Out-of-Field Dose Calculation by a Commercial Treatment Planning System and Comparison by Monte Carlo Simulation for Varian TrueBeam®

N. S. Shine, Raghukumar Paramu[1], M. Gopinath[2], R. C. Jaon Bos[2], P. M. Jayadevan[2]

Department of Physics, Banasthali University, Jaipur, Rajasthan, [1]Division of Radiation Physics, Regional Cancer Center, Thiruvananthapuram, [2]Department of Radiation Oncology, Aster Medcity, Kochi, Kerala, India

Abstract

Purpose: The calculation accuracy of treatment planning systems (TPSs) drops drastically when the points outside the field edges are considered. The real accuracy of a TPS and linear accelerator (linac) combination for regions outside the field edge is a subject which demands more study. In this study, the accuracy of out-of-field dose calculated by a TPS, used with a TrueBeam® (TB) linac, is quantified. **Materials and Methods:** For dose calculation, Eclipse™ version 13.7 commissioned for TB machine was used. For comparison, Monte Carlo (MC) methods, as well as the measurements, were used. The VirtuaLinac, a Geant 4-based MC program which is offered as a cloud solution, is used for the generation of input phase-space (PS) files. This PS file was imported into PRIMO (PENELOPE based MC program) for the simulation of out-of-field dose. **Results:** In this study, the accuracy of the out-of-field dose calculated by a TPS for a TB linac was estimated. As per the results in comparison with MC simulations, the TPS underestimated the dose by around 45% on an average for the off-axis-distance range considered in this study. As the off-axis distance increased, the underestimation of the dose also increased. **Conclusion:** In this work, it was observed that the TPS underestimates doses beyond the edges of treatment fields for a clinical treatment executed on a TB machine. This indicates that the out-of-field dose from TPSs should only be used with a clear understanding of the inaccuracy of dose calculations beyond the edge of the field.

Keywords: Geant 4, Monte Carlo methods, out-of-field dose, PRIMO, TrueBeam®, VirtuaLinac

Received on: 07-08-2018 **Review completed on:** 20-05-2019 **Accepted on:** 20-05-2019

Introduction

Treatment planning systems (TPSs) used in radiotherapy are not adequate for handling out-of-field dose calculations;[1,2] beyond the edges of the treatment fields, the accuracy of the TPS dose estimation is decreased drastically. Comparative effectiveness studies of radiation therapy techniques are used more frequently now[3-7] and because these studies involve comparison of dose–volume histograms generated by TPS for the target volume and organs at risk (OAR), including those organs outside the treatment field, it is becoming more critical for predicting the out-of-field dose accurately.

In a study, Weber *et al*.[8] compared intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) for clinical scenarios and found that the TPS may have underestimated (20%–50%) the dose to the OARs outside the field because of its inability to estimate the dose accurately. By considering the potential consequences of under- or over-estimation of dose, it would be essential to document the accuracy of out-of-field dose for commercially available TPSs. Such information would help clinicians and researchers to take decisions when TPS data need to be supplemented by phantom measurements or by other dependable calculation methods such as Monte Carlo (MC) simulation.

Access this article online	
Quick Response Code:	Website: www.jmp.org.in
	DOI: 10.4103/jmp.JMP_82_18

Address for correspondence: Mr. N. S. Shine, "Shangri-La," Alathara, Sreekariyam P.O., Thiruvananthapuram - 695 017, Kerala, India.
E-mail: shinenairns@gmail.com

How to cite this article: Shine NS, Paramu R, Gopinath M, Jaon Bos RC, Jayadevan PM. Out-of-field dose calculation by a commercial treatment planning system and comparison by monte carlo simulation for varian TrueBeam®. J Med Phys 2019;44:156-75.

This study aims to determine the accuracy of the out-of-field dose estimated by a commonly used commercial TPS, Eclipse™ version 13.7 (Varian Medical Systems, Palo Alto, CA, USA). More precisely, we compared the TPS-calculated dose with the MC-simulated dose as well as by measurements on water-equivalent phantoms on a Varian TrueBeam® (TB) machine (Varian Medical Systems, Palo Alto, CA, USA). The MC simulation part is performed in two steps: as the first step, a TB phase-space (PS) file is generated by enabling the "head shielding." Then, this PS file is used as an input source for generating out-of-field dose using a PENELOPE-based code called PRIMO version 0.3.1.1600 MC simulation program.

