Comparison Study of Monte Carlo Simulations and Measurements of Relative Output Factors of 6 MV Photon Beam

Nakorn Phaisangittisakul[1*], Wanchaloem Saprangsi[2],
Chirapha Tannanonta[2] and Sivalee Suriyapee[3]

[1]*Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand.*
[2]*Division of Radiation Oncology, Department of Radiology, Faculty of Medicine,*
Ramathibodi Hospital, Bangkok 10400, Thailand.
[3]*Division of Radiation Oncology, Department of Radiology, Faculty of Medicine,*
Chulalongkorn University, Bangkok 10330, Thailand.

ABSTRACT: In this study, Monte Carlo method is applied to estimate the relative output factors of 6 MV therapeutic photon beam. The photon beam is produced from Varian Clinac 2100C medical linear accelerator, located at the Department of Radiology, Ramathibodi Hospital. The linear accelerator head is modeled by the EGSnrc/BEAMnrc code with the detailed descriptions of the accelerator supplied by the manufacturer. The absorbed dose in water was calculated using the EGSnrc/DOSXYZnrc code. The unknown parameters of an incident electron beam on the x-ray target are its energy and radial Gaussian width of an intensity distribution. The determination of these values was based on comparisons between the measurement and simulation of the central-axis percent depth doses and dose profiles for a field size of 20 x 20 cm^2 at 100 cm source-to-surface distance. The parameters had been adjusted systematically so that the absolute difference of the local dose was less than 1%. The energy was found to be 6.2 MeV and the full width at half maximum of the radial spread was 1.0 mm. Based on the linac model with the optimal beam parameters, the relative output factors at 5.0 cm in depth were determined in the simulation for five square field sizes; 5 x 5, 10 x 10, 15 x 15, 20 x 20 and 30 x 30 cm^2. The calculated results are in excellent agreement (better than 1%) with the measured values. In conclusion, we obtain Monte Carlo model of the 6 MV photon beam, which is able to estimate the relative output factors with good accuracy. The model may be used to accompany other dosimetric measurement or to confirm complicated manual measurement.

Key words: Monte Carlo, output factor, medical linear accelerator

INTRODUCTION

Interactions between particles with matter have been extensively studied and well established. The computer simulation of such interaction has been developed by the integration of sampling method. The kind of interaction (for example, elastic scattering, Compton scattering, photoelectric effect, pair production, Bremsstrahlung radiation, etc.) is chosen along particle's track depending on the probability calculated from each interaction's cross-section. Similarly, the kinematics variables describing the interaction such as a scattering angle, an energy transfer, etc. are randomly selected in which they must satisfy the physical constraints such as energy and momentum conservation.

At first, simulations of interaction of particles were developed at large research centers using mainframe computer systems and with a strong emphasis on the simulation of electron transport. The codes were typically related to either reactor neutron/photon physics (e.g. MCNP) or high-energy physics (e.g. EGS). With the emergence of new efficient computer, simulation became applicable in medical physics, both in radiotherapy and radiation imaging and other fields in which radiation transport was involved. The use of Monte Carlo method was accepted as an accurate method to calculate an absorbed energy in a media per unit mass or dose. Good agreements between measured and calculated dose distribution had been extensively verified.[1-6]

Sponsored by the National Research Council Canada, the BEAMnrc and the DOSXYZnrc[7-10] code systems were the widely used Monte Carlo package for simulating radiotherapy beams and calculating dose distributions in phantoms or in patients. The BEAMnrc code system was designed to simulate radiation beams from a medical linear accelerator, including Co-60 and low energy x-rays machine. The model of treatment head was built in the BEAMnrc from the existing component modules (CM) which geometrically imitated various parts of the treatment head. The DOSXYZnrc code was used to calculate dose distributions in a phantom. It gave dose in a defined volume when irradiated by a beam described by the output phase-space from BEAMnrc. The DOSXYZnrc offered an option to create an inhomogeneous phantom by defining the properties of each individual volume element. Both codes were based on an updated electron-gamma-shower user code (EGSnrc), running under the Linux/Unix and Window NT/2000/XP systems.

