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VALIDATION OF A MATHEMATICAL PHANTOM FOR DOSE ASSESSMENT OF RADIOLOGICAL ACCIDENTS

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ABSTRACT

Sealed radioactive sources are widely used in the industry with the purpose of well logging, non-destructive testing, food irradiation, process control systems, elemental analysis and others. Among the most used sources, it can mention: ^{137}*Cs,* ^{60}*Co,* ^{192}*Ir,* ^{85}*Kr and Americium-Beryllium with radiation activities ranging between a few MegaBecquerels (MBq) to million of GBq, as the case of food irradiation. In general, these sources present sufficient activity to represent a significant health hazard when inadequately shielded or not handled according to proper safety procedures, producing radiation exposures to workers and to members of public. In cases of overexposure to ionizing radiation, an estimative of the dose received by victims of radiation accidents, as well as its distribution within the organism, can be provided by use an anthropomorphic phantom associates with a theoretical simulation Monte Carlo method to simulate the radioactive source and its interactions with the phantom. In this work is presented the validation results of application of a mathematical phantom modeled in Geant4, as a tool to reconstruct dose of radiological accidents due to external exposure. The results are compared with the dosimetry of real accidents.*

1. INTRODUCTION

The use of radioactive sources offers a wide range of benefits throughout the world in medicine, research and industry. Precautions are, however, necessary in order to protect and limit the exposure of people to the radiation. Where the amount of radioactive material is substantial, extreme care is needed to prevent accidents that may have severe consequences. The consequences of such accidents can be significant, even fatal, and can impact on both workers and the public. Nevertheless, in spite of the precautions taken, accidents with radiation sources continue to occur.

In any accident in which people have been irradiated, it will be important to assess the absorbed dose. The evaluation of a high absorbed dose received from external irradiation in an accident can be an extremely complex matter. If the irradiated person was not wearing a personal dosimeter at the time of exposure, the assessment of absorbed dose will require a reconstruction of the accident. The dose distribution depends on the condition of exposure and the circumstances of the accident. If a radioactive source were in a pocket or touched by the hand, only local exposure could take place. Otherwise, if a person were relatively far from the source, then this would result in a whole body exposure with a more or less uniform dose distribution. It should be noted that the movements made by the irradiated person has a strong influence on the uniformity of the dose distribution. The duration of the exposure, or dose rate, is also important. If the same dose were delivered within a shorter time (higher dose rate) a more severe radiation effect would be observed (1) (2).

The estimative of the dose received by victims of radiation accidents, as well as its distribution within the body, can be provided by use an anthropomorphic phantom associates with a theoretical simulation Monte Carlo method to simulate the radioactive source and its interactions. Currently, there are three different types of human phantom available for Monte Carlo dose simulation (3) (4):

- Mathematical or stylized phantom – Defined by simple mathematical equations, and thus it cannot precisely model the details of the human body´s complicated internal structures. However, the computational speed is very fast, with a minimum memory requirement.

- Voxel or Tomographic phantom – Defined by tomographic images which allow the visualization of the internal structures of the body in three dimensions. It should be noted that a tomographic image data set is composed of many slices, each showing a bi-dimensional pixel map of the anatomy, thus, unlike mathematical phantoms which are based on quadratic surface equations, voxel phantom contains a huge number of tiny cubes grouped to represent various anatomical structures. Thus, the computational time required to process a voxel phantom is higher than that required by a mathematical phantom. The voxel phantom is not easily deformable, and it is impossible to change the posture of the phantom to model specific exposure situations such as, for example, during accident conditions.

- BREP or Polygon-surface phantom – Developed recently, the surface human phantom were constructed by converting voxel phantoms to polygon surface, initially to simulate the respiratory movement of the human body, is now widely used in medical imaging simulations. BREP phantom also was developed based directly on 3D anatomical models of organs and tissues (5).

For the purpose of this work, due to the required computational characteristics, an anthropomorphic mathematical phantom, based on male MIRD phantom and PIMAL phantom(6), with arms and legs separated allowing moving abilities was developed to enable flexible positioning of the arms and legs aiming the adequate assessment of radiation dose for different postures in occupational exposures. The size and shape of the body and its organs were described by analytical expressions, based in the Geant4 advanced example (7).

