Original Article

Monte Carlo Simulation of Siemens ONCOR Linear Accelerator with BEAMnrc and DOSXYZnrc Code

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Submission: 12-03-2013 Accepted: 19-07-2013

ABSTRACT

The Monte Carlo method is the most accurate method for simulation of radiation therapy equipment. The linear accelerators (linac) are currently the most widely used machines in radiation therapy centers. In this work, a Monte Carlo modeling of the Siemens ONCOR linear accelerator in 6 MV and 18 MV beams was performed. The results of simulation were validated by measurements in water by ionization chamber and extended dose range (EDR2) film in solid water. The linac's X-ray particular are so sensitive to the properties of primary electron beam. Square field size of 10 cm × 10 cm produced by the jaws was compared with ionization chamber and film measurements. Head simulation was performed with BEAMnrc and dose calculation with DOSXYZnrc for film measurements and 3ddose file produced by DOSXYZnrc analyzed used homemade MATLAB program. At 6 MV, the agreement between dose calculated by Monte Carlo modeling and direct measurement was obtained to the least restrictive of 1%, even in the build-up region. At 18 MV, the agreement was obtained 1%, except for in the build-up region. In the build-up region, the difference was 1% at 6 MV and 2% at 18 MV. The mean difference between measurements and Monte Carlo simulation is very small in both of ONCOR X-ray energy. The results are highly accurate and can be used for many applications such as patient dose calculation in treatment planning and in studies that model this linac with small field size like intensity-modulated radiation therapy technique.

Key words: *BEAMnrc code, film dosimetry, X-ray modeling*

INTRODUCTION

In new radiotherapy techniques such as intensity-modulated radiation therapy (IMRT) and stereotactic radiotherapy, dose calculation and planning are difficult because in traditional dose calculation algorithms some variation with measurements can appear like media inhomogeneity.[1] This variation is the main source of error in new methods of radiotherapy. Moreover, electronic disequilibrium could be produced in the planning of the multi-leaf collimator (MLC) based IMRT.[1,2] These errors could be reduced by Monte Carlo simulation in dose calculation.[3] In utilizing Monte Carlo simulation in treatment planning two main problems exist: First, the slow speed of the calculation and second, commissioning a Monte Carlo treatment planning system.

Although some Monte Carlo codes are available, calculations with proper accuracy need accurate parameters of linear accelerator (i.e. linac head), such as geometry and combination of pieces. In the entire linear accelerator modeling, many variables are involved.

The manufacture of data is necessary to begin linear accelerator modeling, but this is insufficient. This information did not cover all the data that is necessary for full modeling of a linear accelerator. Therefore, some data must be specified such as primary electron energy and spot size diameter. Several articles have studied the photon beam spot size in radiotherapy accelerators and primary electron energy.[4-12]

Simulating the linear accelerator head with Monte Carlo code is the most accurate and detailed method of obtaining the influence for treatment planning software.[3] In this method, modeling details are modulated to reach a good match between the calculation and measured dose distributions. In order to use Monte Carlo codes to calculate the dose of a patient requires good estimates of the distribution of charge, energy, position and direction of particles at the exit of the treatment head of linear accelerator. All this information is included in a file called the phase-space data.

In this study, we investigate full width of half maximum (FWHM) of the intensity distribution of primary

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electron that simulate the target of Siemens ONCOR linac by BEAMnrc[13] and DOSXYZnrc, Monte Carlo codes. In order to estimate the accuracy of dose calculations achieved by the Monte Carlo model of the linear accelerator head, it needs to be compared with direct measurements, such as ion chamber and film measurement.

METHODS

In this study, the radiation transport software packages of BEAMnrc[14-16] and DOSXYZnrc,[17,18] based on the EGSnrc code are used to perform the simulation. For dosimetry, the Siemens ONCOR linac with 41 leaf pairs MLC installed in Milad Hospital for clinical treatment and operating at nominal energies of 6 MV and 18 MV was used.

According to the American Association of Physicist in Medicine TG-105, Monte Carlo simulation should be implemented under the same conditions as the measurements.[3]

Accelerator simulation with BEAMnrc to simulation of linac's head by the BEAMnrc, the specifications of linear accelerator model obtained from the manufacturer was used.

At the first step of dose deposition calculated by the Monte Carlo simulations, a phase-space file was produced from the linac head simulation positioned after the MLC by BEAMnrc code. The number of history for Monte Carlo calculation was 2×10^8 particles, resulting 4×10^7 particles in a phase space after the ONCOR linac head. The number of the primary electrons that hit the target on top of the linac head equals the number of history.

