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Optimization study of a medical phantom allowing the mapping of absorbed dose induced by ionizing radiations

Safa ELJ[#1], Ahmed BEN ISMAIL [#2]

[#] *Laboratory for Research on Energy and Matter: Development of Nuclear Sciences / LR16CNSTN02,*
National Centre for Nuclear Sciences and Technology, Sidi Thabet technopark - 2020 BP 72. Tunisia.

[1]*eljsafa@gmail.com*
[2]`ahmed.t.benismail@gmail.com`

***Abstract*—Monte Carlo codes are among the most used tools for calculations and simulations relating to medical physics and particularly for studies of low dose medical applications.**

The results, presented in this paper, were focused on the optimization of a medical phantom for mapping the absorbed doses produced by ionizing radiation. The cobalt 60 irradiator of the CNSTN (the National Centre for Nuclear Science and Technology) served as the experimental validation platform for the present study. Monte-Carlo modeling of the irradiator was carried out with Geant4 tool. Part of dose deposition results, obtained with this model, has been validated using as reference previous experimental data, performed on the same irradiator. The same Geant4 model was then adapted to our study case, with the development of a more specific configuration, suitable for the diagnosis of the effects induced by gamma radiation beams at different energies.

The distribution study of doses produced by these photons, inside a water filled phantom, was thus realized. The numerical results obtained, with the Geant4 model, show variable behaviours according to the studied energies. An analytical model is then proposed, for the prediction of these dose distributions.

Keywords **— Applications in medicine, Geant4 Monte Carlo calculations, Nuclear techniques, Radiation protection.**

I. INTRODUCTION

Monte Carlo computational methods are increasingly demonstrating their reliability in modelling physics governing energy deposition in particular environments. In line with this statement, we have used one of the most widely used Monte Carlo tools: the Geant4 tool [1], for the deposit dose calculation in the case of medical physics applications.

Optimization study of a medical phantom, in the case of gamma beams, was performed, in this paper, with the Geant4 tool. This study investigates the behaviour of the absorbed dose profile in a water filled phantom, taking into account the energy variation of the incident beams.

Photon attenuation in matter complies with the conventional Beer-Lambert law:

$$D = D_0 exp^{-\mu x} \quad (1)$$

Conditions allowing the application of this same law, for the case of intensity attenuation through a materiel, are: beam mono-chromaticity and absorbing material homogeneity and stability. In our study, the absorbing material undergoes some generated different secondary radiations: Compton effect, fluorescence and annihilation. Part of these scattered radiations contributes to increasing the dose rate of in the objects studied.

For radioprotection studies, the most widely used method [2] for determining gamma beam attenuation applies an accumulation factor, universally designated by the symbol B. Equation (1) becomes then:

$$D = BD_0 exp^{-\mu x} \quad (2)$$

Equations describing the accumulation factor B are a function of the attenuation coefficient, the photon energy, the material nature, the screen dimensions and the distance from the source.

Several methods are possible for calculating the dose accumulation factor. Among these methods, figure (1) the linear formula $B(\mu r) = 1 + k(\mu r)$; one of the simplest and least accurate approximations [3]; (2) Berger's formula: $B(\mu) = 1 + a\mu r \times e^{b\mu r}$; establishing a good compromise between accuracy and computational complexity [4]; (3) the formula of Capo: B $(E_0$,μr)$= \sum_i^3 \beta_i (\mu r)^i$ [5] and (4) the formula of Taylor: $B = A exp^{-\mu x \alpha_1} + (1 - A) exp^{-\mu x \alpha_2}$, which appears as the formula, relatively, the most used and the most accurate [6]. The coefficients A, α1 and α2 of this formula are commonly explained. [7]

To overcome the different limits of these models, we propose a new analytical model based on the results of the Geant4 modeling of the phantom, described above, for the case of gamma beams, at energies ranging from 0.32 to 12 MeV; the conventional maximum energy delivered by a linear medical accelerator. Preliminary validations of this model have been made using as reference previous numerical and experimental data, also performed on the CNSTN's gamma irradiator.

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II. USED MATERIAL AND METHOD

A. *Background and experimental equipment*

An experimental validation setup has been installed close to the CNSTN's gamma irradiator source. This irradiator has, today, an activity of 10 kCi [8], employs cobalt-60, as radioactive source, and has a vertical structure, with two built-in cylinders, each containing 4 cobalt pencils of 0.37 cm diameter and 40.6 cm length.

The experimental setup included a phantom and a lead brick mask with 1cm slit. Among the radiation produced by the irradiator, only a beam, of a 1 cm width, irradiated thus the phantom (cf. Fig 1).

Absorbed dose distribution, induced by the incident beam, was measured using Fricke dosimeters [9].

