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EXTREMITY RING DOSIMETRY INTERCOMPARISON IN REFERENCE AND WORKPLACE FIELDS

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An intercomparison of ring dosemeters has been organised with the aim of assessing the technical capabilities of available extremity dosemeters and focusing on their performance at clinical workplaces with potentially high extremity doses. Twenty-four services from 16 countries participated in the intercomparison. The dosemeters were exposed to reference photon (^{137}Cs) and beta (^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y) fields together with fields representing realistic exposure situations in interventional radiology (direct and scattered radiation) and nuclear medicine (^{99m}Tc and ^{18}F). It has been found that most dosemeters provided satisfactory measurements of $H_p(0.07)$ for photon radiation, both in reference and realistic fields. However, only four dosemeters fulfilled the established requirements for all radiation qualities. The main difficulties were found for the measurement of low-energy beta radiation. Finally, the results also showed a general under-response of detectors to ^{18}F, which was attributed to the difficulties of the dosimetric systems to measure the positron contribution to the dose.

INTRODUCTION

A coordinated network for radiation protection dosimetry, the CONRAD project, was founded in 2005 within the 6th EU Framework Programme. One of the working groups in the network dealt with the coordination and promotion of European research in the field of radiation protection dosimetry for medical staff. A thorough review of the literature on this topic was undertaken during the course of the project. The fact that extremity doses in interventional radiology (IR) and nuclear medicine (NM) could be high and even exceed occupational limits was highlighted$^{(1,2)}$. It was also found that there was a wide range of recorded doses for similar situations together with an important lack of data for some identified critical working conditions.

In these medical applications, the extremities (hands and fingers) are often in contact or very close to the radiation beam or radiopharmaceuticals. Furthermore, a wide variety of radiation fields must be monitored, low- and medium-energy X-ray beams in IR and photon, positron and beta emitters in NM. 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. Moreover, there have been very few international intercomparisons for these types of dosemeters and none, to the best of authors' knowledge, specifically focused on the analysis of performance in typical workplaces both in IR and NM.

The increasing number of such procedures has led to an increased interest in studying doses received by workers in NM and radiology departments and also to the improvement of extremity dosemeter design. An intercomparison was organised within the CONRAD project from January to May 2007 in order to verify the performance of different extremity dosemeters in use in Europe, in radiation fields that represent exposure situations of staff in hospitals. This paper summarises the main results of the intercomparison and completes the preliminary analysis presented in Carinou *et al*$^{(3)}$.

METHOD

Organisation of the intercomparison

The scope of the intercomparison was limited to ring dosemeters because previous studies$^{(2)}$ demonstrated that, in general, they provide a better estimate

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*Corresponding author: merce.ginjaume@upc.edu of the maximum skin dose than wrist dosemeters. According to ICRP recommendations(4), the operational quantity used in the intercomparison was the personal dose equivalent at a depth of 0.07 mm, $H_p(0.07)$, defined in ICRU 47(5). Four types of irradiation fields were selected: reference gamma fields, reference beta fields and realistic interventional and NM fields. The participants were selected on the basis of being a representative sample from different EU countries and of various types of dosimetric systems.

Participants

Twenty-four dosimetric services from 16 countries participated in the intercomparison. Participants included both small and large services. In total, they are responsible for monitoring of extremity exposure of 33 000 people a year.

Most of the dosemeters (21/24) used LiF phosphors as detectors with different types of dopants, isotopic concentration of ^{7}Li and thicknesses. Two services used $Li_2B_4O_7$ and another CaF_2:Mn. The tested detector holders were manufactured by Rados, TLD Poland, Panasonic, Harshaw/Thermo Instruments or by the service itself. The filter was plastic except for one service that used Cu + Sn. The overall thicknesses of the detectors and filters ranged between 12 and 300 mg cm^{-2}. More information on the types of dosemeters can be found in Carinou *et al.*(3)

Four services decided only to participate in the photon fields, the rest were tested in all the selected irradiation fields. In some cases, the dosemeters were irradiated in conditions in which they are probably not normally used, e.g. for beta radiation.

Most services used ^{137}Cs for dosemeter calibration but only very few tested them with beta radiation.