In this work are presented the validation results of application of a mathematical phantom modeled in Geant4 code, as a tool to reconstruct dose of radiological accidents due to external exposure. The results are compared with the dosimetry of real radiological accidents occurred with radioactive sources during industrial radiography.

2. METHODOLOGY

2.1The Simulation Code

Geant4 is a full object-oriented simulation tool that simulates accurately the passage of particles through matter. The code provides a complete range of functionalities including tracking, geometry and physics models, including electromagnetic and hadronic interactions. The code is being widely used in many different fields, such as nuclear physics, radioprotection, radiation dosimetry, high energy physics, medical physics, accelerator design and astrophysics (8) (9).

In this work was used the package *Livermore* for low-energy electromagnetic physic processes, for photons, electrons and positrons. The production thresholds (*DEFAULTCUTVALUE* parameter) were set to 0.1 mm for all particles. Thus, in each material, this value is transformed to an energy below which the continuous slowing down approximation is used; otherwise, secondary particles below this energy are not generated, however their energy is deposited locally. The Livermore model describes the interactions of electrons and photons with matter and extends its application range down to 250 eV, including Rayleigh scattering and atomic relaxation process, using interpolated data tables based on evaluated data libraries from Lawrence Livermore National Laboratory. All the Geant4 MC calculations presented in this work have been performed using the 4.9.5 Geant version install in a Linux operational system (Scientific Linux 6.1 64-bits) with quad-core processors Intel core i7 running at 2.40/2.70 GHz and 4 GB RAM.

2.2 The Phantom

In order to estimate the doses received by the victims of the accident, an anthropomorphic mathematical phantom with arms and legs separated allowing moving abilities was developed with the purpose to enable flexible positioning of the arms and legs and set the desired posture of the victims. The modeled phantom was based on male MIRD phantom, where the size and shape of the body and its organs were described by analytical expressions, based in the Geant4 advanced example (7).

In the original MIRD phantom, the arms and arm bones are included into trunk region and the legs structure is rigid, which does not allow movement. In this work, a different positioning of the arms and legs is needed to match the irradiation conditions of the accident as closely as possible, as shown in the figure 1. The arms, including arm bones, of the original phantom were extracted from the trunk and modeled using cones. Spheres were used for the joints similarly the ORNL PIMAL phantom (6).

Additionally, taking into account that in some accidents the radioactive source is placed in the back pocket of his trousers, a revised geometric representative model of the lower part of the colon, including the rectum, was implemented in the phantom used in this work in order to obtain more accurately dose reconstruction of the victims. The lower segment of the sigmoid colon as described in MIRD phantom does not accurately expresses a more valid representation of the human anatomy (10). The rectum was not included as a separate segment of the lower large intestine on the male MIRD reference phantom. The lower portion of the sigmoid colon did not adequately represent the rectum with distinct geometrical description.

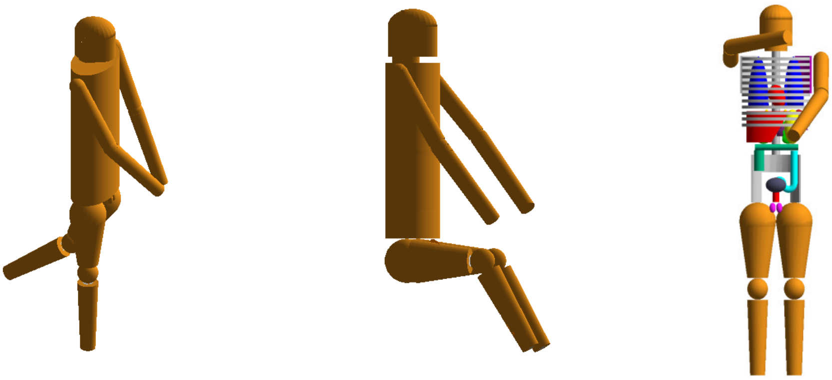

Figure 1: Phantom with movement in arms and legs. A different posture is needed to match the irradiation conditions of the accident as closely as possible

2.3 The Irradiation Source

It should be emphasized that the activity of the source shall be determined by measuring its output at 1 meter and expressing its activity in Becquerel (11), thus, the quantity of radioactive material on the license and source certificates referred to “effective” activity not “physical” activity. Since iridium is a very dense material at 22.4 g/cm^3, sources are prepared with extra activity to account for self-absorption within the source capsule. This extra factor varies with specific nuclides (12). In this way, the iridium source was modeled as an unshielded source, with the activity given by the IAEA report.