Materials and Methods

Parameters and calculation formulae used in this study

The out-of-field dose was estimated using different methods (TPS calculation/MC simulation/measurement) in different locations, in plane, and outside the field edge for different field sizes in the isocentric plane (5-cm depth and source-to-surface distance [SSD] = 95 cm). The distance of each out-of-field dose point was taken from the center of the field and was referred to as "off-axis distance." The dose comparison throughout this study was performed with respect to the dose to isocenter, at 5 cm depth (95 cm SSD), for a 10 cm × 10 cm field at the central axis for each energy. This location is called "reference point." The parameter, "relative dose (%)," used in Tables 1a-e and 2a-e represents the out-of-field dose value at an off-axis point with respect to the reference point. The formula used to calculate the relative dose is shown below:

$$\text{Relative dose }(\%)=\frac{(\text{Dose at off-axis distance point})}{(\text{Dose at reference point})}\times 100$$

Five sets of readings were taken for each off-axis distance point, and mean, minimum, median, maximum, variance, and standard deviation were calculated for relative dose, and these values are shown in Table 1a-e. The difference in out-of-field dose obtained by various methods (TPS calculation and MC simulation and measurement) is represented by "percentage dose difference (% diff)" in Table 2a-e.

The formula used to calculate % diff is shown below:

- TPS versus MC:

$$\%\text{ Diff}=\frac{(\text{Monte Carlo Dose}-\text{TPS dose})}{(\text{Monte Carlo dose})}\times 100$$

- TPS versus measurement:

$$\%\text{ Diff}=\frac{(\text{Measurement dose}-\text{TPS dose})}{(\text{Measurement dose})}\times 100$$

- MC versus measurement:

$$\%\text{ Diff}=\frac{(\text{Monte Carlo dose}-\text{Measurement dose})}{(\text{Monte Carlo dose})}\times 100$$

Varian's VirtualLinac

The MC simulation environment used for PS file generation is Varian's VirtuaLinac. It is a simulation of the TB head and water phantom hosted in Amazon cloud (Amazon Web Services Inc., Seattle, WA, USA). Dynamic delivery is achieved by Developer Mode XML files. The VirtuaLinac consists of a precise and modifiable model of the TB head. The resulting dose distributions may be recorded to tissue-equivalent phantoms (water tanks and computed tomography [CT] datasets). Another output option is PS files. PS files may be recorded for studying particle distributions or could be used as an input for another simulation code.

Physical parameters needed for the simulation are defined through a web interface. Both input and output files are stored in a single online directory (vl_files). Input files consist of PS files, phantom material files, and Developer Mode trajectory files. Output files include dose distribution files and output PS files depending on the user's output selection. PS and dose distribution files can be plotted online using the web interface. Python scripts used for plotting the output files are "plotdose.py" and "readphsp.py."

There are numerous benefits of using VirtuaLinac; (1) the geometry is already in place, and hence users can run the simulations on an already-established geometry and (2) because of multiple users, a strong validation of the entire simulation setup takes place. All the physical details of the treatment head are not available for users due to proprietary rights. Those details include a flattening filter model, position, and structure of the components and the target model. Meanwhile, parameters such as incident electron energy, spot size, energy spread, and angular divergence are available for users. Changes could be made to these physical parameters to match their specific machine parameters. "PhysicsList" used in this study was "QGSP_BIC_EMZ."

Amazon Web Services

The base infrastructure framework for orchestrating Varian's VirtuaLinac was made available in the Amazon Cloud (Amazon Web Services [AWS], Inc., Seattle, WA, USA]. AWS presented a subscription-based, on-demand, cloud computing model. As per this model, users have access to a full-fledged virtual cluster of computers at their disposal through the Internet. AWS's virtual computers possessed all the elements of a real computer including hardware (random access memory, hard disk/solid-state drive [SSD] storage, and central processing unit [CPU] for processing), operating systems, and networking. The hardware specifications used for this study were family – computer optimized; Type – C3.8x large; vCPUs – 32; memory – 60 GB; internal storage – 2 × 320 GB (SSD); network performance – 10 GB.

