Dosimetric estimation of workers involved in oil prospecting: an approach using the Monte Carlo method

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Abstract. This study aims to computationally evaluate the exposure of workers subjected to natural radiation emitted by ^{40}K, ^{238}U and ^{232}Th radionuclides present in crude oil during prospecting activities in oil fields, in which professionals are directly exposed. The workers were represented by female (FASH3) and male (MASH3) computational anthropomorphic phantoms coupled with the radiation transport code MCNPX2.7.0. Due to the diversity of petroleum exploration environments, this study presents conversion factor (CF) data for effective dose for three exposure conditions: soil, scale (oil encrusted on pipe walls), and sludge. Effective doses, expressed in Sv/Gy, were calculated by taking the average of the equivalent doses of FASH3 and MASH3 organs. The main results obtained, and the Monte Carlo simulation relative percentage errors (in parentheses) showed that the highest CF calculated was 1.4 (0.7) in the sludge case with ^{40}K scenario, and the lowest of 0.52 (0.8) with the soil and the ^{238}U radionuclide. These results suggest that the scenario composed of scale is the most critical for workers and that ^{40}K is the radionuclide that contributes the most to individual exposure, especially when the sludge scenario is used.

Keywords: Oil exploration, dosimetry, Monte Carlo simulation, computational anthropomorphic phantoms.

1. Introduction

Naturally occurring radioactive materials (NORM) are present in our world. Our planet and its atmosphere contain many naturally occurring radioactive species almost everything contains NORM. During everyday life, both humans and other living organisms are subject to low-level exposure to natural nuclear radiation.

Radionuclides belonging to the natural radioactive series of uranium and thorium occur throughout the Earth, and their concentrations depend on the composition of the soil. In addition, ^{40}K is also present. All these radionuclides contribute to the radiation dose received by humans [1]. Industrial activities, such as the oil extraction industry, contribute to the radionuclides accumulation in their processes, resulting in radioactive materials that pose a risk to the health of workers [2,3].

The presence of radionuclides can lead to occupational exposure and potentially deleterious effects on workers' health. Furthermore, certain industrial processes can accumulate these radionuclides in significant amounts, resulting in technologically enhanced naturally occurring radioactive materials called TENORM. Therefore, radionuclide concentrations can reach levels where radiological protection becomes essential [1,4].

The main objective of this work is to use Monte Carlo simulations and anatomically realistic anthropomorphic phantoms to determine the absorbed doses in the organs and tissues of workers involved in oil prospecting activities. These individuals are exposed to natural ionizing radiation emitted by the ^{238}U and ^{232}Th series and by the ^{40}K, which are present in petroleum materials. The dosimetric data calculated in this work is important in assessing the risk of individuals exposed to natural radiation sources, which are widely found in different mining activity environments. These data can be used to obtain absolute values of equivalent and effective doses for workers in real situations.

2. Material and Methods

In this research, the general-purpose Monte Carlo radiation transport code MCNPX2.7.0 [5] was used. Through this code, a computational model of workers exposure in the oil industry was developed. MCNPX2.7.0 is a code that has been successfully used and validated in several radiological applications [6,7,8,9]. Furthermore, a variety of different anthropomorphic phantoms have been developed for this code. Another important feature is that this code is capable of simulating spontaneous photon emission from pipeline materials contaminated by NORM [8, 10, 11, 12].

To represent the professionals during the procedures in the oil fields, the male (MASH3) and female (FASH3) adult voxel anthropomorphic phantoms were used. MASH3 has a height of 175 cm and a body mass of 73 kg and FASH3 has a height of 163 cm and a body mass of 60 kg. They have anthropometric characteristics of references from the International Commission on Radiation Protection (Figure 1) [13]. These anthropomorphic phantoms have a set of organs and tissues with dosimetric importance recommended in the publication ICRP 103 [14] and, therefore, are often used in radiological studies to simulate the effects of radiation on specific parts of the human body.

