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Nuclear Instruments and Methods in Physics Research B 213 (2004) 662–665
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Monte Carlo simulation for dose distribution calculations in a CT-based phantom at the Portuguese gamma irradiation facility

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Abstract

In preview works the Portuguese Gamma Irradiation Facility, UTR, has been simulated using the MCNP code and the product to be irradiated has been drawn using the boolean operators with the MCNP surfaces. However, sometimes the product to be irradiated could have an irregular shape. The paper describes an alternative way for drawing the corresponding volume based on CT image data in a format of a 3D matrix of voxels. This data are read by a specific code called SCMS which transforms it into a MCNP input file. The dimensions of each MCNP voxel depend on the number of elements in the CT-based matrix. Additionally, the new approach allows one to know dose distributions anywhere without extra definitions of surfaces or volumes. Experimental dose measurements were carried out using Amber Perspex dosimeters. This work presents the results of MCNP simulations using both modeling modes – the standard mode and the voxel mode.

PACS: 02.70.Lq; 87.53.Bn
Keywords: Monte Carlo; CT; Dosimetry; SCMS

1. Introduction

Monte Carlo simulations of gamma irradiation facilities for dose distribution previsions have been performed for several authors and the benefits of the knowledge of dose values, before the experimental work, have been emphasized [1,2]. In preview works, the Portuguese Gamma Irradiation Facility, UTR, has been simulated using the MCNP [3] code and dose calculations have been performed as for in-cycle irradiation as for static irradiation [2,4,5]. In these simulations, the product to be irradiated has been drawn using boolean operators with the MCNP surfaces.

However, sometimes the product to be irradiated could have an irregular shape. Weiss [6] mentioned the need to validate dose distribution of complex geometries applying the Monte Carlo model. He also emphasize the effort required to

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doi:10.1016/S0168-583X(03)01682-3

build up the model description. For these situations the drawing of the corresponding volume, using the MCNP surfaces (standard mode), could be prone to mistakes being always a hard and very consuming time task. Taking into account these special cases a new approach to model the volume, based on CT image, is presented (voxel mode). In this model, the CT data are read by a specific code, called SCMS code [7], which transforms the CT data into a MCNP input file. At each element in the CT-based matrix, the SCMS code creates a MCNP voxels which dimensions depend on the CT-image resolution. Besides to be able to calculate dose in each voxel, this approach also allows the knowledge of dose distributions anywhere without extra definitions of surfaces or volumes.

This work presents the results of MCNP simulations using the two modeling modes – the standard mode and the voxel mode. Experimental results are compared with calculated results.

2. Experimental

The irradiation was performed in the UTR facility already described elsewhere [2]. At the time of the irradiation (December 2001) the irradiator activity of this facility was 2.1×10^{15} Bq. The product to be irradiated is placed on carriers suspended from a monorail conveyor. For this irradiation there were no more products to be irradiated. The irradiated phantom is a polymethyl methacrylate cylinder with dimensions of diameter 16 cm and height 15 cm. It was a static irradiation and the chosen irradiation position was in the central carrier, second level and inner row. According to this, the bottom of the phantom was placed closer to the center of the source rack than the top. The irradiation time was 1 h and 40 min.

Taking into account the expected dose in these conditions, the dose measurements were carried out using the Amber Perspex dosimeters. Four sets of three dosimeters each were placed on the phantom as can be seen in Fig. 1. The first set (dosimeters 1, 2 and 3) was placed on the cylindrical surface facing the source rack. The second set (dosimeters 4, 5 and 6) was placed on the surface in the back. The third and fourth sets (7, 8 and 9 and 10, 11 and 12) were placed on the cylindrical surface between the first and second sets, one on each side.

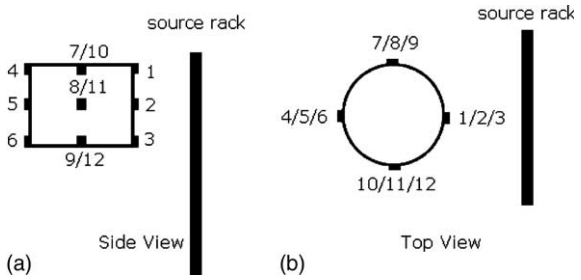

Fig. 1. Schematic views of phantom with the 12 dosimeters and the position relative of source rack. (a) Side view – the position of phantom is dislocated from center of the source rack; (b) top view – the position of phantom is centered with the source rack.

3. Simulation

MCNP4C was used for simulation. The calculations have been performed using the tally F4 which corresponds to the volume average photon flux. Dose values have been obtained with the appropriate modifications (FM4) which includes the total cross-section, the total heating number, the source activity and conversion constants giving results in units kGy per hour.

Two different inputs have been written corresponding to the two modes of calculation. The first one – the standard mode – contains the geometry of the phantom built with the MCNP surfaces. In the second one – the voxel mode – the geometry of the phantom was built with the output of the SCMS code, based on the CT data. The irradiation chamber description is the same for both modes. In order to validate calculated data the first input also includes 12 dosimeters according to the experimental set-up.