The phase-space includes all the information of the particles, which exit from the linac head, such as energy, position, incident angle and charge. At the second step, the phase-space files were used as a source for DOSXYZnrc that performed dose calculation in the water phantom.[19]

The ONCOR accelerator components are shown in Figure 1, including the exit window, target, primary collimator, flattening filter, monitor chamber, Y jaws and MLC. In an ONCOR accelerator, the MLC is used instead of the X-jaws. In that linac, the flattening filter used for 18 MV beam is different from that used in 6 MV beam. Since the parameters under study are between fields, a precise simulation of MLC is not essential as a result it become as an X solid jaw in the simulation.[20] In BEAMnrc code each piece of linear accelerator has been produced by existing component modules (CM).[13,16] Each CM has special properties. For exit window and target, we used slabs because this CM supports multilayer structures. For primary collimator and flattening filters flatfilt is used, this CM could model multilayer cone shape structures. For monitor chamber, we have utilized chamber that could provide multilayer structures with different radial section. For X and Y jaws CM was applied; this CM could support multi sheet jaws with a different focus points and has a powerful calculator for defining X and Y coordinate at the front or back of the jaws using field size and source to surface distance (SSD).[16] The details of each CM that are used to model the ONCOR head are shown in Tables 1-5.

Dose results were analyzed by producing the percentage depth dose (PDD) in the central axis and dose profiles.

The global cut-off energies used in the simulations were electron cut-off energy (ECUT) =500 KeV for electrons and photon global cut-off (PCUT) =10 KeV for photons. Monte Carlo simulations were performed for mono-energetic beams ranging from 5.7 to 6.8 MeV and FWHM varied from 0.2 cm to 0.4 cm for 6 MV beam. the simulation was

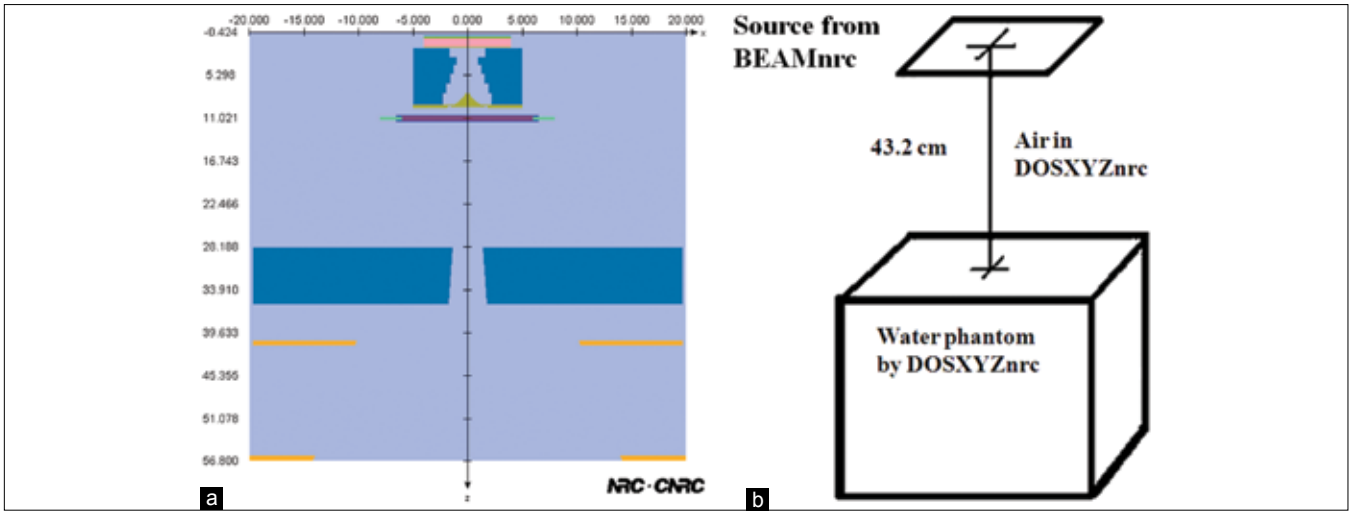

Figure 1: the schematic of simulation; (a) the simulated schematic of ONCOR linac (X-Z view) and (b) simulated phantom in DOSXYZnrc

Table 1: Details of CMs parameters

CMs name	CMs identifier	Outer square boundary	Distance to reference plane (cm)	Number of layers
Slabs	Target and exit window	4	−0.424	13
Flatfilt	Primary collimator and flattening filter	10	1.7	11 (6 MV) 23 (18 MV)
Chamber	Monitor chamber	16	10.734	5
Mirror	Mirror assembly	14	16.603	1
Jaws	Y-jaws and X-jaws	40	22.581	2

