$Hp(0.07)$ Photon and Beta Irradiations for the EURADOS Extremity Dosemeter Intercomparison 2015

Leon de Prez and Frans Bader
VSL - The Netherlands
www.vsl.nl
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VSL, located in Delft, near Rotterdam and The Hague, is the Netherlands’ National Metrology Institute.
Available measurement standards for:


Via the Mutual Recognition Arrangement (MRA), it was established that VSL’s measurement standards and the measurement results would be internationally accepted.

**K999**: Implementation of calibrations (ISO/IEC 17025:2005)

**P002**: Production and certification of reference materials (ISO Guide 34:2009)

**R006**: Organisation and implementation of inter-laboratory investigations (ISO/IEC 17043:2010)
The Ionizing Radiation Department offers a wide range of services in the field of ionizing radiation.

Primary standard (transportable water-calorimeter) for calibrations in terms of Co-60 absorbed dose to water at 5 g/cm².
Best $U = 0.8 \% \ (k = 2)$

Calibration of Well-Type ionization chambers in RAKR for Ir-192 HDR and PDR sources.
Best $U = 2 \% \ (k = 2)$
A parallel-plate free-air-chamber serves a primary air-kerma standard for x-rays to 320 kV. Radiation qualities available according to ISO 4037 and IEC 61267. Best $U = 1\% \,(k = 2)$. 

For radiation protection purposes a low scatter facility is available for air-kerma rates from 300 nGy/h to 0.5 Gy/h for Cs-137 and Co-60. Collimated with a conical ring collimator according ISO 4037. Best $U = 1.5\% \,(k = 2)$

At present characterising a well-type ionization chamber and develops methods to serve as a secondary standard. I-125 LDR seeds for Brachytherapy and I-124 for PET-CT purposes.
Irradiations, restricted to photons and betas, will be performed in European irradiation facilities in terms of $Hp(0.07)$ in the following ranges:

- Photon energy: 16 to 662 keV
- Beta mean energy: 250 to 1000 keV
- Dose: 0.5 mSv to 1 Sv
- Angle of incidence: $\pm 60^\circ$
- The Irradiation Plan were developed by WG2 and described in the EURADOS IC2015ext Irradiation Plan,

- The Coordinator arranged the transit (by car) between Seibersdorf Lab and VSL,

- The irradiation lab did not know the participants,

- Radiation qualities, radiation fields and irradiations according to ISO and IEC standards,

- ISO Rod phantom for finger tip and ring dosemeters,

- ISO Pillar phantom for ankle/wrist dosemeters,

- Per system a random choice of which dosemeters for each irradiation,

- Random varied of delivered $H_p(0.07)$ within the range of the irradiation plan.
## Irradiation plan: Radiation Qualities

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Radiation quality</th>
<th>$E_{\text{mean}}$ or $\beta_{\text{max}}$ keV</th>
<th>According to</th>
<th>Angle of incidence, $\alpha$</th>
<th>Number of dosemeters</th>
<th>Range $Hp(0.07)$ mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>W-80</td>
<td>57</td>
<td>ISO 4037</td>
<td>0°</td>
<td>4</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Photon</td>
<td>RQR 3</td>
<td>33</td>
<td>IEC 61267</td>
<td>0°</td>
<td>2</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Photon</td>
<td>RQR 3</td>
<td>33</td>
<td>IEC 61267</td>
<td>60°</td>
<td>2</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Photon</td>
<td>RQR 9</td>
<td>57</td>
<td>IEC 61267</td>
<td>0°</td>
<td>2</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Photon</td>
<td>RQR 9</td>
<td>57</td>
<td>IEC 61267</td>
<td>0°</td>
<td>2</td>
<td>300 - 600</td>
</tr>
<tr>
<td>Photon</td>
<td>S-Cs</td>
<td>662</td>
<td>ISO 4037</td>
<td>0°</td>
<td>2</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Photon + Beta</td>
<td>S-Cs + Sr-90/Y-90</td>
<td>662 + 2274</td>
<td>ISO 4037 + ISO 6980</td>
<td>0°</td>
<td>2</td>
<td>2 - 5</td>
</tr>
<tr>
<td>Beta</td>
<td>Sr-90/Y-90</td>
<td>2274</td>
<td>ISO 6980</td>
<td>0°</td>
<td>2</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Beta</td>
<td>Sr-90/Y-90</td>
<td>2274</td>
<td>ISO 6980</td>
<td>60°</td>
<td>2</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Beta</td>
<td>Kr-85</td>
<td>687</td>
<td>ISO 6980</td>
<td>0°</td>
<td>2</td>
<td>5 - 10</td>
</tr>
</tbody>
</table>
Irradiation Plan: ISO and IEC Standards