Over the past, Monte Carlo studies on photon beams were focused on several topics such as (i) the investigation of the physical characteristics of photon beams from medical linacs; (ii) the influence of certain parts of the linac on the characteristics of the beam, such as collimators, flattening filter, or target; (iii) evaluation of the production of head scatter; (iv) improving the calculation of stopping power for electrons and electron-beam dosimetry; (v) building better algorithms for treatment planning or improving available algorithms.[12-24] Some of the past studies on Monte Carlo simulation have been adequately reviewed as follows.

Tzedakis et al.[2] investigated the effects of initial electron beam characteristics on Monte Carlo calculated absorbed dose distribution for a 6 MV photon beam. The mean energy and radial intensity distribution were the most important parameters of the initial electron beam. The values of these parameters were derived, so that the dose distribution differences between the measured and calculated doses were within 1%. Thus in simulating the radiation source of a photon beam, two of the examined parameters (mean energy and radial intensity) of the electron beam should be tuned accurately, so that the resulting absorbed doses were within acceptable precision.

The feasibility of using Monte Carlo methods to assist the commissioning of photon beam output factors from a medical accelerator was reported by Ding.[20] With the use of machine's details and appropriate initial electron beam parameters, the 6 and 18 MV photon beams from a Varian linear accelerator (Clinac 2100EX) were modeled. The subsequent comparison of the calculated and measured relative output factors for several rectangular field sizes characterized by the X and Y jaws revealed very good agreement (<1.5%) between the calculated and measured values for both the 6 and 18 MV beam energies.

This study aimed to estimate the relative output factors of 6 MV photon beam using Monte Carlo simulation. Not only the characteristics of photon beams produced from medical accelerators vary between manufacturers but also the beams from the same type of linacs might have different dosimetric properties due to differences in an on-site installation and beam adjustment. The characterization of the initial electron beam as it left the accelerator vacuum and hit the bremsstrahlung target is very important in the beam model. Thus, the beam parameters should be investigated first. This required a tuning of the parameters so that the Monte Carlo calculated dose distributions and measured values were in a satisfactory agreement. Then, the model was used to calculate the relative output factors (ROFs) for various square field sizes. The agreement between the calculated and measured relative output factors supports the satisfactory model of the linear accelerator. Hence, it could be use to estimate other dosimetric values as well as to use as a benchmark for other measurement in radiotherapy involving our linac.

MATERIALS AND METHODS

Materials

Linear accelerator

The medical linear accelerator, Clinac 2100C (Varian Oncology Systems, Palo Alto, CA), is used in this study. The machine is located at the Ramathibhodi Hospital, Bangkok, Thailand. It produces photon beams with energies of 6 or 10 MV and five electron beams with energies of 6, 9, 12, 16 and 20 MeV. For photon beam mode, the structure of the machine's head consists of x-ray target, primary collimator, flattening filter, monitor chamber, field light mirror, upper (Y) and lower (X) jaws.

Dose scanning system

The Scanditronix RFA-300 Radiation Field Analyzer is a high precision system used for dose scanning in a water phantom. The three main parts are 3-D water tank, reference and field semiconductor detectors and the RFA-300 control unit. The water phantom is accompanied with a precision servo mechanism for a full three-dimensional detector positioning. It allows positioning of the field detector to measure both vertical and horizontal dose.

The water tank of Radiation Products Design, Inc has the dimensions of 35 x 35 x 37 cm^3. It is made of acrylic with wall thickness of 0.25 inches. The reference and field detectors are made of p-type semiconductors. The small size of the active chip (2.5 x 2.5 x 0.45 mm^3) allows the field measurement with high spatial resolution. The reference detector was placed in air to achieve a stable reference signal

in both photon and electron beams. By detecting a fluctuation in the beam, the inaccuracy of the relative measurement due to varying accelerator output is reduced. The control unit is a computer interface hardware and software that manages the position of the field detector and processes its position as well as the dose reading.