CMs – Component modules; MV – Mega voltages

Table 2: Target and exit window parameters

Number of layer	Thickness of layer (cm)	Material
1 (exit window)	0.005	Titanium (Ti)
2 (exit window)	0.066	Water (H_2O)
3 (exit window)	0.005	Titanium (Ti)
4	0.465	Air
5	0.064	Tungsten (W)
6	0.004	Nickel (Ni)
7	0.011	Gold (Au)
8	0.165	Cupper (Cu)
9	0.0015	Nickel (Ni)
10	0.0035	Gold (Au)
11	0.102	Stainless steel
12	1.016	Graphite
13	0.004	Stainless steel

Table 3: Flattening filter and primary collimator parameters for 6 MV beam

Number of layer	Layer thickness (cm)	Number of cone	Top/bottom radius (cm)	Material
1	1.19	1	1.635	Tungsten (W)
2	1.12	1	0.955	Tungsten (W)
3	1.24	1	1.275	Tungsten (W)
4	1.265	1	1.586	Tungsten (W)
5	1.24	1	1.897	Tungsten (W)
6	0.31	2	0.2385/0.2865	Stainless steel
			2.219	Tungsten (W)
7	0.7635	2	0.2865/0.835	Stainless steel
			2.219	Tungsten (W)
8	0.4295	2	0.835/1.2885	Stainless steel
			2.219	Tungsten (W)
9	0.072	1	4.5	Stainless steel
10	0.31	2	1.67/1.372	Stainless steel
			1.67/1.85	Stainless steel
11	0.0954	1	1.85/1.91	Stainless steel

MV – Mega voltages

done for energy of beam in a range of 14-18.8 MeV and FWHM varied from 0.2 cm to 0.4 cm for 18 MV beam. The results were compared with direct measurements to find the best match. Cross-section data of materials received from the 521 ICRU PEGS4 (International Commission on Radiation Units and Measurements, Preprocessor for Electron Gamma Shower) cross-section data available in EGSnrc.

Table 4: Flattening filter and primary collimator parameters for 18 MV beam

Number of layer	Layer thickness (cm)	Number of cone	Top/bottom radius (cm)	Material
1	0.0865	2	0.612	Aluminum (Al)
			1.635	Tungsten (W)
2	0.0742	2	0.544	Aluminum (Al)
			1.635	Tungsten (W)
3	0.445	2	0.643	Aluminum (Al)
			1.635	Tungsten (W)
4	0.581	2	0.896	Aluminum (Al)
			1.635	Tungsten (W)
5	1.12	1	0.955	Tungsten (W)
6	0.68	1	1.275	Tungsten (W)
7	0.7635	2	0.2865/0.835	Stainless steel
			2.219	Tungsten (W)
8	0.074	3	0.0803/0.0433	Stainless steel
			0.085/0.1545	Tungsten (W)
			1.275	
9	0.247	2	0.1545/0.198	Stainless steel
			1.275	Tungsten (W)
10	1.265	2	0.309/0.68	Stainless steel
			1.586	Tungsten (W)
11	0.692	2	0.68/0.89	Stainless steel
			1.897	Tungsten (W)
12	0.593	2	0.89/1.088	Stainless steel
			1.897	Tungsten (W)
13	0.544	2	1.088/1.261	Stainless steel
			2.219	Tungsten (W)
14	0.124	2	1.261/1.347	Stainless steel
			2.219	Tungsten (W)
15	0.124	4	0.606/0.34	Stainless steel
			0.606/0.878	Stainless steel
			1.347/1.4215	Tungsten (W)
			2.219	
16	0.134	4	0.34/0.278	Stainless steel
			0.878/0.9765	Stainless steel
			1.4215/1.4895	Tungsten (W)
			2.219	
17	0.235	4	0.278/0.216	Stainless steel
			0.9765/1.1805	Stainless steel
			1.4895/1.644	Tungsten (W)
			2.219	
18	0.0865	4	0.216/0.1845	Stainless steel
			1.1805/1.224	Stainless steel
			1.644/1.681	Tungsten (W)
			2.219	
19	0.1607	3	0.1845/0.13	Stainless steel
			1.224/1.323	Air
			2.608	Stainless steel
20	0.0742	5	0.13/0.111	Stainless steel
			1.323/1.36	Air
			1.829/1.792	Stainless steel
			2.009/2.04	Air
			2.608	
21	0.0742	4	1.36/1.4215	Stainless steel
			1.792/1.749	Air
			2.04/2.064	Stainless steel
			2.608	Air
22	0.111	2	1.4215/1.014	Stainless steel
			2.608/2.503	Air
23	0.0865	1	2.503/2.423	Stainless steel

MV – Mega voltages

Table 5: Parameters of chamber, mirror and jaws

Number of layer	Layer thickness (cm)	Material
1	0.152	Ceramic (Al_2O_3)
2	0.184	Nitrogen (N_2)
3	0.152	Ceramic (Al_2O_3)
4	0.184	Nitrogen (N_2)
5	0.152	Ceramic (Al_2O_3)
6 (mirror)	0.209	Glass
7 (Y-jaw)	7.798	Tungsten (W)
8 (X-jaw)	7.493	Tungsten (W)

All simulations had a minimum requirement of 100,000 particles/cm^2 for each field; this was done to ensure reliable statistics in the phase space file generated by the BEAMnrc simulation.[18]

Phantom simulation with DOSXYZnrc dose calculation in the water phantom was simulated using DOSXYZnrc. The water phantom size that used in simulation was 40 cm in length and width and 30 cm in depth. The voxels size was 0.5 cm × 0.5 cm × 0.5 cm in all direction. The voxel size can be different because dose gradient change in some region of phantom.