Fig. 1: Experimental setup

B. *Geant4 Tool*

Geant4 is a computational tool, succeeding the series of GEANT software developed by CERN, and allowing simulation of radiation transport for many types of particles and many radiation geometries. Its fields of application include high energy, nuclear and accelerator physics, as well as studies of medical and spatial sciences. [8]

Version 10.0 of Geant4 was initially used to model our CNSTN's gamma irradiator and to calculate the dose distribution around this installation. A more specific model of the source, using gamma beams, was then developed for the calculation of the dose in the water filled phantom.

The entire installation geometry, as well as the experimental setup, was modeled with regard to the real dimensions and disposition of each component.

Primary particles were generated with random directions and positions; according to the actual characteristics of the source. These primary particles are distributed between beta radiation at 0.318 MeV energy and two gammas at 1.17 MeV and 1.33 MeV. [10]

We used this experimental configuration for the validation of the model Geant4 at a mean energy, gammas, of 1.25 MeV. Then we modeled gamma beams at varying energies from 0.32 MeV to 12 MeV.

III. DEVELOPED WORK

A. *Preliminary validation of the model*

The first part of the validation has consisted of reproducing the dose mapping (dose absorbed in the air) around the gamma irradiator. This part uses, for the validation, already elaborated experimental and numerical results (cf.Fig2).

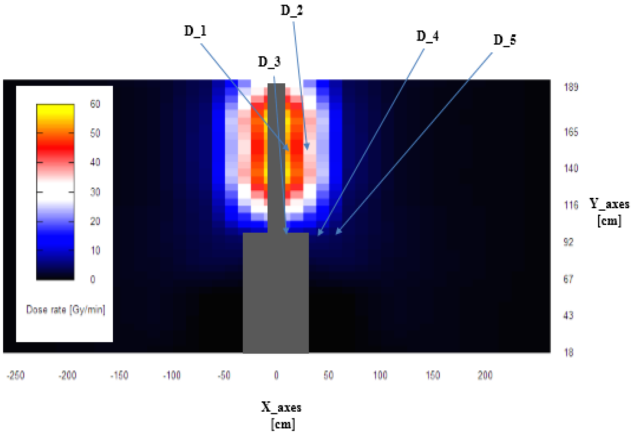

Fig. 2: Dose mapping around the gamma irradiator

Results obtained with the present Geant4 model are quite comparable with the previous results of experimental measurements and also numerical calculations (cf. Table I). Some rather significant deviations are however recorded and can be justified by parameters uncertainties when elaborating these previous data.

TABLE I :
COMPARISON OF PREVIOUS NUMERICAL/ EXPERIMENTAL DATA AND CURRENT MODEL DATA

Dosimeters	**Difference between previous experimental results and results developed with the current model [%]**	**Difference between previous numerical results and the results developed by the current model [%]**
D_1	9.79	37.34
D_2	2.3	38.95
D_3	24.78	9.98
D_4	52.85	97.4
D_5	33.3	20.06

The second part of the validation used results of calculations (numerical and experimental), also already elaborated. These calculations were performed for the case of a water-filled phantom, Fricke's dosimeters and beam extraction using a mask. Comparison of the results, obtained by the current model and these previous numerical and experimental results has been established.

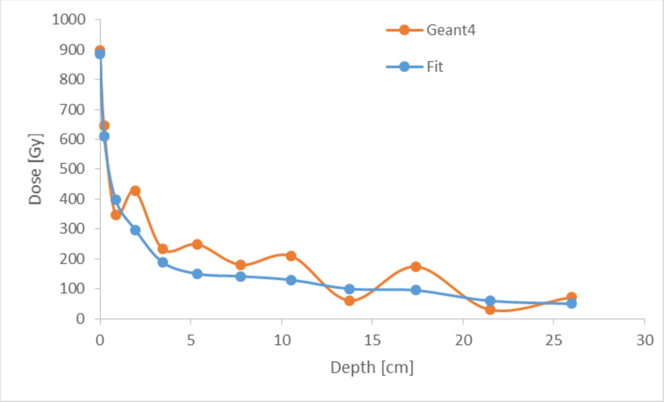

Fig. 3: Absorbed dose and profile obtained with Geant4

Comparison of our model results and the previous Geant4 results of the absorbed dose in depth, as well as their fit (cf. Fig. 3), are presented in the following table:

TABLE III:
COMPARISON OF THE NUMERICAL AND EXPERIMENTAL RESULTS AND THE RESULTS OF THE CURRENT MODEL

	Dosimeters		
Dose[Gy]	**D1**	**D2**	**D3**
Experimental. results	456.66	56 .63	55.14
Numerical results	429.3	49.63	51.84
Geant4 fitted dose	407.084	98.030	51.329

The new results obtained compare fairly well with the previous experimental results.

