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MCMEG: Simulations of both PDD and TPR for 6 MV LINAC photon beam using different MC codes

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ABSTRACT

The Monte Carlo Modelling Expert Group (MCMEG) is an expert network specializing in Monte Carlo radiation transport and the modelling and simulation applied to the radiation protection and dosimetry research field. For the first inter-comparison task the group launched an exercise to model and simulate a 6 MV LINAC photon beam using the Monte Carlo codes available within their laboratories and validate their simulated results by comparing them with experimental measurements carried out in the National Cancer Institute (INCA) in Rio de Janeiro, Brazil. The experimental measurements were performed using an ionization chamber with calibration traceable to a Secondary Standard Dosimetry Laboratory (SSDL). The detector was immersed in a water phantom at different depths and was irradiated with a radiation field size of $10 \times 10\ cm^2$. This exposure setup was used to determine the dosimetric parameters Percentage Depth Dose (PDD) and Tissue Phantom Ratio (TPR). The validation process compares the MC calculated results to the experimental measured PDD20,10 and TPR20,10. Simulations were performed reproducing the experimental TPR20,10 quality index which provides a satisfactory description of both the PDD curve and the transverse profiles at the two depths measured. This paper reports in detail the modelling process using MCNPx, MCNP6, EGSnrc and Penelope Monte Carlo codes, the source and tally descriptions, the validation processes and the results.

1. Introduction

Monte Carlo (MC) methods have been used worldwide in radiotherapy applications, including radiation dosimetry, different treatment modalities and sources, and treatment planning calculations (Andreo et al., 1991; Rogers, 2006; Scott et al., 2008, Paixão et al., 2012; Fonseca et al., 2016). The Monte Carlo Modelling Expert Group (MCMEG) (Fonseca, 2016a), was created in 2014 by Brazilian researchers to promote an expert network dedicated to laboratory inter-comparisons for computational dosimetry simulations for a wide range of real-world applications. Today, the MCMEG has 32 members from various institutes of different countries such as: SCK-CEN in Mol/Belgium; National Cancer Institute (INCA), COPPE and IRD in Rio de Janeiro/Brazil; CDTN and UFMG in Belo Horizonte/Brazil; The Institute of Cancer Research: Royal Cancer Hospital in England and the National University of San Agustin of Arequipa - EFM in Arequipa/Peru; Instituto Federal de Educação Ciência e Tecnologia de São Paulo in Matão/Brazil.

Several MC packages are used by these different scientific institutes such as MCNPX (Pelowitz et al., 2011) and MCNP6 (Goorley et al., 2012), PENELOPE (Salvat et al., 2008), and EGSnrc (Kawrakow et al., 2000). The objective of this working group (WG) is to share information and develop a common 'best practice' to help researchers using Monte Carlo simulations. The long term goal is to document and disseminate standardized methodologies to validate mathematical models and MC simulations. As a first inter-comparison exercise, a 6 MV LINAC photon beam was modelled and simulated using the MCNPx, MCNP6, EGSnrc and Penelope MC codes.

The determination of a beam photon spectrum produced by a clinical megavoltage linear accelerator (LINAC) is essential for accurate

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clinical dosimetry. However, it is difficult to measure the X-ray spectra from a clinical LINAC directly. Currently, dosimetry protocols recommend the use of a beam quality parameter, such as the TPR20,10 and the PDD20,10 (Andreo et al., 2000; Almond et al., 1999). Usually, the detector is immersed in a water phantom at two depths: 20 and 10 g/cm^2 and a radiation photon beam energy positioned at 100 cm distance from the detector. The radiation beam should also project a field size of 10×10 cm^2 at the surface of the water phantom. This parameter is called the Source Chamber Distance (SCD). This setup is prepared to determine the following dosimetric parameters: Percentage Depth Dose (PDD) and Tissue Phantom Ratio (TPR) The PDD20,10 parameter is defined as the ratio of the percentage depth dose at 20 and 10 g/cm^2 with a Source Surface Distance (SSD) of 100 cm (Andreo et al., 2000). TPR20,10 can be related to PDD20,10, through Eq. (1) (Followill et al., 1998)

$$\text{TPR20, 10} = 10.2661\ \text{PDD20, 10}–00.0595 \quad (1)$$

The main aim of this work was to calculate the PDD20,10 and TPR20,10 using various MC codes and validate their results with experimental measurements carried out in a clinical LINAC.