Figure 1 represents a diagram of phantom calculation in DOSXYZnrc. At the second step, Monte Carlo dose calculations were performed using the phase space files described above as the source of input. The energy cut-offs in all the phantom simulations were ECUT = 500 keV for electrons and PCUT = 10 keV for photons. The default parameters were used for the Parameter Reduced Electron-step Transport Algorithm (PRESTA) (ICRP 1991). PRESTA is an electron transport algorithm for use with electron Monte Carlo transport codes. PRESTA components are a path-length correction algorithm, which is based on the multiples scattering theory of Moliére.[21]

At the end, 3ddose files produced by DOSXYZnrc were analyzed by homemade MATLAB software, for extracting PDD's and profiles graph from 3ddose.

The 3ddose file is one of the DOSXYZnrc outputs. This file consists of 6 blocks. In the first block are shown the number of voxels in x, y, z directions by three numbers. In the three, next blocks voxel boundaries (cm) in x, y, z directions by (nx + ny + nz + 3) values are represented. The fifth block displays dose values array by (nx × ny × nz) values. The sixth block consists of error values array (relative errors) by (nx × ny × nz) values.[17] MATLAB is a powerful software for the evaluation of dosimetry results.[22]

Experimental Measurements

All PDD and profiles calculated at various depths using the Monte Carlo model were compared with ion chamber measurements. Commissioning data were taken through PTW ionization chamber (PTW 31010 Semiflex, Germany) in the water tank (PTW MP3 large water phantom, Germany) with a step size of 5 mm for PDD and 2 mm for profiles.

All simulations and measurements were implemented using the same geometric setup at 100 cm SSD. Profiles obtained at different depths in water were measured using ionization chamber and in solid water polymethyl-metacrylate by extended dose range (EDR2) film. Film calibration was performed to convert optical density into dose by irradiating different parts of the film to the known doses from 0 cGy to 600 cGy at 1 cm depth in solid water by Co-60 gamma ray that shown in Figure 2. The film was scanned by a Microtek Scan Maker 1000 × L (Microtek, Inc., Taiwan) and analyzed by homemade program in MATLAB version R2007b (The Mathworks Inc., U.S. patents).

Measurements were done for square fields defined by jaws in Y direction and the MLC was set in X direction. For PDD curves measurements in square fields and dose profiles measurements at the maximum dose depth in square fields, ionization chamber was used in the water tank for both 6 MV and 18 MV X-ray beams.

Results the maximum statistical uncertainty in Monte Carlo calculations was 0.5%. Figure 3 illustrated the PDD obtained from simulation for the field 10 cm × 10 cm in 6 MV beams. The solid lines show the PDD's measured with ion chamber and the PDD's calculated by Monte Carlo simulation is represented as circles with dash lines. The 6 MV profile results were shown in Figure 4 and film measurement of profile was shown in Figure 5.

All the values are divided by the number of particle history.[17] In some of the results, voxel size used in phantom by DOSXYZnrc code was bigger than the other result, because in large voxel errors are so small, especially in PDD results.

The PDD obtained from simulation for the field 10 cm × 10 cm in 18 MV beams illustrated in Figure 6. the solid lines show the PDD's measured with ion chamber and the PDD's calculated by Monte Carlo simulation are represented as circles with dash lines, respectively. The profile dose at 18 MV was shown in Figure 7 and film measurement of dose profile was shown in Figure 8.

In 18 MV beam simulation such homemade MATLAB program was used, which also was used in 6 MV beam simulation and the same position phantom set up was utilized.