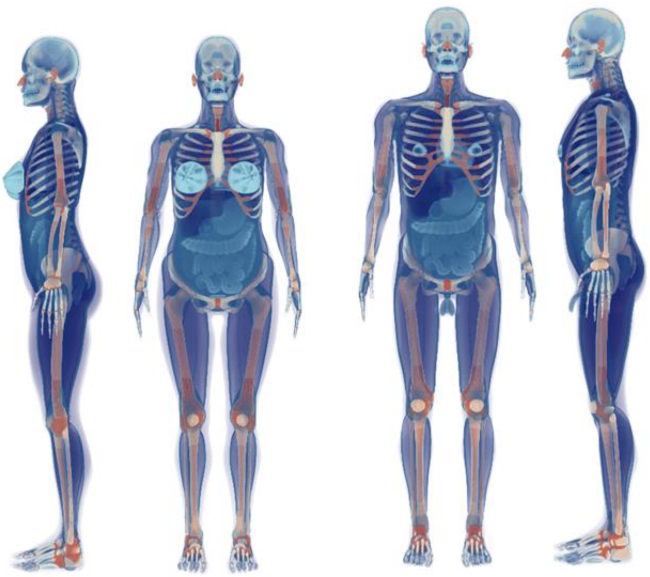

Figure 1. Graphical representation of the anthropomorphic adult female FASH3 (A) and male MASH3 (B) phantoms. Source: The authors, 2023.

To simulate the extensive pipelines commonly seen in oil fields, three coaxial cylinders were defined to represent the pipeline surfaces, crust contaminated with NORM, and a mixture of oil and water carried by the pipeline [15], with the anthropomorphic phantoms and the detector positioned 1 m away from the 15 m long pipe (Figure 2).

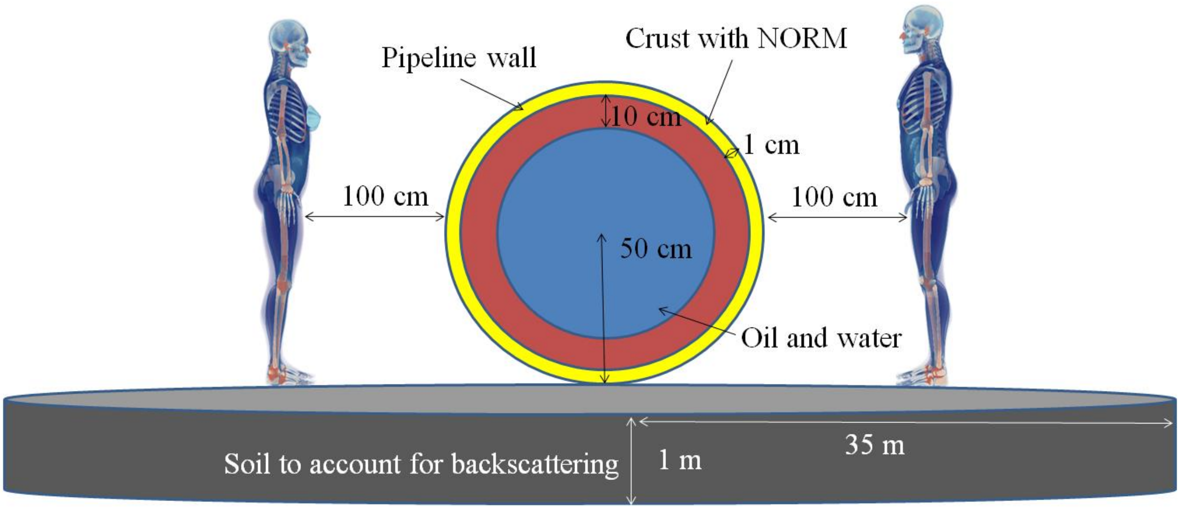

Figure 2 - Model of the NORM-contaminated crust of the pipeline developed with the MCNPX2.7.0 code. Source: The authors, 2023.

To model large-scale NORM sources, an exposure scenario was developed for comparison with calculated photon absorbed dose rate data in the air at 1 m above ground due to ^{40}K, ^{238}U and ^{232}Th series in natural oilfield soil [15]. The soil radius was defined by a 35 m long cylindrical disk to simulate a semi-infinite planar source composed of a 5 cm layer uniformly contaminated with NORM in an open field (Figure 3) [9]. An additional 1 m layer of soil will normally be placed below the contaminated layer to account for backscatter. Likewise, backscattering also occurs in air, especially for photons below 100 keV. The effect, called Skyshine (radiation scattering in the air, symbolized by K_{air}), is considered when expanding the air above the anthropomorphic phantom.

