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

Clarita Saldarriaga Vargas, Corinne Amalberto, Lara Struelens, Filip Vanhavere

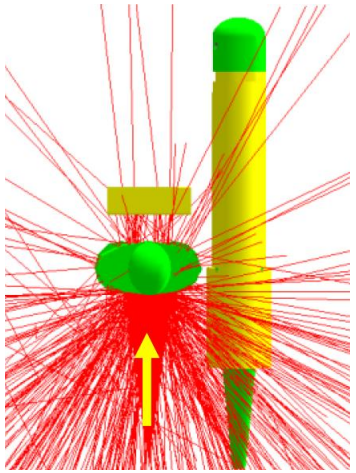
Belgian Nuclear Research Centre (SCK•CEN)
Institute for the Environment, Health and Safety
Radiation Protection, Dosimetry and Calibrations
csvargas@sckcen.be

SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

BVS-ABR Young Scientist Event
19 October 2018 – Ghent, Belgium

Introduction

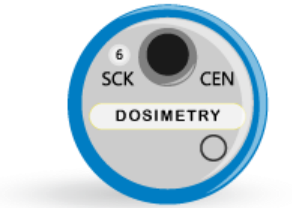
- In **IR/IC procedures** medical staff wears **leaded RP garments (RPG)** for protection against scattered ionizing radiation coming from the patient

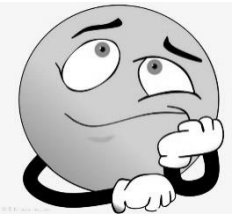


- **Challenge** for WB personal dosimetry:

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

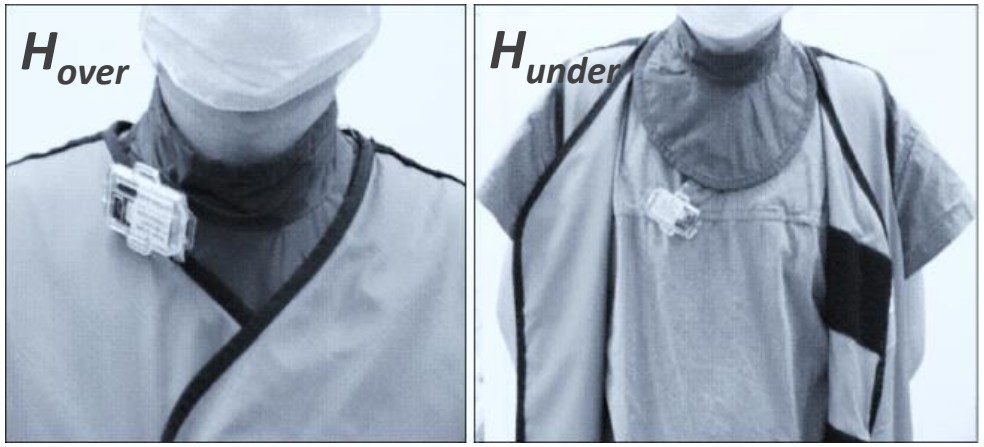
  - Dose **over apron**, H_{over} → **overestimation** of E_{RPG} (ignores shielding of RP garments)
  - Dose **under apron**, H_{under} → **underestimation** of E_{RPG} (ignores exposure of uncovered body parts)





Introduction – **Current personal dosimetry of IR/IC medical staff**

- Proposed personal methodologies currently used:
  - Single dosimetry (SD) with corrective factor: $E_{SD} = H_{over} / \gamma$ $E_{SD} = \delta H_{under}$
  - 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…

  - **Overestimations** = 200% to >1000%
  - **Underestimations** >50%

→ **Providing a good estimation** of E_{RPG} for *all* relevant exposure conditions **remains a challenge**

- Saldarriaga Vargas C. *et al.* Radiat. Prot. Dosim. 178(1), (2018).
- Järvinen, H. *et al.* Radiat. Prot. Dosim. 129(1-3), (2008).

Introduction – **Current personal dosimetry of IR/IC medical staff**

- ICRP recognizes the limited accuracy of these methods

ICRP Publication 139

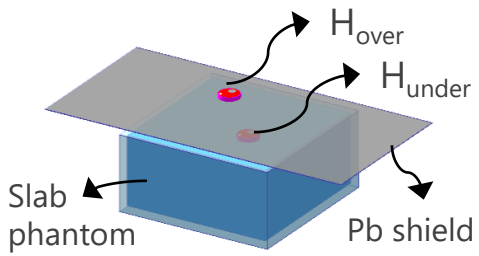
(Tsapaki et al., 2009). In addition, there is difficulty in comparing reported dosimetry results because of significant differences in dosimetric methods used in each study (Kim et al., 2008), as well as lack of consensus on the number of dosimeters that may be used, and where the dosimeters should be 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.

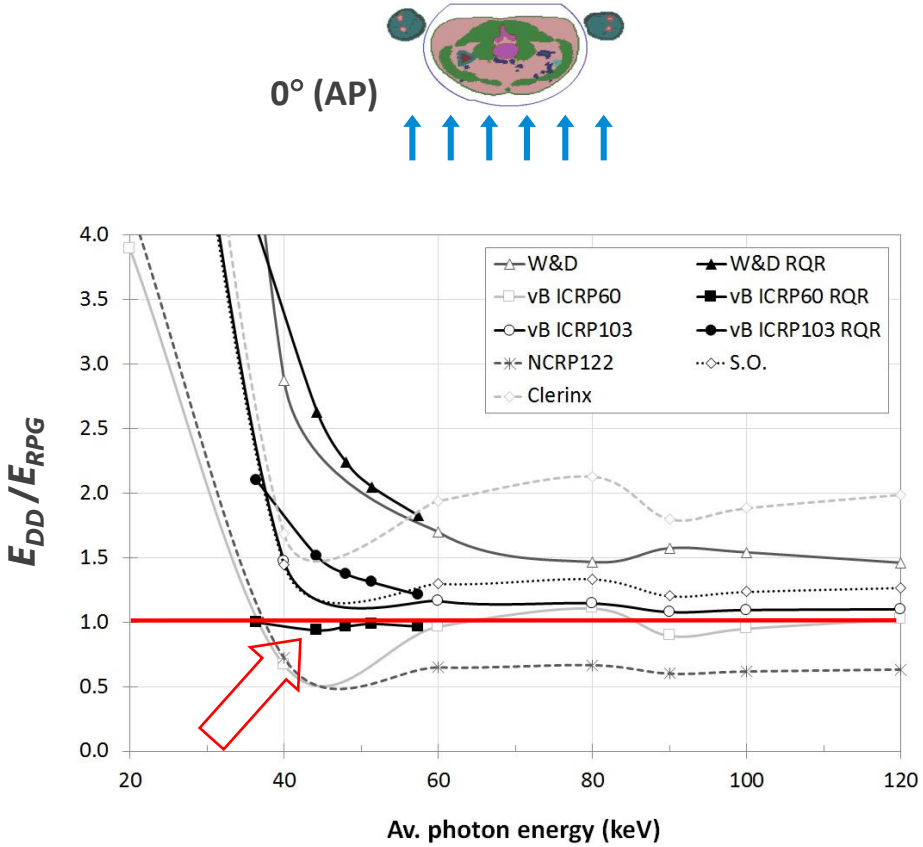
- ICRP Publication 85. Ann ICRP 30(2), (2000).
- ICRP Publication 139. Ann ICRP 47(2), (2018).