B. *Results of the upgraded configuration of the model*

Following the preliminary validations, presented above, we modeled the gamma beam cases, with the calculation of the dose profiles and the depth yields, in homogeneous water phantom and as a function of the primary photons energy (cf. Fig 4).

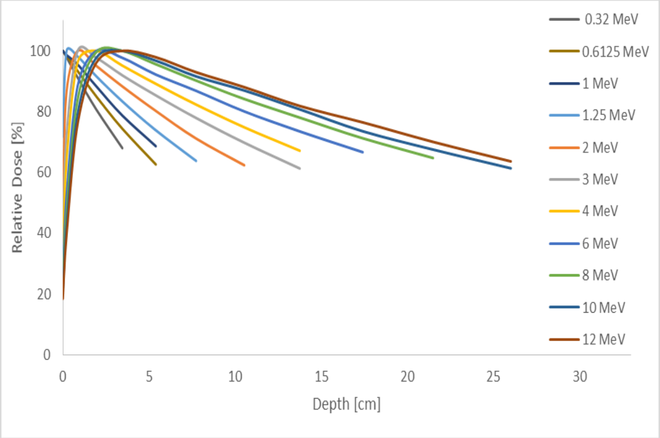

Fig. 4: Comparison of dose deposition for photons

The objective here was to develop new analytical model, reproducing our results of Monte Carlo calculations and also overcoming the limits of the models described in paragraph I. In order to fit resulting numerical results, produced by Geant4, we have used the calculation tool Matlab [11] for each case of studied energy.

Matlab tool provided a mathematical model for each dose profile and we have noticed that obtained models are always following this equation:

$$D = a \times exp^{bx} + b \times exp^{dx} \quad (3)$$

Numerical values of the coefficients *a*, *b*, *c* and *d*, obtained at each beam energy, are indicated in the following table (cf. Table III). *x* being the depth through the phantom, in cm.

TABLE IIII:
COEFFICIENT NUMERICAL VALUES OF DEVELOPED MODEL

Energy [MeV]	**a**	**b**	**c**	**d**
0.32	101.2	-0.1152	-1.098	-1.112
0.6125	100.9	-0.08833	-0.9497	-1.638
1	95.67	-0.07493	4.786	-0.04603
1.25	103.5	-0.06264	-31.72	-12.51
2	104.7	-0.04917	-52.7	-5.297
3	106	-0.03977	66.35	-3.39
4	107.2	-0.03402	-73.61	-2.589
6	107.6	-0.0278	-80.99	-1.866
8	109	-0.02442	-86.34	-1.558
10	108.9	-0.02212	-88.71	-1.361
12	109	-0.02059	-90.51	-1.232

The compilation of these obtained data, using the Geant4 and Matlab calculations, has enable to elaborate the following proposal of analytical model, that describes the behavior of the absorbed dose as a function of the incident radiation energy and the depth *x* through the phantom:

$$D = D_{max} \times e^{-\mu x} + (D_{max} - D_0) \times e^{dx} \quad (4)$$

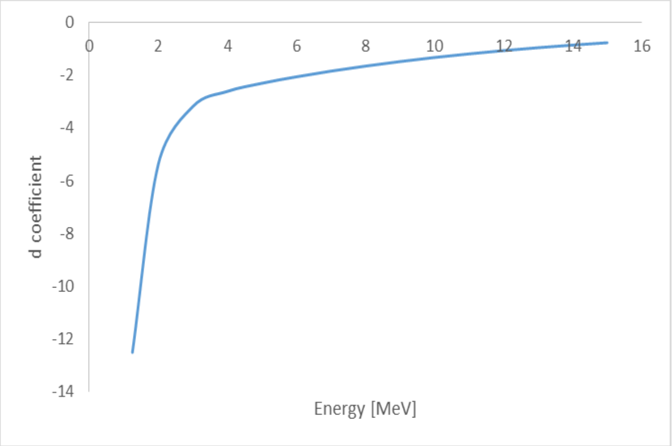

Fig. 5: Coefficient *d*, as a function of the incident beam energy

Coefficients D_{max} and D_0 correspond respectively to the maximum dose and the surface dose that can be obtained for each case of energy. The coefficient μ is the same as the conventional attenuation factor [12]. The coefficient d varies according to the incident radiation energy and was determined from a fitting with Matlab (cf. Fig 5).
The mathematical equation related to this coefficient d is then given by :

$$d(E) = f \times e^{iE} + j \times e^{kE} \quad (5)$$

where, f= -97.02, i= -1.899, j= -3.972 and k= -0.1095.

The illustrations below show some examples of dose profiles obtained (1) with our proposed mathematical model, (2) Matlab and (3) the latest Geant4 simulation results.