Normally, the iridium source was used as being monochromatic spectrum at average gamma energy of 356 keV. In this work was modeled the real spectrum, as shown in figure 2. It should be emphasized that the real spectrum is important in dose calculation.

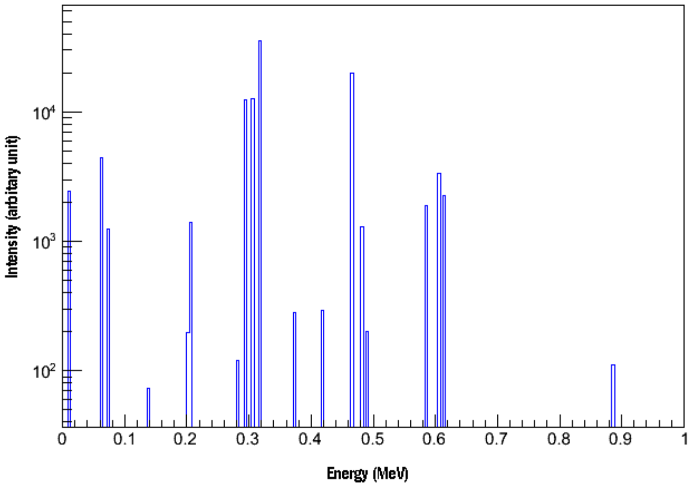

Figure 2: Photon spectrum for ^{192}Ir source used as input spectrum for GEANT.

3. RADIOLOGICAL ACCIDENTS AND RECONSTRUCTED DOSES

In this work were reconstructed the dose of the two radiological accidents occurred in Yanango (February, 1999) (13) and Nueva Aldea (December, 2005) (14).

3.1 The Yanango Accident

According the IAEA report (13), on 20 February 1999, a serious radiological accident occurred at theYanango hydroelectric power plant in Peru when a welder picked up an unshielded ^{192}Ir industrial radiography source (1.37 TBq) and put it in the back pocket of his trousers, where it remained for 6.5 hours. During for at least three hours the worker was sitting.

After the welder had picked up the radioactive source he continued to work, spending much of the time in the pipe. He claims that he was sitting there for at least three hours. The worker received a high radiation dose that necessitated the amputation of one leg. His wife and children were also exposed, but fortunately to a much lesser extent.

Previously, the Yanango accident was simulated using a voxel phantom model (15). The simulation produced reasonable results, however an explanatory discussion of agreements and disagreements remains difficult, because the IAEA report does not reveal sufficient details about the irradiation conditions.

Tracking of twenty million γ-histories has been carried out in the Monte-Carlo. Each measurement (Monte Carlo run) was repeated five times with different random starting point, to obtain statistical uncertainties. The error results presented in this work are the standard deviation of the mean of the Monte Carlo runs.

The table 1 shows the simulated absorbed dose to the worker in comparison with results informed by IAEA.

Table1: Distribution of doses in IAEA report in comparison with the results obtained.

Organ	IAEA Report	This Paper	
	Dose (Gy)	Dose (Gy)	Error (Gy)
Femur	143	96.50	0.12
Gonads	23	25.44	0.45
Bladder	18	11.64	0.16
Rectum	18	29.90	0.38
Soft tissue (depth 1 cm)	9966	7968	92
Soft tissue (depth 2 cm)	2508	2505	58
Soft tissue (depth 3 cm)	1110	1187	44
Soft tissue (depth 4 cm)	617	697	44
Soft tissue (depth 5 cm)	388	430	27
Soft tissue (depth 6 cm)	265	286	21
Soft tissue (depth 7 cm)	191	222	17
Soft tissue (depth 9 cm)	111	126	10
Soft tissue (depth 10 cm)	88	20	5

In this work, it was also determined the average absorbed doses to another organs of the body, not informed in IAEA report, as shown in table 2.

Table 2: Average organ absorbed doses.