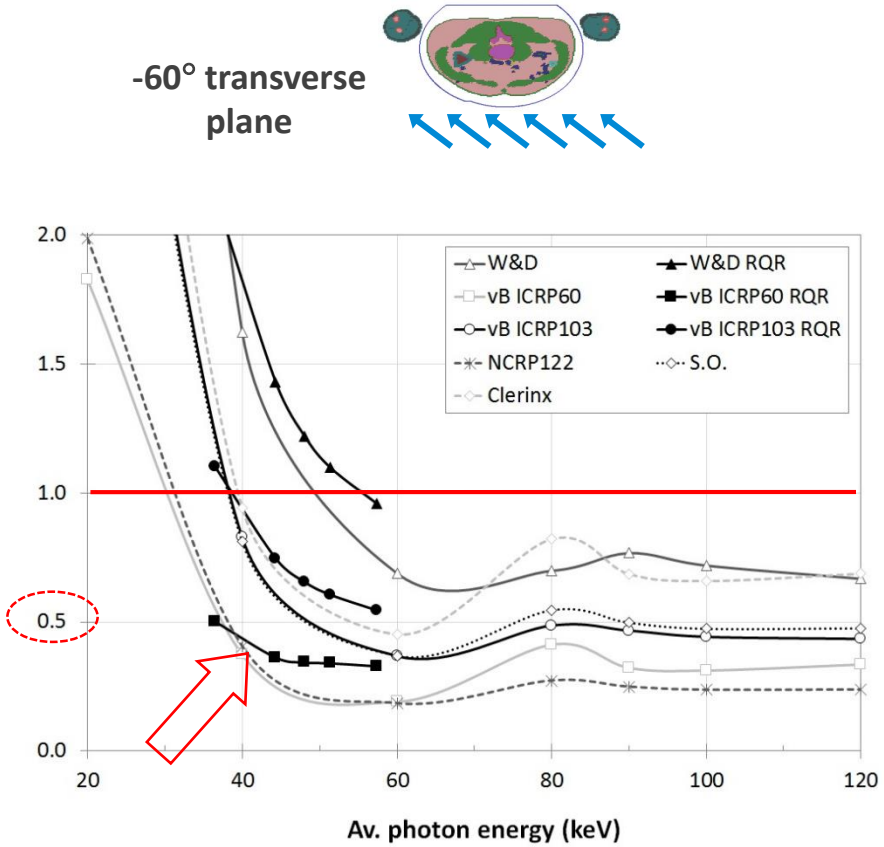
Introduction – **Performance of DD methods**

- **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

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







large uncertainties in estimation of E_{RPG}

- Saldarriaga Vargas C. *et al.* Radiat. Prot. Dosim. 178(1), (2018)

Final goal

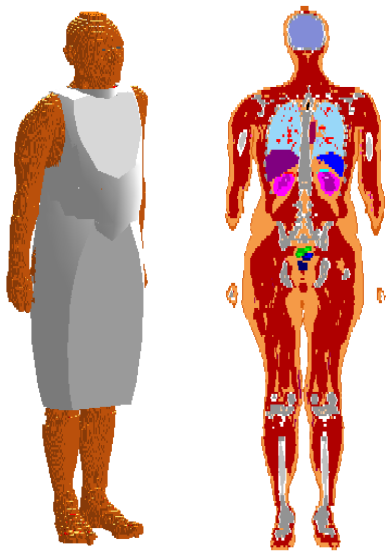
To develop a passive personal **whole body dosimeter** suitable for **IR/IC medical staff** wearing **RP garments**

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

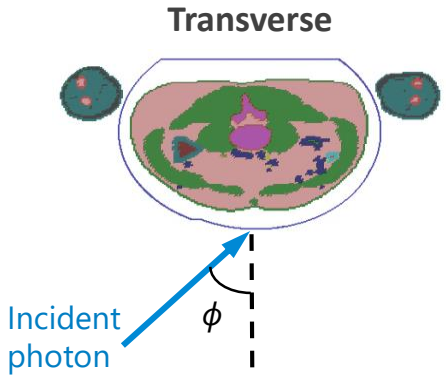
1. Calculate angular & energy dependence of the effective dose when RPG are worn (E_{RPG}) → reference for dosimeter design
2. Design new dosimeter using Monte Carlo calculations

Materials and Methods – **Effective dose with RPG**

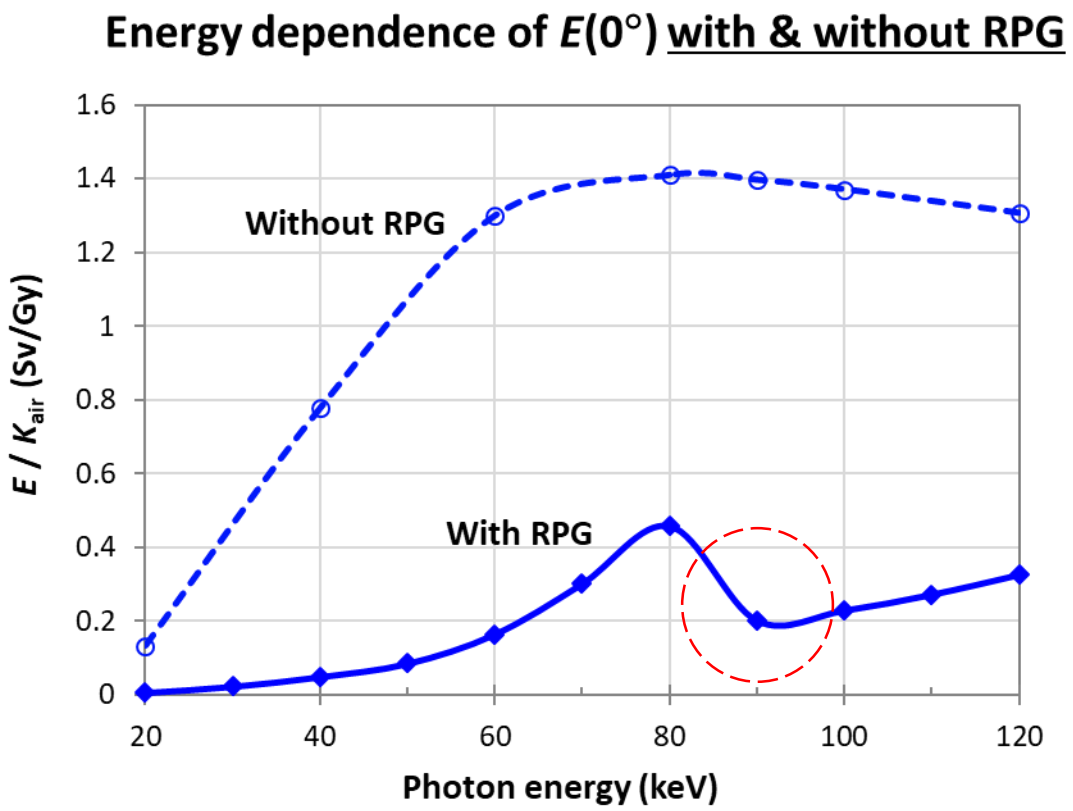
Characterisation of the effective dose wearing RP garments (E_{RPG}):

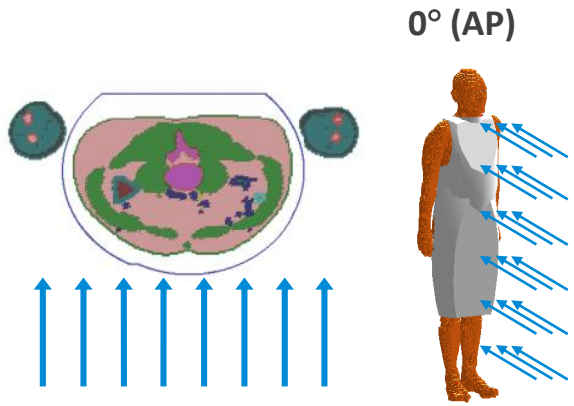


- **Effective dose / air kerma** coefficients
  - According to ICRP 103
- ICRP 110 reference male phantom
- **RP apron + thyroid collar**
  - 0.5 mm Pb, realistic geometry
- Whole-body exposures:
  - Unidirectional **photon beams**
  - **Monoenergetic** and **X-ray qualities N, W, RQR** with max energy **≤ 120 keV**
  - ≠ angles on transverse plane
- Radiation transport Monte Carlo code **MCNPX 2.7.0**