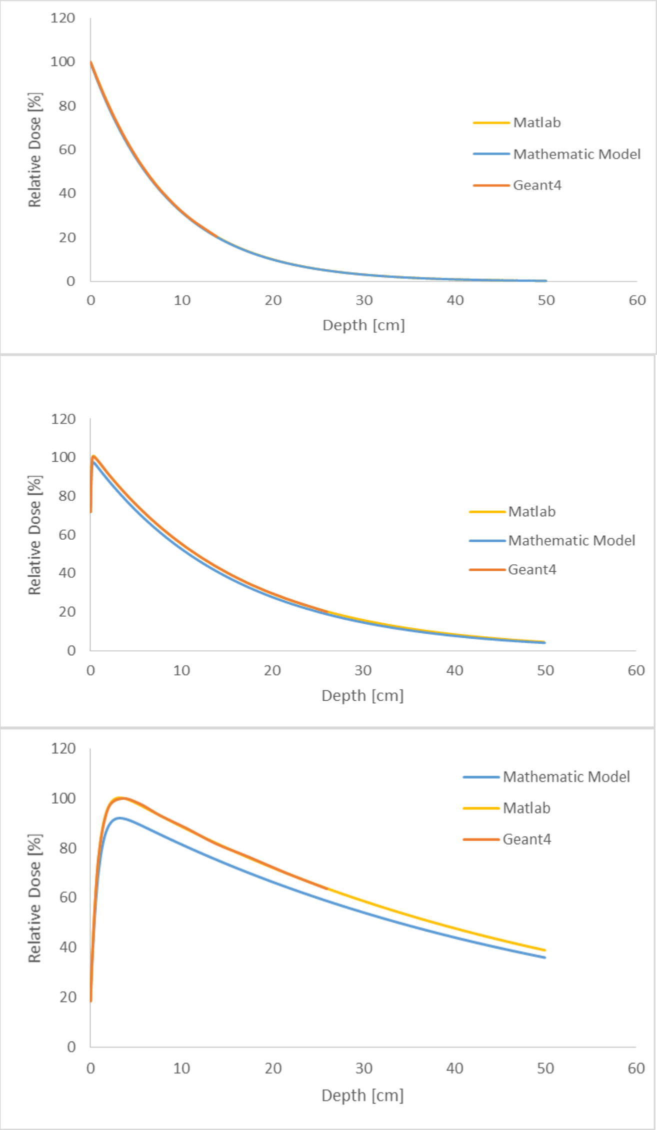

Fig. 6: Dose profiles obtained respectively, for E = 0.32, 1.25 and 12 MeV. Cases of Geant4 results, Matlab fit and the resulting mathematical model.

The three curves representing the dose profile in the water-filled phantom for the case of 0.32 MeV are almost the same. Fig. 9 illustrates comparison between these same three dose profiles, using relative differences, starting from the depth of 3cm inside the phantom.

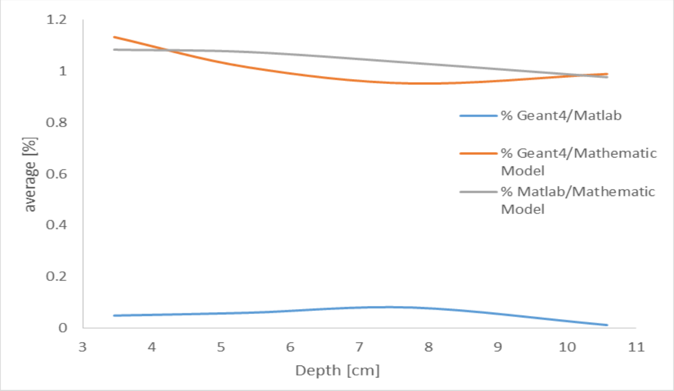

Fig. 7: Relative differences between the dose values obtained with Geant4, Matlab and the mathematical model, for the case of E = 0.32 MeV.

The model results developed demonstrate perfect agreement for relatively low energies. An accentuated disparity is however noted for cases of higher energies. This discordance, at high energies, will be corrected by revising the coefficients calculations of the model.

IV. CONCLUSIONS

The objective of this work was to study phantom dimension optimization by proposing analytical model that results from carrying out experimental manipulations and validations of numerical modeling, elaborated with the Monte-Carlo Geant4.

The numerical model performed with Geant4 allowed the study of the dose distributions produced by CNSTN's gamma irradiator. This same numerical work has enables preliminary validations by comparisons with experimental and numerical results previously carried out.

Specific numeric model configuration for cases of gamma beams, at different energies, has been then developed. The results obtained by this configuration were fitted using Matlab tool.
An analytical model, that describes the behavior of the absorbed dose, as a function of the incident radiation energy and the depth x through the phantom, was afterward proposed.

The obtained results are promising. An improvement of the present model, as well as the transition to a 2D modeling are planned.

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