TrueBeam® phase-space generation using Varian's VirtuaLinac

An already-available modified Geant4 MC model including the head shielding of the Varian TB was used in this study.

Table 1a: Statistical analysis of treatment planning system calculated, Monte Carlo simulated, and measured out-of-field dose for field size 2 cm×2 cm for different energies

Off-axis distance (cm)	TPS calculation						MC simulation						Measurements					
Energy=6 MV, field size=2 cm×2 cm																		
Relative dose (%)	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.210	0.205	0.210	0.213	0.00001	0.0032	0.393	0.392	0.393	0.393	0.0000	0.0005	0.390	0.389	0.390	0.392	0.000001	0.001
7.5	0.081	0.080	0.081	0.081	0.00000	0.0003	0.269	0.268	0.269	0.269	0.0000	0.0003	0.266	0.264	0.266	0.267	0.000002	0.001
10	0.036	0.036	0.036	0.037	0.00000	0.0004	0.225	0.224	0.225	0.225	0.0000	0.0003	0.223	0.221	0.223	0.225	0.000004	0.002
12	0.021	0.021	0.021	0.022	0.00000	0.0004	0.204	0.200	0.204	0.205	0.0000	0.0018	0.203	0.202	0.203	0.205	0.000002	0.001
Energy=6 MV FFF, field size=2 cm×2 cm																		
Relative dose (%)	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.199	0.197	0.199	0.200	0.000001	0.0011	0.334	0.331	0.334	0.336	0.0000	0.002	0.327	0.322	0.328	0.330	0.00001	0.003
7.5	0.091	0.090	0.091	0.091	0.000000	0.0003	0.216	0.211	0.216	0.220	0.0000	0.003	0.209	0.207	0.209	0.210	0.00000	0.001
10	0.044	0.043	0.044	0.044	0.000000	0.0003	0.163	0.160	0.163	0.166	0.0000	0.002	0.159	0.157	0.159	0.160	0.00000	0.001
12	0.027	0.027	0.027	0.028	0.000000	0.0004	0.138	0.135	0.138	0.140	0.0000	0.002	0.136	0.132	0.136	0.140	0.00001	0.003
Energy=10 MV, field size=2 cm×2 cm																		
Relative dose (%)	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.138	0.137	0.138	0.140	0.0000	0.0011	0.405	0.401	0.405	0.409	0.0000	0.003	0.396	0.392	0.396	0.400	0.0000	0.003
7.5	0.054	0.053	0.054	0.054	0.0000	0.0004	0.279	0.277	0.279	0.280	0.0000	0.001	0.273	0.270	0.273	0.276	0.0000	0.002
10	0.024	0.023	0.024	0.024	0.0000	0.0004	0.239	0.235	0.239	0.241	0.0000	0.002	0.234	0.230	0.234	0.239	0.0000	0.004
12	0.014	0.014	0.014	0.014	0.0000	0.0001	0.223	0.220	0.223	0.225	0.0000	0.002	0.216	0.211	0.216	0.220	0.0000	0.004
Energy=15 MV, field size=2 cm×2 cm																		
Relative dose (%)	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.136	0.133	0.136	0.140	0.0000	0.0025	0.384	0.380	0.384	0.389	0.0000	0.003	0.376	0.370	0.376	0.381	0.0000	0.005
7.5	0.051	0.051	0.052	0.052	0.0000	0.0004	0.270	0.268	0.270	0.276	0.0000	0.003	0.264	0.260	0.264	0.269	0.0000	0.003
10	0.023	0.023	0.024	0.024	0.0000	0.0006	0.254	0.250	0.255	0.256	0.0000	0.002	0.251	0.250	0.251	0.253	0.0000	0.001
12	0.013	0.013	0.013	0.013	0.0000	0.0002	0.224	0.222	0.224	0.226	0.0000	0.001	0.222	0.220	0.222	0.225	0.0000	0.002