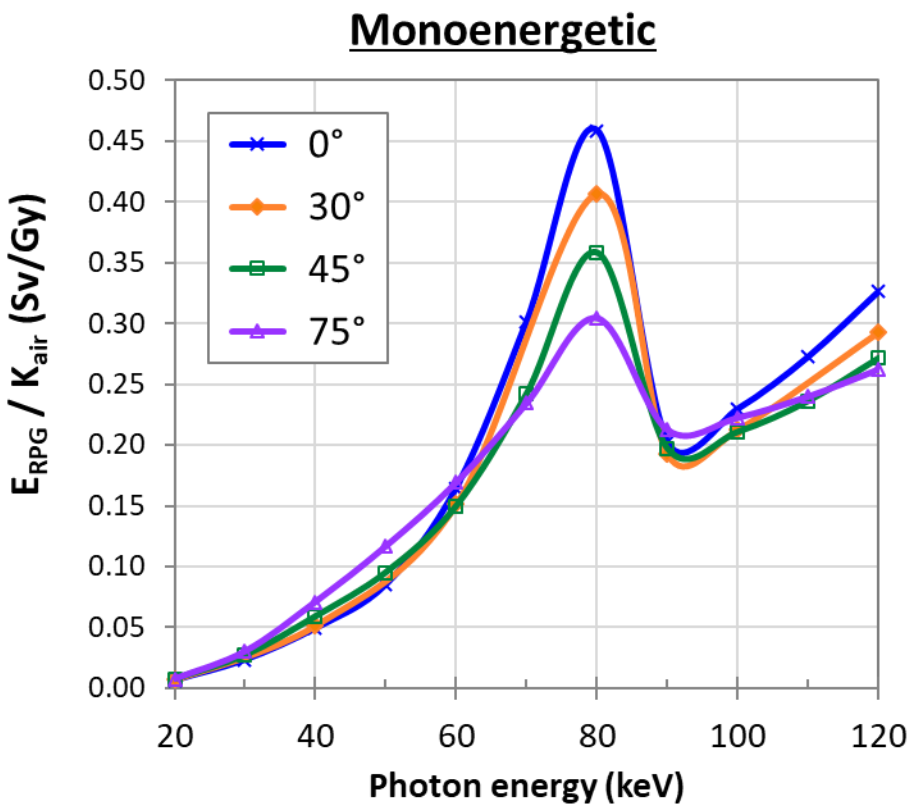
Materials & Methods – **Effective dose with/without RP garments**

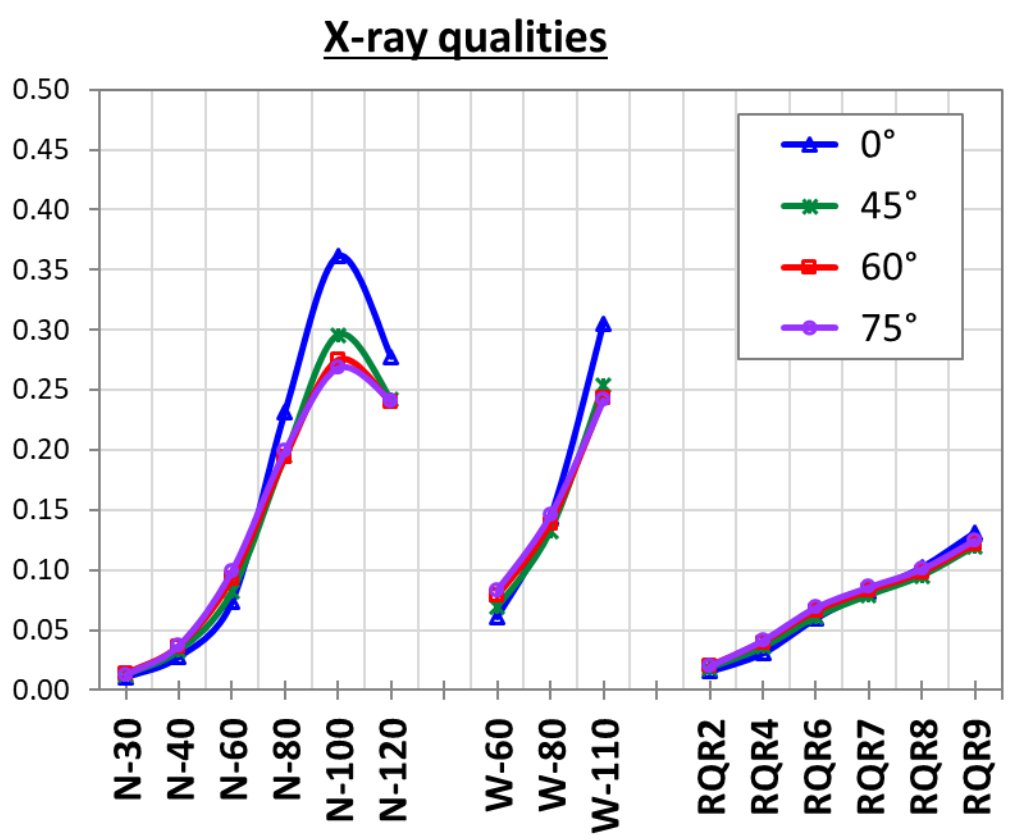


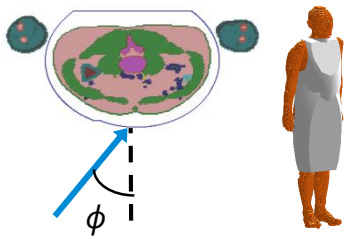


- E_{RPG} lower (attenuating effect of RPG)
- **Different energy response**: effect of the **K-edge of Pb** at 88 keV

Materials & Methods – **Effective dose with RP garments**





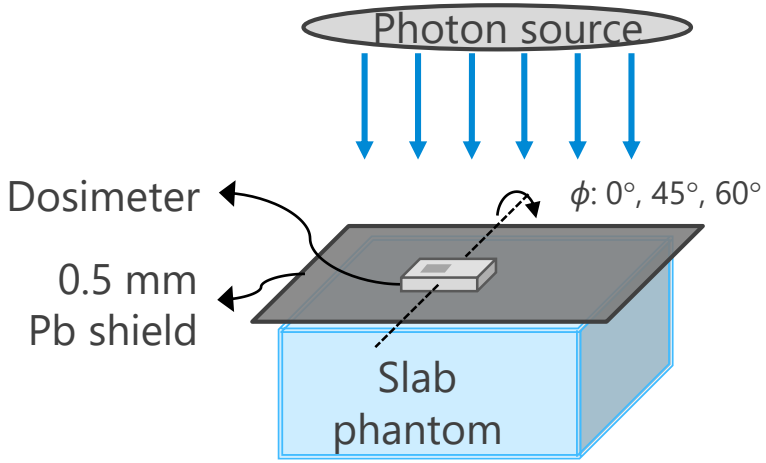


- **Non-monotonic angular dependence** due to partial coverage of RP garments
- **Reference data** for designing new dosimeter

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

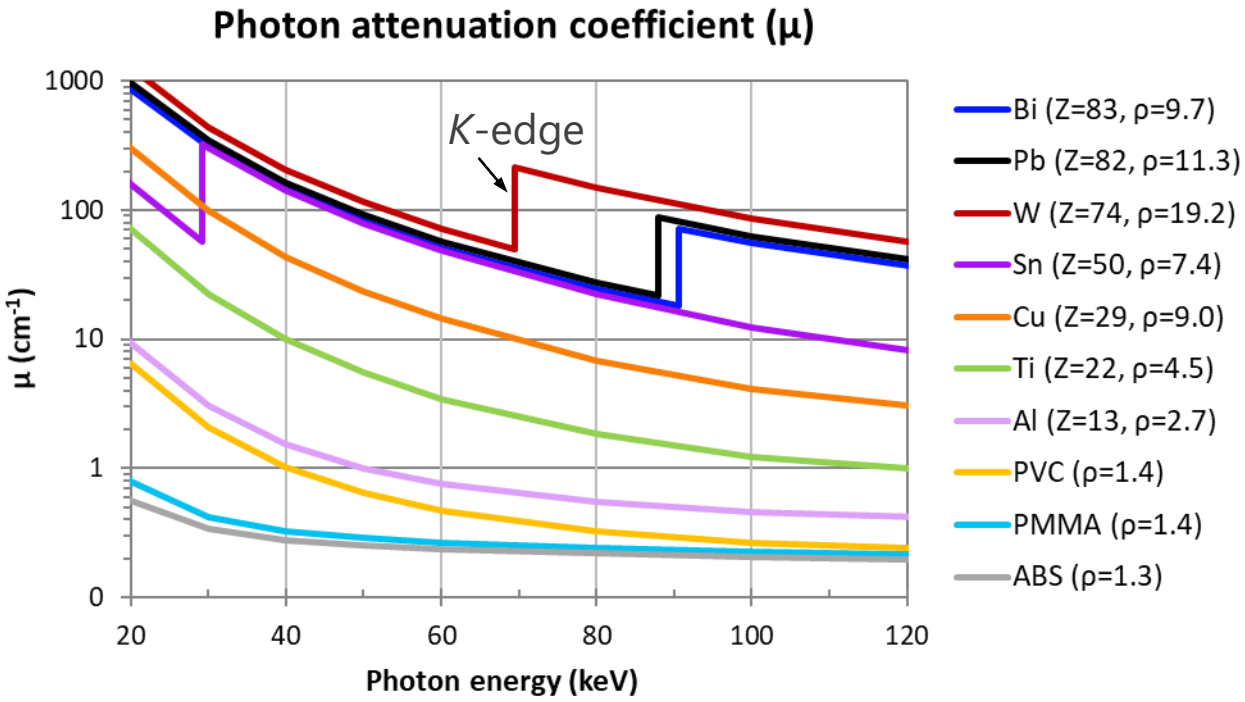
Optimized so that energy and angular response of **new dosimeter ≈ E_{RPG}**

