Improving personal dosimetry of medical staff wearing radioprotective garments: Design of a new whole-body dosimeter using Monte Carlo simulations

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In **IR/IC procedures** medical staff wears **leaded RP garments (RPG)** for protection against scattered ionizing radiation coming from the patient.

**Challenge** for WB personal dosimetry:

$H_p(10)$ dosimeter gives **wrong estimation** of effective dose **when wearing RP garments ($E_{RPG}$)**

- Dose **over apron**, $H_{over}$ → **overestimation** of $E_{RPG}$
  (ignores shielding of RP garments)
- Dose **under apron**, $H_{under}$ → **underestimation** of $E_{RPG}$
  (ignores exposure of uncovered body parts)
Proposed personal methodologies currently used:

- **Single dosimetry (SD)** with corrective factor:
  \[ E_{SD} = \frac{H_{over}}{\gamma} \]
  \[ E_{SD} = \delta H_{under} \]

- **Double dosimetry (DD)** with algorithm:
  \[ E_{DD} = \beta H_{over} + \alpha H_{under} \]

- **High uncertainties**
- **Less cost effective (DD)**
- **Not practical (DD)**
- **No consensus on best method...**

→ **Providing a good estimation** of \( E_{RPG} \) for all relevant exposure conditions remains a challenge
Introduction – **Current personal dosimetry of IR/IC medical staff**

- ICRP recognizes the limited accuracy of these methods

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ICRP Publication 139

(Tsapaki et al., 2009). In addition, there is difficulty in comparing reported dosimetry results because of significant differences in dosimetric methods used in each study (Kim et al., 2008), as well as lack of consensus on the number of dosimeters that may be used, and where the dosimeters should be worn on the body. The fact that none of the algorithms estimate effective dose adequately for all types of procedures poses difficulties in reaching a worldwide consensus regarding which of them should be used.

Introduction – **Performance of DD methods**

- **Simulated performance** of different DD algorithms for monoenergetic photons and X-ray spectra
- $H_p(10)$ dosimeters placed over and under a 0.5 mm-thick Pb shield

$$E_{DD} = \beta H_{over} + \alpha H_{under}$$

**Simulated performance of different DD algorithms** for monoenergetic photons and X-ray spectra. $H_p(10)$ dosimeters placed over and under a 0.5 mm-thick Pb shield.

- Large uncertainties in estimation of $E_{RPG}$
Final goal

To develop a passive personal **whole body dosimeter** suitable for IR/IC medical staff wearing RP garments

- One single dosimeter
- Direct estimation of effective dose (without intermediate step of $H_p(10)$)

1. Calculate **angular & energy dependence** of the effective dose when RPG are worn ($E_{RPG}$) → reference for dosimeter design

2. Design new dosimeter using Monte Carlo calculations
Characterisation of the effective dose wearing RP garments ($E_{RPG}$):

- **Effective dose / air kerma** coefficients
  - According to ICRP 103

- ICRP 110 reference male phantom

- **RP apron + thyroid collar**
  - 0.5 mm Pb, realistic geometry

- Whole-body exposures:
  - Unidirectional **photon beams**
  - **Monoenergetic** and X-ray qualities N, W, RQR with max energy ≤ 120 keV
  - ≠ angles on transverse plane

- Radiation transport Monte Carlo code **MCNPX 2.7.0**
Materials & Methods – **Effective dose with/without RP garments**

### Energy dependence of $E(0^\circ)$ with & without RPG

- $E_{RPG}$ lower (attenuating effect of RPG)
- **Different energy response**: effect of the K-edge of Pb at 88 keV
Materials & Methods – Effective dose with RP garments

- **Non-monotonic angular dependence** due to partial coverage of RP garments
- **Reference data** for designing new dosimeter
Materials & Methods – **Design of new dosimeter**

- Design optimization aided by radiation transport simulations in MCNPX 2.7.0
- **Preliminary dosimeter model** as a proof-of-concept → principle applied in a **realistic model**

- **Imposed condition:** **dosimeter worn over RP garments**
  - 0.5 mm Pb flat shield modelled below dosimeter
- Energy and angular response for **same photon exposures as for** $E_{RPG}$