Cylindrical ionization chamber and electrometer

For the measurement of the relative output factors, 0.6 cc Farmer-type ionization chamber was used. It consists of a thin walled high purity graphite thimble and a pure aluminum electrode, supported by a thin walled aluminum stem, sensitive volume of 0.69 cm^3, length of volume 24.1 mm, wall thickness 0.36 mm, thimble outside diameter of 6.99±0.04 mm and stem outside diameter of 8.62±0.04 mm. This chamber is connected to the PTW-UNIDOS electrometer which is a microprocessor-controlled dosimeter for measuring either absorbed dose or dose rate. It could measure radiation dose up to 3 MGy.

Computational system

The Monte Carlo simulation and dose calculation were done on a desktop computer with Pentium III 1 GHz processors with 256 MB DDR RAM. The operating system is Red Hat® Linux version 9. The Monte Carlo code system is based on the EGSnrc package which consists of BEAMnrc and DOSXYZnrc code for the simulation of a linac head and for the calculation of absorbed dose, respectively. Both codes are available at the website http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html. In addition, the analyses of both measured and calculated dose data were done with MATLAB and Microsoft EXCEL.

Methods

Measurements

The essential data for the tuning of beam parameters in our study were the percent depth dose (PDD) and the lateral dose profile. These dose data were completed by the RFA-300 system in water for the 20 x 20 cm^2 field size with the source-to-surface distance (SSD) of 100.0 cm. The PDD was obtained by scanning the detector along the beam central axis, which started from the water surface down to 25.0 cm in depth. The beam profiles were obtained by scanning across the field area at the depth of 10.0 cm.

For the determination of relative output factor, the doses at depth of 5 cm on the central beam axis for various square field sizes were measured using the cylindrical ionization chamber. The measured field sizes are 5 x 5, 10 x 10, 15 x 15, 20 x 20 and 30 x 30 cm^2 at a 100.0 cm SSD. The dose ratio of each field size at 5-cm depth to that of 10 x 10 cm^2 is defined as the relative output factors for that particular field size.

Monte Carlo methods

Linac head simulation

The geometries of the medical linac head are put together in the BEAMnrc code from the existing component modules (CMs). They are specifically designed to model common component in a typical linac head. It is possible to modify the CM, physical dimensions and material, to match the specific components. All the dimensions and the materials of the parts in the accelerator head were incorporated according to the manufacture's detailed specifications. Since some of the CMs were used for several different components in the linac head, a unique name was given for each CM as shown in Table 1. The representation of the linac head components is illustrated in Figure 1.

Table 1. Physical components in the linear accelerator treatment head as used to generate the 6 MV photon beam and their corresponding component modules defined in BEAMnrc.

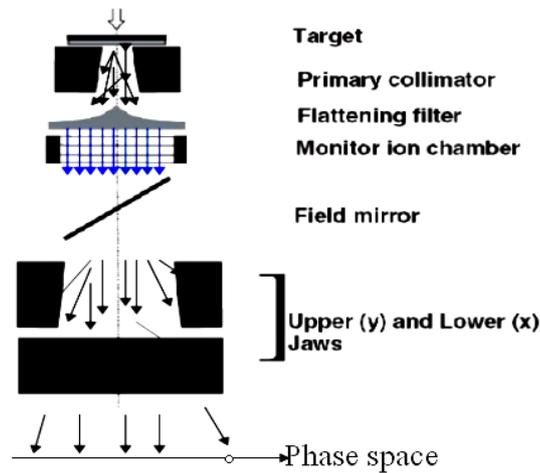| Physical components in the linac head	CM in BEAMnrc
x-ray target	SLABS
primary collimator	CONS3R
flattening filter	FLATFILT
vacuum window	SLABS
monitor chamber of the linac	CHAMBER
Field light mirror	MIRROR
Y jaws and X jaws (secondary collimator)	JAWS

Figure 1. The components of medical linear accelerator head.
The bottom plane is where the particle's information is saved in a phase space file.

