Intercomparison of Extremity Dosimeters in Beta, Photon and Medical Realistic Fields

Performance of ring dosimeters in typical medical fields

M. Ginjaume\textsuperscript{a*}, E. Carinou\textsuperscript{b}, L. Donadille\textsuperscript{c}, J. Jankowski\textsuperscript{d}, A. Rimpler\textsuperscript{e}, M. Sans Merce\textsuperscript{f}, F. Vanhavere\textsuperscript{g}, M. Denoziere\textsuperscript{h}, J. Daures\textsuperscript{h}, J.M. Bordy\textsuperscript{h}, C. Itié\textsuperscript{c} and P. Covens\textsuperscript{i}

\textsuperscript{a}Institut de Tècniques Energètiques, Universitat Politècnica de Catalunya (UPC), Diagonal 647, 08028 Barcelona, Spain.

\textsuperscript{b}Greek Atomic Energy Commission (GAEC), Ag. Paraskevi, 15310, Greece.

\textsuperscript{c}Institut de Radioprotection et de Sûreté Nucléaire (IRSN), BP 17, 92262 Fontenay-aux-Roses Cedex, France.

\textsuperscript{d}Nofer Institute of Occupational Medicine (NIOM), St. Teresa Street 8, 90-950 Lodz, Poland

\textsuperscript{e}Bundesamt für Strahlenschutz (BfS), Koepenicker Allee 120-130, 10312 Berlin, Germany.

\textsuperscript{f}Institut Universitaire de Radiophysique Appliquée (IRA), rue du Grand Pré 1, 1007 Lausanne, Switzerland.

\textsuperscript{g}Belgian Nuclear Research Centre (SCK-CEN), Boeretang 200, 2400 Mol, Belgium.

\textsuperscript{h}CEA, LIST, Laboratoire National Henri Becquerel, Gif sur Yvette, F-91191, France.

\textsuperscript{i}University of Brussels and Academic Hospital (AZ-VUB), Radiation Protection Department, Brussels, Belgium.

Abstract. The EURADOS Working Group 9 is presently coordinating research activities on the assessment of occupational exposures at workplaces in therapeutic and diagnostic radiology as well as in nuclear medicine. A recent literature review showed that extremity doses, especially in nuclear medicine and interventional radiology, can be quite high. However, the use of extremity dosimeters in hospitals is still not very common. Furthermore, there is very little information on the performance of these dosimeters in typical medical fields. Within this framework, EURADOS organized an intercomparison of extremity dosimeters aimed at assessing the technical capabilities of these dosimeters and focusing on their performance at workplaces with potentially high extremity doses. 24 services from 16 European countries participated in the intercomparison. The dosimeters represented in this study are used to monitor over 30,000 workers. The dosimeters were exposed to reference photon ($^{137}$Cs) and beta ($^{147}$Pm, $^{85}$Kr and $^{90}$Sr/$^{90}$Y) fields as well as to realistic interventional radiology (direct and scattered radiation) and nuclear medicine fields ($^{99m}$Tc and $^{18}$F). This report presents the main results of the intercomparison. It is shown that most dosimeters provided satisfactory measurements of $H_{E}(0.07)$ for photon radiation, both in reference and realistic fields. However, only four dosimeters fulfilled the requirements given by the trumpet curves for all tested radiation qualities. The main difficulties were found for the measurement of low energy beta radiation. A clear correlation was found between filter and detector thickness and response to beta particles. 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.

* Presenting author, E-mail: merce.ginjaume@upc.edu
KEYWORDS: intercomparison, extremity dosimetry; nuclear medicine; interventional radiology; brachytherapy; TLD

1. Introduction

The European Radiation Dosimetry Group, EURADOS (www.eurados.org), is a scientific network of European laboratories involved in research in radiation dosimetry. The objective is to advance the scientific understanding and the technical development of the dosimetry of ionising radiation by stimulating collaboration between European facilities. In 2005, a new working group, (working group 9, WG 9) was created to coordinate research activities on the assessment of occupational exposures at workplaces in therapeutic and diagnostic radiology as well as in nuclear medicine. The group was funded through the CONRAD Project, within the 6th EU framework programme. The rapidly evolving medical practices and the introduction of new techniques require the implementation of special monitoring programmes. For some of these applications the skin of the fingers is the limiting organ for the individual monitoring of external radiation [1].

