the K_a ratio between point 0 and point 3 of 621 and 771, respectively, with K_a at point 0 almost insensitive to this change.

This sensitivity study showed that the K_a ratio between point 0 and point 3 is very sensitive to a change in the distance source-collimator, and in the position of the source spot on the target of the X-ray tube. Although this effect was not investigated, it is expected that the size of the source has also a large effect on the K_a rate at point 3, with almost no effect on the rate at point 0. Hence, it was concluded that the observed differences between both installations and between experiments and calculations come from the lack of knowledge of the exact geometry of the X-ray tubes and that the simulation models of the X-ray tubes are too simple.

V. CONCLUSIONS, RECOMMENDATIONS AND PROPOSED DEDICATED STUDIES

Active personal dosemeters measure dose equivalents and dose equivalent rates in real time and provide adjustable audible alarms. They are efficient tools to help reducing doses by optimising practices as well as collective and individual protection. They are of particular interest in situations with possible high doses and/or dose rates as in the medical field. During interventional procedures the staff is standing close to the primary X-ray radiation field and is exposed to radiation scattered by the patient. In these situations, APDs should accurately respond to low energy (10-100 keV) and pulsed photon fields.

An intercomparison of selected APDs was carried out in continuous and pulsed radiation fields similar to the field characteristics met at interventional medical workplaces.

Quite large discrepancies (up to 14 %) were found between two dosemeters of one specific type. This emphasises the necessity to check the dosemeter calibration at reception.

The intercomparison also showed that five dosemeters out of six were sensitive to the single-pulsed radiation used for this comparison. Moreover, the capability of measuring the pulsed radiation depends on the detection principle of each dosemeter, GM detectors are not able to record the very short pulses. The standards dealing with the characteristics of active dosemeters do not include criteria for pulsed radiation fields.

Additional type tests would be necessary of these active dosemeters in multi-pulsed radiation fields in metrological conditions by varying the frequency and the intensity of the pulsed radiation. It would be useful to carry out a specific calibration for the radiation fields in which the APDs will be used.

Other issues like the development of APDs for the extremities and the eye lens are necessary. Specific values of the conversion coefficients to calculate the dose equivalent to the eye lens for X-rays do not exist so far, nor specific calibration procedures for eye lens dosimetry.

These concerns (calibration for eye lens dosimetry and the characterisation of APDs in multi-pulsed fields) will be studied in the FP7-ORAMED contract which starts in February 2008 and will last for 3 years.

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