DISCUSSION

The primary electron parameter was changed to adjust matching calculated results and measurements less than 2%. The dose difference between the calculated dose value and measurements for both energies were under 2%. The 2%

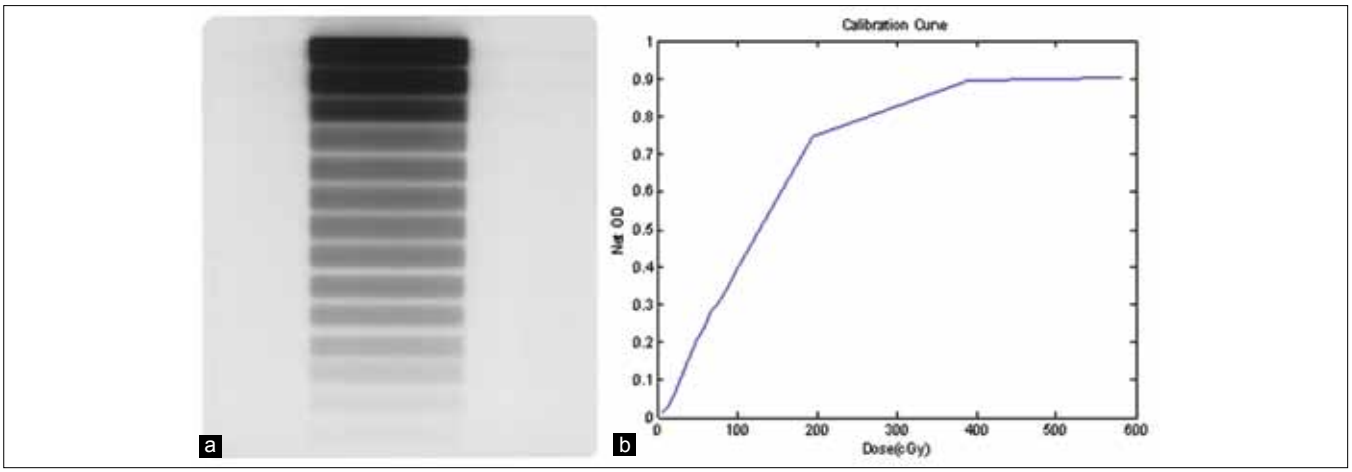

Figure 2: The extended dose range film calibration, (a) the exposed film, (b) calibration plot