WG9 investigations also highlighted that there was very few available information about official extremity dose records [2] and that the registered doses were much lower than the estimations of annual extremity doses published in dedicated studies. These discrepancies were assumed to be due to the fact that (i) the dosimeters may not be systematically worn (ii) the most exposed workers may not be monitored and/or (iii) the dosimeters may be worn at not adapted positions or may not be suitable for the radiation field of interest, thus leading to significant underestimations of the doses.

Only few extremity dosimeter intercomparisons have been reported. In 2000 EURADOS organised an intercomparison as part of a performance test of services for dose assessment [3], which included some tests for extremity dosimeters. The results of the extremity dosimeters showed that, in general there were difficulties to obtain suitable results for low beta measurements. Seven years ago, another intercomparison was organized by the PTB (Germany) for extremity dosimeters in beta and/or photon radiation fields [4]. The study was more oriented towards the testing of the extremity dosimeters for the German requirements.

Based on the above mentioned observations, the organization of a European intercomparison, which would address ring dosimeter performance in reference and realistic fields, was considered of great value to the dosimetric community. EURADOS WG 9, in cooperation with several calibration laboratories and a hospital, organized such an exercise in 2007. The intercomparison is, to the best of our knowledge, the first organized on international basis that analysed the response of extremity dosimeters to typical medical fields. This paper describes the intercomparison set up and its main results.

2. Materials and Methods

2.1 Organization of the intercomparison exercise

In most situations where the extremities are irradiated, the skin is the part of the extremity receiving the highest dose and as the dose limits for skin and for the extremities are the same, the skin of the extremities is, generally, the limiting organ. The corresponding operational quantity is the personal dose equivalent, $H_p(0.07)$. The scope of the intercomparison was aimed at testing the capacity of ring dosimeters to measure the quantity $H_p(0.07)$. The irradiation programme included photon and beta fields in both reference and realistic conditions.

The following irradiation conditions were selected:

**Reference fields**:
- Photon: $^{137}$Cs sources at $0^\circ$, $60^\circ$ and $180^\circ$.
- Beta: $^{90}$Sr/$^{89}$Y, $^{85}$Kr and $^{147}$Pm sources at $0^\circ$ and $60^\circ$. 
Realistic medical fields:
° Interventional radiology (IR): 70 kVp, with a filtration of 4.5 mm Al and 0.2 mm Cu, produced by a medical X-ray generator MPH65 (GEMS) (in two positions, within the geometrical limits of the primary radiation beam - direct radiation - and in the penumbra in the scattered field at the edge of the patient phantom - scattered radiation).
° Nuclear medicine: A 3 ml polyethylene unshielded syringe with $^{99m}$Tc (gamma emitter) and $^{18}$F (positron emitter).

The delivered doses varied from 1 mSv to about 11 mSv. The relevant ISO standards were used for the reference irradiations, ISO 4037 and 6980 series [5,6]. The irradiations were performed using the ISO rod phantom, which is a PMMA cylinder of 19 mm diameter and 300 mm length [7,8].

Irradiations were performed in four laboratories: Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Commissariat à l’énergie atomique, LIST, Laboratoire National Henri Becquerel (CEA-LIST-LNHB), (France); Bundesamt für Strahlenschutz (BfS) (Germany); and the University of Brussels and Academic Hospital (AZ-VUB) (Belgium) in collaboration with the Belgian Nuclear Research Centre (SCK-CEN), (Belgium).