Irradiation fields

The irradiation programme was performed by four laboratories. All irradiations were performed on an ISO rod phantom (solid PMMA 30 cm cylinder, 19 mm diameter)(6,7).

The Laboratory of Ionising Radiation Dosimetry at the Institute for Radiological Protection and Nuclear Safety (IRSN) (France) was in charge of the ^{137}Cs irradiations at 0, 60 and 180°. $H_p(0.07)$ was determined as follows:

$$H_p(0.07) = h_{p,K}(0.07, \alpha) \cdot K_{air}, \qquad (1)$$

where $h_{p,K}(0.07, \alpha)$ is the conversion coefficient from kerma free-in-air to $H_p(0.07)$ for an irradiation angle α provided by Grosswendt(8). The K_{air} value was measured at IRSN by using a secondary standard ionisation chamber.

Reference values ranged between 4 and 6 mSv and the associated uncertainty was 4.8% ($k = 2$). Uncertainty estimates included an uncertainty of 4.0% ($k = 2$) for $h_{p,K}(0.07, \alpha)$ as indicated in ISO 4037-3.

The beta irradiations were carried out at the Bundesamt für Strahlenschutz (BfS) (Germany). Reference sources from the series 1 specified in ISO 6980-1(9), ^{90}Sr/^{90}Y, ^{85}Kr and ^{147}Pm were selected for the intercomparison. Irradiations were performed at 0° and 60° for each source. The reference values of $H_p(0.07)$ were provided directly by the software of a BSS-2 type secondary standard, traceable to the primary laboratory at the PTB(10), according to expression (2):

$$H_p(0.07) = h_{p,D}(0.07, \alpha) \cdot D_t(0.07), \qquad (2)$$

where $h_{p,D}(0.07, \alpha)$ is the conversion coefficient from the 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 $h_{p,D}(0.07, 0°)$ is equal to 1 Sv Gy^{-1}. For an incidence of 60°, $h_{p,D}(0.07, 60°)$ from ISO 6980-3(7) 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 ($k = 2$). By convention, no uncertainty was assigned to the conversion coefficient in this case.

The IR fields were reproduced at the Laboratoire National Henri Becquerel at the Comissariat à l'Energie Atomique CEA/LIST (LNHB) (France). A typical spectrum of 70 kVp with a filtration of 4.5 mm Al and 0.2 mm Cu produced in a medical X-ray generator MPH65 (GEMS) was used. Dosemeters were tested at two locations above the phantom, 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. $H_p(0.07)$ was determined using equation (1). The K_{air} value was measured at CEA using an ionisation chamber traceable to primary standards. The photon spectra in terms of fluence were calculated with the MCNPX Monte Carlo code(11,12) 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 folded with the individual conversion coefficients taken from ICRU 57(13). 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 associated uncertainty was 6.5% ($k = 2$). The uncertainty for the IR fields comes mainly from the uncertainty on the air kerma measurement (5%, $k = 2$) and the uncertainty in the calculation of the conversion factors (4%, $k = 2$).

The realistic NM fields were simulated at the Free University of Brussels (Belgium) with the collaboration of the Belgian Nuclear Research Center (SCK-CEN) (Belgium). The dosemeters on the corresponding rod phantoms were situated at 14.05 cm from an unshielded syringe filled, with ^{99m}Tc and ^{18}F solutions, respectively. The reference values of $H_p(0.07)$ were calculated using the MCNPX2.5.0 code(11). As compared with the experimental geometry shown in Figure 1, a simplified set-up was defined in the model. The radiopharmaceutical was simulated as a cylindrical water source limited by a 0.75 mm thick, 0.93 g cm^{-3} polyethylene syringe wall(14). The whole geometry was surrounded by 1.205 g cm^{-3} dry-air(14). For each solution (^{99m}Tc and ^{18}F), decay data were taken from Browne and Firestone(15) and Stabin and da Luz(16). For the ^{18}F problem, 511 keV annihilation gamma rays were taken into account as created where each positron 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. 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 Shaart *et al.*(17). 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% 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 normalised 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.