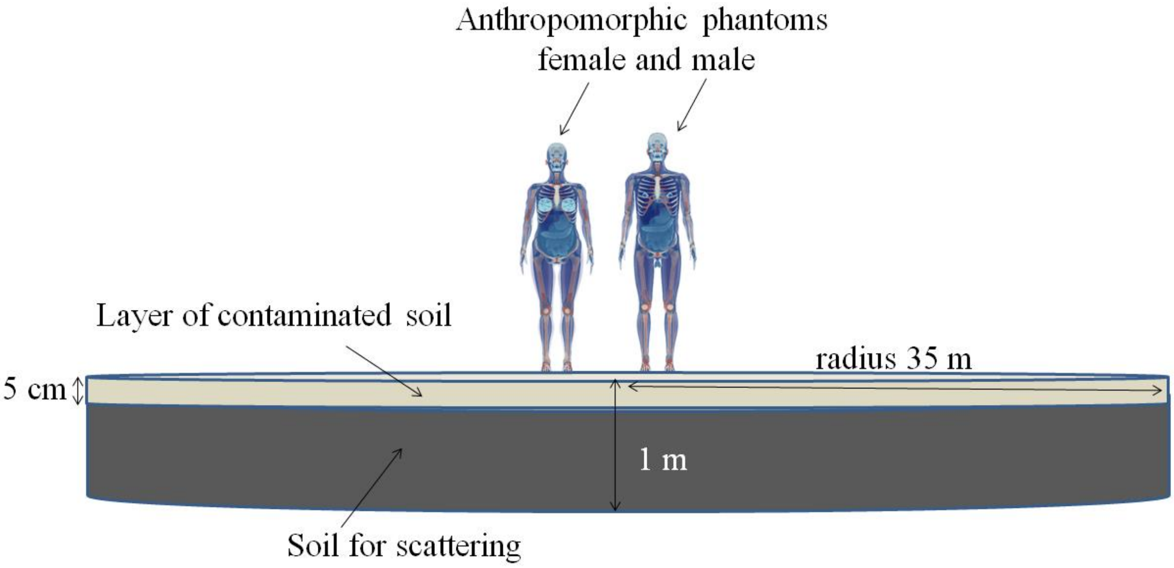

Figure 3 - Geometric model of the soil contaminated with NORM developed in the MCNPX2.7.0 code. Source: The authors, 2023.

Separators are complex instruments and, therefore, evidently the model developed by this study is a simplified model. The constructed model has a cylindrical shape with a length of 300 cm and a radius of 45 cm. The contents of the separator are layers of natural gas, oil-water mixture, and mud. For backscatter effects, the soil was added at the bottom of the separator and the anthropomorphic phantom. Each irradiation scenario was composed of two anthropomorphic phantoms on opposite sides of the separator and positioned 1 m away from the separator surface (Figure 4).

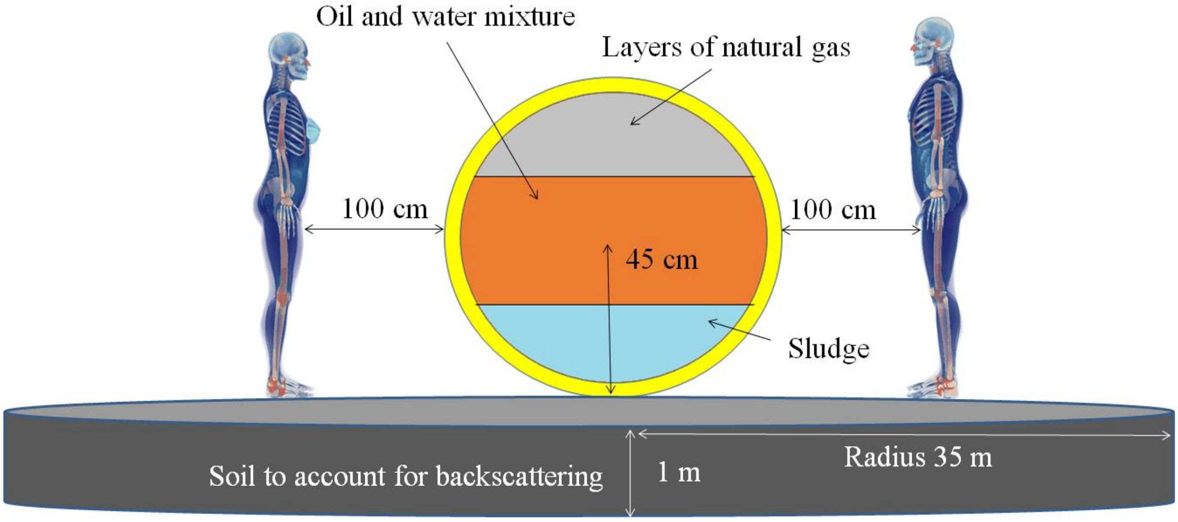

Figure 4 - Model developed for the separator with code MCNPX2.7.0. Source: The authors, 2023.