The $^{137}$Cs source of IRSN (France) was used in the horizontal beam configuration as part of the photon irradiation programme. The second part of the photon irradiation programme was performed at CEA-LIST-LNHB (France) using a diagnostic X-ray facility in order to simulate irradiation at interventional radiology fields. The beta irradiations were performed at the BfS (Germany). Finally, the realistic nuclear medicine irradiation set-up was performed at AZ-VUB (Belgium). A syringe filled with the selected radiopharmaceutical was placed vertically, encircled by 22 rod phantoms equidistant to the syringe and located at 14.05 cm distance from the dosimeters. The extremity dosimeters were placed on the surface of each phantom, centred on it and facing the syringe [9]. The tests were designed to reproduce fields of interest in medical applications and to verify the ability of the participating dosimeters to determine $H_p(0.07)$.

Twenty four services from sixteen countries participated in the intercomparison. Most of the dosimeters (21/24) used LiF phosphors as detectors with different types of dopants, isotopic concentration of Li and thicknesses. Fifteen services used as sensible material LiF:Mg,Ti of standard thickness 0.9 mm (commercial name: TLD-100, MTS-N, DTG4). Nine services used the more sensitive material, LiF:Mg,Cu,P, four of them of standard thickness, 0.9-0.4 mm, (TLD-100H, TLD-700H), the other five with a thin sensitive layer of approximately 8 mg/cm² (MCP-Ns). Two services used Li$_2$B$_4$O$_7$ detectors and one service CaF$_2$:Mn. The filter material was, in most of the cases (18/24), plastic of thickness 3-30 mg/cm². The overall thickness of the detectors and filters ranged between 12 and 300 mg/cm². More information about the type of detector and filter used by each service can be found in Carinou et al. [10]. Most of the dosimeters were calibrated to Cs$^{137}$ sources, while five services also used X-rays from the ISO 4037 series [5] to calibrate their dosimeters. Each participating service was asked to prepare two dosimeters per irradiation field, 26 dosimeters for the irradiations and 8 detectors for background correction. Four of the services participated only in the photon fields: $^{137}$Cs sources and interventional radiology fields.

2.2 Determination of reference $H_p(0.07)$ values

For $^{137}$Cs irradiation fields, $H_p(0.07)$ was determined according to equation (1):

$$H_p(0.07) = h_p(0.07, a) \cdot K_{air}$$

(1)

where: $h_p(0.07, a)$ is the conversion coefficient from air kerma free in air to $H_p(0.07)$ for an irradiation angle a, provided by Grosswendt [11]. $K_{air}$ is the reference air kerma free in air.

$K_{air}$ is measured at IRSN using a secondary standard ionization chamber traceable to the primary laboratory at the CEA-LIST-LNHB. The overall uncertainty for $H_p(0.07)$, for $^{137}$Cs irradiation, is equal to 4.8% (k=2). The main contribution of the uncertainty budget being due to the uncertainty on the air
kerma free-in-air to \( H_p(0.07) \) conversion coefficients, taken as 4\% (k=2), following ISO 4037-3 recommendations [7].

For **interventional radiology fields**, \( H_p(0.07) \) was determined using equation (1). \( K_{air} \) value was measured at CEA using an ionization chamber traceable to its French primary standards. The photon spectra in terms of fluence were calculated with the MCNPX Monte Carlo Code [12] at the two points of tests [13]. The average conversion coefficients from air kerma free-in-air to personal dose equivalent, \( h_{p,k}(0.07, a) \), 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 [14]. The total uncertainty on the reference value is 6.5\% (k=2). The uncertainty budget includes the uncertainty on the air kerma measurement (5\%, k=2), the statistical uncertainties on the calculated spectra (0.1\%, k=2) and the uncertainty on the calculation of the conversion factors \( h_p(0.07, a) \) (4\%, k=2). Extra calculations have been done to evaluate the influence of multiple scattering between patient and worker phantom, but the influence of this was smaller than 0.1\%.

For **beta fields**, reference values of \( H_p(0.07) \) were provided directly by a BSS-2 secondary standard traceable to the primary laboratory at the PTB. The reference value is calculated according to equation (2):

\[
H_p(0.07) = h_{p,D}(0.07, a) \cdot D_t(0.07),
\]

where \( h_{p,D}(0.07, a) \) 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 \( a \).