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

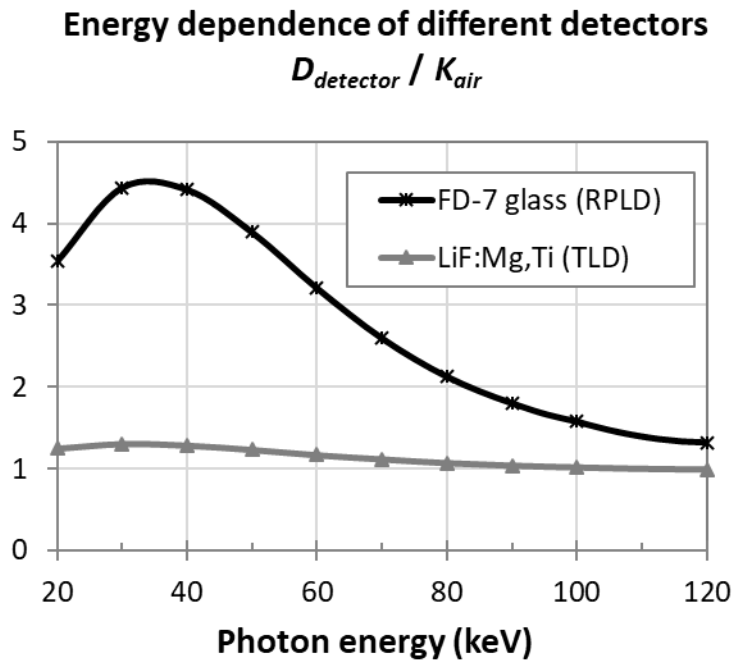
} ***K*-edge**: *selectively* favor these effects in specific energy ranges

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



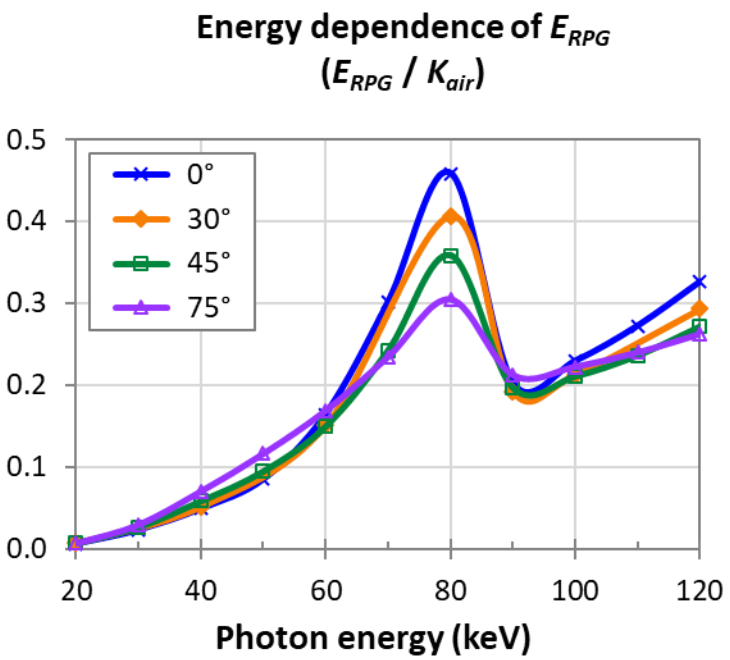
- From NIST photon mass attenuation coefficients. https://dx.doi.org/10.18434/T4D01F

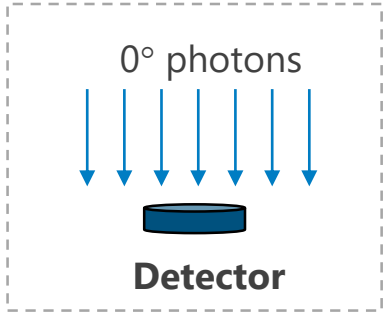
Materials & Methods – **Design of new dosimeter**



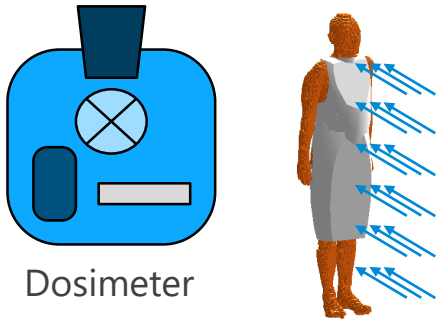
Design of new dosimeter

~~$H_p(10)$~~





Free space



Dosimeter

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/Φ) calculated with ICRP110 phantoms
  - More faithful estimation of E

Concept for new approach (a)

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 (a)

- Personal dose equivalent

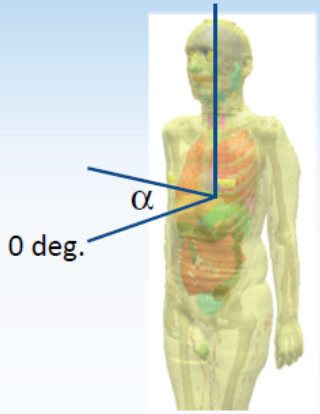
$$H_p = h_E \, \Phi$$

- Personal absorbed dose to the lens

$$D_{p,\,lens} = d_{lens} \, \Phi$$

- Personal absorbed dose to the local skin

$$D_{p,\,local\ skin} = d_{local\ skin} \, \Phi$$



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

ICRP INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

21

(a) Extracts from: Endo A. The Operational Quantities and New Approach by ICRU. ICRP 2015 Symposium Presentations. http://www.icrp.org/page.asp?id=246
(b) Endo A. Operational Quantities and New Approach by ICRU. Annals of the ICRP 45(1), (2016).

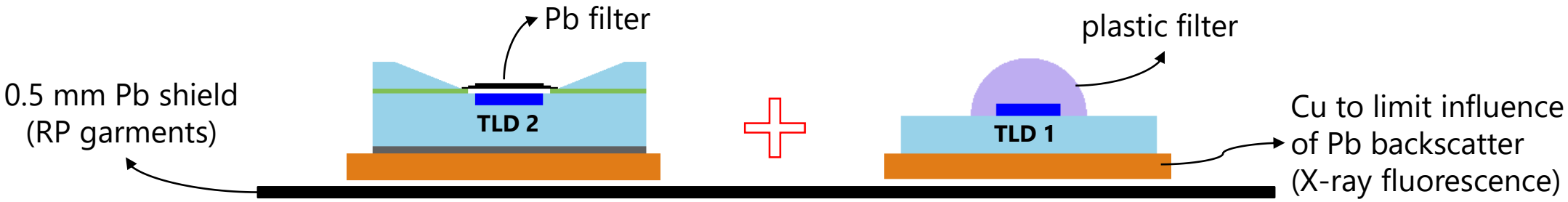
New dosimeter – Proof of concept

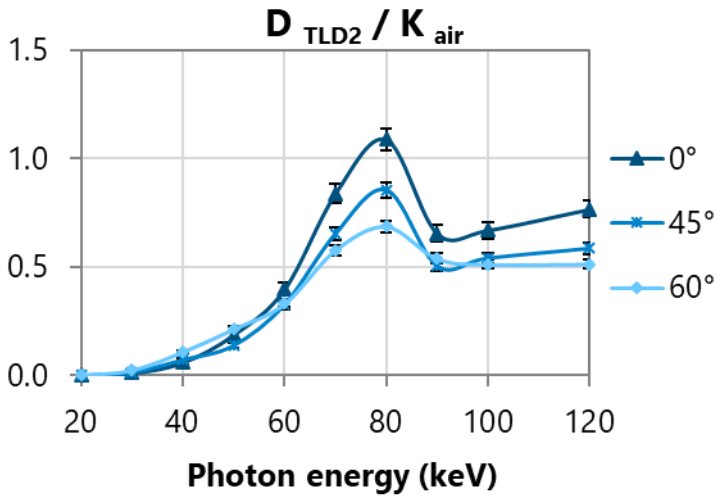
Preliminary model based on
thermo-luminescent detectors (TLDs)