Design parameters:
- Dosimetric detectors:
  - **Type:** TLD, RPLD
  - **Number:** 1, 2, … (combined dose)
- Elements around detectors:
  - Material composition, shape, thickness, position

**Optimized** so that energy and angular response of **new dosimeter** $\approx E_{RPG}$
Materials & Methods – Design of new dosimeter

- **Filter attenuation properties** → shape energy response
  - Front filters → attenuate incident beam (reduce response)
  - Rear filters → produce backscatter (enhance sensitivity) and/or attenuate backscatter from components below

- **Filter shape and frontal area** → shape angular response

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**K-edge**: selectively favor these effects in specific energy ranges

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- From NIST photon mass attenuation coefficients. [https://dx.doi.org/10.18434/T4D01F](https://dx.doi.org/10.18434/T4D01F)
Materials & Methods – **Design of new dosimeter**

### Energy dependence of different detectors

\[ D_{\text{detector}} / K_{\text{air}} \]

- **FD-7 glass (RPLD)**
- **LiF:Mg,Ti (TLD)**

### Design of new dosimeter

\[ H_p(10) \]

### Energy dependence of \( E_{RPG} \)

\[ (E_{RPG} / K_{air}) \]

- **0°**
- **30°**
- **45°**
- **75°**

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Materials & Methods – Estimation of $E_{RPG}$ instead of $H_p(10)$

- Dosimeter measurement approach (direct estimation of $E_{RPG}$) similar to
- New proposed ICRU/ICRP approach for operational quantities \(^{(a,b)}\)
  - Personal dose ($H_p$) based on effective dose conversion coefficients ($E/\phi$) calculated with ICRP110 phantoms
  - More faithful estimation of $E$

**Concept for new approach**

*For control of effective dose*

Operational quantities are defined based on effective dose

- We have reference values of effective dose conversion coefficients calculated using the reference phantoms (ICRP110, 116)

**Individual monitoring**

- Personal dose equivalent
  \[ H_p = h_E \phi \]

- Personal absorbed dose to the lens
  \[ D_p,\text{ lens} = d_{\text{lens}} \phi \]

- Personal absorbed dose to the local skin
  \[ D_p,\text{ local skin} = d_{\text{local skin}} \phi \]

- Conversion coefficients, $h_E$, $d_{\text{lens}}$, and $d_{\text{local skin}}$, are given for various angles, $\alpha$
- Calibration phantoms for personal dosimeters remain unchanged


New dosimeter – Proof of concept

Preliminary model based on thermo-luminescent detectors (TLDs)
Results – Simplified model using TLDs

- Dosimeter’s dose calculated from the dose of 2 TLDs of LiF:Mg,Ti

\[ D_{\text{dosimeter}} = \alpha (D_{\text{TLD2}} + \beta D_{\text{TLD1}}) \]

- 0.5 mm Pb shield (RP garments)
- Cu to limit influence of Pb backscatter (X-ray fluorescence)

Simulation error \( D_{\text{dosimeter}} < 4\% \)
Results – Performance of simplified model using TLDs

- Comparison of $D_{\text{dosimeter}}$ with $E_{\text{RPG}}$
- Monoenergetic beams parallel to transverse plane

\[ D_{\text{dosimeter}} = 0.33 \left( D_{\text{TLD2}} + 0.1 D_{\text{TLD1}} \right) \]

$E_{\text{RPG}}$ overestimation $\leq 30\%$
$E_{\text{RPG}}$ underestimation $\leq 20\%$
Results – Performance of simplified model using TLDs

- More realistic beams (spectra) parallel to transverse plane

\[ D_{\text{dosimeter}} = 0.33 (D_{TLD2} + 0.1 D_{TLD1}) \]

All X-ray qualities:

\[ D_{\text{dosimeter}} = E_{\text{RPG}} \pm 20\% \text{ deviation} \]

Concept proved ✓
New whole-body dosimeter

Realistic model based on radio-photo-luminescent (RPL) detectors
**Materials & Methods – Reference badge geometry**