3.1. Voxel mode

The cylindrical shaped phantom was submitted to CT process and the generated file is constituted by a 3D matrix of $256 \times 256 \times 15$ voxels, divided in

15 slices being each slice constituted by a 2D 256×256 matrix of voxels. Each voxel has a dimension of $0.097 \times 0.097 \times 1.0$ cm, so that the voxels height determines the slices height. At each CT number (or ranges of CT numbers) corresponds one material and/or one different density. This file is read by the SCMS software which transforms it into a MCNP input format file based on lattice, fill and universe, concepts of the MCNP code. The SCMS code attributes one universe number to each CT number (or ranges of CT numbers). The file generated by the SCMS code would be integrated in the geometric part of the input which describe the irradiation chamber.

For specific purposes it is sometimes convenient to know the dose at any zone which can be large or very small. This model takes advantage of its structure in voxel to access that information. It becomes possible to know the dose in each voxel or in any union of voxels without extra geometry design. To illustrate this feature, two dose distributions have been calculated. For both distributions a larger union of voxels was performed. So, 225 elemental voxels was jointed to constitute a large ''voxel''. One distribution considers a sequence of 15 of these large voxel on longitudinal axis centered on cylinder parallel to the source rack, the zz' distribution, and the other distribution a sequence of 14 of these large voxel on transversal axis, perpendicular to the source rack and going through the center of the cylinder, the xx' distribution.

4. Results and discussion

The simulation results carried out using the standard mode and the experimental results are represented in Fig. 2. The straight line represents the average dose in the (the) whole phantom calculated with Monte Carlo. The differences between the simulated and experimental values are, in general, lower than 10%. It can be noted that the measurable errors are the errors associated to dosimeters (6%) and the error associated to the MCNP – 3%, for these cases. For each set of dosimeters it can be noted that the dose is higher for the dosimeters nearest the bottom of the phantom. There is a good agreement between experimental and calculated values.

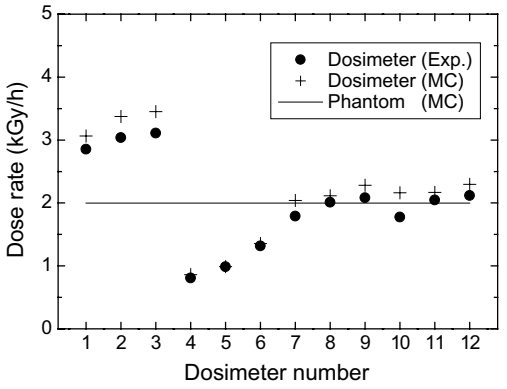

Fig. 2. Experimental (●) and simulated (+) dose values in the dosimeters. The straight line represents the average dose value calculated for the phantom using the standard model.

The calculated average dose of the two set of dosimeters positioned in front and in back of the irradiator is 2.18 kGy/h while the calculated average dose in the phantom is 2.00 kGy/h. The difference is due to the fact that inside the phantom the attenuation of the radiation decrease exponentially being its average value lower than the arithmetic media of these two set of dosimeters.

The calculated average dose in the phantom using the voxel mode is 1.94 kGy/h. Although the difference between the two values (3%) is higher than the sum of the each standard deviation the values are acceptable. For all these calculus the computing time was 24 h.

The voxel mode is especially adequate to calculate dose distributions or to calculate dose in volume with complexes shapes. To illustrate the first feature, Fig. 3 shows the calculated dose values for the two distributions already mentioned. For the xx' distributions it is evident an exponential decreases due to the increase thickness that the radiation have to cross; for the zz' this increase is not so evident.

Due to small dimensions of each voxel (0.0094 cm^3) the calculus of dose inside it is very time consuming. Without any computing time (ct) optimization the errors associated to each voxel and to each voxel association above considered are 25% and 7%, respectively for a ct of 20 days.

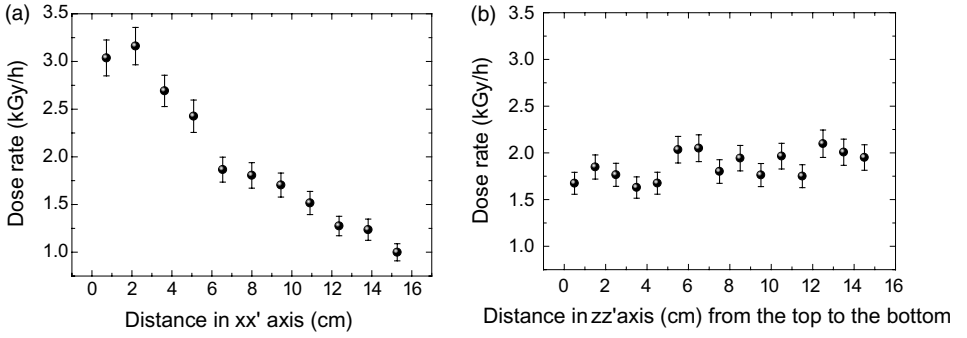

Fig. 3. Calculated dose values using the voxel mode. (a) Longitudinal dose distribution; (b) transversal dose distributions.

5. Conclusions

Although dose calculations have been done in a cylindrical shaped phantom the approach presented – voxel mode – is adequate for any complex geometry. It allows calculating dose values at any voxel or at any zone (union of voxels). However, due to very small dimensions of voxels, the dose calculation inside each voxel can be of a large time consuming process. It will be a good practice to ensemble a given number of voxels to build a zone and calculate the dose inside it.

Acknowledgements

This work has been developed under the support of Fundação de Amparo e Pesquisa do Estado de São Paulo (FAPESP) and the ICCTI providing financial resources for technical collaboration between authors.

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