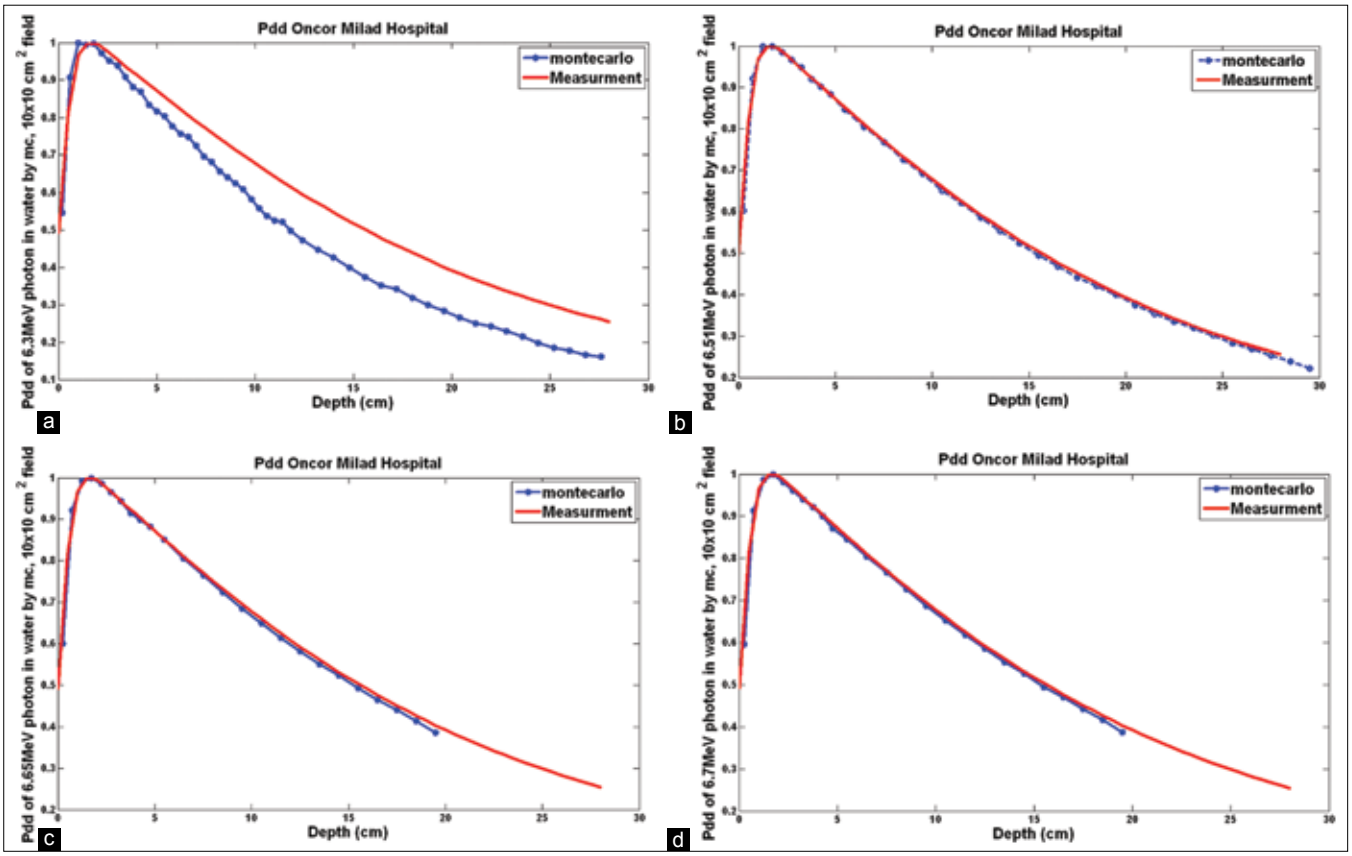

Figure 3: Percentage depth dose results in different energy simulation at 6 MV beam and field size 10 cm × 10 cm, (a) 6.3 MeV, (b) 6.5 MeV, (c) 6.6 MeV, (d) 6.7 Mev

turnover was chosen as a standard to set the useful results for linac modeling.[23]

Noticing this result, a good agreement for 6 MV beam was obtained in 6.5 MeV primary electron energy with 0.31 FWHM of the intensity distribution. At 18 MV beam, a good agreement was obtained in 15 MeV primary electron energy with 0.29 FWHM of the intensity distribution. In this situation, the difference between calculation and measurements of PDD values were under 1% in the tail region. In superficial depths, dose variation between Monte Carlo and measurement was less than 2%. In profile dose results, the difference between calculated and measured dose values was not well-matched, especially in border points. It can be caused by the uncertain setup of the ionization chamber, leveling of the ionization chamber, water tank and imprecise modeling of the linac head. This point is observed in some studies.[23-27]

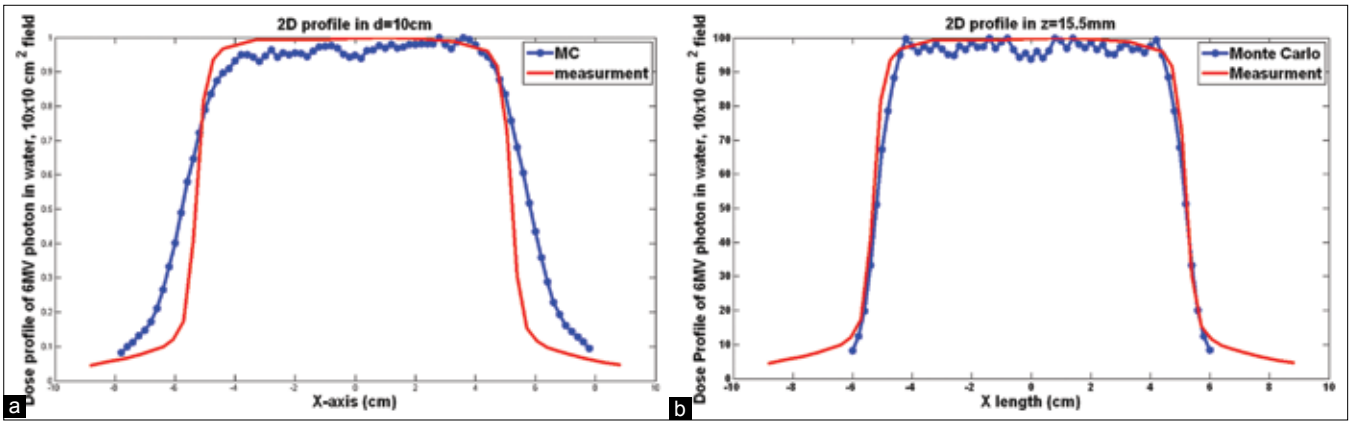

Figure 4: Profile results at 6 MV, (a) 6.5 MeV and full width of half maximum (FWHM) 0.2, (b) 6.5 MeV and FWHM 0.3