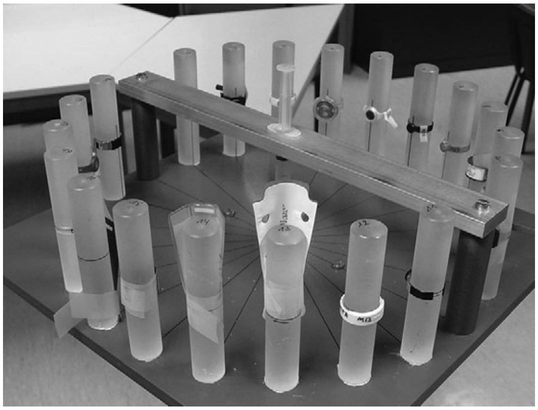

Figure 1. Photograph of the experimental set-up to simulate NM workplace conditions.

Performance criteria

The performance requirements of passive extremity dosemeters are described in ISO 12794(18). 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 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(19) and ISO 6980-1(9), within the energy range of the scope, does not vary by more than ±50%. The standard defines performance criteria for the angular response of 60 kV photon beams but does not detail 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 workplace fields.

In the overall analysis of the results, the general dosimetric requirements established by ICRP(4,20) and represented by the so-called 'trumpet curves'(21) were applied.

RESULTS AND DISCUSSION

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:

$$R_i = \frac{(L_{i,1} + L_{i,2})/2 - Bk_i}{H_p(0.07)_{\mathrm{ref},i}}, \tag{3}$$

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

Table 1 shows the response of the participants, for each irradiation field, classified in the following categories.

1. *Category I:* participants that comply with the trumpet curve in the 13 tested fields. Four services belong to this group. A *sub-category I Ph* is considered in this group to include three of the four services that only were tested for photons and presented results within the requirements of the intercomparison.
2. *Category II:* participants that comply with ISO 12794 and with the trumpet curves limits in the realistic fields, but do not belong to the first category. There are three services in this group; they are outside the limits for the ^{147}Pm and for the ^{85}Kr at 60°.
3. *Category III:* participants that do not belong to categories I and II, but that are within the limits for photon fields and ^{90}Sr normal incidence. There are 10 services in this group.
4. *Category IV:* participants outside the previous categories. There are four services in this group, who had difficulties in the measurement of the tested photon beams. The service that uses CaF_2:Mn (id: 15) belongs to this category and presented an important overestimate for X-rays compared with the response to ^{137}Cs.

Each service is identified by an anonymous number, *id*. Values outside the trumpet curve limits are indicated in Table 1 in italic-bold case. Table 2 shows 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.

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

Table 1. Participant response for each tested radiation quality.