ISO 6980
Nuclear energy – Reference beta-particle radiation
Part 1 and Part 2

ISO 4037
X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy;
Part 1 and Part 3

ISO 12794
Nuclear energy – Radiation protection – Individual thermoluminescence dosemeter for extremities and eyes

ISO 29661
Reference radiation fields for radiation protection – Definitions and fundamental concepts

IEC 61267
Medical diagnostic X-ray equipment – Radiation conditions for use in the determination of characteristics
For ankle/wrist dosemeters:
The ISO Pillar phantom (center) is a water-filled hollow cylinder with PMMA walls an outer diameter of 73 mm and a length of 300 mm. The cylinder walls have a thickness of 2.5 mm and the end faces have a thickness of 10 mm.

For ring and finger tip dosemeters:
The ISO Rod phantom (right) is a solid PMMA cylinder of 19 mm diameter and a length of 300 mm.

(The ISO water slab phantom (left) is intended for whole-body dosemeters. Not used in EURADOS IC2015ext.)
Determination of $Hp(0.07)$ - Photons

\[
Hp(0.07) = K_{a,\text{ref}} \cdot h_{p,K}(0.07;E,\alpha) \cdot \Delta t \cdot k_{\text{decay}} \cdot k_{\text{attenuation}}
\]

$Hp(0.07)$ : is the personal dose equivalent at 0.07 mm tissue, Sv;

$K_{a,\text{ref}}$ : is the reference air-kerma rate, Gy/s;

$h_{p,K}(0.07;E,\alpha)$ : is the corresponding conversion coefficient for the photon energy $E$, Sv/Gy;

$\Delta t$ : is the irradiation time, s;

$k_{\text{decay}}$ : is the correction factor for decay (S-Cs);

$k_{\text{attenuation}}$ : is the correction factor for air-attenuation (S-Cs)
**Determination of \( H_p(0.07) \) - Betas**

\[
H_p(0.07) = D_{g,\text{ref}} \cdot h_{p,D}(0.07;E,\alpha) \cdot \Delta t \cdot k_{\text{decay}}
\]

- \( H_p(0.07) \): is the personal dose equivalent at 0.07 mm tissue, Sv;
- \( D_{g,\text{ref}} \): is the reference absorbed dose rate at 0.07 mm tissue, Gy/s;
- \( h_{p,D}(0.07;E,\alpha) \): is the corresponding conversion coefficient for the beta energy \( E \), Sv/Gy;
- \( \Delta t \): is the irradiation time, s;
- \( k_{\text{decay}} \): is the correction factor for decay.
## Used Conversion Coefficients, $hp$

<table>
<thead>
<tr>
<th>Radiation quality</th>
<th>Angle of incidence, $\alpha$</th>
<th>Rod $h_{p,K}(0.07;E,\alpha)$ Sv/Gy</th>
<th>Pillar $h_{p,K}(0.07;E,\alpha)$ Sv/Gy</th>
<th>Conversion coefficients adopted from</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-80</td>
<td>0º</td>
<td>1.13 ± 4 %</td>
<td>1.36 ± 4 %</td>
<td>ISO 4037-3</td>
</tr>
<tr>
<td></td>
<td>60º</td>
<td>1.07 ± 4 %</td>
<td>1.20 ± 4 %</td>
<td>VSL spectrum</td>
</tr>
<tr>
<td>RQR 3</td>
<td>0º</td>
<td>1.07 ± 4 %</td>
<td>1.20 ± 4 %</td>
<td>VSL spectrum</td>
</tr>
<tr>
<td>RQR 9</td>
<td>0º</td>
<td>1.12 ± 4 %</td>
<td>1.33 ± 4 %</td>
<td>ISO 12794</td>
</tr>
<tr>
<td>S-Cs</td>
<td>0º</td>
<td>1.12 ± 4 %</td>
<td>1.15 ± 4 %</td>
<td>ISO 12794</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiation quality</th>
<th>Angle of incidence, $\alpha$</th>
<th>Rod $h_{p,D}(0.07;E,\alpha)$ Sv/Gy</th>
<th>Pillar $h_{p,D}(0.07;E,\alpha)$ Sv/Gy</th>
<th>Conversion coefficients adopted from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kr-85</td>
<td>0º</td>
<td>1.00 ± 4 %</td>
<td>1.00 ± 4 %</td>
<td>ISO 6980-3</td>
</tr>
<tr>
<td>Sr-90/Y-90</td>
<td>0º</td>
<td>1.00 ± 6 %</td>
<td>1.00 ± 4 %</td>
<td>ISO 6980-3</td>
</tr>
<tr>
<td></td>
<td>60º</td>
<td>1.16 ± 6 %</td>
<td>1.16 ± 4 %</td>
<td>ISO 6980-3</td>
</tr>
</tbody>
</table>
$h_{p,k}(0.07; E, \alpha)$ for RQR 3 and RQR 9 (example RQR-9)