According to previous studies the depth dose curve past the depth of maxima is mainly affected by the initial electron beam energy whilst the lateral dose profile is sensitive to both the beam energy and the radial distribution.[18,21] Thus, the initial beam parameters were determined following the three steps. Initially, the beam energy was varied whilst the full width at half maximum (FWHM) was fixed and the central axis depth doses were inspected. The energy that provided the best match was chosen for the next dose calculation where the energy was kept constant and the FWHM was varied. In the second step, the dose comparison was performed using the dose profile and, as a result, the optimal FWHM was obtained. Finally, the beam energy was checked using both dose profile and depth dose data.

A number of planes could be introduced at the back of any CM in the linac model in which a phase-space file is scored. The phase-space file is probably the most important output from BEAMnrc where information of each particle's history, energy, position, incident angle and charge are stored. The phase-space file is used as an input file in DOSXYZnrc for further Monte Carlo dose calculations. In this study the phase-space was obtained under the linac head at 100.0 cm SSD (100.0 cm from the bremsstrahlung target). The numbers of incident electrons on target ranged from 100 to 300 million, in order to obtain a statistical uncertainty of less then 1% in an interested voxel. The size of the phase space file varies from 350 MB to 5 GB depending on the number of incident particles.

Some of the parameters in BEAMnrc controlling the particle transport are: AE = ECUT = 0.700 MeV and AP = PCUT = 0.010 keV. ECUT is the global cut-off energy for electron transport. An electron with energy less than ECUT is no longer tracked and its energy is deposited in the current region. The PCUT is the global cut-off energy for photon transport. Similarly, photon with energy below PCUT are disregarded and their energy is deposited locally. The description of other parameters could be found in BEAMnrc and DOSXYZ manual.[9,10]

Dose calculation
The water phantom was divided into 67 x 3 x 27 slices for the 20 x 20 cm^2 field. These divisions were not equal in size in order to minimize the total number of voxels while maintaining good resolution. In the penumbral region of the profiles, where there is a high dose gradient, the width of voxels was 0.5 cm. Using the DOSXYZnrc code, the central axis depth dose curves were calculated in the area of 2 x 2 cm^2. The dose profile was calculated at depth of 10.0 cm since at this depth it is insensitive to the electron contamination.

Beam data simulation
After the accurate physical details of the linear accelerator and initial electron parameters were obtained, the phase space files were generated for various field sizes with the BEAMnrc user-code. The field sizes are 5 x 5, 10 x 10, 15 x 15, 20 x 20 and 30 x 30 cm^2. For each phase space file used in DOSXYZnrc, the following data were sampled: depth-dose on the central axis; dose-profile at depth 10 cm; and dose on the central beam axis at 5 cm depth.

Comparison

The influence of the energy and radial intensity distribution of the initial electron beam on dose distribution was examined for the 20 x 20 cm^2 field size. To obtain the optimal parameters for the initial electron beam, the measured and Monte Carlo calculated depth-dose as well as the dose-profile curves were compared. For the depth-dose curve, all doses were normalized to the central dose at 10.0 cm depth. The lateral dose profiles were normalized to one at the beam center.

In order to compare dose with the MC simulation, the measured PDD was fitted by the fourth order polynomial function for the depth starting from 5.0 cm to 25.0 cm. The fitting introduced additional deviation from the measured PDD of less than 0.3%. To compare the calculated and measured depth dose data, local dose differences were determined. This was defined as the percentage difference of the calculated to the measured dose at a certain depth. The dose profiles for the optimal radial intensity distribution were compared within the ranges of -10.0 to -5.0 cm and 5.0 to 10.0 cm along the X axis. For the investigation of the energy the dose profiles were compared between the ranges of -10.0 to -9.0 cm and 9.0 to 10.0 cm along the X axis. The calculated dose-profiles were estimated only the X axis since the MC linac simulation was assumed to be symmetrical on both side of X and Y coordinates. The ranges ± 5.0 to ± 10.0 cm and ± 9.0 to ± 10.0 cm off-axis were used at the edges of the umbral region of 20 x 20 cm^2 field at a depth of 10.0 cm. The percent dose difference of these calculated and measured dose values was examined for various initial electron beam parameters. After having the optimal incident beam parameters, the ROFs were estimated for several field sizes and they were compared with the measurement.