It was assumed that the conversion coefficient \( h_{p,D}(0.07, 0^\circ) \) is equal to 1 Sv/Gy. For the irradiation at 60\°, \( h_{p,D}(0.07, 60^\circ) \), the ISO 6980-3 value was used [8].

The total uncertainty in the reference values 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, those for the correction factors for the air density and attenuation (temperature, humidity and pressure), the irradiation time span and the uncertainty due to the geometry of the set-up because several detectors were irradiated on the rod phantom simultaneously. By convention, no uncertainty was assigned to the conversion coefficient in this case.

For **nuclear medicine fields**, the reference values of \( H_p(0.07) \) were calculated using the MCNPX [12] and the PENELOPE [15] Monte Carlo codes, normalized by the measured activity of the radioactive solution. A simplified set-up was defined in the simulation model compared to the experimental geometry. 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 [16] and Stabin and da Luz [17]. 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 \( 7\pm1 \) 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 MCNPX calculations, following the method recommended by Schaar et al. [18]. 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 estimated uncertainty for the reference \( H_p(0.07) \) values for \(^{99m}\)Tc and for \(^{18}\)F is equal to 10.5\% and 8\% (k=2), 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 different Monte Carlo codes and the geometry simplifications in the results.

2.3 Performance criteria

The analysis of the results is based on the general dosimetric requirements established by ICRP [19, 20]. The ratio between a measured dose value and the conventionally true value, \( \frac{H_m}{H_t} \) should be;

a) for a dose value equal to or approaching the annual limit: \( 1.5 \geq \frac{H_m}{H_t} \geq \frac{1}{1.5} \)

b) for a dose value less or equal to the reporting level: \( 2.0 \geq \frac{H_m}{H_t} \geq 0 \)

The annual dose limit for the skin is 500 mSv. In some of the participating countries the recording level for \( H_p(0.07) \) is 0.1 mSv and in others it is 1.0 mSv. For this analysis, the most restrictive value, 0.1 mSv, has been taken.

These two requirements are summarized considering that the ratio \( \frac{H_m}{H_t} \) is within the limits defined by the so-called “trumpet curves” [21, 22] and given by equations (3) and (4).

The upper limit is given by,

\[
\left( \frac{H_m}{H_t} \right)_{\text{upper limit}} = 1.5 \left( 1 + \frac{H_0}{2H_0 + H_t} \right)
\]  

(3)

The lower limit is given by,

\[
\left( \frac{H_m}{H_t} \right)_{\text{lower limit}} = \frac{1}{1.5} \left( 1 - \frac{2H_0}{H_0 + H_t} \right)
\]  

(4)

where,

\( H_0 \) is the recording level for monthly monitoring (0.1 mSv in this work),
\( H_m \) is the participant measured dose value,
\( H_t \) is the reference dose value.

3. Results and discussion

Table 1 summarizes the main results of the intercomparison. It indicates, for each radiation field, the reference equivalent dose and its uncertainty (k=2), the mean response of the 24 participants, the response range of the participants (maximum and minimum response for each field), the number of services that fulfil the requirements (number of services with response within the trumpet curve limits).

The response of a participant, \( j \), to a given radiation field \( (Q_f) \), \( R(Q_f, j) \) is defined as the ratio between the participant measured dose value and the reference dose value for this radiation field.

\[
R(Q_f, j) = \frac{1}{2} \left( \sum_{i=1}^{2} L_{Q_f, i}(j) \right)
\]  

(5)

The participant measured dose value for \( (Q_f) \) is estimated as the mean value of the two dosemeters exposed at this radiation field.
The mean response tabulated in the third column of table 1 is calculated as,

\[
\text{Mean response} (Q_r) = \frac{1}{n} \sum_{j=1}^{n} R(Q_r, j)
\]

where, \(n\) is the number of participants, \(n=24\) for \(^{137}\text{Cs}\) and IR fields, and \(n=20\) for beta qualities, \(^{18}\text{F}\) and \(^{99m}\text{Tc}\).

