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Abstract. In the event of an environmental contamination with radioactive materials, one of the most dangerous materials is ^{137}Cs. In order to evaluate the radiation doses involved in an environmental contamination of soil, with ^{137}Cs, we carried out a computational dosimetric study. We determined the radiation conversion coefficients (CC) for effective (E) and equivalent (H_T) doses, using a male and a female anthropomorphic phantoms. These phantoms were coupled with the MCNPX (2.7.0) Monte Carlo simulation software, for three different types of soil. The highest $CC[H_\mathrm{T}]$ values were for the gonads and skin (male) and bone marrow and skin (female). We found no difference for the different types of soil.

1. Introduction

As a consequence of the radiological accidents of Chernobyl (Ukraine) in 1986 [1], Goiânia (Brazil) in 1987 [2] and, recently, Fukushima (Japan) in 2011 [3], there is a great concern regarding the radiation doses from these accidents. In such accidents, several radioactive materials may have been released in the environment. Among these radioactive materials, ^{137}Cs is one of the most common heavy fission products, and it may spread for several km^2 [4, 5, 6].

It is hard to evaluate the doses from these accidents, mainly because they may spread on a variety of soils and depths. Experimental measurements may also be difficult to be carried out, since ^{137}Cs is a dangerous material. Therefore, one of the most safest and confident way to evaluate these doses is with the use of Monte Carlo simulations.

Some papers previously evaluated the doses from ^{137}Cs in soil, using mathematical phantoms, to represent the exposed individuals [7]. These phantoms, however, present a simplified anatomical structure. Intending a more detailed simulation, we proposed, in this work, the use of a more realistic scenario.

The main objective of this work was to carry out a detailed dosimetric evaluation of exposures from different soils contaminated with ^{137}Cs, using Monte Carlo simulations [8] coupled with

adult anthropomorphic phantoms, named FASH3 and MASH3 [9, 10].

2. Materials and Methods
The dosimetric evaluation was carried out using a ^{137}Cs radioactive source, which emits photons with energy of 662 keV. We considered this source as soil contaminant, from spill of radioactive material from a radiological accident [6].

This source emits photons isotropically, which are interacting with the individuals at the surface. The results were obtained using the radiation transport code MCNPX (version 2.7.0) [8], and the absorbed doses were determined over the organs and tissues of the adult virtual anthropomorphic phantoms MASH3 (male, 1.76 m height and 73 kg) and FASH3 (female, 1.63 m height and 60 kg). A detailed description of these phantoms may be found elsewhere [9, 10].

The geometrical arrangement, used in the MCNPX code, is presented in Figure 1. The soil was represented by a cylinder with a depth of 2 cm and 5 m of radius, and the radioactive material was uniformly distributed.
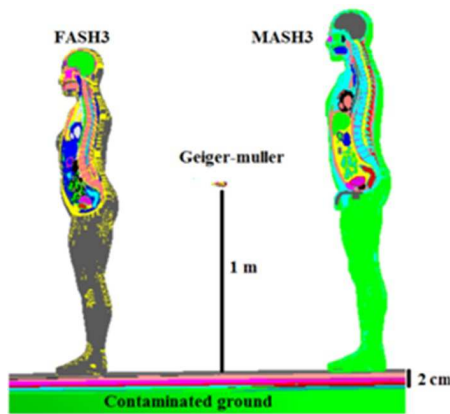

Figure 1. Exposure scenario with the FASH3 and MASH3 phantoms placed on a contaminated soil.

We also investigated the influence of chemical and physical characteristics of the soil, named soils 1, 2 and 3, on the CC values. Their description is presented in Table 1.

The absorbed doses were estimated separately for each source and soil, and calculated for several organs and tissues. The weighting factors w_{T} for each organ and tissue, recommended by ICRP 103 [11] were applied to the equivalent dose (H_{T}) to each organ and tissue. These values were normalized by the air kerma, measured with a Geiger-Müller Pancake Probe (GM), computationally modeled (Figure 2), and positioned 1 m above the ground. A detailed description of the GM may be found at the manufacturer website [12]. The Monte Carlo simulations were carried out with 1E8 particle histories.
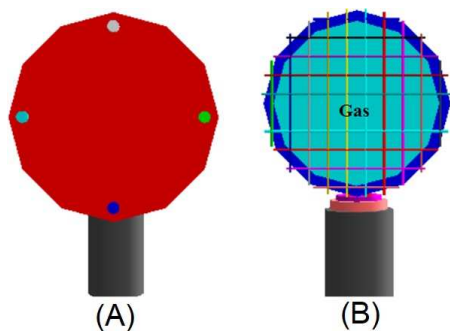

Figure 2. Geometry of the GM counter - external (A) and internal (B) frontal views.