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, FFF: Flattening filter free

Table 1b: Statistical analysis of treatment planning system calculated, Monte Carlo simulated, and measured out-of-field dose for field size 4 cm×4 cm for different energies

Energy=6 MV, field size=4 cm×4 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	1.155	1.128	1.155	1.175	0.000	0.018	1.400	1.365	1.400	1.435	0.0011	0.033	1.389	1.366	1.389	1.409	0.0004	0.019
7.5	0.495	0.489	0.495	0.499	0.000	0.005	0.696	0.687	0.696	0.702	0.0000	0.006	0.691	0.671	0.691	0.710	0.0003	0.017
10	0.219	0.215	0.219	0.222	0.000	0.003	0.477	0.468	0.477	0.488	0.0001	0.008	0.472	0.465	0.472	0.477	0.0000	0.005
12	0.116	0.115	0.116	0.118	0.000	0.001	0.398	0.390	0.398	0.404	0.0000	0.006	0.386	0.380	0.386	0.394	0.0000	0.006
14	0.067	0.066	0.067	0.068	0.000	0.001	0.348	0.346	0.348	0.350	0.0000	0.002	0.343	0.345	0.349	0.000	0.0021	0.020

Energy=6 MV FFF, field size=4 cm×4 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.879	0.865	0.879	0.892	0.0001	0.012	1.127	1.091	1.127	1.163	0.0008	0.027	1.104	1.091	1.105	1.116	0.0001	0.009
7.5	0.382	0.375	0.381	0.391	0.0000	0.006	0.557	0.553	0.557	0.561	0.0000	0.003	0.541	0.535	0.541	0.546	0.0000	0.004
10	0.193	0.189	0.193	0.198	0.0000	0.003	0.372	0.369	0.372	0.375	0.0000	0.003	0.365	0.352	0.365	0.376	0.0001	0.009
12	0.118	0.117	0.118	0.120	0.0000	0.001	0.299	0.288	0.299	0.310	0.0001	0.009	0.293	0.285	0.295	0.298	0.0000	0.005
14	0.077	0.076	0.077	0.079	0.0000	0.001	0.244	0.240	0.244	0.250	0.0000	0.004	0.238	0.232	0.238	0.244	0.0000	0.005

Energy=10 MV, field size=4 cm×4 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.809	0.794	0.809	0.821	0.0001	0.012	1.415	1.388	1.415	1.435	0.0004	0.019	1.372	1.364	1.372	1.382	0.0000	0.007
7.5	0.334	0.323	0.334	0.343	0.0001	0.009	0.727	0.724	0.726	0.733	0.0000	0.004	0.715	0.703	0.717	0.724	0.0001	0.008
10	0.142	0.140	0.142	0.143	0.0000	0.002	0.493	0.491	0.493	0.496	0.0000	0.002	0.482	0.475	0.482	0.490	0.0000	0.006
12	0.073	0.072	0.073	0.075	0.0000	0.001	0.419	0.409	0.422	0.424	0.0000	0.006	0.410	0.401	0.410	0.421	0.0001	0.008
14	0.043	0.042	0.044	0.044	0.0000	0.001	0.370	0.363	0.370	0.379	0.0000	0.006	0.362	0.357	0.362	0.367	0.0000	0.004

Energy=15 MV, field size=4 cm×4 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
5	0.815	0.808	0.815	0.826	0.0000	0.007	1.338	1.324	1.340	1.346	0.0001	0.009	1.296	1.284	1.296	1.308	0.0001	0.011
7.5	0.332	0.330	0.331	0.335	0.0000	0.002	0.692	0.676	0.692	0.705	0.0002	0.013	0.677	0.654	0.677	0.698	0.0003	0.017
10	0.145	0.143	0.145	0.146	0.0000	0.001	0.467	0.463	0.467	0.470	0.0000	0.003	0.462	0.456	0.462	0.470	0.0000	0.005
12	0.075	0.074	0.075	0.077	0.0000	0.001	0.407	0.403	0.407	0.414	0.0000	0.005	0.398	0.390	0.398	0.403	0.0000	0.005
14	0.042	0.042	0.043	0.043	0.0000	0.000	0.367	0.363	0.367	0.370	0.0000	0.003	0.363	0.356	0.363	0.370	0.0000	0.005