- **Realistic geometry**: personal badge of Chiyoda Technol Corporation (Japan) used as reference
  - Passive dosimeter
  - Currently used for $H_p(10)$ and $H_p(0.07)$ monitoring in Japan, France, Switzerland
  - Radiosensitive detector: **Ag-doped phosphate RPL glass**
  - 5 RPL measurement volumes with different radiation filtration

- **New dosimeter:**
  - Only plastic case and RPL glass modelled

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Results – **Design concept of the New Dosimeter**

- Only 2 detection volumes required for estimating $E_{RPG}$
- High and low Z filters fitting within Chiyoda’s plastic case → RPL readout with current reader

$$D_{dosimeter} = \alpha (D_{det2} + \beta D_{det1})$$

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Material</th>
<th>Thickness (mm)</th>
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<td>Case front</td>
<td>ABS</td>
<td>Case back</td>
<td>ABS</td>
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<tr>
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<td>Al, Ti</td>
<td>Front filters</td>
<td>Bi, Pb, Cu</td>
</tr>
<tr>
<td>Back filters</td>
<td>-</td>
<td>Back filters</td>
<td>W, Sn</td>
</tr>
<tr>
<td>Case back</td>
<td>ABS</td>
<td>Case back</td>
<td>ABS</td>
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</tbody>
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$D_{det1}$ and $D_{det2}$ are the RPL measurement volumes. $\alpha$ and $\beta$ are coefficients determined empirically. $\phi$ is the incident photon angle.

Results – New dosimeter dose response

- Energy and angular dependence for monoenergetic beams

Simulation error $D_{\text{dosimeter}} < 7\%$
Results – **Performance of new dosimeter**

\[ D_{\text{dosimeter}} / E_{\text{RPG}} : \text{Monoenergetic beams} \]

\[ D_{\text{dosimeter}} = 0.48 \left( D_{\text{det2}} + 0.01 D_{\text{det1}} \right) \]

\( E_{\text{RPG}} \) overestimation ≤ 30%

\( E_{\text{RPG}} \) underestimation ≤ 50% (or ≤ 25% above 20 keV)
**Results – Performance of new dosimeter**

\[ D_{\text{dosimeter}} = E_{\text{RPG}} \pm 20\% \text{ deviation} \]

\[ E_{\text{RPG}} \text{ overestimation} \leq 5\% \]
\[ E_{\text{RPG}} \text{ underestimation} \leq 15\% \]

Energy qualities more similar to radiology X-rays
\[ E_{\text{RPG}} \text{ overestimation} \leq 10\% \]
\[ E_{\text{RPG}} \text{ underestimation} \leq 15\% \]

\[ D_{\text{dosimeter}} = E_{\text{RPG}} \pm 15\% \]

**SD and DD methods:**
- \( E_{\text{RPG}} \) underestimations > 50%
- \( E_{\text{RPG}} \) overestimations > 200%
Conclusions

- Concept of a personal dosimeter suitable for estimating the effective dose when wearing lead garments proved feasible using Monte Carlo simulations
  - Single over-apron dosimeter for direct estimation of $E_{\text{RPG}}$
  - Realistic model based on RPL detectors

- Dosimeter performance in silico significantly better than current methods
  - N, W, RQR spectra: $D_{\text{dosimeter}} = E_{\text{RPG}} \pm 20%$

- This dosimeter has the potential to improve personal dosimetry of IR/IC staff
  - Reduce uncertainty in the estimation of the effective dose
  - Offer more practical & reliable solution: one single dosimeter worn over RP garments
Angular dependence of $E_{\text{RPG}}$ more pronounced in sagittal plane (flat geom RPG)

- Further optimization of dosimeter dose response required
Perspectives

- Verify dosimeter performance for clinical IR/IC (realistic) exposures
  - Physician & dosimeter exposures using scatter beams from typical patient irradiations

- Investigate $E_{RPG}$ and dosimeter performance for other RPG specifications
  - Further development of dosimeter required?

- Manufacturing & experimental testing of first prototype
  - Collaboration with Chiyoda Technol Corporation


New dosimeter:


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