

# Monte Carlo simulation for photon energy response from the RADOS dosimeter

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## Abstract

Ionizing radiation interaction models are commonly included in Monte Carlo codes. However, as there are different models and different output quantities available, it is important to understand the physical phenomena used. So, the aim of this study is to analyze the photon interaction model called Simple Physical Treatment of the Monte Carlo code MCNPX to estimate the energy dependence of photons from the RADOS dosimeter and to validate this calculation method by comparing it with experimental results found in the literature. The energy deposition in the MTS-N detector and the air kerma were obtained accompanied by their uncertainties, which varied between 1.5% and 3.0%. The RADOS dosimeter simulation and the calculation methodology applied in this study have been validated. Therefore, when using the Simple Physical Treatment model, the effective dose can be corrected by a correction factor calculated from the simulated results.

## Introduction

Individual full-body dosimeters are routinely used to monitor occupationally exposed individuals (OEI) who work using photons in different sectors of the radiological and nuclear areas, and together with the dosimetry system, when there is no recording of internal dose in the body of the OEI, they can provide an estimate of the worker's monthly effective dose through the personal dose equivalent quantity ( $H_p(10)$ ) [1]. The RADOS dosimeter is a type of individual full-body dosimeter that uses thermoluminescent detectors (TLD) LiF:Mg,Ti (MTS-N) and is one of the dosimeters that can be used to evaluate the  $H_p(10)$  from photons. Different studies demonstrate that the energy dependence of individual dosimeters can be calculated through simulations with Monte Carlo codes [2, 3], normally presented as the relative response as a function of the energy of the incident photon. However, to carry out the simulation, the modeling of the simulated components must be analogous to the experimental components, and in addition, another crucial point is the physical treatment that is used. Even if the simulation has the correct modeling, the wrong choice of physical interactions between the incident and secondary radiation with the modeled materials can

result in the wrong estimate or in undesired quantities for the problem [4]. Therefore, the aim of this study is to analyze the photon interaction model called Simple Physical Treatment of the Monte Carlo code MCNPX to estimate the energy dependence of photons from the RADOS dosimeter and to validate this calculation method by comparing it with experimental results found in the literature.

## Interactions of the secondary electron with the matter

The photons of interest for individual monitoring are X and gamma radiation, and depending on the energy, these radiations can penetrate the body of an OEI, travel through great thicknesses, and cause ionization in radiosensitive organs. This penetrating power is related to the probability of interaction (cross section) for each type of event that can absorb or scatter the incident photon, and this largely depends on the value of its energy and the material in which it is interacting. In the energy range that varies from 20 keV to the mean energy of  $^{60}\text{Co}$  (1250 keV), the photoelectric effect, the Compton scattering, and the pair production are the main events that can occur after the interaction

of the incident photon with the material. However, as the electron is a charged particle that can cause new ionizations through many collisions, the main reason for depositing energy in the detector of an individual dosimeter are the electrons ionized after some event with the incident photons. These electrons receive part of the kinetic energy of the photons and create new ionizations in the material. The energy of the secondary electron is lower than the energy of the incident photon, but the number of events that can happen from the interaction of this electron with matter is significantly greater [5].

Secondary electrons are relatively light particles and lose energy mainly due to the constant direct ionizations (collisions) in the material and the sporadic production of braking radiation (bremsstrahlung), making the electron's trajectory irregular. The electrons interact with the material until their kinetic energy comes into thermal equilibrium with the atoms of the material or until they leave the material. The importance of these events is that the energy lost in each collision is normally deposited in material close to the trajectory, while the energy lost by bremsstrahlung produces photons that can deposit their energy far from the point at which they were generated [5].

The quantity kerma (kinetic energy released per unit of mass), which can be used in calibration or analysis of the energetic response of individual dosimeters, can be defined as the sum of all initial kinetic energies of all charged particles released by neutral particles or photons incident on a material. As kerma considers the energy received by secondary electrons, the estimate of this quantity can be calculated through the energy deposition caused by photons, successive electron collisions, and ionization from the bremsstrahlung. Thus, in addition to the main photon events, the kerma in the air or in the individual dosimeter detector can be quantified by the sum of the collision kerma, when energy is deposited locally after secondary electron collisions, and the radiation kerma, when the energy is deposited far from the place of origin, through bremsstrahlung [5].