Practically the amount of beam delivery is detected by the monitor chamber, the back scattering of the beam, especially from the collimator jaws into the monitor chamber causes an over reading of beam delivery. However, the number of incident electrons on x-ray target determines the amount of beam in the simulation. To take this discrepancy into account, the correction factors from Liu et al.[15] were applied to the calculated ROFs. Although they were extracted from the 10 MV photon beam data, they are assumed to be applicable to our data on 6 MV photon beam in this study since the linac head is the same model made by the same manufacturer. Moreover, the beam energy is not drastically different. Therefore, in case of the ROFs, the comparisons are done without and with the backscattering correction factor.

RESULTS AND DISCUSSION

Optimal parameters for the incident electron beam on the x-ray target

In this study, the parameters for the incident electron beam on x-ray target are the energy and the radial intensity distribution. They are determined from the best matches between the measured and simulated dose data. The depth dose curves along the central axis were simulated for different settings of beam energy and the preliminary beam energy was selected. The dose profiles at 10 cm depth were also produced for various beam FWHMs and the optimal FWHM was chosen. Finally, the dose profiles were investigated by varying the preliminary beam energy. Thus, the optimal beam energy is obtained.

Depth dose curve: preliminary energy of the initial electron beam

The influence of electron energy on the depth-dose curves was investigated with electron energy 6.0, 6.3, 6.5 and 7.0 MeV with FWHM of 1.2 mm. The percentage difference between the simulated and measured depth dose data was inspected. At 6.3 MeV, the local dose differences of the depth between 5 and 25 cm were mostly within ±1%. At other energies there were more points that out of the ±1% region. The comparison between the measured and calculated depth dose curves for the beam energy of 6.3 MeV and 1.2 mm FWHM are illustrated in Figure 2.

Dose profiles: the radial intensity distribution of the initial electron beam

The intensity of photons creates in the forward direction and electron scatter would influence the shape of the dose profiles as the energy is lost in the phantom. The influence of radial intensity distribution of electron beam on the lateral dose profiles was explored for the field size of 20 x 20 cm^2 at the phantom surface. Table 2 shows the absolute percentage dose differences between the measurement and calculation at various FWHMs in the off-axis regions ranging from -10.0 to -5.0 cm and from 5.0 to 10.0 cm. We found that the FWHM of 0.5 and 1.0 mm result in the dose differences no greater than 1%. However, in case of the 0.5 mm FWHM the asymmetry of the right and left region is larger. This mainly come from the measurement data since the calculated data was already averaged out between the left and right sides of the beam axis. Hence, we chose the optimal FWHM to be 1.0 mm.

Table 2. Percentage differences of the local dose between measurements and calculated dose profiles for the radial intensity distribution ranging from 0.5 to 3.0 mm in FWHM whilst the electron energy was fixed at 6.3 MeV.