Mono energetic conversion factors weighted over the measured spectrum
Data from ISO 4037

<table>
<thead>
<tr>
<th>Rod:</th>
<th>RQR-3 = 1.07 Sv/Gy</th>
<th>RQR-9 = 1.12 Sv/Gy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pillar:</td>
<td>RQR-3 = 1.20 Sv/Gy</td>
<td>RQR-9 = 1.33 Sv/Gy</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>4 %</td>
<td></td>
</tr>
</tbody>
</table>
For W-80, RQR3, and RQR9, the quantity air-kerma was realized with the VSL primary air-kerma standard (free-air-chamber) with a standard uncertainty of 0.48 %.

For S-Cs the quantity air-kerma was realized with the VSL primary air-kerma standard (cavity ionization chamber) with a standard uncertainty of 0.75 %.

For $^{90}\text{Sr}/^{90}\text{Y}$ beta rays a Buchler BSS-1 was used. The BSS-1 is traceable to PTB. The standard uncertainty in the quantity $D_g(0.07)$ is 1.2 %.

For $^{85}\text{Kr}$ beta rays an ISOTrak BSS-2 were used. The BSS-2 is traceable to PTB. The standard uncertainty in the quantity $D_g(0.07)$ is 0.8 %.
HV-generator : Philips MG324 320 kV CP
X-ray tube : Philips MC321, 4 mm Be, W-anode (26°).
HV calibration : HPGe-spectrometer, uncertainty 1.1 %.

The primary x-ray beam was collimated by two tungsten diaphragms to define a homogeneous circular field. The monitor is an unsealed transmission ionization chamber.
For the irradiations with S-Cs a low scatter collimated-beam facility from Veenstra Instruments, type DIR-101, was used. 

\[ Hp(0.07) \text{ nominal} = 150 \text{ mSv/h} \]

The primary gamma ray beam is collimated with a conical ring collimator according to ISO 4037.

Available air-Kerma rate:
Cs-137: 300 nGy/h – 0.5 Gy/h
Co-60: 300 nGy/h – 0.2 Gy/h

Conversion coefficients for \( H_p(d) \) and \( H^*(10) \) adopted from ISO 4037 and ISO 12794.
The BSS-1 complies with the recommendations of ISO 6980 for series 2 reference radiation fields.

\[ D_g(0.07) \text{ nominal: } 120 \text{ mGy/h} \]
The BSS-2 complies with the recommendations of ISO 6980 for series 1 reference radiation fields. $Dg(0.07)$ nominal: 50 mGy/h

The irradiations with Kr-85 were carried out in the laboratory of LCW in Dongen (NL). (Sep 2, 2015 – Sep 9, 2015)
The location of the dosemeter reference point was not always specified by the participant’s application form.

Decided: reference point at the rear-side of the dosemeter and position in the point of measurement (= phantoms’ surface at SDD).

- Differences are 5 mm at maximum and were considered in the uncertainty budget,
- Adjustments in positioning between irradiations were not necessary.
Decided dosemeter reference point = reference point of measurement = rear side at phantoms' surface

Beam axis and dosemeter reference-direction

Source-Detector-Distance (SDD)
Preparation of the phantoms and dosemeters at VSL and LCW.
Preparing of the Phantoms

The dosemeters were fixed with a mutual center-to-center distance of approximately 40 mm.
The phantom was positioned perpendicular to the beam axis. The point of measurement (phantom’s surface) was aligned with cross-lasers.
According to ISO 4037 a PMMA build-up plate of 2 mm thickness was used.

The distance between the build-up plate and the front surface of the phantom was approximately 15 mm.
Set-up for Sr-90 and Kr-85 (0°)

Alignment of the point of measurement (phantom’s surface) at the source-detector-distance (SDD) of 30 cm with the distance spacer.
Set-Up for Angle of Incidence, $\alpha = 60^\circ$

$SDD$  
$\alpha = 0^\circ$  
$SDD$  
$\alpha = 60^\circ$  
$SDD + (\frac{1}{4}d)$  
$\alpha = 60^\circ$  
$SDD$

Reference point
Set-Up for Sr-90/Y-90 and $\alpha = 60^\circ$

Moving from $0^\circ$ to $60^\circ$ and aligned the reference point at the point of measurement using the distance spacer at SDD. (Same for the Rod phantom).
Set-Up for RQR3 and $\alpha = 60^\circ$