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, FFF: Flattening filter free

Table 1c: Statistical analysis of treatment planning system-calculated, Monte Carlo-simulated, and measured out-of-field dose for field size of 10 cm×10 cm for different energies

Energy=6 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
7.5	3.749	3.705	3.749	3.797	0.002	0.042	4.437	4.391	4.437	4.480	0.0016	0.040	4.350	4.307	4.350	4.396	0.0016	0.039
10	1.950	1.905	1.950	1.995	0.001	0.037	2.323	2.285	2.323	2.362	0.0012	0.034	2.236	2.205	2.228	2.291	0.0011	0.032
12	1.251	1.231	1.251	1.275	0.000	0.019	1.499	1.497	1.499	1.501	0.0000	0.002	1.477	1.455	1.477	1.498	0.0004	0.021
14	0.900	0.891	0.900	0.910	0.000	0.010	1.092	1.076	1.092	1.104	0.0001	0.011	1.081	1.055	1.081	1.102	0.0004	0.021
16	0.595	0.586	0.595	0.606	0.000	0.008	0.842	0.817	0.844	0.855	0.0002	0.015	0.830	0.813	0.830	0.845	0.0002	0.014

Energy=6 MV FFF, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
7.5	2.816	2.802	2.816	2.832	0.0002	0.013	3.257	3.226	3.266	3.271	0.0003	0.018	3.155	3.145	3.154	3.164	0.000	0.007
10	1.393	1.379	1.393	1.404	0.0001	0.010	1.648	1.625	1.648	1.665	0.0002	0.015	1.627	1.613	1.631	1.634	0.000	0.009
12	0.849	0.825	0.855	0.860	0.0002	0.014	1.125	1.121	1.124	1.133	0.0000	0.004	1.101	1.097	1.102	1.104	0.000	0.003
14	0.543	0.524	0.543	0.560	0.0002	0.016	0.830	0.809	0.833	0.843	0.0002	0.013	0.812	0.801	0.812	0.820	0.000	0.007
16	0.360	0.337	0.360	0.376	0.0002	0.014	0.641	0.624	0.641	0.654	0.0001	0.012	0.628	0.624	0.628	0.633	0.000	0.004

Energy=10 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
7.5	3.312	3.301	3.312	3.321	0.0001	0.007	4.312	4.301	4.312	4.323	0.0001	0.010	4.263	4.243	4.263	4.286	0.0004	0.019
10	1.700	1.650	1.700	1.741	0.0015	0.039	2.221	2.202	2.221	2.234	0.0002	0.013	2.190	2.159	2.190	2.219	0.0005	0.023
12	0.980	0.966	0.980	0.998	0.0002	0.013	1.441	1.435	1.437	1.454	0.0001	0.008	1.422	1.409	1.422	1.435	0.0001	0.012
14	0.536	0.521	0.536	0.545	0.0001	0.009	1.027	1.005	1.027	1.043	0.0002	0.014	0.995	0.988	0.995	1.001	0.0000	0.005
16	0.298	0.280	0.301	0.308	0.0001	0.011	0.796	0.780	0.796	0.816	0.0002	0.013	0.777	0.760	0.777	0.791	0.0002	0.013