### Simulation of the RADOS dosimeter with MCNPX

As shown in Fig. 1, the RADOS dosimeter consists of a plastic case (which provides the charged-particle equilibrium) involving a card holder, and this involves a card that has four compartments to place the MTS-N. Two of these positions are under aluminum filters fixed to the card holder, and the other two positions do not have a filter.

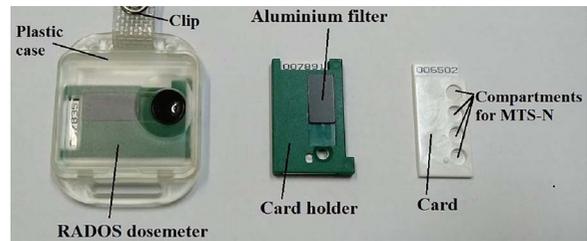


Figure 1. RADOS dosimeter with the description of its components.

The RADOS dosimeter response ( $R$ ) is normalized by the response obtained from irradiation with the  $^{60}\text{Co}$  source and is calculated according to (1)

$$R = \frac{\text{TLD}_x / H_p(10)_x}{\text{TLD}_{\text{Co}} / H_p(10)_{\text{Co}}} \quad (1)$$

The thermoluminescent signal originating from the incident field of a certain energy ( $x$ ) and emitted by the MTS-N ( $\text{TLD}_x$ ) is divided by the value of the dose applied in this irradiation ( $H_p(10)_x$ ). Likewise,  $\text{TLD}_{\text{Co}}$  is the thermoluminescent signal resulting from irradiation with  $^{60}\text{Co}$ , and  $H_p(10)_{\text{Co}}$  is the value of the dose applied from irradiation with  $^{60}\text{Co}$ .

The simulations were carried out with the Monte Carlo code MCNPX version 2.5.0 [6]. The problem consisted of simulating the response in  $H_p(10)$  of the RADOS dosimeter for different monoenergetic photon beams. The energy of the monoenergetic fields was defined based on the mean energy of the radiation qualities found in ISO 4037-3, ranging from 20 to 1250 keV. Photon fields were simulated with the mean energy from the following radiation qualities: N25, N40, N60, N80, N100, S-Cs, and S-CO [7].

As the measurements were made in  $H_p(10)$ , the dosimeter was simulated positioned in the center of the front face of an ISO water slab phantom, and the photon fields were simulated as parallel beams of 30 cm  $\times$  30 cm at 1.5 m away from the dosimeter, in a vacuum environment, as shown in Fig. 2. Table 1 presents the composition, size, and density of each object modeled in the simulation. For each energy, a second simulation was performed to calculate the value of the applied dose ( $H_p(10)_x$  or  $H_p(10)_{\text{Co}}$ ), and for this, only an air plate measuring 30 cm  $\times$  30 cm  $\times$  0.01 cm was constructed in place of the dosimeter (without phantom), and incident field parameters were kept identical. The energy deposited in the air plate and in the MTS-N was calculated by the MCNPX code using Tally F6 [4]. To estimate the value of the applied dose in  $H_p(10)$ , the results of the second simulation

Table 1. Information about the materials used in the simulation.

Material		Weight fraction	Dimension (cm)	Density (g/cm <sup>3</sup> )
Plastic case		Hydrogen (4.196%)	4.21 × 3.86 × 1.01	1.30
		Oxygen (33.3024%)		
		Carbon (62.5016%)		
Card holder		Hydrogen (12.916%)	3.50 × 4.00 × 2.12	1.16
		Carbon (87.084%)		
Aluminum filter MTS-N		Aluminum (100%)	1.45 × 0.75 × 0.10	2.70
		Lithium (26.7585%)	Diameter: 4.5 mm	2.635
		Fluorine (73.2415%)	Thick: 0.9 mm	
ISO water slab phantom	PMMA	Hydrogen (8.0538%)	30 × 30 × 15	1.19
		Oxygen (31.9614%)		
	Water	Carbon (59.9848%)	28 × 28 × 13.75	1.00
		Hydrogen (11.1894%)		
	Oxygen (88.8106%)			