Category	ID	Beta reference fields						NM		Gamma reference			IR	
		^{90}Sr–^{90}Y		^{85}Kr		^{147}Pm		Workplace		Fields ^{137}Cs			Workplace	
		0°	60°	0°	60°	0°	60°	^{18}F	^{99m}Tc	0°	60°	180°	In beam	Outside beam
I	10	1.02	0.93	0.89	0.79	0.49	0.69	0.75	0.81	0.60	0.73	0.75	1.12	1.20
	11	0.94	0.67	0.88	0.72	0.81	0.51	0.73	1.14	0.59	0.79	0.80	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	1.00	0.65	0.87	0.88	0.92	0.95	0.89	0.95	0.90	1.51	1.42
I Ph	4									1.02	1.03	1.04	1.67	1.57
	17									0.65	0.61	0.67	1.10	1.06
	19									0.70	0.81	0.88	0.76	0.64
II	2	1.33	0.78	0.70	***0.39***	***0.01***	***0.01***	0.69	1.01	0.81	0.81	0.80	1.25	1.36
	14	1.17	1.06	0.88	***0.50***	***0.08***	***0.04***	0.73	0.93	0.78	0.77	0.83	1.27	1.00
	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
III	1	0.84	***0.46***	0.74	***0.31***	***0.00***	***0.00***	***0.45***	1.14	1.03	0.68	0.90	1.38	1.81
	6	1.15	0.63	***0.20***	***0.11***	***0.01***	***0.01***	***0.51***	1.27	1.08	1.07	1.00	1.50	1.40
	7	1.09	***0.44***	***0.10***	***0.03***	***0.00***	***0.00***	***0.43***	0.85	1.05	0.96	0.99	0.89	0.94
	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
	16	1.14	0.55	***0.15***	***0.06***	***0.00***	***0.00***	***0.50***	1.03	1.07	1.09	1.05	1.28	1.43
	18	0.82	***0.43***	***0.10***	***0.02***	***0.00***	***−0.01***	***0.42***	1.06	0.88	0.85	0.97	1.50	1.23
	20	0.94	***0.48***	***0.07***	***0.07***	***0.00***	***0.01***	***0.48***	1.17	1.00	0.96	0.95	1.42	1.52
	21	1.00	***0.46***	***0.13***	***0.04***	***0.00***	***0.00***	***0.37***	0.73	0.77	0.76	0.75	0.71	0.68
	23	0.59	***0.10***	***0.00***	***0.00***	***0.00***	***0.00***	***0.26***	1.29	0.99	0.97	0.95	1.57	1.53
	24	1.03	***0.43***	***0.17***	***0.04***	***0.00***	***0.01***	***0.42***	1.11	0.92	0.92	0.89	1.46	1.43
IV	3									***2.3***	***2.2***	***2.4***	***3.5***	***2.6***
	5	***0.42***	***0.36***	***0.06***	***0.04***	***0.00***	***0.00***	***0.26***	0.56	0.63	***0.43***	***0.42***	***0.46***	0.51
	8	0.70	***0.44***	***0.13***	***0.03***	***0.01***	***0.01***	***0.43***	1.19	1.03	1.06	1.10	1.56	***2.0***
	15	0.94	***0.47***	***0.11***	***0.07***	***0.01***	***0.01***	***0.40***	***2.3***	0.87	0.87	0.90	***12***	***11***

Services are classified into four categories and responses outside trumpet curve limits are highlighted in bold-italic case. (Each service is identified by an anonymous number from 1 to 24.)

Table 2. 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	No. 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

satisfactory except in one case, the average relative response is 1.00. The performance is slightly worse at 60°, 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 60° 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 the 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 $Li_2B_4O_7$.

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 seven services were within the trumpet curve for this field. It must be mentioned 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. From the 24 services, three reported that they had not evaluated their uncertainties. Four others reported their 'total' uncertainties, but did not give any specification on how they were calculated. All the others gave some information, and, as expected, the description on how it was calculated varied significantly.

The technical recommendations for monitoring individuals occupationally exposed to external radiation (EUR 14852)$^{(21)}$ consider as main sources of uncertainties in thermoluminescence individual monitoring energy and directional dependence, the non-linearity of the response, calibration errors and uncertainty in individual calibration factors. Only three services reported that they took all these parameters into account. However, in the intercomparison, the main source of uncertainty is expected to be energy dependence and, therefore, the 13 services that took energy dependence into account should provide an acceptable estimate of the uncertainty. When dividing the participants into two groups: those that included energy dependence in their uncertainty budget (13), and 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 uncertainties did not justify some of the measurements outside the trumpet curve limit, in either of the two groups.

CONCLUSION

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 IR and NM.

Summarising the main results of the study, it can be pointed out that, in general, there is a satisfactory response for photon fields: ^{137}Cs, IR direct and scattered fields and ^{99m}Tc. Major difficulties were encountered in the measurement of beta radiation (category III services). The study highlights the fact that this limitation is also a matter of concern when handling ^{18}F because in this case the contribution of positrons to the dose cannot be neglected. The importance of dosemeter design, in particular, the thickness of the filter and the detector has been shown. Four services performed within established criteria for all tested fields and seven services fulfilled requirements in the tested medical fields.

It was confirmed that CaF_2:Mn is not a good detector to be used for extremity dosimetry in the medical field because it presents a high over-response for X-ray fields.

Finally, 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 harmonisation in this field. Results also highlight the fact that the contribution of energy response dependence on the measurement uncertainty cannot be neglected and has to be estimated for all fields of interest. The calibration procedures should also be reviewed depending on the fields where the dosemeters will be used.

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