Organ/structure	Dose (Gy)	Error (Gy)
Trunk	6.09	0.01
Head	0.018	0.001
Right Arm	1.35	0.01
Left Arm	0.52	0.01
Left Leg	22.82	0.02
Right Leg	118.28	0.04
Pelvis	14.19	0.07
Brain	0.012	0.001
Right Kidney	0.99	0.02
Left Kidney	0.79	0.03
Large Intestine	3.43	0.02
Spleen	0.44	0.03
Pancreas	0.76	0.05
Stomach	0.59	0.02
Liver	0.61	0.01
Right Lung	0.14	0.01
Left Lung	0.11	0.01
Heart	0.15	0.01
D. Colon + Sigmoid	24.19	0.17

3.2 The Nueva Aldea Accident

The accident occurred on 14 December 2005 at a cellulose plant under construction in Nueva Aldea, Concepción, Chile. After completing radiography one evening on the platform at one of the towers under construction, a radiographer dismantled the radiography equipment, not noticing that the source (^{192}Ir – 3.33 TBq) had fallen out on to the tower platform. The following day a scaffolding worker, identify in the IAEA publication as worker A (14), found the source, picked it up and closely examined it, trying to discover what this object was. The worker A showed the source to two other workers but no one knew what this was.

While examining the source in his supervisor's office an electronic alarm dosimeter in a neighboring office was activated. The worker was instructed to put the object into a 'container'. He threw the source into a metal pipe lying in the yard near the office facility. From there, it was then recovered and put back into the gammagraphy equipment container.

The simulation, concerning the worker A, was performed under the following four assumptions for how long the source was at various locations, as informed on IAEA accident report (14) : 10 min in his rear left pocket; 1 min in his front left pocket; 20 min in his hands; 3 min at a distance of 10 cm from his eyes. The table 3 shows the simulated absorbed dose to the worker A.

According the IAEA report, the physical dose reconstruction for worker A was calculated to the whole body dose as 1.3-1.5 Gy. Blood samples were analyzed and, on the basis of chromosome aberrations, estimated the dose for worker to be about 1.3 Gy. On the basis of the clinical manifestations of the exposure, the whole body dose was estimated to be between

1 and 2 Gy. In this work was obtained to whole body dose 1.73 Gy. This result is in agreement whit IAEA report on the Nueva Aldea Accident.

Table 3: Average organ absorbed doses to the worker A (Nueva Aldea accident).

Organ	Dose (Gy)	Error (Gy)
Trunk	0.96	0.02
Rib Bones	1.15	0.01
Head	0.44	0.002
Skull	0.47	0.006
Right Arm	10.10	0.02
Left Arm	0.80	0.007
Left Leg	3.43	0.01
Right Leg	1.77	0.005
Pelvis	1.53	0.02
Brain	0.42	0.004
Rins	0.19	0.01
Intestine	0.58	0.02
Baço	0.27	0.01
Gonads	4.52	0.17
Bexiga	2.56	0.07
Pancreas	0.30	0.03
Stomach	0.43	0.01
Liver	0.32	0.008
Left Lung	0.83	0.01
Right Lung	0.25	0.01
Hearth	0.52	0.006
Rectum	2.61	0.12
D. Colon + Sigmoid	3.48	0.04
Whole Body	1.73	0.001

4. CONCLUSIONS

The use of a phantom with arms and legs separated, allowing moving abilities and different postures, proved to be adequate to the assessment of Yanango and Nueva Aldea accidents.

The results are in agreements with IAEA reports, however it is necessary a review on the femur position in the legs. It should be noted that the femur, in current phantom, presents a uniform diameter in all length.

A disagreement was observed in the average dose calculated to soft tissue (depth 1 cm), because in the current phantom was not modeled the adipose tissue. This fact produces inaccuracy in the estimated dose to the more external soft tissue layer.

The results concerning the simulation of radiological accidents demonstrates that the phantom model can be revised to make the shapes of the arms and legs more realistic, as well as the inclusion of hands and fingers. It is necessary to review the structure of the legs of the phantom, which was compromised due to the modeling to enable flexible positioning. A new model of joints based in "internal spheres" is in development. On the other hand, a surface phantom is being implemented in Geant4, using *G4TessellatedSolid* Class for importing human organ models, aiming the comparison of required computer time and accuracy of the results.

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