3. Results and Discussions

The purpose of this study was to determine conversion factors for equivalent and effective doses normalized by the absorbed dose in the air (D_{air}) in different scenarios related to exposure to natural radioactivity. Concentrations in soil, produced sludge, and scale were evaluated, which are commonly found in oil prospecting sites. Table 1 shows the average conversion factors for effective dose obtained for each scenario and type of radionuclide.

3.1. Contaminated Soil

Regarding specific scenarios, in the case of contaminated soil, workers' irradiation was considered more critical for red bone marrow and skin, both male and female. There was no significant difference between the two anthropomorphic phantoms in terms of skin and marrow, although the equivalent dose values in female skin tissues are slightly higher compared to the male phantom.

3.2. Scale

In the scenario involving the scale, the results were similar between male and female phantoms, but red bone marrow, stomach, and skin showed higher values in the female phantom data. The ^{238}U decay series showed the highest dosimetric values, followed by the ^{232}Th series.

3.3. Sludge Produced

In the scenario with produced sludge, the skin, bladder, red bone marrow and gonads of the female phantom were the most irradiated organs. Again, the ^{238}U decay series yielded the highest results compared to ^{40}K and ^{232}Th. Female exposure to this scenario was close to twice that of male exposure.

In the overall set of results, the female anthropomorphic phantom (FASH) obtained the highest results. In addition to organ size differences, the characteristics of radiation fields change with height above the ground, thus, especially for ground sources, and therefore body height and – by extension – the different locations of internal radiosensitive organs can affect the magnitude of the equivalent dose in the evaluated organ. For example, after the Fukushima accident, in the early stages, it was reported that the dose rate in the air decreased with increasing height above the ground, which caused many concerns regarding the reliable assessment of exposures to children.

Table 1. Mean CFs for effective dose (in Sv/Gy) calculated for male and female anthropomorphic phantoms for the three exposure scenarios evaluated. In parenthesis are the relative percentage errors.

Soil			Scale			Sludge		
^{40}K	^{232}Th	^{238}U	^{40}K	^{232}Th	^{238}U	^{40}K	^{232}Th	^{238}U
0.57	0.53	0.52	0.69	0.72	0.85	1.4	0.76	0.66
(0.7)	(0.9)	(0.8)	(0.7)	(1.1)	(1.1)	(0.7)	(1.1)	(1.1)

In all scenarios simulated in this study, there was symmetry of the most irradiated tissues for male and female anthropomorphic phantoms, in other words, tissues with both higher and lower values, of absorbed dose, were the same for both genders in all cases. However, the dose values showed expressive difference considering the genders. In the scenario involving the sludge produced, the values of the coefficients for the equivalent dose of the female phantom were doubling (red marrow, colon, gonads, skin, and bladder) the male phantom, with ^{40}K being what caused the highest radiological risks in the three studied scenarios.

The scenario that provided the greatest biological damage to the simulated workers in this study is attributed to the source in the produced sludge. In this configuration, ^{40}K presented an effective dose in workers of 1.4 Sv/Gy. On the other hand, the scenario that presented the lowest result was the soil distribution, with a maximum equivalent dose coefficient of approximately 0.57 Sv/Gy.

It should be noted that the conversion factors were calculated for idealized and hypothetical source geometries, such as semi-infinite and uniform distributions, for the unclothed anthropomorphic phantoms, and for idealized upright postures. As a result, they do not fully reflect actual exposures for any situation or exposed individual.

4. Conclusion

In this work, a set of conversion coefficients for organ-equivalent dose and the effective dose was calculated using the MCNPX2.7.0 radiation transport code and two adult voxel-based computational anthropomorphic phantoms, one male and one female, built based on anthropometric characteristics from the ICRP 89 reference male and female. The conversion coefficients were derived from the ^{238}U, ^{232}Th, and ^{40}K radionuclides, and calculated for three types of exposure scenarios involving workers involved in oil prospecting activities: (1) distribution of radionuclides in the soil surface; (2) scale and (3) sludge. These CF can be used to evaluate the external dose of environmental exposure of these individuals for selected ideal environmental conditions. The results showed that the most critical scenario was the sludge produced. In this scenario, the organs that obtained the highest results were the red marrow, gonads, skin, and bladder, respectively. In addition, it is important to highlight that the female worker was the most exposed, presenting a result that was 54% higher than the male worker.

The scenario that expressed the greatest difference between the male and female phantoms was the sludge produced, where the skin, red marrow, and bladder organs stand out with the greatest differences.

Acknowledgment

The authors would like to thank the Brazilian agencies: CNPq project (309675/2021-9) (W.S.S); UNIVERSAL Project (407493/2021-2); INCT Project (406303/2022-3).

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