E = 6.3 MeV FWHM (mm)	% Difference		
	-10 to -5 cm	5 to 10 cm	Average
0.5	1.4	0.5	0.9
1.0	1.2	0.8	1.0
1.2	2.1	1.6	1.8
1.6	2.4	1.9	2.2
3.0	3.3	4.3	3.8
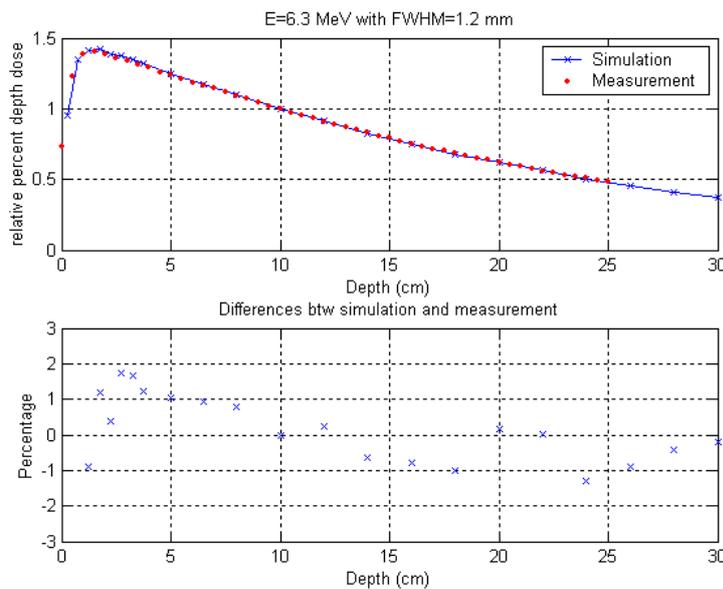
Figure 2. The measured and calculated depth dose of the 6 MV photon beam. The depth dose from the calculation was obtained from the phase space file with the beam energy of 6.3 MeV and 1.2 mm FWHM.

Dose profiles: energy of the initial electron beam

The energy of initial electron beam not only affects the depth-dose curve but also the shape of the dose-profile curve, especially near the field edge. Hence, the influence of the initial beam energy was re-inspected using the dose profile data. The phase space files were additionally generated for energies of 6.2 and 6.4 MeV with 1.0 mm FWHM. They were used by DOSXYZnrc to obtain the dose profiles at 10 cm depth.

Table 3 shows the absolute percentage dose differences between the calculated and measured dose values near the beam edges: -10 to -9 cm and 9 to 10 cm and the average of both sides. In these regions the measured data was fitted by the polynomial function for the comparison since the simulated points were not the same as that of the measured values. From the comparison the only profile that satisfied the 1% difference was obtained from the beam energy of 6.2 MeV. Figure 3

demonstrates the agreement of the dose profiles between the measurement and simulation.

Relative output factor

Using beam energy of 6.2 MeV and 1.0 mm FWHM, the phase space files were generated for various field sizes. They were imported into DOSXYZ for the estimation of the doses on the beam central axis that were used to obtain the ROFs. Table 4 presents the calculated ROFs together with those obtained from the measurement for the five square fields: 5 x 5, 10 x 10, 15 x 15, 20 x 20 and 30 x 30 cm^2. The statistical uncertainties on the ROFs were approximated by the simulation code to be less than 1%. The comparisons were made between the measured and calculated ROFs. In addition, there are the corrected ROFs in which the backscattering from jaws into monitor chamber was included. Without such correction the difference as much as 2% was

found in the 30 x 30 cm² field size. After including the correction, the ROFs for the field size bigger than the standard one, in this case 10 x 10 cm², became larger and they were smaller for the smaller field sizes. As a result, the largest discrepancy was reduced to less than a percent. Generally speaking, the corrected ROFs were found in excellent agreement (<1%) with the measured values.

Table 3. Percentage local dose differences between measured and calculated values of dose profile curves for the electron energy varied between 6.2 to 6.4 MeV with radial intensity distribution 1.0 mm FWHM for field size 20 x 20 cm².