Table 1: Summary of the intercomparison results for each tested radiation quality: reference dose equivalent dose and uncertainty (\(k=2\)), mean response, response range and number of services that fulfil the “trumpet curve” limits.

<table>
<thead>
<tr>
<th>Radiation quality ((Q_F))</th>
<th>(H_p(0.07)) (± Uncertainty, (k=2)) (mSv)</th>
<th>Mean response</th>
<th>Response range</th>
<th>Number of services within the trumpet curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{137}\text{Cs}, 0^\circ)</td>
<td>4.5 ± 0.2</td>
<td>0.92</td>
<td>0.6 – 2.3</td>
<td>23/24</td>
</tr>
<tr>
<td>(^{137}\text{Cs}, 60^\circ)</td>
<td>4.8 ± 0.2</td>
<td>0.91</td>
<td>0.4 – 2.2</td>
<td>22/24</td>
</tr>
<tr>
<td>(^{137}\text{Cs}, 180^\circ)</td>
<td>5.2 ± 0.2</td>
<td>0.96</td>
<td>0.4 – 2.4</td>
<td>22/24</td>
</tr>
<tr>
<td>(^{90}\text{Sr-}^{90}\text{Y}, 0^\circ)</td>
<td>8.2 ± 0.2</td>
<td>1</td>
<td>0.4 – 1.4</td>
<td>19/20</td>
</tr>
<tr>
<td>(^{90}\text{Sr-}^{90}\text{Y}, 60^\circ)</td>
<td>9 ± 0.2</td>
<td>0.63</td>
<td>0.1 – 1.3</td>
<td>10/20</td>
</tr>
<tr>
<td>(^{85}\text{Kr}, 0^\circ)</td>
<td>10.3 ± 0.2</td>
<td>0.45</td>
<td>0 – 1.2</td>
<td>8/20</td>
</tr>
<tr>
<td>(^{85}\text{Kr}, 0^\circ)</td>
<td>11 ± 0.2</td>
<td>0.29</td>
<td>0 – 0.9</td>
<td>5/20</td>
</tr>
<tr>
<td>(^{147}\text{Pm}, 0^\circ)</td>
<td>5.8 ± 0.2</td>
<td>0.25</td>
<td>0 – 1.2</td>
<td>5/20</td>
</tr>
<tr>
<td>(^{147}\text{Pm}, 60^\circ)</td>
<td>8.3 ± 0.3</td>
<td>0.16</td>
<td>0 – 0.9</td>
<td>4/20</td>
</tr>
<tr>
<td>IR in beam</td>
<td>2.6 ± 0.2</td>
<td>1.86</td>
<td>0.5 – 12</td>
<td>21/24</td>
</tr>
<tr>
<td>IR outside beam</td>
<td>0.70 ± 0.05</td>
<td>1.86</td>
<td>0.5 – 11</td>
<td>21/24</td>
</tr>
<tr>
<td>(^{18}\text{F})</td>
<td>10 ± 1</td>
<td>0.55</td>
<td>0.3– 1.1</td>
<td>7/20</td>
</tr>
<tr>
<td>(^{99m}\text{Tc})</td>
<td>4.2 ± 0.3</td>
<td>1.08</td>
<td>0.6 – 2.3</td>
<td>19/20</td>
</tr>
</tbody>
</table>

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

There was a wide range of responses in the realistic interventional fields, from 0.21 to 12.5. Two services reported very high doses. One of them was the service who used CaF\(_2\):Mn, that provided an acceptable response for \(^{137}\text{Cs}\), but that overestimated the dose for IR (\(R_{IR}=12\)), this was justified by the energy response of this type of TL material. The other one was the service that had a response of 2.35 for \(^{137}\text{Cs}\), thus highlighting that this participant had some problems with the calibration of the dosimetric system. Finally, one service underestimated significantly the given dose (\(R_{IR}=0.4\)). This result could also be due to a problem of calibration of the system since the response of this service for \(^{137}\text{Cs}\) was 0.6 for a normal incidence and 0.4 for 60° and 180°. The other 22 participants presented results 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 were excluded. It was shown that, generally, there was an overestimation of approximately 30% of the reported doses by the services that used LiF detectors and an underestimation of 15% for those that used Li\(_3\)B\(_4\)O\(_7\).
The results obtained for the \textsuperscript{99m}Tc irradiation were satisfactory in 19 out of 20 cases and the average relative response was 1.08. The service which did not fulfil the requirement is the one that used CaF\textsubscript{2}:Mn, that, as mentioned before, is not suitable for other energies than the energy of calibration.