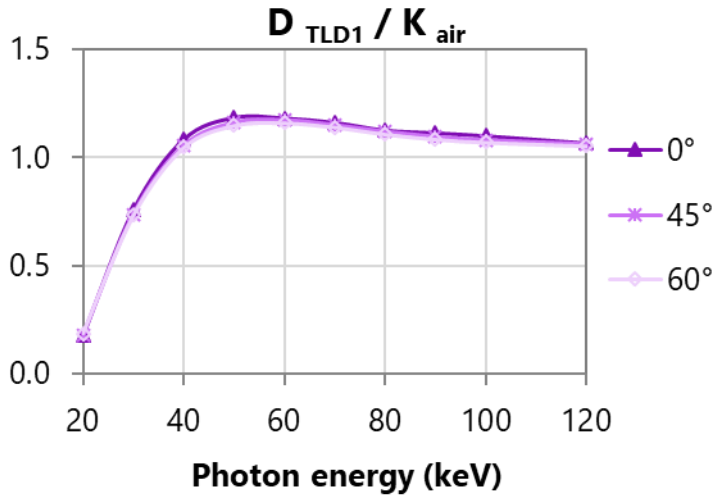
Results – **Simplified model using TLDs**

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

$$D_{dosimeter} = \alpha \left(D_{TLD2} + \beta D_{TLD1}\right)$$



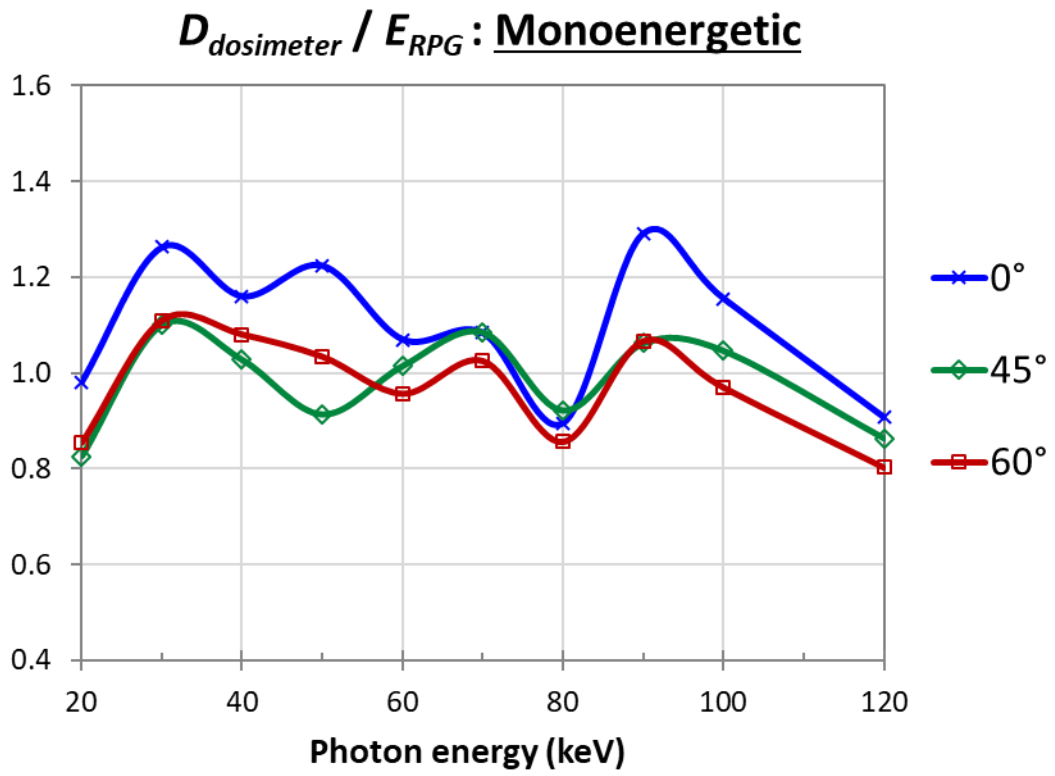




Simulation error $D_{dosimeter}$ < 4%

Results – **Performance of simplified model using TLDs**

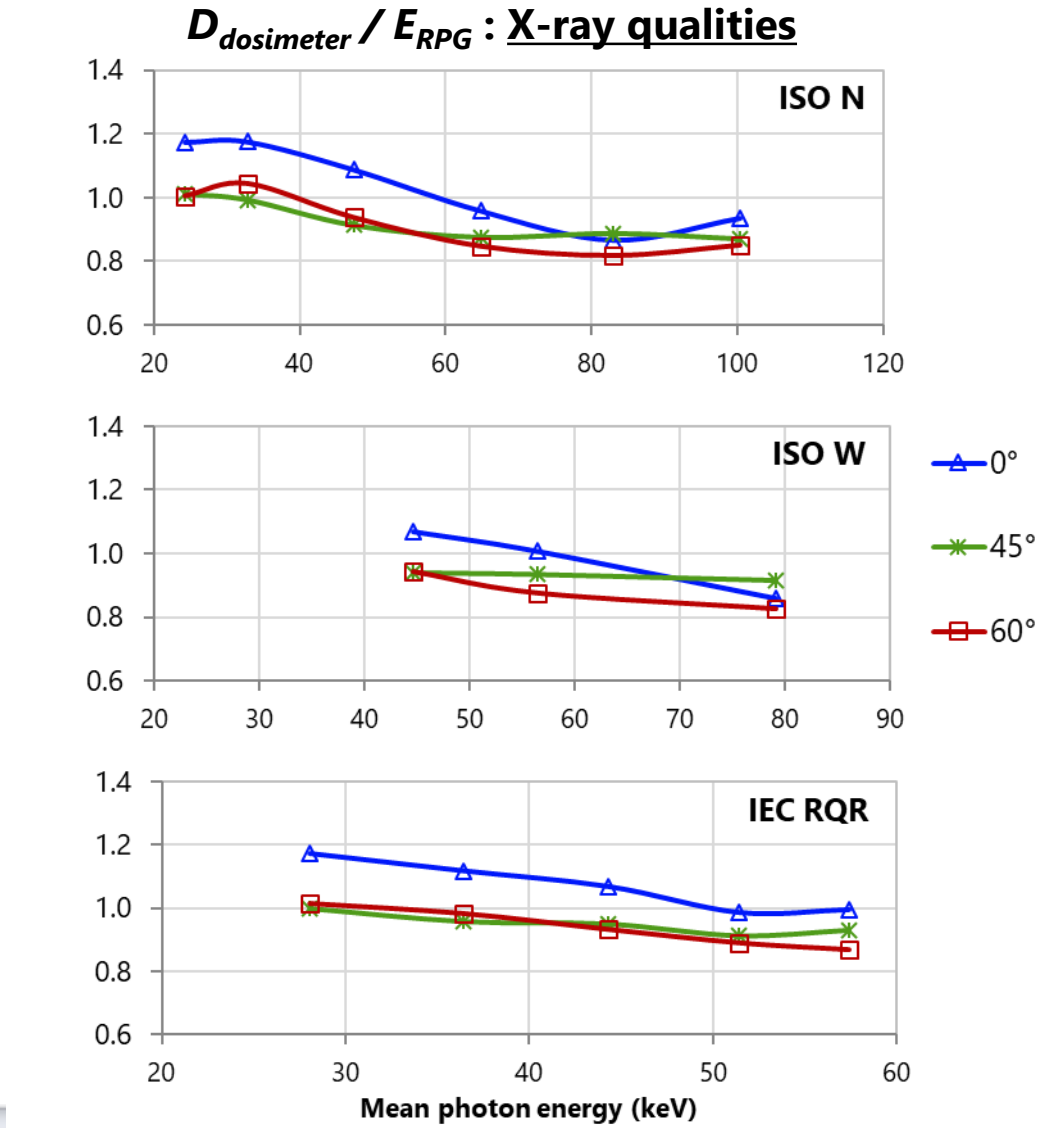
- Comparison of $D_{dosimeter}$ with E_{RPG}
- Monoenergetic beams parallel to transverse plane



$$D_{dosimeter} = 0.33\,(D_{TLD2} + 0.1\,D_{TLD1})$$

E_{RPG} overestimation ≤ 30%
E_{RPG} underestimation ≤ 20%

Results – **Performance of simplified model using TLDs**



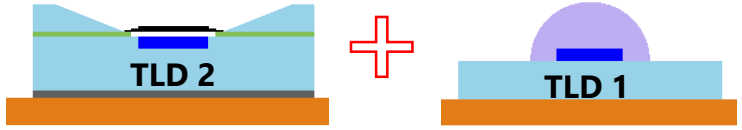
- More **realistic beams (spectra)** parallel to transverse plane

$$D_{dosimeter} = 0.33\,(D_{TLD2} + 0.1\,D_{TLD1})$$

All X-ray qualities:

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

Concept proved ✓

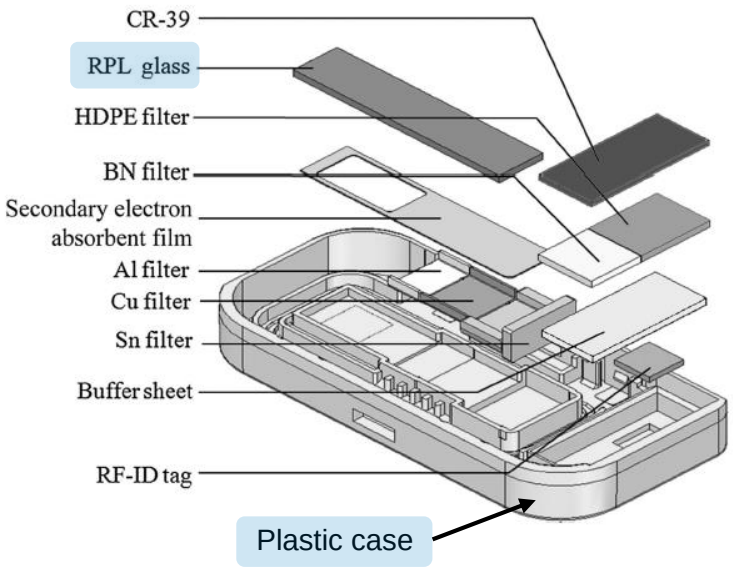


New whole-body dosimeter

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



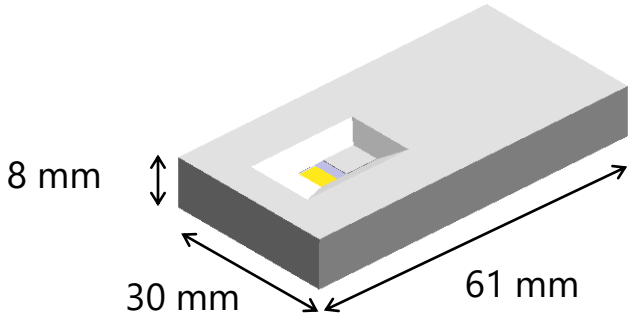
- **New dosimeter:**
  - **Only plastic case and RPL glass modelled**

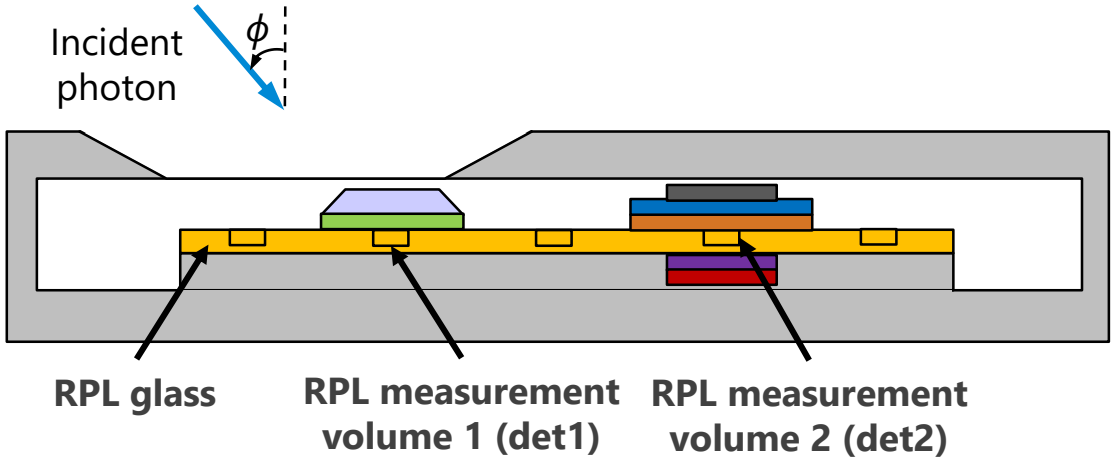
- Maki D. *et al.* Rad. Prot. Dosim. 171(3), (2016).

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

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



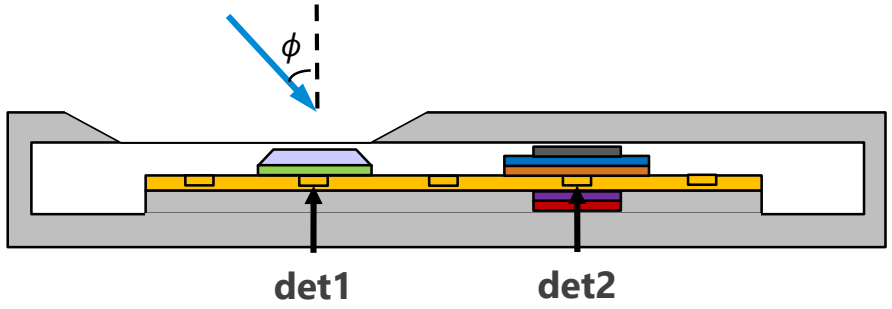


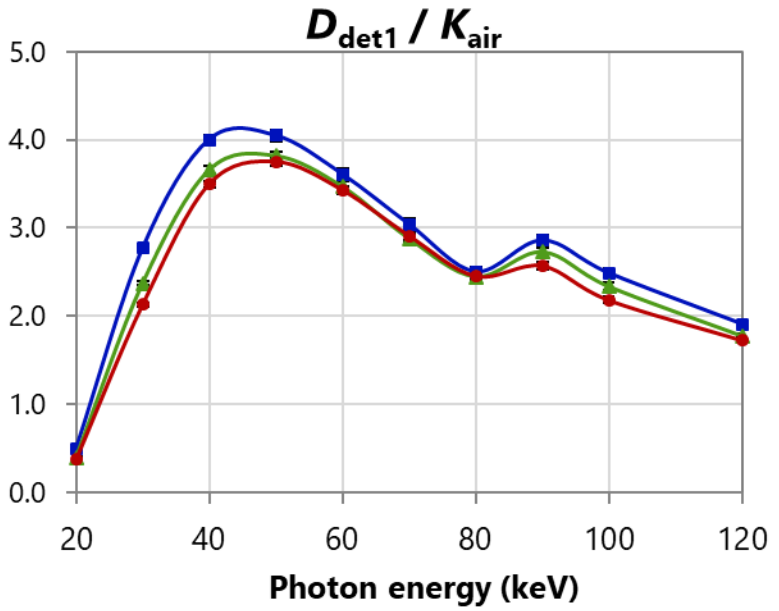
	det1		det2	
	Material	**Thickness (mm)**	**Material**	**Thickness (mm)**
Case front	ABS	< 1.0	ABS	< 2.0
Front filters	**Al, Ti**	**< 1.5**	**Bi, Pb, Cu**	**< 1.5**
Back filters	-	-	**W, Sn**	**< 1.0**
Case back	ABS	4.0	ABS	< 4.0

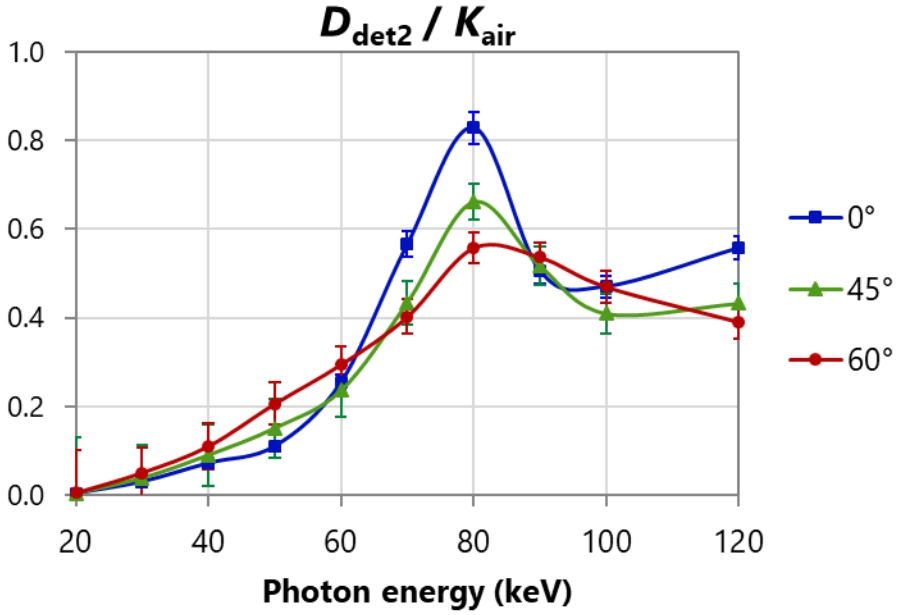
- Saldarriaga Vargas C, *et al.* (submitted to Physica Medica – EJMP).