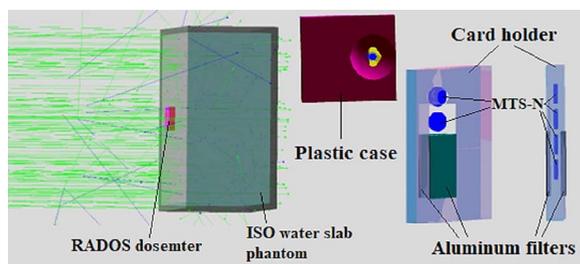


Figure 2. RADOS dosimeter modeled for this study at the center of a simulated ISO slab phantom, irradiated perpendicularly by a simulated parallel plane photon beam.

were multiplied by the conversion coefficient from the air kerma to  $H_p(10)$ , according to the radiation qualities [7].

### Incident photon interactions at MCNPX

In these simulations, the photon interaction model called Simple Physical Treatment was used, which ignores coherent scattering and fluorescent photons arising from photoelectric absorption. This treatment model is aimed at problems with incident photons, where secondary electrons can cause new interactions with atoms, causing collisions or producing bremsstrahlung. The probability of each photon physical process is calculated according to the cross section of the photoelectric effect ( $\sigma_{pe}$ ), pair production ( $\sigma_{pp}$ ), and Compton scattering ( $\sigma_{ce}$ ) for each modeled material. Thus, the simulation calculated the energy deposited in the MTS-N, and it was assumed to be proportional to the TL signal emitted. The events were estimated from the total photon cross section ( $\sigma_t$ ), which is the sum of these three interactions ( $\sigma_t = \sigma_{pe} + \sigma_{pp} + \sigma_{ce}$ ) [3, 4].

In MCNPX, the photoelectric effect is treated as a capture absorption, and the uncaptured photon is forced to undergo pair production or Compton scattering, according to its energy and material. For interactions, when the photon is captured, it is assumed that its energy has been deposited locally. Therefore, a secondary electron is produced in each interaction, which then collides, or Bremsstrahlung is generated [4].

In the calculation based on pair production, the incident photon disappears, and an electron-positron pair is created. It is assumed that the kinetic energy of the produced electron-positron pair is deposited with the isotropic production of two photons with an energy of 511 keV emitted in opposite directions. Compton scattering is an alternative to pair production. In this event, the energy deposited at the point of collision is immediately accounted for, and the new direction and energy of the scattered photon and deflection angle are determined. The ionized electron at the collision point can be used for further collisions later or with bremsstrahlung [4].

### Secondary electron interactions in MCNPX

In MCNPX, the transport of electrons is fundamentally different from that of photons. The interaction of neutral particles is characterized by isolated and relatively infrequent collisions. On the other hand, electron transport is dominated by the long-range Coulomb force, resulting in a large number of small interactions. For example, an electron in aluminum that is attenuated from 0.5 MeV to 62.5 keV will have ~105 individual interactions, while the neutron and photon will have ~30 and 10 collisions, respectively [4].

To follow an electron through a significant loss of energy, it is necessary to divide its path into several events. These events are defined to be long enough

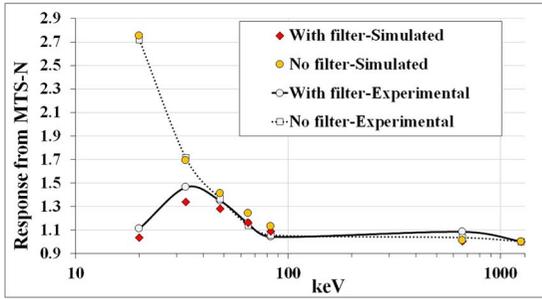


Figure 3. Simulated and experimental responses of the RADOS dosimeter as a function of the photon energy from the incident field.

to encompass many collisions but short enough so that the energy loss in each event is small. The energy loss and angular deflection of the electron during each of the steps can then be estimated from probability distributions [4].