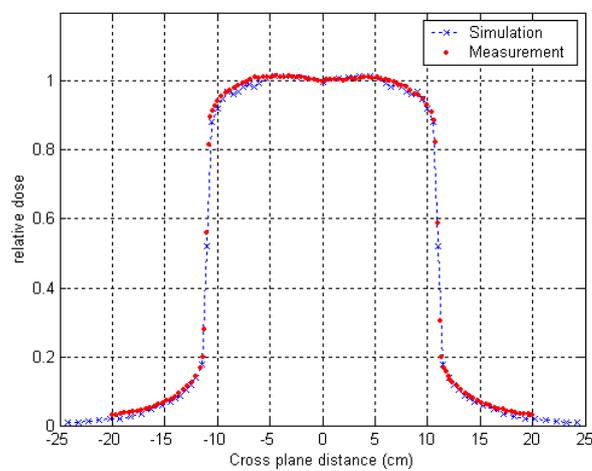| FWHM = 1.0 mm Energy (MeV)	% Difference		
	- 10 to - 9 cm	9 to 10 cm	Average
6.2	0.8	0.6	0.7
6.3	2.1	1.4	1.8
6.4	1.9	1.2	1.6

Figure 3. The dose profiles at 10 cm depth from the measurement and simulation of the incident beam energy of 6.2 MeV and 1.0 mm FWHM.

Table 4. Percentage deviations between calculated and measured relative output factors for the 6 MV photon beam. The correction is from the backscatter radiation described in text.

Field size (cm²)	Measured ROF	NO correction		Correction included	
		Calculated ROF	% difference	Calculated ROF	% difference
5x5	0.9233	0.9301	0.74	0.9272	0.42
10x10	1.0000	1.0000	0	1.0000	0
15x15	1.0410	1.0475	0.62	1.0511	0.97
20x20	1.0677	1.0604	-0.68	1.0678	0.01
30x30	1.1040	1.0817	-2.03	1.0970	-0.64

CONCLUSIONS

In this work, the relative output factors of the 6 MV photon beam from the Varian Clinac 2100C medical linear accelerator were estimated using Monte Carlo method. The computer model of the linac and the dose calculation in water phantom were performed using the EGSnrc code system, BEAMnrc and DOSXYZnrc, respectively. The detailed descriptions of the linac supplied by the manufacturer are the main input in BEAMnrc. As the result of the simulation, the phase space file that contains particle's information such as charge, momentum, energy and position is recorded on the specified plane. The DOSXYZnrc user code is able to track each particle from the phase space file through the phantom and gave the deposited dose.

The unknown parameters of the incident electron beam for the model were determined by the comparisons of the central percent depth-dose and the lateral dose profile at 10 cm depth between the measurement and calculation of the 20 x 20 cm^2 field size at 100 cm SSD. The unknown parameters, the energy and the FHWM of radial distribution, were searched in three steps. In the first step, the energies were varied, while the FWHM was unchanged and the calculated percent depth doses were compared with those of the measurement. The energy was chosen and then used in the later step. In the second step, the lateral dose profiles at depth of 10 cm were compared for different values of FWHM. The optimal FWHM was selected from the best agreement between the calculated and measured dose profile. In the third step, the FWHM was fixed and the energy obtained in the first step was adjusted slightly. With the agreement on both depth doses and dose profiles, the optimal parameters of 6.2 MeV in energy and 1.0 mm for the FWHM were obtained and the resulted dose differences were less than 1%.

Using the best estimates of the linac model, the ROFs were extracted for the four field sizes; 5 x 5, 15 x 15, 20 x 20 and 30 x 30 cm^2. They were determined by the division of the dose of a specific field size in water at 5 cm depth on the central beam axis by that of the 10 x 10 cm^2 field. For each field size, the positions of X and Y jaws were different whilst the parameters of incident electron beam were identical in the machine model. Preliminary, the calculated ROFs differed from the measured ones by as much as 2%. However, the agreement was improved as a result of the inclusion of the backscattered radiation from collimator jaws into the monitor chamber. We found excellence agreement (<1%) between the calculated and measured ROFs.

The model is demonstrated to be an alternative tool in the extraction of the ROFs. In general, it could be used to obtain other dosimetric values or verify a manual measurement that requires sophisticate skill of a personnel or involving complicate devices. If the discrepancy is found to be unacceptable, then further investigation should be pursued, in order to minimize further mistakes.

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