Results – **New dosimeter dose response**

- Energy and angular dependence for monoenergetic beams

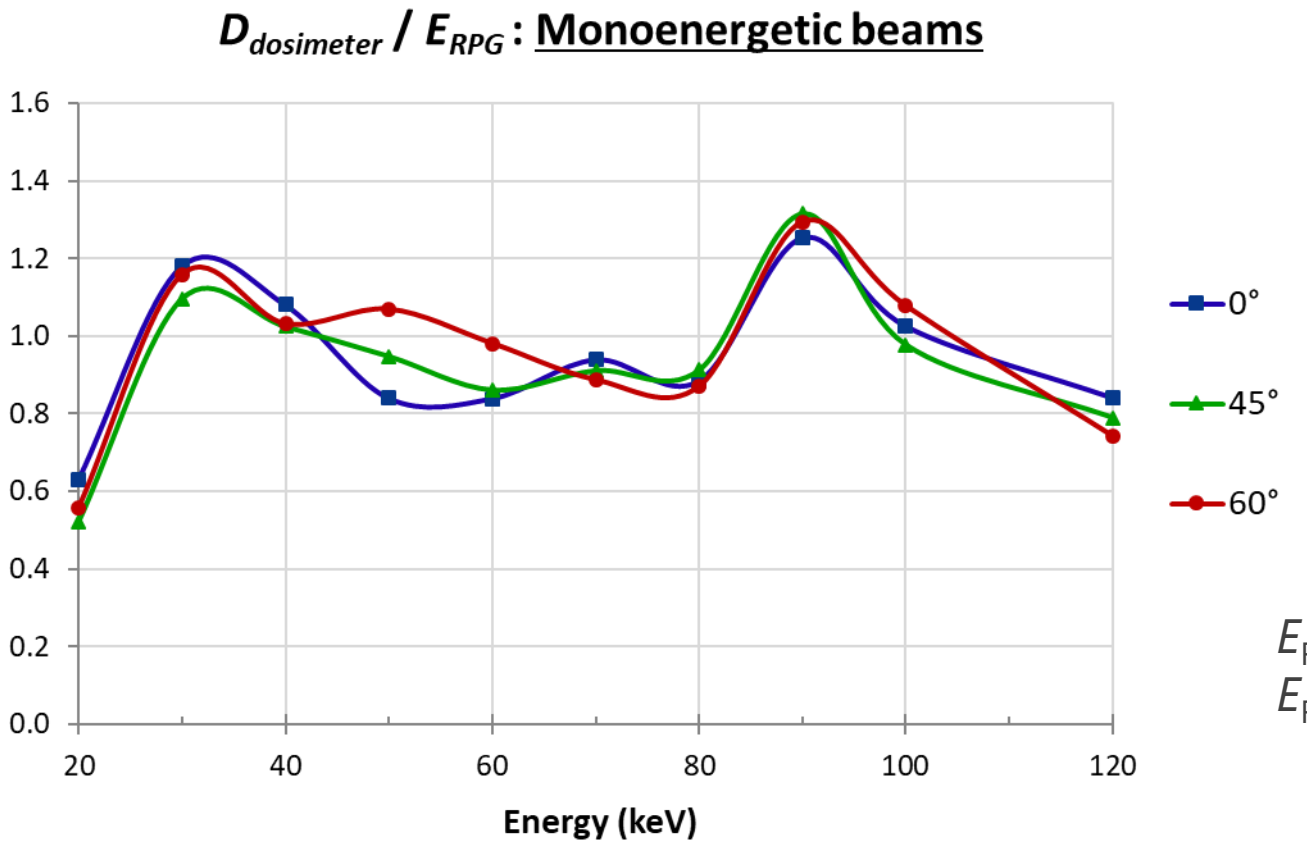


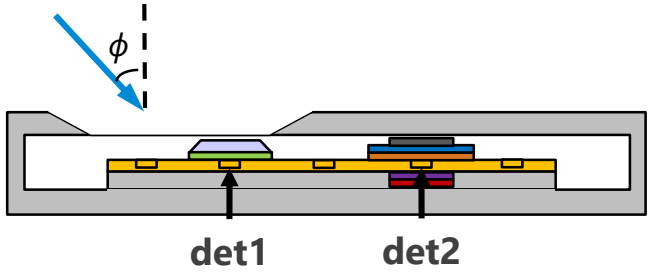




Simulation error $D_{dosimeter}$ < 7%

Results – **Performance of new dosimeter**

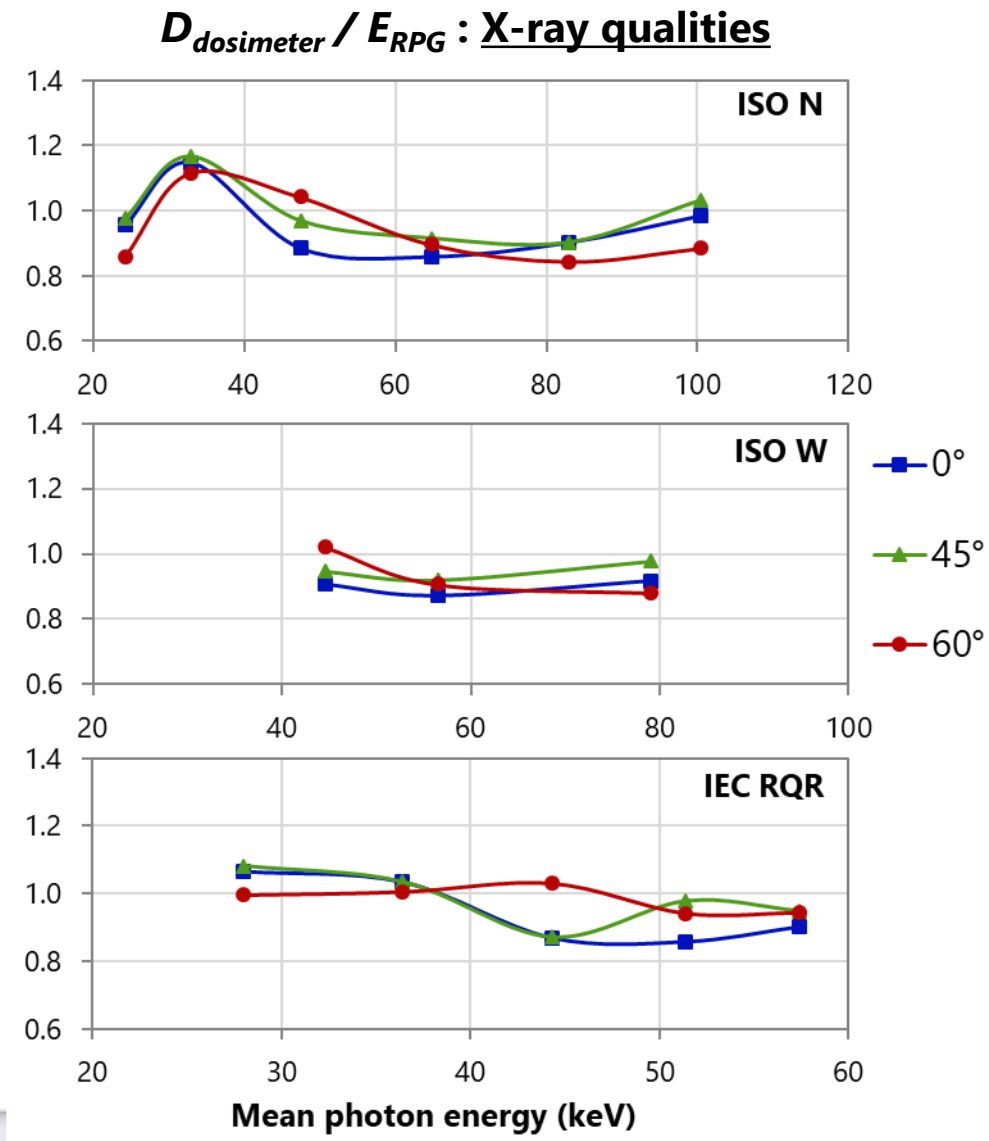




$$D_{dosimeter} = 0.48\,(D_{det2} + 0.01\,D_{det1})$$

E_{RPG} overestimation ≤ 30%
E_{RPG} underestimation ≤ 50% (or ≤ 25% above 20 keV)