2. Materials and methods

2.1. Experimental apparatus

Experimental PDD20,10 and TPR20,10 were determined for a 6 MV LINAC Varian Clinac 2300 at the National Cancer Institute (INCA) in Rio de Janeiro, Brazil. Measurements were performed using a water phantom and a PTW 30013 ionization chamber with a 0.6 cm^3 sensitive volume. This ionization chamber was connected to a PTW Unidos E electrometer. The calibration of that detector set was traceable to a Secondary Standard Dosimetry Laboratory (SSDL).

The phantom is constructed as an acrylic box of 40×40 cm3 filled with water. It has a vertical support which allows the movement of the detector and connected cables at different depths. The water phantom was placed below the LINAC gantry and the ionization chamber was immersed in the water phantom in the central axis of the radiation field at two different depths: 10 cm and 20 cm. The set-up consists of a Source Surface Distance (SSD) of 100 cm providing a 100 cm^2 field size at the surface of the water phantom. The experimental apparatus was in accordance with the TRS398 dosimetry protocol (Andreo et al., 2000). The PDD20,10 was calculated using the following equation:

$$\text{PDD20, 10} = \text{Q20 cm/Q10 cm} \quad (2)$$

where Q10 cm and Q20 cm are the ionization chamber readings corrected for influence quantities, at depths 10 and 20 cm, respectively. The TPR20,10 was calculated using the Eq. (1). Fig. 1 shows the experimental apparatus used for the measurements. The water phantom and the ionization chamber are shown below the gantry of the 6 Clinac 2300 accelerator.

2.2. Computational modelling

Six research groups took part in this exercise initiative representing six science institutes or commercial companies as well as the INCA institute where the experiments were carried out. The model of the apparatus set-up, detector, geometric distances and dimensions and all relevant simulation data needed were provided to the participants. The main goal was to calculate TPR20,10 and PDD20,10 parameters and compare them with the experimental results. As an additional validation step, the simulated percentage depth doses (PDD) curve was compared with the experimental values obtained from IAEA (2016). All the participants managed to implement the experimental set-up in their Monte Carlo code. A water phantom was modelled and positioned under the head of the energy photon beam to score absolute and relative absorbed doses at different depths.

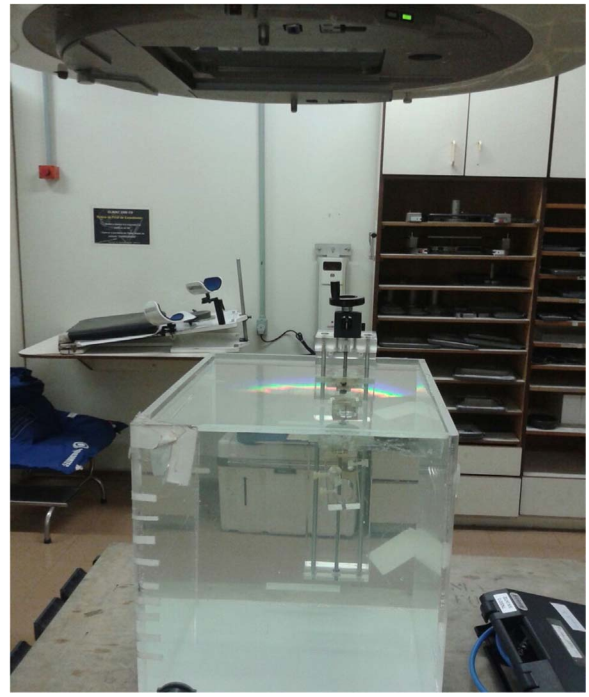

Fig. 1. Experimental apparatus at the INCA hospital in Rio de Janeiro. The water phantom and the ionization chamber are shown below the gantry of the 6 MV Clinac 2300 accelerator.

The dose calculation was performed in two steps. First, an initial MC simulation of the Source Surface Distance was performed to score the percentage depth doses at 10 cm and 20 cm. The values for PDD20,10 was obtained and the TPR20,10 was calculated using Eq. (1). The Depth Dose Profile and the Maximum Dose Depth (dDmax) were determined after the value of TPR20,10 was determined. The second step was to modify the geometric mode for the TPR calculations by changing the Source Chamber Distance to 100 cm. Two cases were simulated, one with chamber positioned at 10 cm depth in the water and the other at 20 cm. The dose in the sensitive volume of the chamber was calculated for these two cases. The TPR20,10 was calculated and the PDD20,10 was then obtained using the Eq. (1). Fig. 2 shows the schematic representation of the simulated model including the water phantom.