### Simulation results and validation

Validation was carried out by comparing the responses simulated by this study with the experimental responses obtained from the study by Ferreira *et al.* [8], which were considered as reference values.

The simulated results were analyzed using the normalized error ( $En$ ), which evaluates whether a given evaluated value ( $X_{\text{simulated}}$ ) is statistically equal to the value considered as a reference ( $X_{\text{experimental}}$ ), considering its uncertainties (2)

$$En = \frac{(X_{\text{simulated}} - X_{\text{experimental}})}{\sqrt{U_{\text{simulated}}^2 + U_{\text{experimental}}^2}}. \quad (2)$$

In this analysis, when  $En < 1$ , the simulated results for this study ( $X_{\text{simulated}}$ ) are considered valid [8].

Figure 3 shows the simulated responses of the RADOS dosimeter together with the experimental responses of the RADOS dosimeter found in the study by Ferreira *et al.* [9] as a function of the photon energy from the incident field. The simulated responses were normalized by the simulated response obtained from the energy of 1.25 MeV, according to (1), and are presented in Table 2, accompanied by their uncertainties. The normalized error was calculated for the response of the MTS-N under the aluminum filter and for the response of the MTS-N without filter and are presented in parentheses.

The response,  $R$ , of both MTS-N for energies above 80 keV does not differ much from the  $R$  for reference energy (1.25 MeV). On the other hand, the  $R$  is strongly

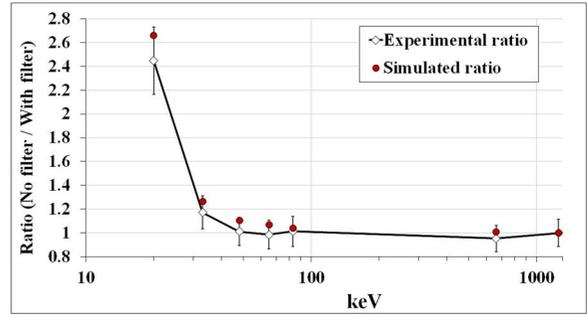


Figure 4. Simulated and experimental ratio of the RADOS dosimeter as a function of the photon energy from the incident field.

affected by low-energy fields. Therefore, the evaluated  $H_p(10)$  at low energies can be excessively overestimated by the RADOS dosimeter if the dose is not corrected. Even calculating the dose using only the MTS-N behind the filter, the dose may be overestimated by more than 30% in some cases. Thus, due to the intrinsic energy dependence of the MTS-N, a correction factor ( $f_{\text{cor}} = 1/R$ ) can be obtained to correct the value of the occupational dose ( $D_H$ ) according to (3)

$$D_H = MTS_i \cdot C_F \cdot f_{\text{cor}}. \quad (3)$$

The  $MTS_i$  is the net value obtained after reading the MTS-N under the filter. The  $C_F$  is the calibration factor obtained from the same reference source used in the response,  $R$ .

As shown in Fig. 4 and Table 3, the value of the ratio between the  $R$  calculated from the MTS-N without filter and the MTS-N with filter is associated with the energy of the photon field. Therefore, from the ratio between the detectors, the energy of the field and the value of  $R$  can be estimated, and the  $f_{\text{cor}}$  can then be calculated.

Table 3 presents a comparison between the ratios obtained from simulated results and experimental results obtained from the study by Ferreira *et al.* The normalized error (in parentheses) was used to validate the ratio calculated from the simulation.

### Conclusion

Through the simulations, the energy deposition in the MTS-N detector and the air kerma were obtained, accompanied by their uncertainties, which varied between 1.5% and 3.0%. As indicated in ISO 4037-3, conversion coefficients must be considered as being associated with a standard uncertainty of 2%, because of the differences between the spectrum used for calculating the conversion coefficients and that used at

Table 2. Simulated results and validation with data obtained from Ferreira *et al.* [9].

Quality	Mean energy (MeV)	Simulated responses <sup>a</sup>		Experimental responses <sup>b</sup>	
		This study		Ferreira <i>et al.</i> [9]	
		Filter	Bare	Filter	Bare
N25	0.020	1.03 ± 0.05 (0.74)	2.75 ± 0.11 (0.14)	1.11 ± 0.09	2.72 ± 0.22
N40	0.033	1.34 ± 0.05 (0.90)	1.69 ± 0.07 (0.15)	1.46 ± 0.13	1.71 ± 0.14
N60	0.048	1.28 ± 0.05 (0.55)	1.41 ± 0.06 (0.39)	1.35 ± 0.11	1.36 ± 0.11
N80	0.065	1.16 ± 0.05 (0.05)	1.24 ± 0.05 (0.87)	1.16 ± 0.09	1.14 ± 0.11
N100	0.083	1.09 ± 0.04 (0.45)	1.13 ± 0.04 (0.77)	1.04 ± 0.10	1.05 ± 0.09
S-CS	0.662	1.00 ± 0.04 (0.82)	1.01 ± 0.04 (0.26)	1.08 ± 0.09	1.03 ± 0.08
S-CO	1.250	1.00 ± 0.04 (0.00)	1.00 ± 0.04 (0.00)	1.00 ± 0.08	1.00 ± 0.08

<sup>a</sup>The simulated spectra correspond to monoenergetic fields. <sup>b</sup>The experimental field corresponds to ISO spectra [7].

Table 3. Simulated ratio and validation with ratio obtained from Ferreira *et al.* [9].

Quality	Mean energy (MeV)	Ratio (Bare/Filter)	
		This study	Ferreira <i>et al.</i> [9]
		Simulated ratio <sup>a</sup>	Experimental ratio <sup>b</sup>
N25	0.020	2.66 ± 0.16 (0.65)	2.45 ± 0.28
N40	0.033	1.26 ± 0.07 (0.59)	1.17 ± 0.14
N60	0.048	1.10 ± 0.06 (0.69)	1.01 ± 0.12
N80	0.065	1.07 ± 0.06 (0.61)	0.99 ± 0.12
N100	0.083	1.04 ± 0.06 (0.18)	1.01 ± 0.13
S-CS	0.662	1.01 ± 0.06 (0.42)	0.95 ± 0.11
S-CO	1.250	1.00 ± 0.06 (0.00)	1.00 ± 0.12

<sup>a</sup>The simulated spectra correspond to monoenergetic fields. <sup>b</sup>The experimental field corresponds to ISO spectra [7].

the time of irradiation [7]. Therefore, the uncertainty of the normalized response in  $H_p(10)$  was calculated by adding this source of uncertainty.

The validation of the simulation is a crucial point for this study, and according to the analysis using the normalized error, when comparing them with experimental results from other studies, it was seen that the RADOS dosimeter simulation and the calculation methodology applied in this study have been validated. However, in addition to the fact that the modeled LiF may have a slightly different composition from the MTS-N, TLD doping materials were ignored in the simulations, and in some cases, the monoenergetic field may not represent the experimental spectrum used, contributing to the divergence between the simulated and experimental responses.

For this energy range, when using the Simple Physical Treatment, it was possible to calculate the energy deposited by photons in the MTS-N and the air kerma as the reference dose. Therefore, when using some Monte Carlo code to calculate the energy deposited in a detector or to estimate air kerma, one can consider only the main events of the incident photon, the collisions, and the bremsstrahlung produced by the secondary electrons.

From the ratio between  $R$  with and without filter,  $f_{cor}$  can be calculated and applied to correct the dose, especially for ratios above 15%, as it indicates that OEI was exposed to lower energy fields. Therefore, in cases where there is a strong influence of the energy dependence of the detectors, the effective dose can be corrected by a correction factor calculated from the simulated results, which have smaller uncertainties and consider more fields than are normally available experimentally. As the evaluated  $H_p(10)$  can be corrected, performance criteria related to energy response found in standards can be met over a wide range of photon energies. However, other studies need to be carried out, covering other individual photon dosimeters with different filters and detectors and simulating them with the Simple Physical Treatment model.

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