Moving the pillar from $0^\circ$ to $60^\circ$ and aligned the reference point with a X-and Y-translation and cross-lasers at the point of measurement.
Impression of the Irradiations Pillar

- W80
- RQR3(60°)
- RQR9
- S-Cs
- Sr-90(60°)
- Kr-85

(Random picture choice)
Impression of the Irradiations Rod

W80  RQR3(60°)  RQR9
S-Cs  Sr-90(60°)  Kr-85

(Random picture choice)
Uncertainty in $Hp(0.07)$

Mainly:

- Standard uncertainty of the conversion coefficients; 2% for photons to 3% for Sr-90/Y-90 and the rod.
- Set-up at the SDD for betas: standard uncertainty of 2%.
- Use of a PMMA build-up plate for S-Cs; standard uncertainty of 1%.

Neglected:

- The mutual influence of dosemeters (two or four) in a simultaneous irradiation.

Determined:

- In accordance with the GUM 'Evaluation of measurement data – Guide to the expression of uncertainty in measurement'.
<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Phantom</th>
<th>Uncertainty at $k = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W80</td>
<td>pillar and rod</td>
<td>4.6 %</td>
</tr>
<tr>
<td>RQR3</td>
<td>pillar and rod</td>
<td>4.6 %</td>
</tr>
<tr>
<td>RQR3(60°)</td>
<td>pillar and rod</td>
<td>4.6 %</td>
</tr>
<tr>
<td>RQR9-L</td>
<td>pillar and rod</td>
<td>4.6 %</td>
</tr>
<tr>
<td>RQR9-H</td>
<td>pillar and rod</td>
<td>4.6 %</td>
</tr>
<tr>
<td>S-Cs</td>
<td>pillar and rod</td>
<td>5.0 %</td>
</tr>
<tr>
<td>Mix</td>
<td>pillar</td>
<td>4.2 %</td>
</tr>
<tr>
<td>Mix</td>
<td>rod</td>
<td>4.8 %</td>
</tr>
<tr>
<td>Sr-90</td>
<td>pillar</td>
<td>6.8 %</td>
</tr>
<tr>
<td>Sr-90</td>
<td>rod</td>
<td>8.1 %</td>
</tr>
<tr>
<td>Sr-90(60°)</td>
<td>pillar</td>
<td>6.8 %</td>
</tr>
<tr>
<td>Sr-90(60°)</td>
<td>rod</td>
<td>8.1 %</td>
</tr>
<tr>
<td>Kr-85</td>
<td>pillar and rod</td>
<td>6.0 %</td>
</tr>
</tbody>
</table>
Period of Irradiation and Storage

July 12, 2015: arrival first batch from Seibersdorf Lab,
August 28, 2015: arrival second batch from Seibersdorf Lab,
September 18, 2015: return to Seibersdorf Lab.

All dosemeters were stored in the control room of the laboratory. Background radiation varied between 90 nSv/h and 120 nSv/h. EPD measurement (almost 70 days): 0.12 mSv

During storage and irradiation:
Temperature: 19 °C and 22 °C,
Atmospheric pressure: 99 kPa and 103 kPa,
Relative humidity: 45 % and 55 %.
Finally…

I know what I did last summer…

receiving 2190 dosemeters,
803 irradiations (and pictures),
1606 irradiated dosemeters,
Consuming of a few rolls of Scotch adhesive tape,
tie wraps and elastic bands,
a lot of patience,
and lessons to learn…

Unfortunately wrong irradiated:
2 systems: 2 dosemeters
1 system: 6 dosemeters
...73 Certificates of Irradiation
…73 Certificates of Irradiation

Thank you for your attention

Information: Frans Bader
fbader@vsl.nl
Relative Measurements Sr-90/Y-90 and Kr-85

For Sr-90/Y-90

\[
\frac{D_{(Sr,LCW)}}{D_{(Sr,VSL)}} = \frac{M_{(Sr,LCW)}}{M_{(Sr,VSL)}} = 
\]

For Kr-85

\[
\frac{D_{(Kr,LCW)}}{D_{(Sr,LCW)}} = \frac{M_{(Kr,LCW)}}{M_{(Sr,LCW)}} = \\
\frac{D_{(Kr,LCW)}}{D_{(Sr,VSL)}} = \frac{M_{(Kr,LCW)}}{M_{(Sr,VSL)}} = 
\]

\[\leq 1.5\%\]

\(D\) is according to PTB certificate

\(M\) is ion-chamber measurement
Set-Up for Angle of Incidence, $\alpha = 60^\circ$

$d$(pillar) = 73 mm $\Rightarrow$ $\frac{1}{4}d = 18.25$ mm
$d$ (rod) = 19 mm $\Rightarrow$ $\frac{1}{4}d = 4.75$ mm