As a result, we obtained the conversion coefficients (CC) for equivalent dose ($CC[H_{\mathrm{T}}]$). With these values, we determined the CC for effective dose ($CC[E]$), as stated in Equation 1.

Table 1. Soil composition used in the Monte Carlo simulations.

Soil	Density (g/cm³)	Composition (%)	
1	2.00	Si (21.61)	Na (0.6)
		Al (8.2)	K (2.33)
		Fe (4.5)	P (0.02)
		Mn (0.1)	H (3.04)
		C (2.4)	O (51.5)
		Ca (5.1)	
2	1.25	H (16.87)	Al (1.976)
		O (27)	Si (8.963)
3	1.60	H (2.1)	Si (27.1)
		C (16)	K (1.3)
		O (57.7)	Ca (4.1)
		Al (5.0)	Fe (1.1)

$$CC[E] = \sum_T w_{\mathrm{T}} \left[\frac{CC[H_{\mathrm{T}}]_{\mathrm{Male}} + CC[H_{\mathrm{T}}]_{\mathrm{Female}}}{2} \right] \tag{1}$$

were w_{T} is the weigting factor for each organ and tissue, $CC[H_{\mathrm{T}}]_{\mathrm{Male}}$ is the conversion coefficient for equivalent dose for the male phantom, and $CC[H_{\mathrm{T}}]_{\mathrm{Female}}$ for the female phantom.

3. Results and Discussion
The $CC[H_{\mathrm{T}}]$ and $CC[E]$, measured 1 m above the ground, are presented in Tables 2, 3 and 4, respectively. All uncertainties are below 1%.

Table 2. $CC[H_{\mathrm{T}}]$ measured 1 m above the ground (Sv/Gy) for the MASH3 virtual anthropomorphic phantom for the different soils. Remainder tissues are: Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymph nodes, muscles, oral cavity, pancreas, uterus, small intestine and spleen.

Organs	Soil 1	Soil 2	Soil 3
Bone marrow	0.63	0.64	0.62
Colon wall	0.61	0.61	0.60
Lung	0.57	0.58	0.57
Stomach wall	0.55	0.55	0.55
Breast	0.75	0.76	0.76
Reminder tissues	0.05	0.05	0.05
Gonads	0.84	0.86	0.82
Bladder wall	0.66	0.67	0.64
Oesophagus	0.48	0.49	0.48
Liver	0.57	0.57	0.56
Thyroid	0.44	0.45	0.43
Bone surface	0.15	0.15	0.15
Brain	0.55	0.55	0.55
Salivary glands	0.21	0.21	0.21
Skin	0.85	0.85	0.84
Eyes	0.61	0.61	0.60

Table 3. $CC[H_{\mathrm{T}}]$ measured 1 m above the ground (Sv/Gy) for the FASH3 virtual anthropomorphic phantom for different soils. Remainder tissues are: Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymph nodes, muscles, oral cavity, pancreas, uterus, small intestine and spleen.

Organs	Soil 1	Soil 2	Soil 3
Bone marrow	0.86	0.87	0.85
Colon wall	0.60	0.61	0.60
Lung	0.64	0.64	0.64
Stomach wall	0.56	0.56	0.56
Breast	0.77	0.77	0.76
Reminder tissues	0.05	0.05	0.47
Gonads	0.64	0.65	0.63
Bladder wall	0.69	0.71	0.68
Oesophagus	0.57	0.56	0.57
Liver	0.57	0.58	0.57
Thyroid	0.55	0.55	0.55
Bone surface	0.13	0.13	0.12
Brain	0.59	0.59	0.59
Salivary glands	0.23	0.23	0.23
Skin	0.86	0.87	0.85
Eyes	0.67	0.65	0.65

Table 4. $CC[E]$ measured 1 m above the ground (Sv/Gy) for the MASH3 e FASH3 virtual anthropomorphic phantoms.

Soil	$CC[E]$
1	0.57
2	0.57
3	0.56

According to the data listed in Tables 2 and 3, we may note that the $CC[H_\mathrm{T}]$ were higher for the gonads and skin, in the male phantom, while the skin and bone marrow presented the highest values for the female phantom. These structures are all located near the ground, were the radioactive sources were inserted.

Considering the different soil constitutions, the $CC[E]$ values presented a small variation, as may be seen at Table 4, which indicates no different shielding effects.

4. Conclusions

In this work we evaluated the doses involved in an environmental contamination of soil, with ^{137}Cs. The results showed that differences in soil composition did not change significantly the CC values. Besides, the highest $CC[H_\mathrm{T}]$ values were for the gonads and skin (male phantom) and bone marrow and skin (female phantom). Therefore, the $CC[H_\mathrm{T}]$ established in this study will be useful to readily estimate the equivalent dose, during an environmental contamination of soil with ^{137}Cs.

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