Generally, all groups had created the source card as a isotropic point-source placed just above the collimator jaws as shown in the schematic model. Four different 6 MV spectra were available for use in the simulations as it was not mandatory to use the same spectrum. All participants developed their own MC model and decided on a specific input spectrum. Fig. 3 shows the four 6 MV photon spectra used in the simulations. Each participating group adopted slightly different approaches in their modelling and simulations. Each group was described

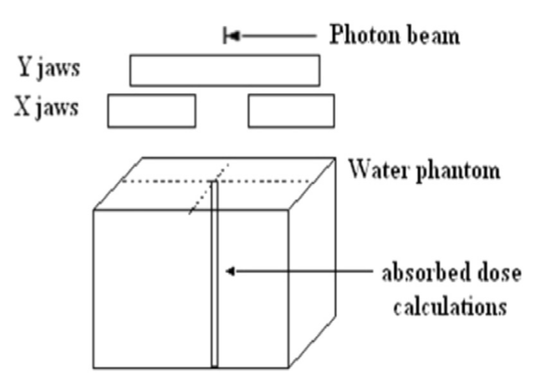

Fig. 2. The schematic representation of simulated geometry including water phantom and the jaws.

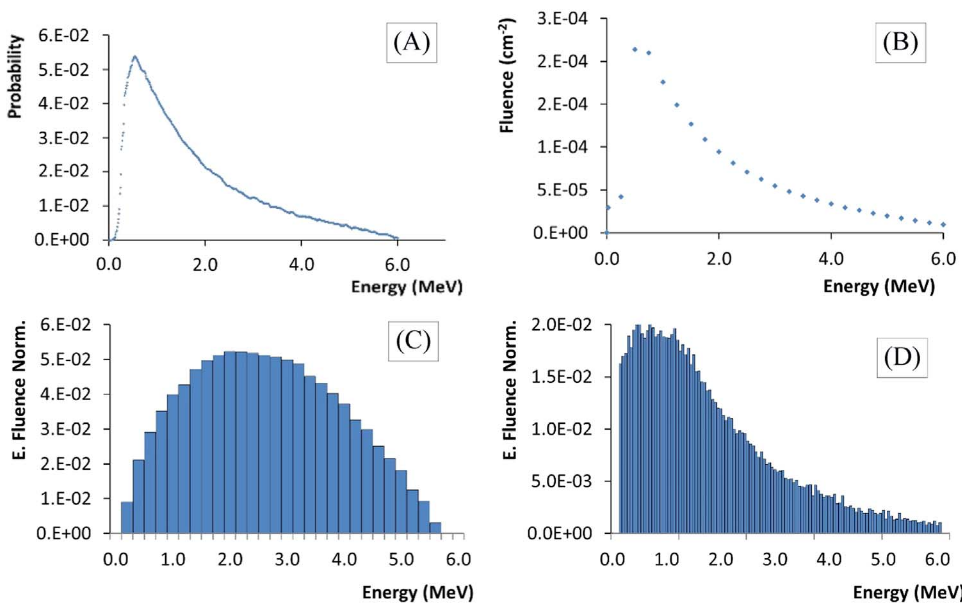

Fig. 3. 6 MV photon spectra used in the simulations. (A) - Mesbahi et al. (2007). (B) – Sheikh et al. (2002). (C) – Vieira (2008). (D) – IAEA (2016).

with a code from G1 to G6. The specificities of each group modelling are described below.

2.3. MCNPx "Monte Carlo N-Particle" – Groups G1, G2 and G3

These groups used a different models for the accelerator spectrum. G1 modelled a cone beam source definition instead of a point-source isotropic configuration. The photon beam is pointed toward to the water phantom surface. The collimated beam formed a 100 cm^2 field size on the surface. G2, in turn, added the collimator jaws in their mathematical model. The cone photon source was positioned above the collimator jaws, in such way that the radiation field size was slightly higher than the square opening of the collimator jaws. A 10×10 cm^2 field was obtained at the water phantom surface. For the energy distribution, G1 and G2 used the 6 MV linear accelerator spectrum from Mesbahi et al. (2007) shown in Fig. 3A. G3 used the energy spectrum from Vieira (2008) shown in Fig. 3C. Groups G1 and G3 chose not to calculate the SCD cases.

