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GEANT4 simulation of Radiation Exposure Device scenario at bus stop

Report on simulation and analysis

Chuanlei Liu
David Waller

Defence R&D Canada – Ottawa

Technical Report
DRDC Ottawa TR 2012-180
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Abstract

In this report, the performance of a GEANT4 radiation exposure device (RED) application has been investigated. Simulations of the radioactive source, bus passengers, and transport of radiation inside the human body are checked. The simulated results are consistent with expectations, verifying the GEANT4 application for the RED scenario.

The absorbed dose rate has been estimated as a function of distance between the source and passengers, and the results have been compared with predictions from RadPro calculator and analytical calculations. GEANT4 works like a realistic scenario simulator in that factors such as the inter-personal shielding and finite body dimension effects have been coherently modelled. The impact of these factors on the dose rate estimation has been investigated and is discussed. As a result, the GEANT4 dose rate results tend to be less than simplified predictions.

The verification of the GEANT4 application makes DRDC Ottawa ready for more advanced radiation simulation work in the future. For example, GEANT4 can be utilized to assist ongoing radiation detector design and optimization work, and dose rate results can be used to update the radiological consequences estimated for the Probabilistic Risk Assessment Tool.

Résumé

Ce rapport porte sur le rendement tiré de l’utilisation de l’application GEANT4 comme appareil d’exposition. On a étudié des simulations de la source radioactive, les passagers d’un autobus et le transport des rayonnements à l’intérieur du corps humain. Les résultats simulés sont conformes aux attentes, ce qui atteste l’utilisation de GEANT4 en tant qu’appareil d’exposition pour scénario. Le débit de dose absorbé a été évalué en fonction de la distance entre la source et les passagers. Les résultats ont été comparés avec les prévisions réalisées à partir d’une calculette RadPro et de calculs analytiques. GEANT4 fonctionne comme un véritable simulateur de scénarios, car il modélise de manière cohérente des facteurs comme le blindage interpersonnel et les effets du gabarit corporel. Les répercussions de ces facteurs sur l’évaluation de la dose ont été étudiées et ont fait l’objet de discussions. On a constaté que la dose calculée par GEANT4 a tendance à être moins importante que celle des prévisions simplifiées. La vérification de l’utilisation de GEANT4 fait en sorte que RDDC Ottawa sera prête à réaliser des travaux plus poussés sur la simulation du rayonnement à l’avenir. Par exemple, GEANT4 peut être utilisé pour la poursuite des travaux de conception et d’optimisation d’un détecteur de rayonnement, et les résultats de doses peuvent servir à la mise à jour des conséquences radiologiques prévues par l’outil d’évaluation probabiliste des risques.

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Executive summary

GEANT4 simulation of Radiation Exposure Device scenario at bus stop

Chuanlei Liu, David Waller; DRDC Ottawa TR 2012-XXX; Defence R&D Canada – Ottawa; September 2012.

Background: To assist the ongoing Radiological and Nuclear (RN) risk assessment work being carried out at DRDC Ottawa, a new RN simulator, the GEANT4 radiation transport simulation toolkit [1], has been successfully installed on the CARDS computing cluster as described in report [2]. A concrete application of GEANT4 for a radiation exposure device (RED) scenario has also been developed and documented in report [3]. Following this previous work, a systematic check on GEANT4's performance for the RED application has been conducted and is described in this report.

Principal results: By checking the simulation results for the radioactive source, bus passengers and radiation transport, the performance of both the GEANT4 toolkit and the specific RED application has been tested and verified. The absorbed dose rate of passengers at the bus stop has also been estimated and compared with results from other predictions. It is found that some realistic factors simulated in GEANT4, such as the inter-personal shielding and body dimension effects, play an important role in the estimation of the absorbed dose rates.

Significance of results: The verification of the GEANT4 toolkit and the RED application has advanced DRDC Ottawa's readiness for future radiation simulation studies. GEANT4 will be beneficial for future and ongoing work on detector design and optimization, and risk assessment. The simulation results for absorbed dose rates will be used to update DRDC Ottawa's Probabilistic Risk Assessment (PRA) Tool.

Future work: This work is the first application of GEANT4 for RN simulation at DRDC Ottawa. In response to future requirements, many additional applications are foreseen. These applications may use the current GEANT4 application framework as-is, or modifications can be made as required. The GEANT4 toolkit and related software (e.g. C++ compilers and Linux distributions) have their own lifecycles so maintenance and updates will be required from time-to-time.

Sommaire

GEANT4 simulation of Radiation Exposure Device scenario at bus stop

Chuanlei Liu, David Waller ; DRDC Ottawa TR 2012-XXX ; R & D pour la défense Canada – Ottawa ; septembre 2012.

Contexte : Pour aider les travaux d'évaluation des risques radiologiques et nucléaires (RN) qui sont en cours à RDDC Ottawa, le nouveau simulateur de RN, soit la trousse de simulation du transport des rayonnements GEANT4, a été installée sans problème sur la grappe d'ordinateurs CARDS, comme le décrit le rapport. On a aussi créé une application concrète de GEANT4 en tant qu'appareil d'exposition au rayonnement pour scénario, ce qui a été documenté dans le rapport. À la suite de ces travaux préalables, une vérification systématique du rendement de GEANT4 en tant qu'appareil d'exposition a été réalisée et est décrite dans ce rapport.

Principaux résultats : En vérifiant les résultats de la simulation de la source radioactive, les passagers de l'autobus et le transport des rayonnements, on a pu tester et vérifier le rendement de la trousse GEANT4 et de l'utilisation de GEANT4 comme appareil d'exposition. On a évalué le débit de dose absorbé par les usagers à l'arrêt d'autobus et on l'a comparé aux résultats d'autres prévisions. On a constaté que certains facteurs réalistes simulés dans GEANT4, par exemple le blindage interpersonnel et les effets du gabarit corporel, jouent un rôle important dans l'évaluation du débit de dose absorbé.

Importance des résultats : Grâce à la vérification de la trousse GEANT4 et à l'utilisation de GEANT4 comme appareil d'exposition, RDDC Ottawa est désormais mieux préparée pour d'éventuelles études sur le rayonnement à venir. GEANT4 sera utile dans les travaux en cours età venir sur la conception et l'optimisation des détecteurs et l'évaluation des risques. Les résultats de la simulation quant au débit de dose absorbé serviront à la mise à jour de l'outil d'évaluation probabiliste des risques de RDDC Ottawa.

Travaux à venir : Ces travaux ont été la première utilisation de GEANT4 dans la simulation de RN à RDDC Ottawa. En réponse aux exigences futures, on prévoit de nombreuses utilisations additionnelles. Ces applications peuvent faire appel au cadre d'utilisation actuel de GEANT4 tel quel ou modifié, au besoin. La trousse GEANT4 et ses logiciels connexes (p. ex. compilateurs C++ et distributions Linux) ont leur propre durée de vie utile. Il faudra donc procéder à des travaux de maintenance et à des mises à jour de temps à autre.

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1 Introduction

After installing the GEANT4 (GEometry ANd Tracking) [1] simulation package on the DRDC Ottawa CARDS computer cluster [2] and building up an application for radiation exposure device (RED) studies [3], a RED scenario with hundreds of millions of radionuclide decays was simulated. The simulation results have been analyzed to emphasize checking GEANT4's performance for this RED application.

The performance checks are conducted by studying the fundamental quantities coming from each component of the GEANT4 simulation, as well as a few other relevant variables such as the absorbed dose rate. These checks are essential during this initial stage of applying GEANT4 for radiological scenarios at DRDC Ottawa.

In this report, the results of these checks are presented and discussed. The results show that GEANT4 performs as expected in terms of simulating the radioactive decay of two radionuclides (^{60}Co, ^{137}Cs), and the transport of resulting radiation. As for the absorbed dose rate results, differences have been observed between GEANT4 simulations and more simplistic predictions. Effort has been put into understanding and interpreting these differences: GEANT4 simulates many complex features of the scenario, such as inter-personal shielding, radiation build-up and finite-body effects, while the simplified calculations (for example using RadPro Calculator) are valid only under the most basic geometries.

1.1 Absorbed dose rate

Two useful quantities for describing the exposure of a human body to radiation are the absorbed dose and the absorbed dose rate. The definition of the absorbed dose rate and related quantities used in the RED study are explained below.

In general, the absorbed dose is defined as the quotient of the energy deposited, ΔE, and the mass of the element volume Δm [4]:

$$D = \frac{\Delta E}{\Delta m}. \tag{1}$$

The absorbed dose is measured in Grays (Gy), where one Gray equals one Joule of energy deposited in one kilogram. The absorbed dose rate is the rate at which the absorbed dose is received, and is specified with units of Gy/sec, Gy/hr etc..

In this study, the absorbed dose rate is obtained using three different methods, each of which serves a specific purpose.

- **GEANT4 simulation**: GEANT4 is used to calculate ΔE which is inserted in Equation (1). The result from this method is obtained on a case-by-case basis and therefore does not have predictive power for other gamma-emitter cases; however, GEANT4 provides a detailed, realistic simulation of the radiation environment so the results from

GEANT4 are more reliable than the results from more simplistic predictions. Note that the absorbed dose rate from this method is the result averaged over the whole human body/trunk.

- **RadPro$^{\text{TM}}$ calculation** [5]: This online calculator provides gamma dose rate calculations with options for different sources, activities, units, distance and shielding. Note that in this case, *air* is assumed to be the standard medium and the absorbed dose rate result is estimated for an object with unit *mass* thickness (g/cm^2). This method is provided as a comparison to the GEANT4 simulations.
- **Theoretical prediction**: This method is based on Equation (6) below. The primary motivation of this method is to provide our own theoretical predictions (with water as the absorbing medium) for RED studies. Note the prediction from this method is calculated in a way that is similar to RadPro [6].

The theoretical expression of the absorbed dose rate $\dot{D}$ is derived for a medium with a *unit of mass* and is given below.

$$\dot{D} = \frac{dD}{dt} = \frac{\Delta I}{\Delta(\rho l)} \simeq I \cdot (\mu_l/\rho)^{water} = I \cdot \mu_m^{water} \tag{2}$$

where ρ (in units of g/cm^3) is the mass density. The variable l (in unit of cm) is the *physical* thickness of the absorber and the product ρl is the *mass* thickness and has units of g/cm^2. The variable I, explained below, represents the radiation energy fluence rate at a distance $d(cm)$, and the $\mu_l^{water}(\mu_m^{water})$ is the linear (mass) *absorption* coefficient in water and has units of $cm^{-1}(cm^2/g)$.

In case of non-shielded gamma radiation, the energy fluence rate I can be rewritten as

$$I = I_0/(4\pi d^2) = \frac{A}{4\pi d^2} \cdot \sum_i E_i \cdot p_i = \frac{A}{4\pi d^2} \cdot E_{\text{eff}} \tag{3}$$

where I_0 is the intensity of the source, which depends on the multiplication of source activity, A, (in Bq) and the effective γ emission energy at a specific distance d. In the case of multiple γ decay modes, E_{eff} is expressed as the sum of the products of each individual energy (E_i in KeV) and its decay branching ratio, or probability p_i (i.e. the branching-ratio-weighted average energy is used).

Combining equations (2) and (3) gives

$$\dot{D} = \frac{A}{4\pi d^2} \cdot (E_{\text{eff}} \cdot \mu_m^{water}) \quad \text{or} \quad \dot{D} = \frac{A}{4\pi d^2} \cdot (E_{\text{eff}} \cdot \mu_m^{water}) \cdot e^{-\mu^{shield} \cdot (\rho l)} \tag{4}$$

These two expressions are for the unshielded and shielded cases respectively. Note that in the shielded case, the variable μ^{shield} is the mass attenuation coefficient.

Re-expressing the unshielded relation in Equation (4) leads to the presence of two relevant experimental distributions (functions) which characterize the RED scenario, as shown in

Equation (5). These two distributions contain the essential information from which the absorbed dose rate can be derived. Therefore it is always good to have these two distributions, not only for cross-checks, but also for a better understanding and comparison, and even for parameterization purposes:

$$\dot{D} \sim \frac{A}{4\pi d^2} \cdot f(E_{abs}^{water}) = f(d) \cdot f(E_{abs}^{water}). \tag{5}$$

Note that the absorbed dose rate is *not* equal, but roughly proportional to the product of $f(d)$ and $f(E_{abs}^{water})$, because the conversion of the initial γ energy into absorbed energy (E_{abs}^{water}) involves the extra exponential factor of the mass absorption coefficient. Even though, these two distributions, $f(d)$ and $f(E_{abs}^{water})$, provide cross-checks since they provide relevant information relating to the final dose rate result.

From Equation (4), one can easily compute the absorbed dose rate given the radiation source and intensity, and the distance between source and exposed target. In the unshielded case, after inserting the appropriat values, one gets

$$\dot{D}(\mu Gy\, hr^{-1}) = 5.76 \cdot 10^{-4} \cdot \frac{A(Bq)}{4\pi d^2(cm^2)} \cdot [E_{\text{eff}}(KeV) \cdot \mu_m^{water}(cm^2/g)] \tag{6}$$

The coefficient $5.76 \cdot 10^{-4}$ converts electron-volts to Joules and seconds to hours (1.6*3.6 = 5.76). As a specific case, the absorbed dose rate from a source shielded with 0.4 cm of iron and having 1.0 *Ci* activity is

$$f(d) \simeq \frac{10.64 \cdot 10^{-4}}{d^2(cm^2)} \quad mGy/Ci/hr \quad \text{for } {}^{60}\text{Co} \tag{7}$$

$$f(d) \simeq \frac{2.49 \cdot 10^{-4}}{d^2(cm^2)} \quad mGy/Ci/hr \quad \text{for } {}^{137}\text{Cs} \tag{8}$$

Since the quality factor for γ is unity, the absorbed dose rate $\dot{D}$ is equal to the equivalent dose rate $\dot{H}$.

2 Simulation of radioactive sources

The primary radionuclide of interest for this study is the gamma emitter cobalt-60. In order to test the extensibility of the RED application, a second gamma emitter, cesium-137, is also considered. Selected properties of these radionuclides are given in Table 1.

In this study, the radioactive source is simulated as a point source with zero kinetic energy. In GEANT4, each "event" represents a disintegration of a radionuclide and each decay follows an angular distribution which is isotropic.

Table 1: *Properties of radioactive nuclides considered in this study.*

Element	Z	A	half-life	Activity	Characteristic γ-ray energy
cobalt-60	27	60	5.26 years	$\sim$1100 Ci/g	1.173 MeV, 1.332 MeV
cesium-137	55	137	30.17 years	$\sim$88 Ci/g	0.661 MeV

The half-life (derived from the mean life-time) and the γ energy spectrum of the simulated cobalt-60 are given in Figures 1 and 2 respectively. The mean life-time of cobalt-60, 7.614 years, implies $\sim$5.3 year half-life after simply multiplying the mean life-time by ln(2). Similarly in Figure 3, the mean life-time of 43.41 years for cesium-137 yields a half-life of $\sim$30.1 year which is also consistent with the value shown in Table 1.

As for the energy spectra, the first bin (the typical energy range is 1$\sim$10 KeV) in Figure 2 is due to the contributions from the low energy X-rays of cobalt-60 decay. The remaining five channels are clearly noticeable and characterize the cobalt-60 decay mode in terms of γ products. In GEANT4, the primary decay of radioactive sources and the following decay of daughter particles are based on the ENSDF (Evaluated Nuclear Structure Data File) data [7].

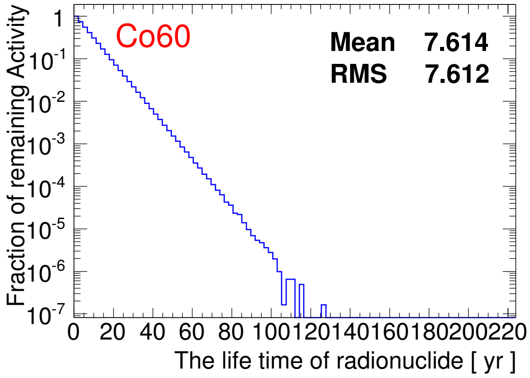


Figure 1: *The simulated life time of cobalt-60 in years.*

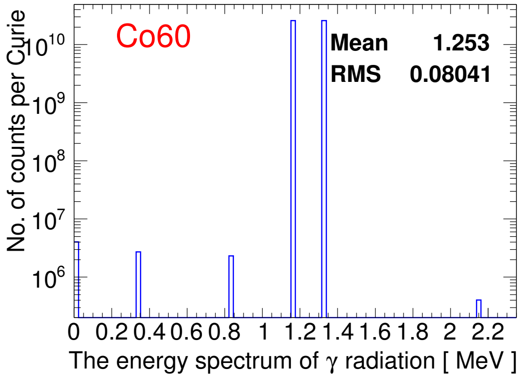


Figure 2: *The simulated energy spectrum of the γ- and X-rays from cobalt-60.*

Similarly in Figure 4, the peak located at $\sim$0.67 MeV corresponds to the characteristic γ radiation from the cesium-137 decay. The structure below 0.1 MeV results from the x-rays of the cesium-137 decay. The less noticeable spike around 0.28 MeV is the other γ-ray which occurs at a very low probability ($\sim$6e-06 chance of a cesium-137 decay).

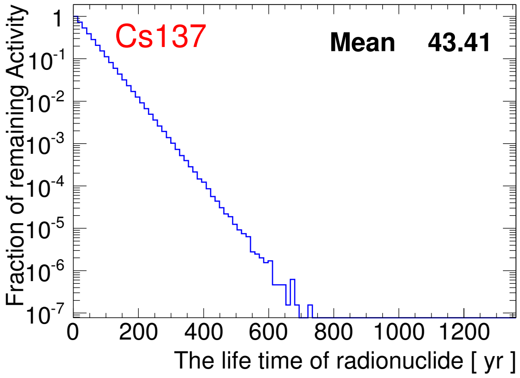


Figure 3: *The simulated life time of cesium-137 in years.*

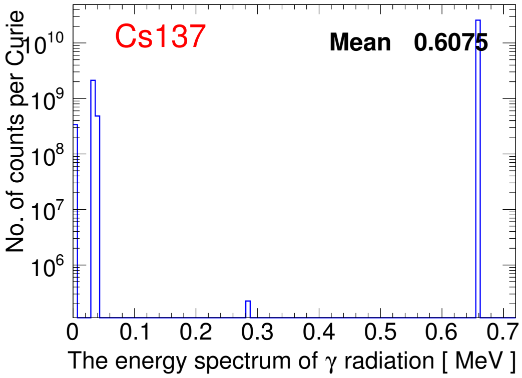


Figure 4: *The simulated energy spectrum of the γ- and X-rays from cesium-137.*

3 Simulation of passengers at bus stop

In this study, a RED scenario is considered: people at a bus stop in an urban area are irradiated by radioactive materials. A total number of 150 runs has been simulated, each of which consists of 200 passengers at a 10x10 m^2 bus stop. A specific amount of radioactive material is assumed to be hidden inside a trash bin which is located at the bus stop. The trash bin is configured to be 120 cm high and 40 cm in diameter. It is made of iron of 0.4 cm thickness, which is estimated to result in approximate 15% of the initial γ rays (1∼2 MeV) to be attenuated. An illustration of the scenario is shown in Figure 5.

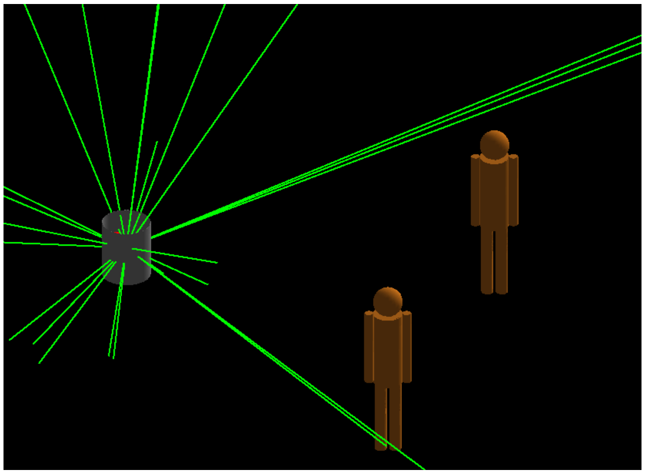


Figure 5: *The RED scenario simulated with GEANT4. Two passengers standing and waiting ata bus stop are technically simulated as "detectors" in GEANT4. The grey bin contains the RED and the γ radiation is shown in green.*

For simplicity, each individual is represented by a cylinder, filled with pure water. The physical size of passengers is randomly computed reflecting different type of people in real life and the position is also randomly assigned. Further information relating to the physical size and position of the simulated passengers are given in the following two sections.

3.1 Physical features of the simulated passengers

Given that the body trunk is quite sensitive to γ radiations, we choose the body trunk, not the whole body, as the default target size for discussions in Section 3. The variables simulated to characterize a passenger's physical features are the trunk height, width and weight. The configuration of the physical quantities in GEANT4 is given Table 2.

Table 2: *Input parameters for passenger simulations in GEANT4.*

Parameter name	Input value to GEANT4 [m]
Trunk height	Gaussian distribution with 0.8 ± 0.08, but in [0.56, 1.04]
Trunk half-width	Gaussian distribution with 0.2 ± 0.01, but in [0.17, 0.23]

The simulated results for these physical quantities are shown in Figure 6. Compared to the input values in Table 2, these simulation results, as shown in Figure 6, are found to be in good agreement with the shape and parameters of the Gaussian-like distribution.

Small spikes are found at the lower and upper edges in Figures 6 (a) and (b). These spikes are located at the position of the cut-off values defined in Table 2. Whenever the GEANT4 simulated value is beyond the cut-off value, it is re-assigned the corresponding cut-off value.

3.2 Positions of the simulated passengers

The distributions shown in Figure 7 represent the positions of the simulated passengers. Figure 7(a) shows the *accumulated* passenger positions at the bus stop for all 150 runs. As mentioned previously, 200 passengers have been arranged randomly (but with no physical overlap) at a bus stop of 10x10 m^2 in each run. The resulting passenger density is 2.0 persons/m^2 so as to characterize a crowd in an urban area. Just for comparison, the maximum accommodation of passengers in a standard designed elevator is about 4 person/m^2 if the weight of each passenger is assumed to be 100 Kg, the same as the mean value of the simulated weight in this study. Note that the empty space found at the origin position of Figure 7(a) corresponds to the trash bin dimension, where no passengers are standing.

The shape of the distribution in Figure (b) reflects the constraints on the passenger location shown in Figure (a). The peak at $\sim$4.5 m in Figure 7(b) is the radius of the internally tangent circle minus the body half-width. Note that whenever the subsequent averaging or

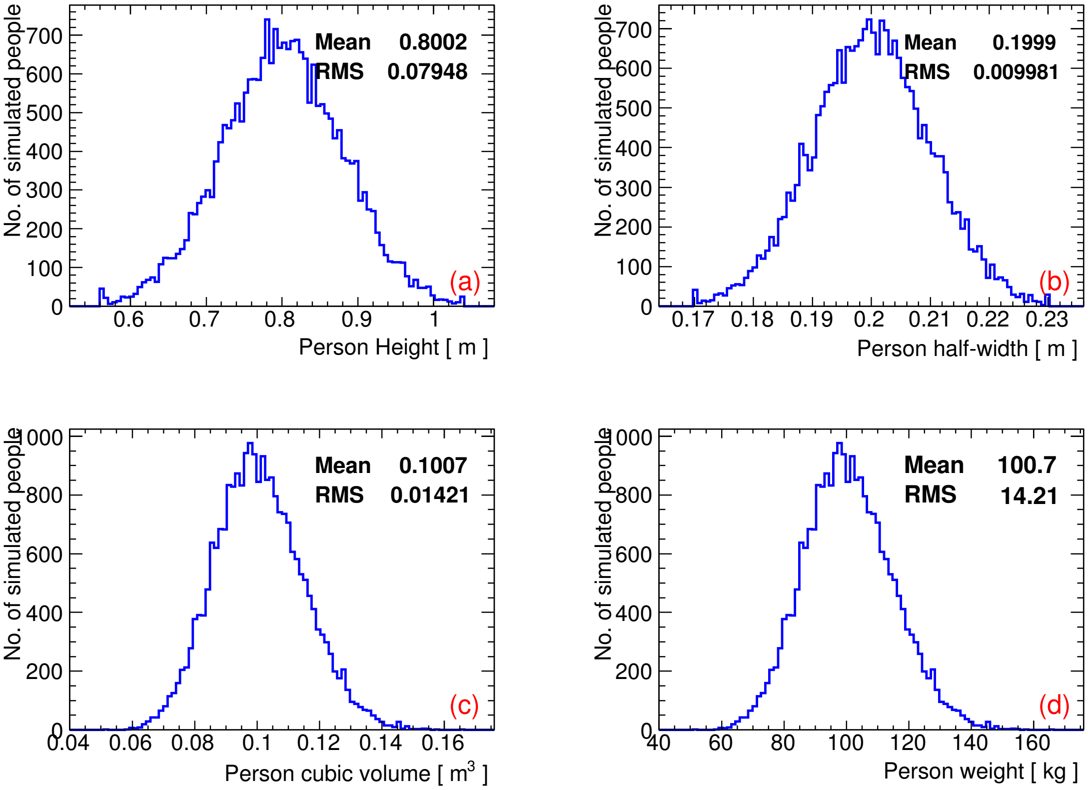
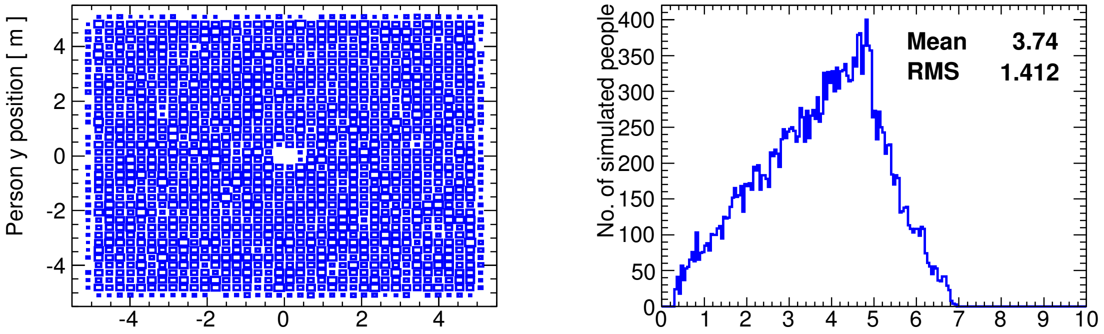
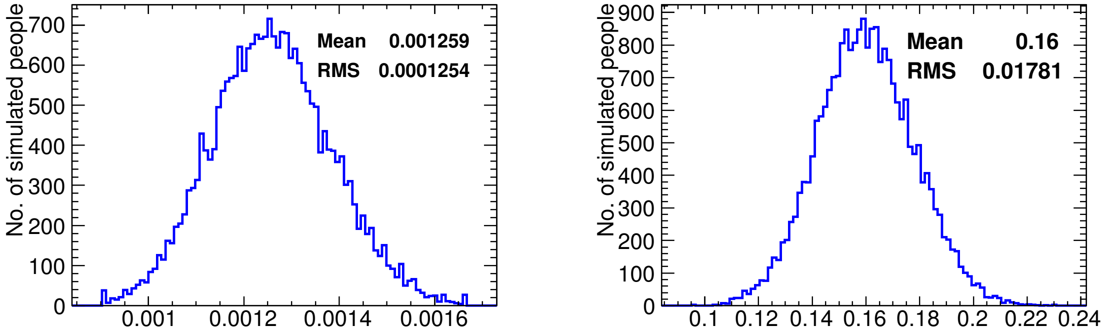


Figure 6: *The physical features of the simulated passengers. Figures (a), (b), (c) and (d) are distributions of the person height, half-width, cubic volume and weight respectively.*



(a) Person x position [m]

(b) Person to source distance [m]



(c) Person area occupying density

(d) Person half surface area [m^2]

Figure 7: *Some statistics for the positions of the simulated passengers. Figure (a) is the position distribution of passengers with respect to the trash bin (i.e. the RED). Figure (b) is the number of simulated passenger as a function of distance with respect to the RED. The fraction of the total area occupied by each passenger is shown in figure (c) and (d) is the cross section of each passenger exposed to the RED.*

fitting of the dose rates is performed on a distance-dependent distribution, the peak position ($\sim$4.5m) plays an important role.

Figure 7(d) reflects how the size of a passenger's cross-sectional area with respect to the RED is simulated. This quantity is an important factor in estimating the dose rate.

4 Simulation of radiation interactions with people

The distributions shown in Figure 8 reflect certain properties of the radiation transport processes inside the body. The primary purpose of having these distributions is to check the transport modelling in GEANT4 without delving into technical details. The other purpose is to have this information available to compare with other Monte Carlo transport codes in the future (e.g. the MCNPX package [8]).

The horizontal axis of Figure 8(a) indicates the number of irradiated passengers per decay (in other words, how many people have a gamma ray or other radiation interact with them per decay). The vertical axis indicates the number of (single, double, triple, etc.) interactions per Curie of cobalt-60. In Figure 8(b), the *total* deposited energy per cobalt-60 decay is depicted. The two energy peaks around 1.1 and 1.3 MeV characterize the γ energies originating from the cobalt-60 decay. The spectrum at the larger energy deposit range ($>$1.3 MeV) indicates the possibility of both γs interacting with the same body and leaving all or part of their energies inside, while the presence of lower energy deposits is due to many effects, such as Compton scattering and secondary photons. This causes attenuation before reaching passengers, or equivalently, a shielding effect between people.

More details about the transport of radiations inside passengers such as the number of interactions (a "step" occurs between two interactions) and the step length are provided in Figures 8(c) and (d) respectively. A rough estimation shows that an initial 1 MeV γ-ray will lose approximately 88% of its energy after travelling through 30 *cm* of water. Figure 8(d) delivers a similar message about the deposition of γ radiation energy inside the body.

5 Results and discussions

The first part of this section (Sec 5.1-5.4) investigates how such realistic factors as the passenger density per unit area, inter-personal shielding and finite body dimensions affect the simulation results on the absorbed dose rate. The following section (Sec 5.5) quantifies the discrepancy between simplified calculations and the detailed GEANT4 simulations for the RED scenarios; the last section (Sec 5.6) checks the stability of the results.

Throughout all the following sections, two body types are considered. First, a "*trunk*" is defined as a cylinder 0.8 m tall and 0.4 m wide (same definition as that in Section 3). The second "body" type, a "*unit*", is defined as a cylinder with 0.1 m height and 0.1 m in width. A *unit* is meaningful if studying the radiation dose to a particular organ (that is

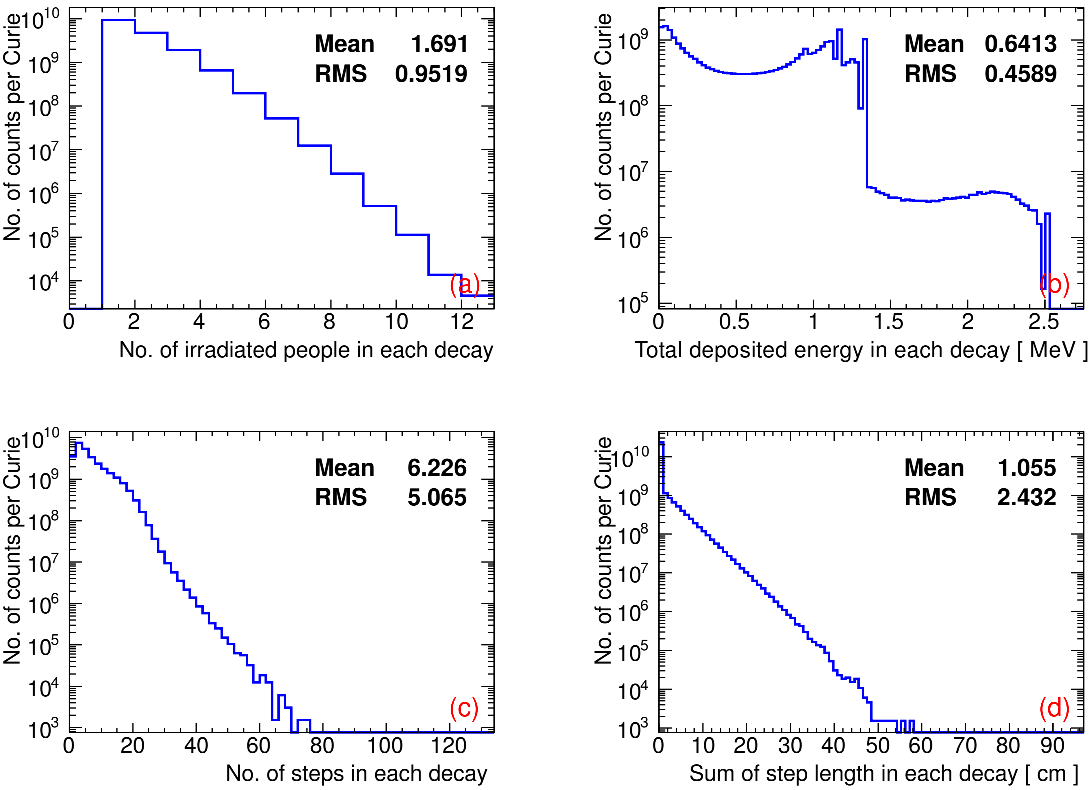


Figure 8: *The hit information of the exposed passengers to 1 Ci cobalt-60 decay. The information here is obtained only from irradiated passengers.*

much smaller than a *trunk*.

$$\begin{aligned} \underline{\textbf{Trunk}}: &\quad \text{Height} = 0.8\text{m}; \quad \text{Width} = 0.4\text{m} \\ \underline{\textbf{Unit}}: &\quad \text{Height} = 0.1\text{m}; \quad \text{Width} = 0.1\text{m} \end{aligned}$$

5.1 Passenger Density (PD) effect

In this study, the PD is a quantity which can be varied to characterize either urban or rural areas. Note that whenever a *passenger* is mentioned, the body should have a realistic size. For example, the *trunk* size is used in PD studies. For GEANT4 simulations, the PD is one of the parameters that controls the inter-personal shielding, multiple scattering and build-up effects. In principle, a higher PD should cause more inter-personal shielding and multiple scattering.

Figure 9 describes the hit number distribution, normalized to a unit cm^2 area and one Curie activity, as a function of the distance. As expected, the number of hits per unit area tends to decrease as the PD is increased. This trend becomes even more clear and significant as the distance from source to target increases. Such kind of behavior is well described by the inter-personal shielding effect explained in the previous paragraph. Note that a higher PD also results in a more distorted shape with respect to a simplistic $\frac{1}{d^2}$ shape. The average energy deposited per hit (Figure 10) also decreases as PD increases due to increased multiple scattetering. This, along with increased inter-personal shielding, affects the shape of the absorbed dose rate distribution as shown in Figure 11.

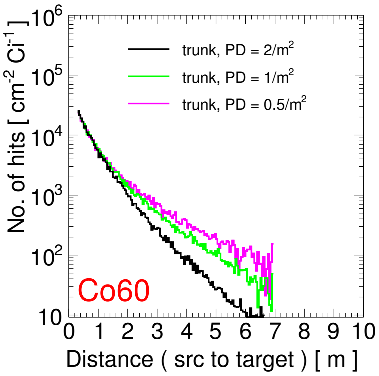


Figure 9: *Number of hits for different passenger density cases.*

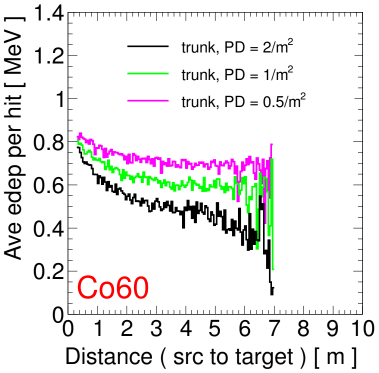


Figure 10: *The energy deposit per hit for different passenger density cases.*

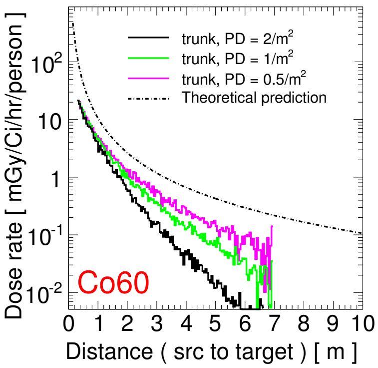


Figure 11: *The measured dose rate for different passenger density cases.*

The PD effect is a compound effect from inter-personal shielding, multiple scattering and build-up effects. In principle, the existing multiple scattering (and build-up) effect should be manifested in the hit number distribution. However, additional checks suggest that these two effects might be not significant enough to be observed (or within the statistical uncertainties). So in this study, the inter-personal shielding is considered to be the dominant factor with respect to the others.

5.2 Body Width (BW) effect

In real life, a human body is an extended object. Together with section 5.3, the impacts of the body heights and widths on the absorbed dose rate is studied.

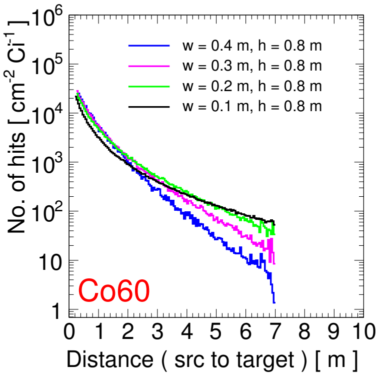


Figure 12: *Number of hits for different trunk width cases.*

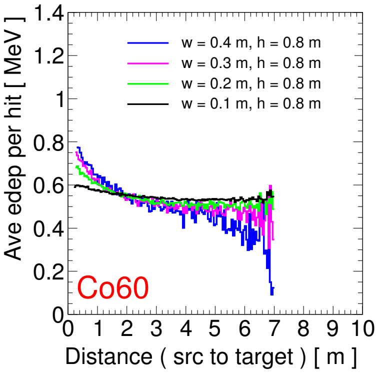


Figure 13: *The energy deposit per hit for different trunk width cases.*

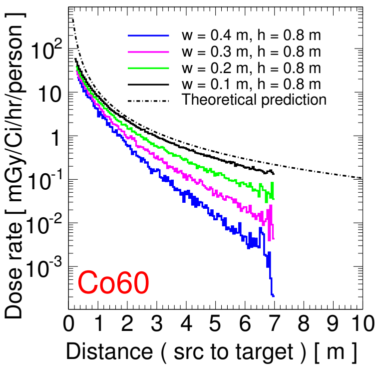


Figure 14: *The measured dose rate for different trunk width cases.*

In this section, four different values for the body width have been assumed while the total number of passengers is fixed for all cases. The results are presented in Figures 12-14, where the BW effects can be clearly observed. In general, these results imply that a slimmer BW will lead to a higher chance for passengers standing far from the source to be hit. The dose rate distribution with the slimmest body width is found to behave most like the theoretical values in term of both shape and magnitude, as shown in Figure 14. This is due to the fact that theoretical prediction does not assume self-shielding inside a wide target/body.

A slim BW also means a higher chance that the gamma radiation will not be fully absorbed in the body (this is also dependent on the initial gamma energy). Accordingly, the total energy deposited in a slim body is on average less than that in a bigger body. This is because the latter case will be likely to absorb more energy per hit and (at larger distance) the number of hits will be larger due to its larger exposure area. The difference observed at the shorter ranges in Figure 13 reflects such an effect.

Changing the BW gives rise to a similar effect as changing the PD. This is because, given that the total number of passengers is fixed in when the BW varied, changing the BW is equivalent to changing the passenger density (or more accurately speaking, the area occupied by passengers). Therefore, similar impacts are found for both PD and BW effects.

On the other hand, BW and PD effects can differentiate each other in these results. Note that for the case where the target is a *Trunk* with PD = 2 person/m^2 case in the PD study, the parameter values are exactly the same as the *w=0.4 m, h=0.8 m* case in the BW study. From this common baseline, a scaling down of the occupied area by four times will be equivalent to the case of 0.5 person/m^2 in the PD study (**Case A**) and *w=0.2 m, h=0.8 m* case in the BW study (**Case B**). A comparison between Case A and B reveals that the dose rate distribution in Case B is much closer to prediction than the one observed in Case A.

The difference between Cases A and B suggests that the width has a specific impact on the absorbed dose rate results after taking out the PD effects. A possible interpretation could be that, in the case where the body width is thicker than necessary to stop the gamma radiation, the resultant dose rate will become less because the energy deposited is unchanged while the mass is larger. On the other hand, as the BW in the GEANT4 simulation approaches the *mass* thickness of water ($\sim$1.0 cm) assumed in the theoretical calculations (Equation 6), the GEANT4 simulation result approaches the theoretical prediction.

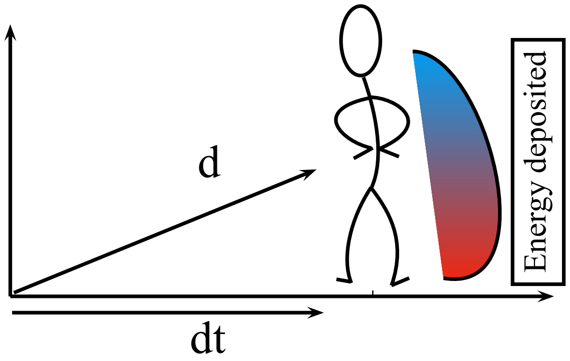


Figure 15: *The illustration of the distance definition. d_t is the transverse distance from the source to the front surface of the passenger. The energy distribution in red is an illustration of energy deposit as a function of the height of irradiated body part. The effective distance d is the energy weighted average distance.*

5.3 Body Height (BH) effect

The body height of the simulated passenger also has an impact on the absorbed dose rate results. The theoretical definition of the distance between a point-like source to a body, denoted as d_t in Figure 15, might not be suitable in practice. This is because in reality, the source will be placed not exactly at the same level as the center of the body, but instead it will probably be close to the ground. In this case, an effective distance, denoted as d in Figure 15, could be more reasonable if considering the energy accumulation effect for the whole body. Note that the difference caused by using different distance definitions is more apparent if the body is closer to the source.

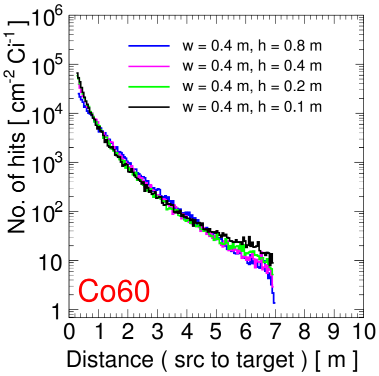


Figure 16: *Number of hits for different trunk height cases.*

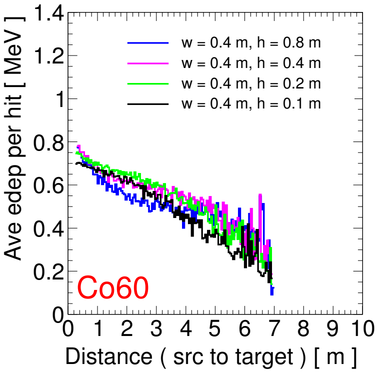


Figure 17: *The energy deposit per hit for different trunk height cases.*

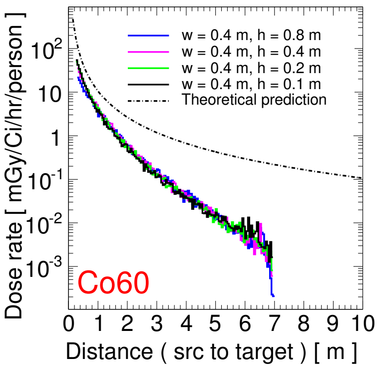


Figure 18: *The measured dose rate for different trunk height cases.*

In order to check the BH effect, four different BH cases have been simulated and checked, as shown in Figures 16-18. These results suggest the impact on the dose rate due to different BHs is not easily noticed. However, a slight difference can be observed in Figures 16 and 18 at the shortest distances.

5.4 Trash bin shielding effect

The source shielding effect has been implemented and simulated in this study by introducing a trash bin, made of iron, surrounding the source location. The shielding effect of the trash bin has been checked by varying the bin thickness and studying the changes to the results. For this purpose, three different bin thicknesses have been assumed.

The simulation results are presented in Figures 19-21 and the dose rate results are compared to theoretical predictions. Based on the discussions in the previous sections, the *Unit*-size target is chosen so that the bin shielding effect can be more clearly quantified when comparing to theoretical predictions.

As expected, a thicker trash bin causes an overall decrease in all the distributions. The explanation is that fewer hits and less energy will be deposited in passengers across the whole distance range as the bin shielding becomes more effective (i.e. thicker). As can be seen in the absorbed dose rate results in Figure 21, the GEANT4 simulations agree well with predictions for 0.4 cm and 4.0 cm bin thicknesses. The theoretical prediction was not calculated for the 12 cm case.

5.5 Absorbed dose rate

In this section, the dose rates from GEANT4 are presented and best-fit parameters are determined for a fitting function. The parameterization aims to extrapolate to a generic

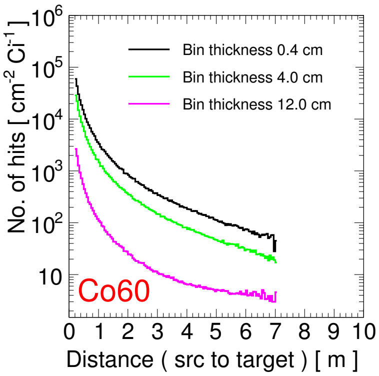


Figure 19: *Number of hits for different shielding cases.*

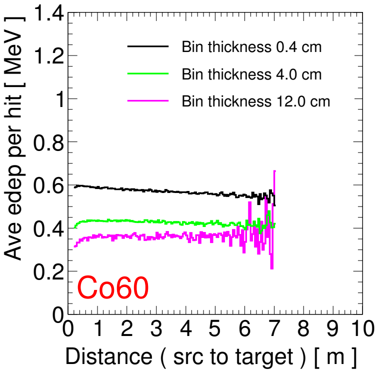


Figure 20: *The energy deposit per hit for different shielding cases.*

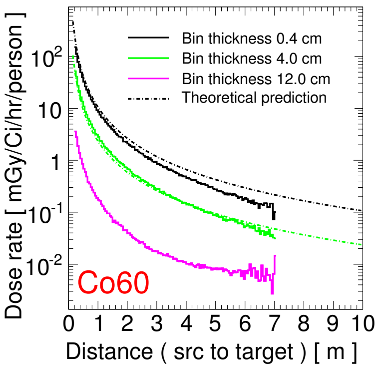


Figure 21: *The measured dose rate for different shielding cases.*

case based on results for a limited number of radiological sources for a specific range of distances.

For comparison purposes, both the *Trunk* and *Unit* results are provided. The *Trunk* results should resemble the dose rates for a person, while the *Unit* case has better agreement with theoretical predictions. The comparison between these two cases sheds light on differences due to various factors.

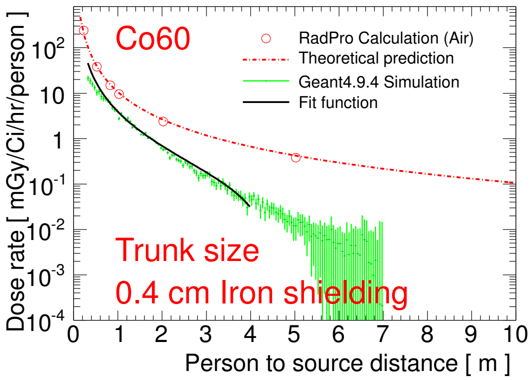


Figure 22: *The absorbed dose rate as a function of d_t in case of Trunk size.*

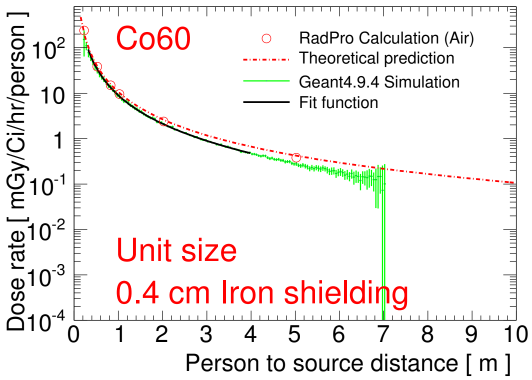


Figure 23: *The absorbed dose rate as a function of d_t in case of Unit body size.*

The absorbed dose rate results from cobalt-60 (cesium-137) are shown in Figures 22 and 23 (24 and 25) for *Trunk* and *Unit* sizes respectively. For all figures, the RadPro results are shown as red circles and the theoretical predictions, in dashed lines, are derived from Equation 7. Note that the RadPro results are calculated by taking air as the interaction medium. Despite this, the energy responses of air and water to γ radiation per *mass* thickness are similar [10], which leads to approximately equal mass absorption coefficients ($\mu_m^{air} \simeq \mu_m^{water}$).

This implies that results from the RadPro calculations can be reasonably used to compare with the GEANT4 results where pure water is the target medium.

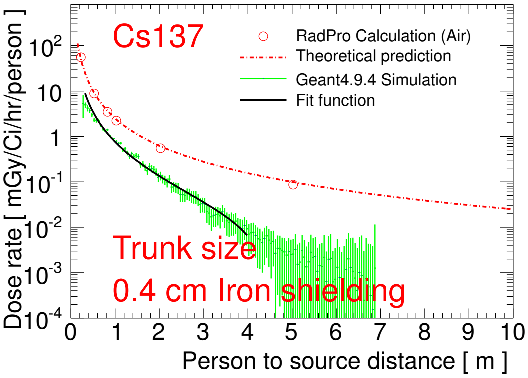


Figure 24: *The absorbed dose rate as a function of d_t in case of Trunk size.*

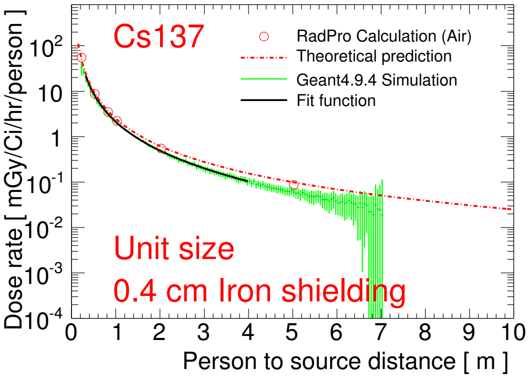


Figure 25: *The absorbed dose rate as a function of d_t in case of Unit body size.*

The GEANT4 simulation results are shown in green in all figures. As explained before, the realistic factors have been taken into account during GEANT4 simulations. As a result, the function to fit the absorbed dose rate distribution might not be simply $\frac{1}{d^2}$, especially in the *Trunk* cases. Therefore, one extra term is introduced to reflect the distortion of the dose rate shape: $f(d) = \frac{A}{d^2} + \frac{B}{d}$. Fitting of GEANT4 simulations has been performed and the fit results are given as black lines in all figures. The two parameters A and B in the revised dose rate expression $f(d) = \frac{A}{d^2} + \frac{B}{d}$ are shown in Table 3.

Table 3: *Results of fitting parameters for both* Trunk *and* Unit *size scenarios*

Radionuclide	Body size	Parameter A	Parameter B
cobalt 60	*Trunk* size	5.0387 ± 0.0406	-1.1393 ± 0.0218
	Unit size	9.4356 ± 0.1994	-0.4647 ± 0.0697
cesium 137	*Trunk* size	0.9711 ± 0.0150	-0.2173 ± 0.0079
	Unit size	2.2851 ± 0.0407	-0.1593 ± 0.0235

The uncertainties given in the fit results on A and B are statistical only. More precise results found in the *Trunk* case reflects the fact that more hits have been accumulated for this case due to a larger flux acceptance area (i.e. the targets are larger) than the *Unit* case.

The possible reason for the observed discrepancy between theoretical predictions and the GEANT4 simulations in Figures 22-25, especially for the *Trunk* case, has been discussed in Sections 5.1-5.4 so will not be repeated here. For more explanations, please refer to these sections.

The difference is also illustrated by the specific absorbed dose rate at one meter distance. For comparison, the results are given in Table 4. For both *Trunk* scenarios, the dose rate result obtained from GEANT4 at 1 meter distance is about one third of the prediction while the *Unit* cases agree reasonably well with predictions.

Table 4: *Comparison of dose rate results at a distance of one metre (mGy/Ci/Hr).*

Radionuclide	Body size	Theory	GEANT4 simulation	$\frac{theory-simulation}{theory}$
cobalt-60	*Trunk* size	10.64	3.90±0.05	63.4%
	Unit size	10.64	8.97±0.21	15.7%
cesium-137	*Trunk* size	2.49	0.75±0.02	69.7%
	Unit size	2.49	2.13±0.05	14.5%

5.6 Stability of simulations

In this section, a stability check of the dose rate simulation is presented. As one starts to do such kinds of checks, issues arise about how to represent the dose rate result run-by-run. As Figures 26 and 27 indicate, the dose rates covers a few orders of magnitude (from 10^{-2} to 10^{2} mGy/Ci/hr/person in this case), depending on the distance under study. A scatter plot (with all individual dose rate values plotted per run) apparently is not a a good choice given such broad dose rate distribution. On the other hand, the mean values shown in these two plots are dependent on the positions of passengers.

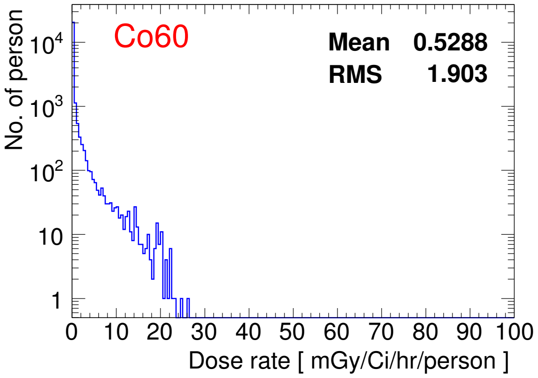


Figure 26: *The dose rate distribution from all passengers of the RED scenario using "Trunk" targets.*

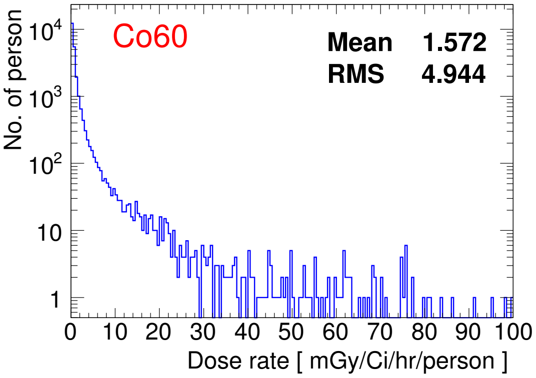


Figure 27: *The dose rate distribution from all passengers of the RED scenario using "Unit" targets.*

For simplicity, the specific dose rates at a distance of one meter, extrapolated from the fit functions, have been used to represent the generic run-by-run dose rate results, as shown in Figures 28 and 29. By comparing these results with those given in Table 4, a slightly lower dose rate result is found in the stability plot for both *Trunk* and *Unit* cases. The reason

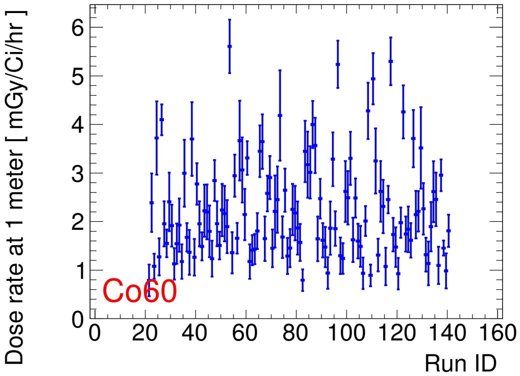


Figure 28: *The specific dose rate run-by-run at 1m distance for Trunk size.*

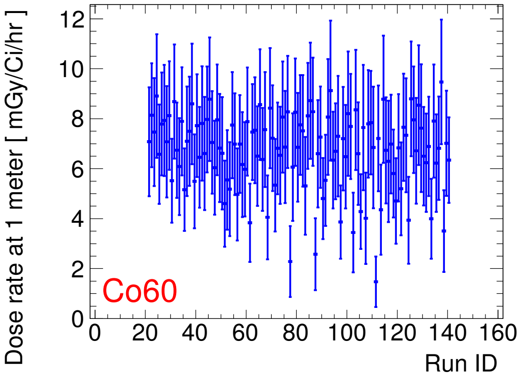


Figure 29: *The specific dose rate run-by-run at 1m distance for Unit size.*

may be due to a large downward fluctuation of the simulated value of the dose rate at 1 m compared to the fit function: see Figures 22 and 23. Note that the stability of the dose rate is heavily dependent on the number of events simulated per run.

6 Summary and future plans

With millions of decays (events) simulated for the RED scenario, the performance of the GEANT4 application has been checked and verified by analyzing the results as a function of the radioactive source, passenger physical size and positioning. These results are in agreement with expectations.

The absorbed dose rate has been measured as a function of distance between the source and the passengers, and is compared with predictions from different sources. The impacts on the absorbed dose rate from the realistic factors simulated in the GEANT4 have been investigated. The realistic factors considered in this study are the passenger density, inter-personal shielding and body dimensions. Discrepancies have been observed between GEANT4 simulations and simplistic theoretical predictions, and the causes are interpreted as being related to these realistic effects that are not taken into consideration by the theoretical predictions.

The verification of the GEANT4 toolkit and the RED application has made DRDC Ottawa ready for the future use of GEANT4 in radiation studies.

The GEANT4 simulation results such as the absorbed dose rate can be estimated for different RED/RDD scenarios and then used to update ongoing risk assessments. For example, the parameters in the Probabilistic Risk Assessment (PRA) Tool (project CRTI-02-0024RD) can be updated.

It is acknowledged that this work has been done in a short period of time, therefore, more checks should be performed and the running of the GEANT4 code could be optimized.

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(Security classification of title, body of abstract and indexing annotation must be entered when document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

GEANT4 simulation of Radiation Exposure Device scenario at bus stop; Report on simulation and analysis

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Liu, C.; Waller, D.

5. DATE OF PUBLICATION (Month and year of publication of document.)

November 2012

6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)

36

6b. NO. OF REFS (Total cited in document.)

10

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

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9a. PROJECT NO. (The applicable research and development project number under which the document was written. Please specify whether project or grant.)

ATIR PA 11036

9b. GRANT OR CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DRDC Ottawa TR 2012-180

10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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In this report, the performance of a GEANT4 radiation exposure device (RED) application has been investigated. Simulations of the radioactive source, bus passengers, and transport of radia-tion inside the human body are checked. The simulated results are consistent with expectations, verifying the GEANT4 application for the RED scenario.

The absorbed dose rate has been estimated as a function of distance between the source and passengers, and the results have been compared with predictions from RadPro calculator and analytical calculations. GEANT4 works like a realistic scenario simulator in that factors such as the inter-personal shielding and finite body dimension effects have been coherently modelled. The impact of these factors on the dose rate estimation has been investigated and is discussed. As a result, the GEANT4 dose rate results tend to be less than simplified predictions.

The verification of the GEANT4 application makes DRDC Ottawa ready for more advanced ra-diation simulation work in the future. For example, GEANT4 can be utilized to assist ongoing radiation detector design and optimization work, and dose rate results can be used to update the radiological consequences estimated for the Probabilistic Risk Assessment Tool.

Ce rapport porte sur le rendement tiré de l’utilisation de l’application GEANT4 comme appareil d’exposition. On a étudié des simulations de la source radioactive, les passagers d’un autobus et le transport des rayonnements à l’intérieur du corps humain. Les résultats simulés sont conformes aux attentes, ce qui atteste l’utilisation de GEANT4 en tant qu’appareil d’exposition pour scénario. Le débit de dose absorbé a été évalué en fonction de la distance entre la source et les passagers. Les résultats ont été comparés avec les prévisions réalisées à partir d’une calculette RadPro et de calculs analytiques. GEANT4 fonctionne comme un véritable simulateur de scénarios, car il modélise de manière cohérente des facteurs comme le blindage interpersonnel et les effets du gabarit corporel. Les répercussions de ces facteurs sur l’évaluation de la dose ont été étudiées et ont fait l’objet de discussions. On a constaté que la dose calculée par GEANT4 a tendance à être moins importante que celle des prévisions simplifiées. La vérification de l’utilisation de GEANT4 fait en sorte que RDDC Ottawa sera prête à réaliser des travaux plus poussés sur la simulation du rayonnement à l’avenir. Par exemple, GEANT4 peut être utilisé pour la poursuite des travaux de conception et d’optimisation d’un détecteur de rayonnement, et les résultats de doses peuvent servir à la mise à jour des conséquences radiologiques prévues par l’outil d’évaluation probabiliste des risques.

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