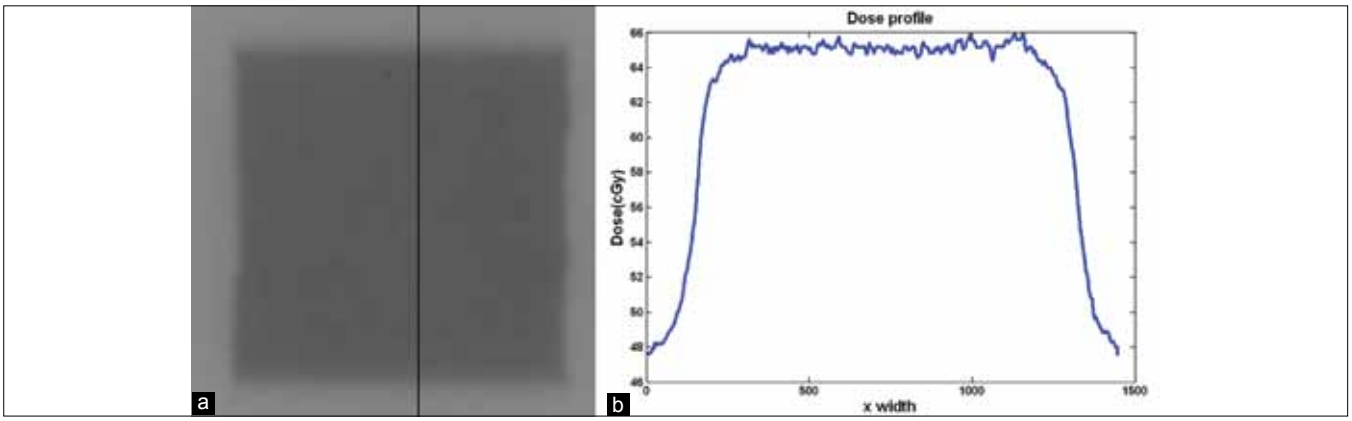

Figure 5: The profile of film dosimetry in 6 MV beam, (a) extended dose range 2 film, (b) profile of corresponding line

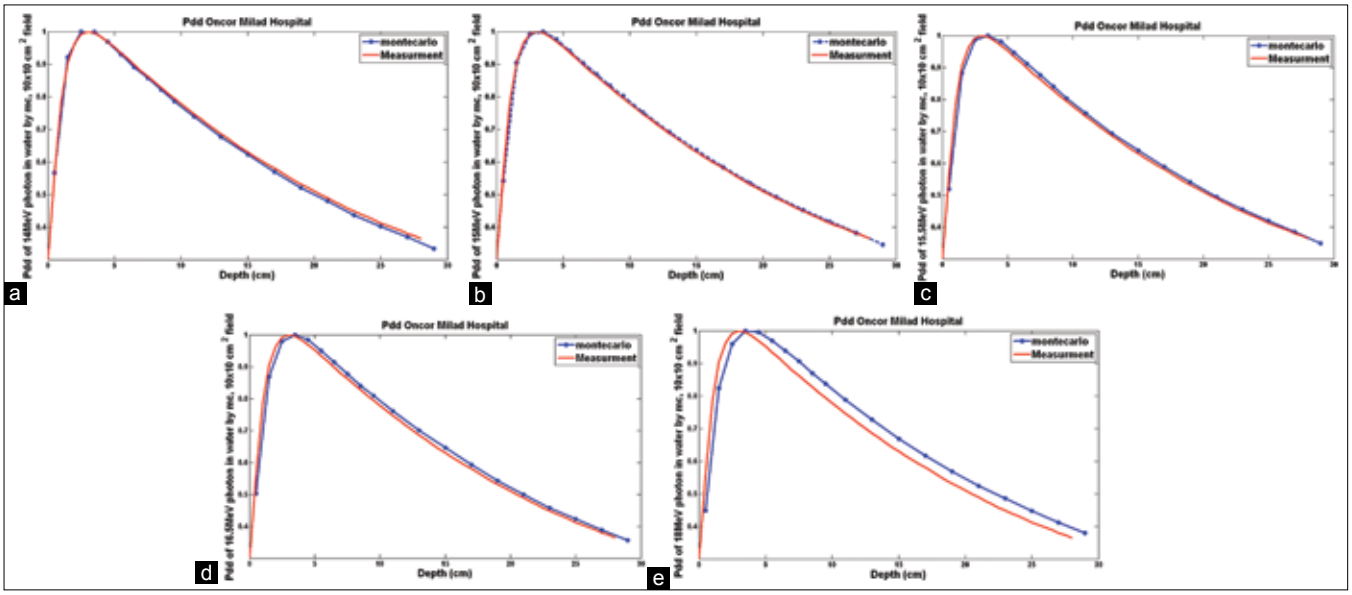

Figure 6: The percentage depth dose results for 18 MV beam and field size 10 cm^2 × 10 cm^2, (a) 14 MeV, (b) 15 MeV, (c) 15.5 MeV, (d) 16.5 Mev and (e) 18 MeV

In some condition for better results, we used voxel with various sizes, for example in the build-up region voxels was so smaller than voxels in the tail region. These decrease the time of simulation and can perform better comparison between the results. In this study, the air between linear accelerator and water phantom is simulated by DOSXYZnrc code as shown in Figure 2. However, when added a thin layer of air in front of water phantom, surface dose is