The water phantom was modelled as a $40 \times 40 \times 40$ cm3 box filled with water and with acrylic walls of 0.5 cm thickness. G1 group had modelled the sensitive volume of the chamber as a 0.6 cm^3 sphere of air and *F8 energy tally was used to score the energy deposition within the sphere. G2 used a +F6 voxel tally to compute the doses involumes of $1 \times 1 \times 0.2$ cm^3 with the z-dimension along the central axis of the water phantom. G3 used a *F8 voxel tally to compute the doses in volumes of $1 \times 1 \times 0.1$ cm^3.

The cut-off energy for photon and electron transport was adopted. The number of simulated particles was such that the relative statistical uncertainty was lower than 3%. The MCNPx software version used was v2.7d using the MPI (Message Passing Interface) support on a parallel computational cluster with 120 processors at the Neutron Laboratory of IRD/CNEN in Brazil.

2.4. MCNP6 "Monte Carlo N-Particle" – Group G5

Here, the model is a water box of $30 \times 30 \times 30$ cm3 dimensions with a 3D lattice of 0.35 cm^3 voxels. The detector sensitive volume was considered as a voxel whose position corresponded to a depth of 10 and 20 cm. In the first simulation, the SSD was assumed as 100 cm. The source was placed just above the collimators in such way that it forms a field of 10×10 cm2 on the surface of the water phantom. The TPR20,10 was calculated using the Source Chamber Distance approach as described previously. The *F8 tally was used to score the dose absorbed computed in the corresponding voxel. To keep the relative uncertainty on the result below 2%, 2×1010 particle histories were simulated. Fig. 3D shows the energy spectrum data used in the simulations. This data was measured from a Varian 600C PHSF and downloaded from the IAEA web site (IAEA, 2016).

2.5. PENELOPE "PENetration and Energy LOss of Positrons and Electrons" - Group G4

The PENELOPE (Penetration and Energy LOss of Positrons and Electrons in matter) Monte Carlo code 2008 (Salvat et al., 2008) was used by Group G4 in the inter-comparison. The experimental geometry model with the dimensions and materials, the input energy spectrum and the detector defination were defined in the PENELOPE IN files format. The ionizing chamber was defined as a cylinder volume with a 0.5 cm radius and a 1 cm heigh at the central axis of the beam. The chamber was immersed in the $30 \times 30 \times 30$ cm^3 water phantom. Two different depths 10 and 20 cm were set to calculate the PDD20,10 parameter. The spectrum used in the simulations was a 6 MeV photon beam of a Siemens accelerator (Sheikh et al., 2002) as depicted in Fig. 3B. The source definition was defined to obtain a 10×10 cm^2 field size at the surface of the water phantom.

2.6. EGSnrc "Electron Gamma Shower" - Group G6

The EGSnrc MC code is widely used and validated for medical physics research (Rogers, 2006). The EGSnrc MC code (Kawrakow et al., 2000) was used in the inter-comparison by group G6. The input files were written according to the egspp EGSnrc C++ class library geometric package (Kawrakow et al., 2009). The egspp EGSnrc C++ class library provides tools for complex geometries and source modelling. The tutor7pp user-code was utilized within the simulations with the deposited energy at the detectors scored. The materials used in the simulations were taken from the EGSnrc materials library.

The phantom was modelled as a water ($\rho = 1.0$ g/cm^3) cube with 30 cm edge for all simulations except for TPR simulations when the detector is at z = 10 cm from surface. In this case, the water phantom is $30 \times 30 \times 20$ cm^3. The simulation universe was defined as an air ($\rho = 0.00120479$ g/cm^3) volume with $40 \times 40 \times 140$ cm^3 for both TPR20,10 and PDD20,10 simulations. The 6 MV photon beam spectrum was taken from Mesbahi et al. (2007) and depicted on Fig. 3A. Photon emission was simulated using a point source collimated source with $10 \times 10\ cm^2$ scoring field size. The use of the EGSnrc collimated source removes the need to model the collimator jaws in the mathematical model.

The deposited energy for TPR20,10 simulations were obtained at water cubes of 1 cm^3 volume. The detector was positioned at z equal to 10 and 20 cm from phantom surface, for TPR10 and TPR20 calculations, respectively. The deposited energy for the PDD simulations were obtained within at water voxel cubes of 0.8 cm edge or 0.51 cm^3. The detectors were at various z positions: 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 8, 9, (…), 25. The ratio between the PDD at z = 20 cm and the PDD at z = 10 cm (PDD20,10) can be used to estimate the TPR20,10 using Eq. (1).

The Monte Carlo transport parameters selected for the electron transport cut-off energy were 1 keV and 10 keV for the photon cut-off energy, XCOM photon and Compton cross sections, NIST Bremsstrahlung cross-sections and Simple mode set for bound Compton scattering. All other EGSnrc MC transport parameters were kept at the default values. No variance reduction options were used. The number of simulated particles is such that the statistical uncertainty is 3% or less on calculated quantities. 1 × 107 and 1 × 108 histories were simulated for TPR and PDD simulations, respectively. The simulations were performed on a desktop computer with an Intel® Xeon® Quad CPU of 3.30 GHz with 4 GB RAM.

3. Results and discussion

Table 1 shows the simulated results for dDmax, PDD10, PDD20, PDD20,10, TPR20,10 obtained from the six different groups (G1,2…6). The experimental values as well as the used reference values from literature are also presented. The mean values with standard deviation and related ranges for dmax, PDD20,10 and TPR20,10 were, respectively: 1.5 ± 0.1 cm (1.4 cm–1.8 cm), 0.58 ± 0.04 (0.55–0.61) and 0.67 ± 0.05 (0.64–0.72). The results obtained from the different MC codes and the experimental measurements of the PDD20,10 and TPR20,10 quality index demonstrate good agreement.

The spectra used in the simulations did not include the effect of generated photoelectron. This may increase the PDD values determined near the surface of the phantom. This may explains why the dDmax simulation values are slightly higher than the experimental one. The G1 group obtained a PDD curve that is different to the experimental result compared to the other groups. This variance between the mathematical and experimental results might be explained by the simplification of the beam shape (conical) in the mathematical mode.

Fig. 4 shows the PDD curves in the central axis for the different MC simulated codes. The deviation on the simulated results were compared with the experimental values obtained from IAEA (2016), was considered satisfactory. Generally, several reasons can account for the small deviations observed:

1. differences in the 6 MV energy spectrum used;
2. differences in beam shape modelling;
3. small uncertainties between the positioning of the ionizing chamber in the water phantom;
4. small differences in the individual modelling methodology and experience used by each group in the inter-comparison;
5. difference in the MC code used.

The influence of some of these parameters in the simulation could provide the deviations in the final results. Nevertheless, it is important to mention that differences in the modelling of the water phantom dimensions with neither the phantom dimensions or the thicknesses of the acrylic walls have no significant deviation in the results. Moreover, it was observed that the geometry definition for the sensitive volume of the detector, if it was spherical, cylindrical, parallelepiped or cubic had no influence in the final results. The cut-off energy was also another

Table 1
Simulated results for d_{Dmax}, PDD_{10}, PDD_{20}, $PDD_{20,10}$, $TPR_{20,10}$ from the six groups compared with experimental reference values.

	Group	Accelerator	Monte Carlo Code	d_{Dmax} (cm)	PDD_{10} (%)	SD (%)	PDD_{20} (%)	SD (%)	$PDD_{20,10}$	SD	$TPR_{20,10}$	SD
Reference and Experimental Values	RV_0 [(a)]	Elekta Precise	–	1.5	67.8	–	39.90	–	0.588	–	0.685	–
	RV_1 [(b)]	Varian True Beam	–	1.41	66.1	0.1	37.88	0.06	0.573	0.001	0.666	0.001
	RV_2 [(b)]	Varian Trilogy	–	1.44	66.1	–	37.98	–	0.575	–	0.668	–
	RV_3 [(b)]	Varian Clinac 2100	–	1.41	66.2	–	37.99	–	0.574	–	0.667	–
	EV	Varian Clinac 2300	–	1.4	–	–	–	–	0.58	0.01	0.67	0.01
Modelling layout - SSD 100	G1	Varian Clinac 2100	MCNPX	1.8	71	2	44	1	0.61	0.02	0.72	0.03
	G2	Varian Clinac 2100	MCNPX	1.5	66	1	38	1	0.58	0.01	0.67	0.01
	G3	Varian Clinac 600 C	MCNPX	1.6	68	1	38	2	0.55	0.01	0.64	0.01
	G4	Siemens	PENELOPE 2008	1.6	67	2	40	2	0.60	0.03	0.70	0.03
	G5	Varian Trilogy	MCNP6	1.5	66	1	37	2	0.57	0.02	0.66	0.02
	G6	Varian Clinac 2100	EGSnrc	1.5	66	1	39	1	0.59	0.01	0.69	0.01
Modelling layout - SCD 100	G2	Varian Clinac 2100	MCNPX	–	–	–	–	–	0.58	0.01	0.67	0.01
	G4	Siemens	PENELOPE 2008	–	–	–	–	–	0.57	0.02	0.67	0.02
	G5	Varian Trilogy	MCNP6	–	–	–	–	–	0.58	0.01	0.67	0.01
	G6	Varian Clinac 2100	EGSnrc	–	–	–	–	–	0.58	0.02	0.67	0.02

RV – Reference Values; EV – INCA Experimental Value.
[(a)] – Almeida and Barreto (2012); [(b)] – Beyer (2013)

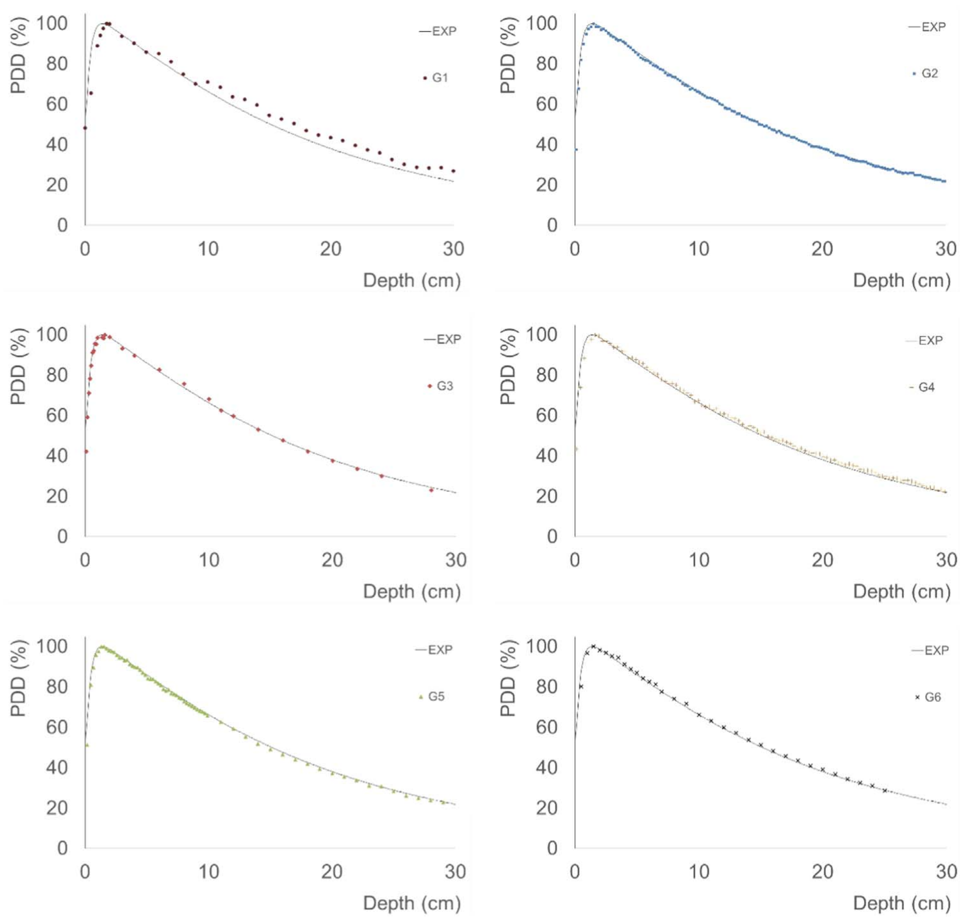

Fig. 4. Simulated and measured PDD for 6 MV LINAC for all the six groups, considering a 10×10 cm^2 field size.

parameter that had no significant effect on the results due to the high X-ray energies of the incident beam. In terms of the sensitive detector volume, the different mathematical models show greater variability: G3 and G4 = 0.1 cm3; G2 = 0.2 cm^3; G5 = 0.35 cm3; G6 = 0.51 cm3 and G1 = 0.6 cm3. Castelo et al. (2016) demonstrated that the sensitive volume of the ionization detector has no influence on the PDD value.