Results – **Performance of new dosimeter**



$D_{dosimeter} = E_{RPG}$ ±20% deviation

E_{RPG} overestimation ≤ 5%
E_{RPG} underestimation ≤ 15%

Energy qualities more similar to radiology X-rays
E_{RPG} overestimation ≤ 10%
E_{RPG} underestimation ≤ 15%

$D_{dosimeter} = E_{RPG}$ ±15%

SD and DD methods:
- E_{RPG} underestimations > 50%
- E_{RPG} overestimations > 200%

Conclusions

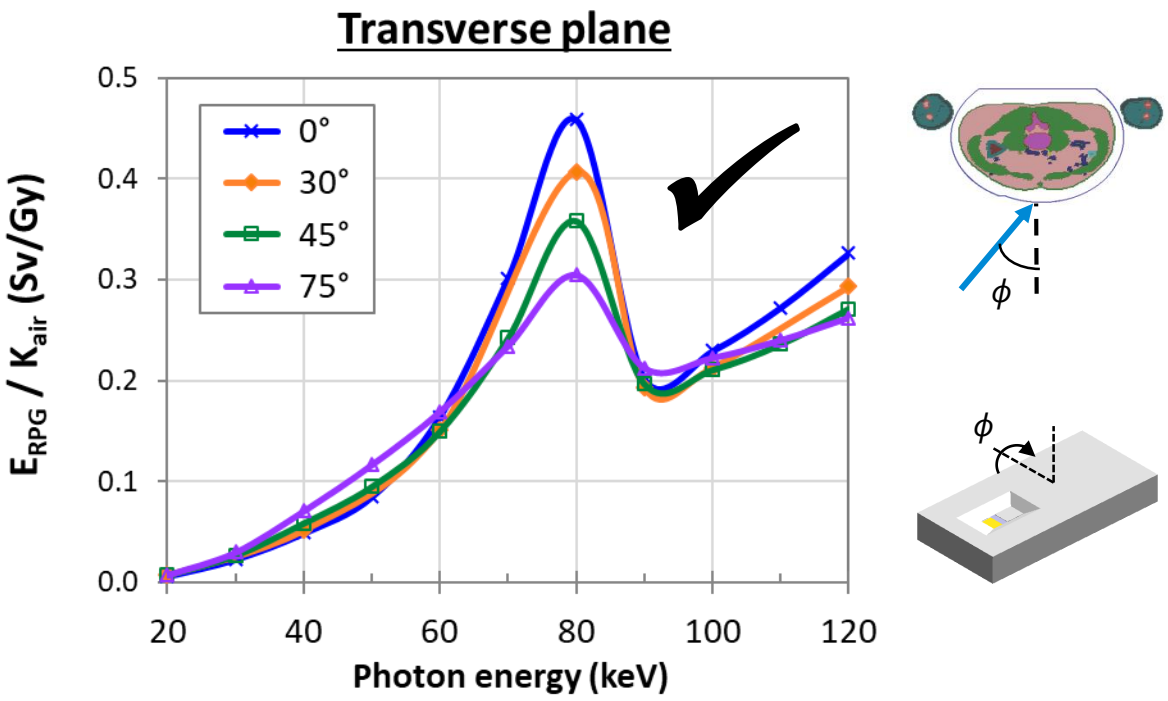
- Concept of a personal **dosimeter suitable for estimating the effective dose when wearing lead garments proved feasible** using Monte Carlo simulations
  - Single over-apron dosimeter for direct estimation of E_{RPG}
  - Realistic model based on RPL detectors

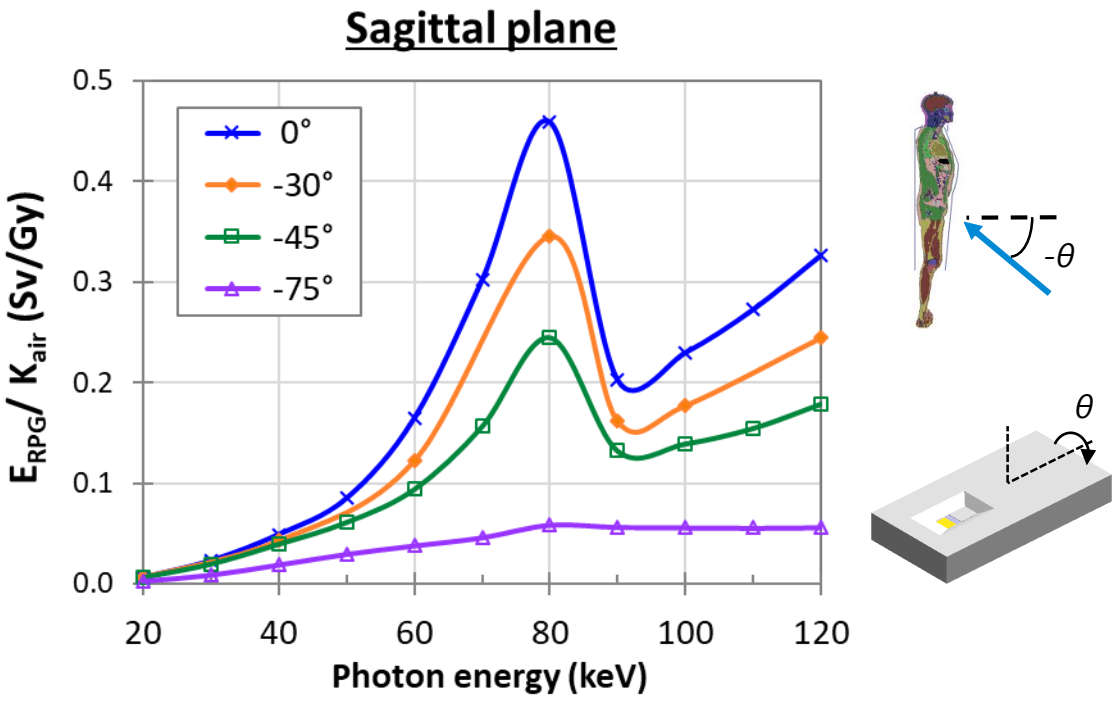
- Dosimeter performance *in silico* significantly **better than current methods**
  - N, W, RQR spectra: $\boldsymbol{D_{dosimeter} = E_{RPG} \pm 20\%}$

- 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

Perspectives

- Angular dependence of E_{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

CHIYODA TECHNOL CORPORATION

References

- Saldarriaga Vargas C, *et al*. The challenges in the estimation of the effective dose when wearing radioprotective garments. Radiat Prot Dosim 178(1), (2018).
- Siiskonen T, *et al*. Monte Carlo simulations of occupational radiation doses in interventional radiology. Br J Radiol 80, (2007).
- Järvinen H, *et al*. Overview of double dosimetry procedures for the determination of the effective dose to the interventional radiology staff. Radiat Prot Dosim 129(1-3), (2008).
- ICRP. Avoidance of radiation injuries from medical interventional procedures. ICRP Publication 85. Ann ICRP 30(2), (2000).
- ICRP. Occupational radiological protection in interventional procedures. ICRP Publication 139. Ann ICRP 47(2), (2018).
- Endo A. The Operational Quantities and New Approach by ICRU. ICRP 2015 Symposium Presentations. http://www.icrp.org/page.asp?id=246
- Endo A. Operational Quantities and New Approach by ICRU. Annals of the ICRP 45(1), (2016).
- Maki D, *et al*. Development of the new glass badge. Radiat Prot Dosim 171(3), (2016).

New dosimeter:

- Saldarriaga Vargas C, *et al*. **Improving Personal Dosimetry of Medical Staff Wearing Radioprotective Garments: Design of a New Whole-Body Dosimeter Using Monte Carlo Simulations.** (submitted to Physica Medica).
- Vanhavere F, Saldarriaga Vargas C, Struelens L, inventors; SCK•CEN, assignee. **Personal dosimeter comprising at least two ionizing radiation detectors.** International patent application no. WO 2016170175A1, (2016).

SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE