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GEANT4 simulations of cosmic muon background in CEMRC BEGe lung detectors and detection sensitivity optimization of trans-uranic radionuclides

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ABSTRACT
In this work, we discuss two results from GEANT4 simulations of the broad-energy germanium (BEGe) lung counting system used by the Carlsbad Environmental Monitoring and Research Center (CEMRC) internal dosimetry laboratory. The first component of the presented research consists of the integration of the cosmic muon background into the environmental background spectra and updated calculations of the minimum-detectable activities (MDAs) that were previously published by the authors. This is followed by an investigation of methods to increase the detection sensitivity to low-energy γ rays produced by the trans-uranic radioisotopes of interest by reducing the number of background counts observed in the region-of-interest (ROI) of the measured γ ray spectra measured by the CEMRC in vivo counting system. Two methods were investigated for improving the MDAs: (1) a reduction in the thickness of the germanium detector crystals, and (2) the addition of a Compton-suppression detection system surrounding the germanium detectors, acting as an anti-coincidence veto counter.

1. Introduction

The detection of low-energy γ rays emitted from radioactive isotopes within the human body is of primary importance in the monitoring of radiological workers at the Waste Isolation Pilot Plant (WIPP), located in Carlsbad, New Mexico, USA, and other related facilities. Routine in vivo radio-bioassay measurements of the WIPP workers and public volunteers from the surrounding community are made at the Carlsbad Environmental Monitoring and Research Center (CEMRC), where broad-energy germanium (BEGe) detectors are used to directly measure the presence of radioisotopes in the lungs of a human body. Of particular interest are the isotopes 241Am and 238Pu, which make up a significant amount of the WIPP radionuclide inventory. The sensitivities for radioisotope detection in these measurements are limited by the presence of background radiation present in the CEMRC dosimetry chamber, in addition to the attenuation and scattering of the low-energy γ rays of interest as they travel through the chest tissues when exiting the body.

While the attenuation and scattering of γ rays of interest cannot be reduced without invasive techniques, various methods for reducing the number of background counts have been proposed (Baburajan, Rao, Ravi, Sudheendran, & Tripathi, 2014; Pillalamarri & Jagam, 2017). It is therefore imperative to attempt to quantify the various contributions to the background radiation field in the CEMRC counting chamber. The primary sources of background radiation relevant to dosimetry at CEMRC are radioactive 40K within human body, airborne 222Rn in the counting chamber, primary cosmic rays and all secondary radiation they produce as they interact with materials in the counting chamber, as well as trace radioactive contaminants in the detectors, their mounting apparatus, and the counting chamber itself. Investigations of the effect of the first two mentioned sources of background (40K and 222Rn) were previously reported on in Turko, Pillalamarri, and Jagam (2018). In this paper, we report on the addition of cosmic muons and the secondary radiation they produce as they interact with the CEMRC counting chamber and detector geometries to the background signal in the BEGe detectors used by CEMRC.

Once an approximate quantification of the background signal observed in the BEGe detectors at CEMRC has been simulated, modifications to the simulated geometries can be made to estimate their effect on the detection sensitivities of the BEGe detectors to the radioisotopes of interest. In this work, we investigate two methods to decrease the simulated detection sensitivity: (1) a reduction in the thickness of the germanium detector crystals, and (2) the addition of a Compton-suppression shielding around the detectors serving as an anti-coincidence counter.

2. Methodology

The GEANT4 toolkit (Agostinelli et al., 2003), version 4.10.04, was used in the presented work to simulate the trajectories and interactions of radiation within the...
2.1. Cosmic muon contribution to the environmental background

While the CEMRC counting chamber has 10 in (25.4 cm) thick iron walls, high-energy cosmic muons ($E_\mu \geq 1$ GeV) can penetrate the chamber walls and generate background counts in the BEGe detectors that interfere with the detection of trans-uranic (TRU) isotopes of interest. In addition to the direct interaction of cosmic muons as they pass through the germanium crystals, their interactions with the surrounding material can produce secondary background radiation in the counting chamber that also produce a signal in the BEGe detectors. A large component of these events are from pair production interactions as the muons traverse the high-Z bulk material of the counting chamber, which creates both a peak at 511 keV and a contribution to the Compton continuum below 340 keV in the BEGe spectra.

The presented simulations of the cosmic muons in GEANT4 used four main quantities for a first-order estimation of the produced background present at CEMRC. The four quantities were: (1) the momentum distribution of the muons, (2) the angular distribution of the muons, (3) the total muon flux, and (4) the muon charge ratio. While the exact determination of these quantities can be challenging as they depend variables such as the latitude, altitude, and magnetic field of the location, estimates can be made by surveying the literature of experimental measurements of cosmic muons. The initial position distribution of the cosmic muons was taken to be uniform across the top surface of the world volume in GEANT4, represented by a 10 m by 10 m by 10 m cube.

The function describing the momentum distribution of muons used in the present simulations was taken from Grieder (2001):

$$I(p_\mu) \propto p_\mu^{-0.4854 - 0.3406 \ln (p_\mu)}$$

(1)

where $p_\mu$ is the muon momentum in units of GeV/c. This parameterization has been shown to be accurate in replicating experimental measurements of cosmic muons at sea level with momenta $0.2 \text{GeV}/c \leq p_\mu \leq 20 \text{GeV}/c$. For these simulations, only muons with energies greater than 1 GeV were considered due to the quoted restriction on the total muon flux used. In the presented simulations, the initial muon energies ranged from 1 to 1000 GeV.

The angular distribution of cosmic muons at sea level can be described by the following relation (Arslan & Bektasoglu, 2013; Bektasoglu & Arslan, 2013; Grieder, 2001; Pethuraj et al., 2017):

$$I(\theta) \propto \cos^n(\theta)$$

(2)

where $\theta$ is the zenith angle and $n$ is an experimental parameter that is dependent on the location of the measurement (e.g. the latitude, altitude, etc.). The muons were assumed to have no azimuthal dependence in the current work.

Typically, the expressions in Equations (1) and (2) are given as equalities with normalizing factors to take into account the magnitude of the muon flux. However, in the present work, the total muon flux that the corresponding number of simulation muons will be calculated by integration over all incident muon angles ($-\pi/2 \leq \theta \leq \pi/2$). The vertical muon flux $I_0$ was taken as $7 \times 10^{-3} \text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$, and $n$ was taken as 2, motivated by a survey of experimental measurements presented in the work by Pethuraj et al. (2017). The charge ratio of $\mu^+$ to $\mu^-$ was taken as 1.3, as quoted by the paper by Arslan and Bektasoglu (2013).

The present simulations consisted of simulating the cosmic muon background generated in the CEMRC counting chamber for the preferred subject counting time of half an hour (1800 s). The simulated geometry used was identical to that which was used in Turko et al. (2018).

The dimensions used for the simulated BEGe detector germanium crystals were taken from data sheets provided by Canberra (Canberra Industries, 2017). The true manufactured parameters provided with each BEGe detector observed to vary by an average of only 0.7% (0.5 mm) and 3.6% (0.725 mm) for the diameter and thickness of the germanium crystal, respectively. A simulated model of the BEGe detector used in these simulations is shown in Figure 1. The typical specifications for a CEMRC BEGe lung detector are an active diameter, surface area, and thickness of 70 mm, 3800 mm$^2$, and 20 mm, respectively. The design for the detector housing was modeled from the work done by Fantinová and Fojtík (2014). The front face of the CEMRC BEGe detector housing was covered with a 0.6 mm thick carbon composite window, 5.5 mm from the germanium crystal. The sides and back of the detector housing were a 1.5 mm thick aluminum can, with a 3.25 in (82.55 mm) diameter and a 3.5 in (88.9 mm) in length. The germanium crystal was held with a 1.5 mm thick copper clamp within the
aluminum detector housing. The rest of the interior volume was filled with a vacuum. The BEGe detector dewar was not included in the present simulations.

The simulated spectra in the BEGe detectors resulting from the cosmic muons was then incorporated with the environmental background simulations presented in Turko et al. (2018) resulting from $^{40}$K within a human body (represented by a BOMAB phantom) and airborne $^{222}$Rn. The minimum detectable activities could then be recalculated using the new environmental background spectra using the expression from Currie (1968):

$$\text{MDA (Bq)} = \frac{4.65\sigma_B + 2.71}{\epsilon I_{\gamma} t},$$

where $\sigma_B$ is the standard deviation in the number of counts in the region-of-interest of the background spectrum ($\sqrt{N_B}$ for one simulated count under Poisson statistics, where $N_B$ is the number of counts in the region-of-interest of the background spectrum), $\epsilon$ is the efficiency for the $\gamma$ ray of interest, $I_{\gamma}$ is the intensity of the $\gamma$ ray of interest, and $t$ is the counting time.

2.2. Optimization of the low-energy detection sensitivity

In order to increase the detection sensitivity for TRU isotopes, it is crucial to limit the number of background counts in the region-of-interest (ROI) of the emitted $\gamma$ ray of interest. There are a multitude of methods to achieve this goal, including the presence of a shielding chamber to reduce radiation from external sources, moving the measurement underground where the cosmic ray flux is reduced, or modifying the detector design, or vetoing unwanted events such as Compton-scattered $\gamma$ rays. The latter two methods are investigated in this work.

In order to investigate the efficacy of these methods, the background simulations outlined in Section 2.1 were repeated with modified geometries described below. The same three sources of background radiation will be considered; $^{40}$K within a BOMAB phantom (representing a human body), airborne $^{222}$Rn, and cosmic muons. Similarly to the work presented in Turko et al. (2018), the maximum simulated activity of $^{40}$K was taken as 160 nCi (the maximum observed activity in a measurement at CEMRC); for $^{222}$Rn, it was taken as 4 pCi/L within the CEMRC chamber (the maximum safe level as stated by the U.S. Surgeon General and the Environmental Protection Agency) (United States Environmental Protection Agency [US EPA], 2016).

2.2.1. Germanium crystal thickness

In previous work by the authors I. Pillalamarri and P. Jagam, the effect of reducing the thickness of the germanium crystal used in the $\gamma$-ray detectors would have on the mean-free path traveled by photons through the crystal was discussed (Pillalamarri & Jagam, 2017). Here it was communicated that by drastically reducing the thickness of the germanium crystal one could...
eliminate almost all interactions of high-energy γ rays (such as the 1461 keV γ ray from 40K) while only moderately reducing the efficiency of detection for the lower energy γ rays, such as the 59 keV γ ray emitted by 241Am. By decreasing the fraction of higher-energy γ rays to the fraction of lower-energy γ rays, the detection sensitivity to the latter could be increased.

The suggested thickness in the aforementioned work was on the order of one mean-free path of the low-energy γ-ray of interest (about 0.04 mm for the 46 keV emitted by 210Pb), which is beyond the capabilities of current germanium crystal manufacturing. Additionally, a germanium crystal with such a minute thickness would greatly sacrifice the photopeak detection efficiency of high-energy γ rays that are also of interest for internal dosimetry at CEMRC. However, a reduction to the germanium crystal thickness by a smaller amount could be made to decrease the Compton contribution of high-energy γ rays without overly sacrificing their photopeak efficiency beyond the requirements of CEMRC.

In the present simulations, three thinner germanium detector thicknesses will be considered: 10, 5, and 2.5 mm. The MDAs were calculated for γ rays from two radioisotopes of particular interest at CEMRC, 17.1 keV from 238Pu and 59.5 keV from 241Am using Equation (3). For these calculations, it is assumed that the detection efficiency for both the γ rays of interest will not change, although in reality they will be reduced by the thinner germanium crystals.

2.2.2. Compton suppression shielding

The other method used to reduce the MDA for the TRU isotopes of interest involves the addition of Compton suppression shielding surrounding each pair of BEGe detectors. The added shielding serves as a high-efficiency detector used to veto γ rays that do not deposit their entire energy in the germanium crystal, and would otherwise contribute to the Compton continuum background in the γ-ray ROI.

For effective Compton suppression, an ideal detector material will have a high efficiency for γ rays of all energies and a fast response time (to accurately discriminate between a scattered γ ray and two independent γ rays). Very little is required by way of energy resolution mainly because all events where the Compton suppression shields register any energy deposition in them will be excluded from the recorded BEGe spectra. A typical choice for this material is bismuth germanate (BGO), a high-density scintillating material (de Voigt et al., 1995). BGO has a primary decay component of 300 ns which is far shorter than the mean time between counts in the BEGe detector background spectra, making it an ideal candidate for a Compton suppression shielding material.

The present simulations will consist of the addition of 5 mm Compton-suppression BGO shielding added around each set of two BEGe detectors (one set of two BEGe detectors for each lung). No exterior casing to the BGO detectors was implemented in the current simulations. This design allows for the CEMRC BEGe counting geometry to remain identical to its current setup, leaving the geometrical detection efficiency for various radionuclides unchanged.

3. Validation of the GEANT4 simulation

Before investigating the influence reducing the germanium crystal thickness or the inclusion of BGO shielding on the MDAs of the radioisotopes of interest, the accuracy of the simulation was tested. This was done by comparing the experimentally measured spectrum of a standard CEMRC calibration source BOMAB (Battelle Standards Laboratory, 1999) to one simulated by GEANT4. The BOMAB phantom calibration source that was used contained detectable activities of 40K (100nCi), 137Cs (249nCi), and 152Eu (143nCi) on the date of the experimental measurement. The activities used in the simulation are decay-corrected to the date of the experimental measurement from the values provided in the BOMAB certificate. The number of simulated decays for each source in the BOMAB was calculated for a counting time of 4 hours, as was the duration of the experimental spectrum. In order to generate the final simulated spectrum, each component of the radiation field within the CEMRC counting chamber was simulated independently, and the resulting BEGe spectra were added together. The final simulated spectrum is a sum of spectra produced by the three radioactive species within the calibration BOMAB, ambient 222Rn at a concentration of 1pCi/L, and a cosmic muon flux of 0.007 s⁻¹sr⁻¹cm⁻².

The agreement between the simulated and experimental spectra is good at energies above about 30 keV; however, the simulation underestimates the number of background counts at lower energies. This is to be expected, as various additional contributions to the experimental spectrum are not accounted for in the simulated spectrum, such as trace radioactive contaminants in the CEMRC counting chamber and detector apparatus or the accumulation of 222Rn and its decay products on the various surfaces within the counting chamber. A discussion of the additional sources and their contribution to the BEGe detector background was included in the previous work (Turko et al., 2018). Figure 4 shows the comparison between the simulated and experimental BEGe signals.

4. Results

4.1. Cosmic muon contribution to the environmental background

An example of a simulated cosmic muon spectra generated in a half hour count at CEMRC is shown in Figure 5. Here, the contribution of the cosmic muons to the total...
environmental background spectrum can be seen. From the simulations, it appears that the main source of counts in the annihilation peak at 511 keV is the cosmic muons. Moreover, the cosmic rays contribute significantly to the low-energy background in the BEGe detectors, likely resulting from Compton scattering of the 511 keV γ rays in addition to particle showers generated by the muons as they interact with the counting chamber.

4.2. Optimization of the low-energy detection sensitivity

4.2.1. Germanium crystal thickness
Simulations of the three sources of background (40K, 222Rn, and cosmic muons) representing a typical half hour counting time at CEMRC were computed for the three thinner germanium crystal thicknesses (10, 5, and 2.5 mm) followed by calculation of the 241Am and 238Pu MDAs using Equation (3). The simulated spectra in the BEGe detectors are shown in Figure 6. The efficiency values used in the MDA calculations were assumed to remain constant with respect to the germanium thickness due to the low energy of the γ rays. The simulated MDA values are presented in Table 2, and are compared as functions of the chest wall thickness in Figures 7 and 8.

4.2.2. Compton suppression shielding
A comparison between simulated spectra with and without the Compton suppression activated is shown in Figure 9. The 5 mm thick BGO Compton-suppression shielding design shown in Figure 2 was added around each pair of BEGe detectors. The simulations outlined in Section 4.2.1 were repeated and the new MDAs were calculated. For these simulations, the BGO shielding was assumed to have 100% veto efficiency – i.e. any energy deposition in the BGO that is in temporal coincidence with an energy deposited in the BEGe crystals is rejected from the Compton-suppressed spectrum. Additionally, the addition of the BGO shielding was assumed to not alter the 241Am and 238Pu detection efficiencies, as the positioning of the BEGe detectors was unchanged from the simulations without the shielding. The simulated MDA values are presented in Table 3, and are compared as functions of the chest wall thickness in Figures 10 and 11.

5. Discussion and conclusions

5.1. Cosmic muon contribution to the environmental background
With the addition of the cosmic ray muons to the simulated environmental background in the first part of the simulations (Sections 2.1 and 4.1), the MDA values presented in Turko et al. (2018) were updated. These values are presented in Table 1 for chest plates of various thicknesses placed on the torso of the BOMAB phantom. While the inclusion of the cosmic ray background does contribute to an increase in the simulated MDAs, all sources of background counts leading to the larger experimental MDAs have not been accounted for which is reflected by the larger experimental MDAs versus the simulated values. This is likely due to contributions from primary cosmic ray neutrons as well as trace radioactive contaminants in the chamber and detector apparatus that have not been accounted for in the current work.

5.2. Optimization of the low-energy detection sensitivity

5.2.1. Germanium crystal thickness
Following the integration of cosmic muons into the environmental background simulations, two methods

Figure 2. (Color online) A rendering of two BEGe detectors surrounded by a 5 mm thick layer of BGO Compton suppression shielding. The aluminum detector can is shown in gray, the carbon composite window in black, and the BGO shielding in blue.
for improving the low-energy γ ray detection sensitivity were investigated. The first involved the reduction in the thickness of the germanium detector crystals. From the spectra in Figure 6, the number of background counts in the low energy region is reduced by about a factor of 2 between the 20 mm and 2.5 mm thick detectors, leading to an MDA reduction of around 20–30% on average. Due to the short counting time and therefore low number of counts, the error bars, which are not shown, are on the order of just under 100% of the MDA value itself. However, this improvement in the low-energy MDA must be balanced with the detector performance at higher energies as well. For example, the dominant peak at 1461 keV resulting from the $^{40}$K decaying inside the BOMAB phantom is greatly reduced for the 10 mm and 5 mm thick detectors, and completely absent in the 2.5 mm thick detector spectrum. As stated in Section 4.2.1,
The germanium detection efficiency for the thinner crystals was not simulated in the presented work, and as stated Section 4.2.1, and instead assumed to be consistent with the experimentally determined value for the default 20 mm thick BEGe detectors used by CEMRC. This can be justified by examining the attenuation of the low energy gamma-rays of interest in germanium. As demonstrated in the previous work by the authors Pillalamarri and Jagam (2017), the percent of absorbed γ-rays at different energies can be calculated for different detector thicknesses. For the thinnest simulated detector (2.5 mm), the absorption percent for the $^{238}$Pu (17.1 keV) and $^{241}$Am (59.5 keV) γ-rays of interest are approximately 100% and 94%, respectively. For the default, 20.0 mm thick BEGe detectors, the absorption percent is 100% for all γ-rays. This implies that the detection efficiency is dominated by the geometric configuration rather than the intrinsic detector efficiency, which should not change depending on the thickness of the simulated germanium crystals.

For the CEMRC facility, where the scope of the internal dosimetry lab goes beyond the detection of only low-energy γ rays, sacrificing the efficiency of detection of the higher energy γ rays is unacceptable. Additional concerns about the ability to manufacture and maintain such thin detectors reliably is also an uncertainty, further limiting their promise as a valid solution to the detection of the low-energy γ rays. For these reasons, the alternative method of Compton suppression was investigated for improvement of the low-energy γ ray detection sensitivity.

Figure 5. (Color online) The spectrum generated in the four CEMRC BEGe lung detectors generated by (1) (red) a cosmic muon flux of 0.007 s$^{-1}$sr$^{-1}$cm$^{-2}$, a $^{40}$K activity of 80nCi, and an airborne $^{222}$Rn activity of 1pCi/L, and (2) (black) just the cosmic ray component from the red spectrum. The simulated counting time was half an hour (1800 s) with no chest plate on the BOMAB phantom.

Figure 6. (Color online) A comparison between the spectra in the four BEGe detectors for various germanium thicknesses.
5.2.2. Compton suppression shielding

The alternative proposed method of reducing the MDA, including an auxiliary Compton suppression shielding system, was then investigated. A comparison between the spectra produced with and without the vetoing of Compton-scattered events, is shown in Figure 9. Here, the advantage of Compton suppression over a reduction in the germanium crystal thickness is seen by the unchanged intensity of the 1461 keV photopeak in the Compton-suppressed spectrum. This is because these events, by nature of complete photo-absorption, deposit their entire energy in the germanium crystal and not activating the BGO shields. This leaves the detection efficiencies unchanged while simultaneously reducing the number of signals produced from scattered γ rays that do not deposit their full energy in the BEGe detectors. The only exception to this is the annihilation peak at 511 keV because these γ rays always come in pairs, meaning it is likely that one of the two γ rays will hit the...
germanium crystal while the other enters the BGO shielding. It is also possible that this could result in fewer counts in the peak from any decay where two $\gamma$ rays are emitted within the time coincidence window used by the Compton suppression system. These events would have a relatively small solid angle for nuclei decaying within the lungs of a patient at CEMRC, and therefore will likely not affect the detection efficiency of any of the TRU isotopes of interest.

One potential downside of the BGO shielding used in the Compton suppression shields is the likelihood of trace contaminants of radioactive $^{207}$Bi, which emits $\gamma$ rays at 470, 1060, 1630, and 2400 keV which will contribute to the background in the BEGe detector (Saint Gobain Crystals, 2016). An alternative material to BGO is NaI(Tl) crystals, which can be produced with only minor contamination of less than 0.5 ppm of $^{40}$K. However, NaI(Tl) is less dense than BGO, leading to a lower efficiency in detecting scattered $\gamma$ rays (BGO and NaI(Tl) have 50% attenuation lengths of 1.0 and 2.5 cm, respectively). Further investigations of comparing the efficacy of both Compton suppression shielding materials are still required.

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**Table 1.** A comparison of experimental (Exp) and simulated (Sim) MDA values calculated using the four BEGe lung detectors at CEMRC for a half hour (1800 s) background count. The experimental MDA values were previously presented in Turkó et al. (2018) using measurements of over 1000 individuals made at CEMRC. The simulated MDA values were calculated using Equation (3). The simulated MDA values represent the upper limit for the MDA with contributions only 1pCi/L of airborne $^{222}$Rn, up to 160nCi of $^{40}$K (the maximum activity observed within a human body at CEMRC), and a cosmic muon flux of 0.007 s$^{-1}$sr$^{-1}$cm$^{-2}$.

| Chest Wall Thickness (cm) | 1.6 | 2.2 | 3.3 | 4.2 | 5.1 | 6.0 |
|---------------------------|-----|-----|-----|-----|-----|-----|
| MDA (nCi)                 |     |     |     |     |     |     |
| Isotope Energy (keV)      |     |     |     |     |     |     |
| $^{241}$Am                |     |     |     |     |     |     |
| 59.5                      | 0.17| 0.21| 0.31| 0.42| 0.58| 0.80|
| $^{238}$Pu                | 17.1| 16  | 36  | 27  | 319 | 1198|

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**Table 2.** MDA values calculated from the simulated background for different germanium crystal thicknesses used in the four CEMRC BEGe lung detectors. The simulated counting time was half an hour (1800 s). The MDA values were calculated using Equation (3), and represent the upper limit for the MDA with contributions only 1pCi/L of airborne $^{222}$Rn, up to 160nCi of $^{40}$K (the maximum activity observed within a human body at CEMRC), and a cosmic muon flux of 0.007 s$^{-1}$sr$^{-1}$cm$^{-2}$.

| Chest Wall Thickness (cm) | 1.6 | 2.2 | 3.3 | 4.2 | 5.1 | 6.0 |
|---------------------------|-----|-----|-----|-----|-----|-----|
| MDA (nCi)                 |     |     |     |     |     |     |
| Isotope Energy (keV)      |     |     |     |     |     |     |
| $^{241}$Am                |     |     |     |     |     |     |
| 59.5                      | 0.08| 0.13| 0.17| 0.21| 0.30| 0.40|
| $^{238}$Pu                | 17.1| 20  | 11  | 94  | 163| 3738|

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**Table 3.** MDA values calculated from the simulated background for different germanium crystal thicknesses used in the four CEMRC BEGe lung detectors and 5 mm thick BGO Compton-suppression shielding. The simulated counting time was half an hour (1800 s). The MDA values were calculated using Equation (3), and represent the upper limit for the MDA with contributions only 1pCi/L of airborne $^{222}$Rn, up to 160nCi of $^{40}$K (the maximum activity observed within a human body at CEMRC), and a cosmic muon flux of 0.007 s$^{-1}$sr$^{-1}$cm$^{-2}$.

| Chest Wall Thickness (cm) | 1.6 | 2.2 | 3.3 | 4.2 | 5.1 | 6.0 |
|---------------------------|-----|-----|-----|-----|-----|-----|
| MDA (nCi)                 |     |     |     |     |     |     |
| Isotope Energy (keV)      |     |     |     |     |     |     |
| $^{241}$Am                |     |     |     |     |     |     |
| 59.5                      | 0.08| 0.11| 0.12| 0.22| 0.29| 0.40|
| $^{238}$Pu                | 17.1| 20  | 7.7 | 16  | 96  | 272 | 986 | 2896|

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Disclosure statement

No potential conflict of interest was reported by the authors.

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