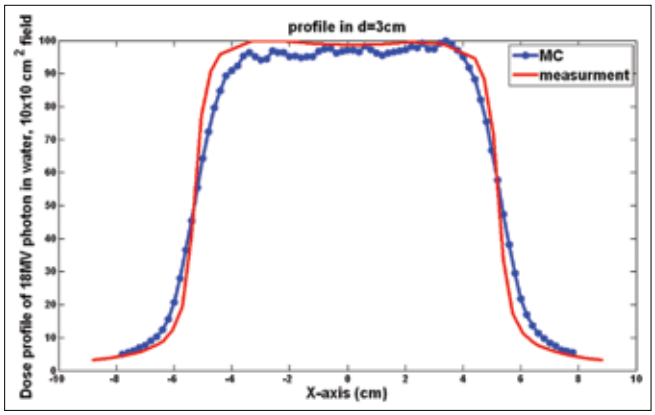

Figure 7: The profile results at 18 MV for 15 MeV and full width of half maximum 0.2

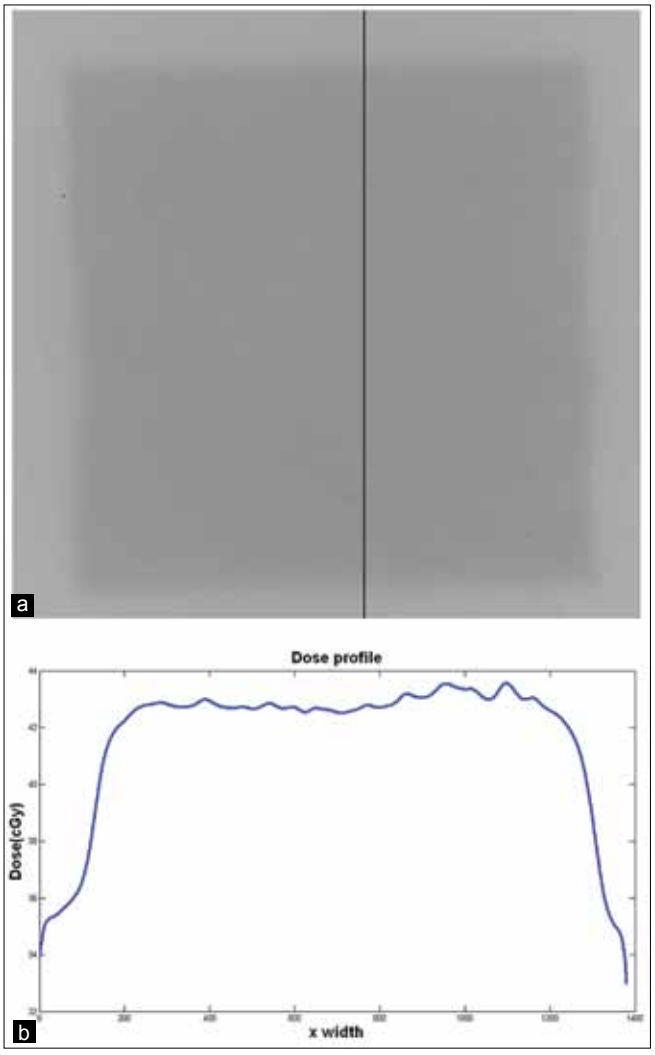

Figure 8: The profile results for 18 MV beam by film dosimetry, (a) extended dose range 2 film, (b) profile of corresponding line

well-matched with measurements. For this reason, in the entire simulation process a thin layer of air about 1-2 mm was considered in front of phantom. This point must be studied that how it can effect on surface dose and results.

The result of photon splitting with particle recycling in some studies was investigated;[15] but in this study, we only used particle recycling from the phase space file source in DOSXYZnrc. The particle recycling can create better accuracy in dose calculation as shown by Vazquez-Quino *et al*.[28]

In the current study, we showed the significant components of primary electron beam in final results. A small change in electron beam properties has strong effects on deposited dose in the water phantom.

A Monte Carlo simulation of a Siemens ONCOR linac has been performed to create phase space files to be utilized in future studies. This phase space result can be used in various researches. For MLC leakage and calculation of scattering due to them one can use the phase space file.

Border profile dose discrepancies may seem more significant than the real effects. This impression in outer field dose is important and in most researches about inner field dose is not important. This effect is investigated in some researches.[23]

ACKNOWLEDGMENTS

In this study, we made use of the equipment of Isfahan Milad Hospital and we must be grateful for good cooperation of the staff.

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How to cite this article: Jabbari K, Anvar HS, Tavakoli MB, Amouheidari A. Monte Carlo simulation of siemens ONCOR linear accelerator with BEAMnrc and DOSXYZnrc code. J Med Sign Sens 2012;3:172-9.

Source of Support: This study is funded by Isfahan University of Medical Science, **Conflict of Interest:** None declared

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