Fig. 5 shows the images from the MCNPx simulation provide by the G2 group. The build-up region can be seen in the depth dose profile: the red region near the surface at Fig. 1A. The relative error per voxel distribution pattern shows lower values (< 3%) near the 10×10 cm^2 field.

In general, the implementations of the mathematical model with the four Monte Carlo software codes used within this exercise resulted in results with good agreement, with most of the experimental results being within the statistical uncertainty of the Monte Carlo simulations. For those differences that exceeded the statistical uncertainty, many differences are within ~7% and 28% of the mean of the results. Some, if not all, of the differences beyond statistical uncertainty could be due to small differences in interpretation of the simulation conditions or even errors in implementation of the exercise by the group members.

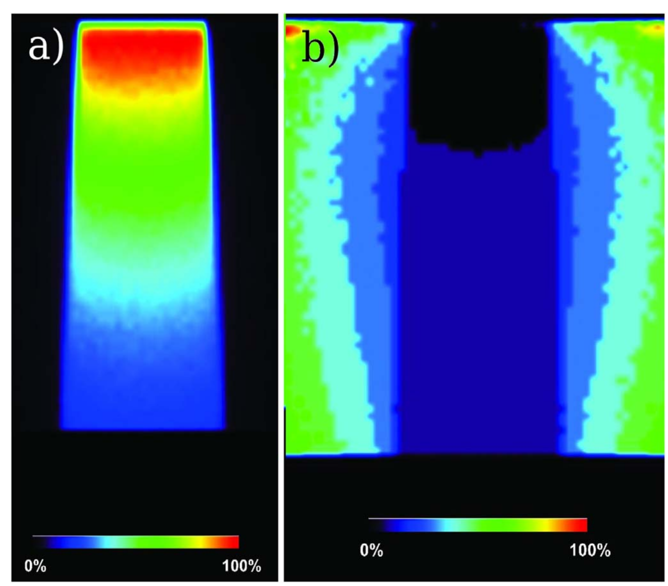

Fig. 5. **G2** MCNPx simulation results. (a) Depth dose profile in the water phantom. (b) The relative error per voxel distribution pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

The goal of this work was to develop and implement Monte Carlo simulations of a typical experiment performed for a 6 MV LINAC photon beam for an internation inter-comparison. These simulations were implemented with four different well-known and publicly available Monte Carlo packages - MCNPx, MCNP6, EGSnrc and Penelope Monte Carlo codes. All the participants were members of an expert network Monte Carlo Modelling Expert Group (MCMEG) and the methods and results have been analysed to study the variability in the participants modelling and simulation. Reference measurements were carried out at the National Cancer Institute (INCA) facility in Rio de Janeiro, Brazil. The set-up model, detector, distances and all relevant data needed for the simulation were provided to the participants.

All the participants managed to implement the model in their Monte

Carlo packages. The results between the PDD curves and in build-up region as well as the depths doses are in good agreement, with most of the results being within the statistical uncertainty of the simulations. Some, if not all, of the differences beyond statistical uncertainty could be due to small differences in interpretation of the simulation conditions or even errors in implementation of the model by the group members. Every attempt was made to minimize this possibility. This exercise is designed to study the variability of the implementation from individual laboratories and then make recommendations for a standardized methodology. This methodology can then be used by researchers who are using Monte Carlo simulations to validate their simulations before embarking on research.

The MCMEG - Monte Carlo Modelling Expert Group has finished its first inter-comparison in the area of radiotherapy simulations. Anyone doing modelling and simulation using MC are welcome to join this group. The MCMEG group website can be found at: Monte_Carlo_Modelling_Expert_Group –groups.google.com. With the success of this initial inter-comparison, the MCNEG group plans future inter-comparison exercise. The main overall goal is to share skills and experience through the group members on the modelling and simulation of any radiation transport problem using any MC code. Of course, each research investigation has different requirements, and therefore the MC simulations needed may include higher levels of complexity compared to the presented in this exercise. This type of inter-comparison exercise can also be useful as an educational tool for MC simulations.

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