As regards the performance for \textsuperscript{18}F irradiation, only 7 services out of 20 participants fulfilled the requirements. The average relative response was found to be 0.55, thus showing a general underestimation of the dose for this field. The 7 services, that performed satisfactorily, had also a good response for the reference beta field, \textsuperscript{85}Kr, normal incidence. This result highlights that for PET applications, a dosemeter, with thin detectors and thin filter should be used.

The services were required to provide an estimate of their uncertainties in the assignment of doses. It was found out that the procedure to calculate the uncertainties and the components of the uncertainty budget varied substantially from one service to another. The uncertainties (k=2) ranged from 12 to 50\%, when the energy dependence was included in the uncertainty budget, and, from 5 to 21\%, when it was not. There is a clear need for harmonization in this field, and a need for many participants to review the calculation of their uncertainties taking into account the recommended components of uncertainty indicated in [21]. The energy response dependence in the fields of interest must, of course, be included in the uncertainty budget and its influence will be higher for non tissue equivalent detectors such as CaF\textsubscript{2}:Mn. In Figures 1 and 2, we present the results of service 10 and 18, as an example. For each service, the figure includes the response, calculated as the ratio of the participant measured dose value and the reference value for each radiation field, $Q_F$, and the corresponding uncertainty (k=2). In this case equation (5) is not used since, every individual measurement is represented. The graphs also indicate the trumpet curves limit for each field, which are calculated from equations (3 and 4). Service 10 is one of the four services that obtained all the results within the trumpet curve limits and that included most of the uncertainty components in their calculations. Service 18 is an example of a participant which obtained results within the trumpet curve limits for \textsuperscript{137}Cs, IR fields, \textsuperscript{99m}Tc and \textsuperscript{90}Sr/\textsuperscript{90}Y normal incidence, but underestimated the dose for the other fields. This is quite a typical behaviour of dosimeters with thick filter or detector. Figure 2 also points out, that in this case the reported uncertainty is clearly too small. Only 2 out of the 26 data points with the error bars show an overlap with the reference value.

\textbf{Figure 1:} Response of service 10 to the tested fields.
4. Conclusion

This intercomparison highlights that extremity dosimetry can be used satisfactorily to estimate finger doses in typical medical fields, such as nuclear medicine and interventional radiology, where there is a potential risk of receiving high doses at extremities. However the study also points out that several services must review their procedures to improve their results. In particular it is shown that when the dosemeter is to be used for PET applications a thin detector capable of detecting beta radiation must be used. From the analysis of the results it can be concluded that a dosimetric service that fulfill ISO 12794 requirements for photon and beta radiation [23] will respond adequately to typical medical fields in interventional radiology, PET and conventional nuclear medicine. This standard does not include as a requirement the verification for $^{147}$Pm. It must be indicated that some detectors were not supposed to be used in beta or mixed beta-gamma fields, and thus would be adequate for use in photon fields.

The results from the service that used CaF$_2$:Mn as detector material evidenced that this is not a good material to be used in medical fields, unless it is possible to introduce some type of energy correction.

Finally, the study showed that there was a need for harmonization among dosimetric services for the calculation of measurement uncertainty. The reported uncertainties ranged between 5% and 50% (k=2). In particular results confirm the need to estimate the contribution of energy response dependence on the measurement uncertainty.

Acknowledgements
Thanks are due to dosimetric services and irradiation laboratories for their collaboration in the intercomparison and to the EU for its support through the CONRAD project.
REFERENCES