Energy=15 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
7.5	3.449	3.405	3.449	3.495	0.0015	0.039	3.962	3.943	3.956	4.000	0.0005	0.023	3.910	3.859	3.910	3.953	0.0018	0.042
10	1.789	1.759	1.789	1.818	0.0006	0.024	2.043	2.010	2.043	2.075	0.0009	0.031	2.001	1.958	2.001	2.046	0.0018	0.042
12	1.099	1.076	1.099	1.120	0.0004	0.020	1.324	1.298	1.324	1.359	0.0006	0.025	1.305	1.283	1.305	1.335	0.0004	0.020
14	0.636	0.621	0.636	0.654	0.0002	0.014	0.959	0.944	0.959	0.973	0.0002	0.013	0.935	0.913	0.935	0.956	0.0004	0.020
16	0.367	0.362	0.367	0.373	0.0000	0.005	0.760	0.745	0.760	0.769	0.0001	0.009	0.756	0.736	0.756	0.776	0.0002	0.016

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, FFF: Flattening filter free

Table 1d: Statistical analysis of treatment planning system-calculated, Monte Carlo-simulated, and measured out-of-field dose for field size of 15 cm×15 cm for different energies

Energy=6 MV, field size=15 cm×15 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
10	5.821	5.727	5.821	5.882	0.004	0.061	6.584	6.487	6.584	6.696	0.0088	0.094	6.455	6.281	6.455	6.646	0.0217	0.147
12	3.688	3.633	3.688	3.747	0.003	0.052	4.299	4.240	4.299	4.363	0.0029	0.054	4.206	4.122	4.206	4.293	0.0048	0.069
14	2.276	2.238	2.276	2.313	0.001	0.031	2.828	2.768	2.828	2.875	0.0022	0.047	2.766	2.740	2.766	2.797	0.0007	0.026
16	1.285	1.251	1.285	1.323	0.001	0.033	1.801	1.759	1.801	1.850	0.0015	0.038	1.788	1.749	1.788	1.828	0.0013	0.036
18	0.911	0.889	0.911	0.931	0.000	0.018	1.385	1.353	1.385	1.416	0.0009	0.030	1.373	1.347	1.373	1.398	0.0004	0.021
20	0.657	0.646	0.657	0.668	0.000	0.010	1.108	1.088	1.108	1.126	0.0003	0.018	1.091	1.069	1.095	1.101	0.0002	0.013
Energy=6 MV FFF, field size=15 cm×15 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
10	3.562	3.504	3.562	3.615	0.0023	0.047	4.140	4.081	4.140	4.212	0.0031	0.056	4.042	3.901	4.042	4.145	0.00960	0.098
12	2.128	2.091	2.128	2.163	0.0009	0.031	2.512	2.485	2.512	2.537	0.0003	0.019	2.475	2.414	2.475	2.529	0.00232	0.048
14	1.348	1.328	1.348	1.379	0.0004	0.020	1.735	1.710	1.735	1.755	0.0003	0.017	1.700	1.670	1.700	1.720	0.00043	0.021
16	0.899	0.880	0.896	0.932	0.0004	0.020	1.287	1.239	1.287	1.331	0.0016	0.040	1.257	1.226	1.257	1.296	0.00069	0.026
18	0.608	0.586	0.608	0.631	0.0003	0.018	0.993	0.959	0.993	1.012	0.0005	0.021	0.984	0.948	0.984	1.020	0.00097	0.031
Energy=10 MV, field size=15 cm×15 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
10	4.601	4.526	4.601	4.666	0.0038	0.061	5.708	5.588	5.708	5.791	0.0073	0.085	5.612	5.474	5.612	5.766	0.0172	0.131
12	2.833	2.788	2.833	2.883	0.0019	0.044	3.530	3.475	3.530	3.583	0.0023	0.048	3.435	3.364	3.435	3.496	0.0031	0.056
14	1.723	1.686	1.723	1.762	0.0012	0.034	2.331	2.287	2.331	2.373	0.0013	0.037	2.301	2.253	2.301	2.350	0.0018	0.043
16	1.027	1.012	1.027	1.051	0.0002	0.016	1.660	1.626	1.660	1.694	0.0009	0.030	1.641	1.604	1.641	1.679	0.0010	0.032
18	0.597	0.590	0.597	0.606	0.0000	0.007	1.271	1.257	1.271	1.287	0.0002	0.014	1.246	1.225	1.246	1.275	0.0004	0.021
20	0.275	0.273	0.274	0.279	0.0000	0.002	1.022	1.009	1.022	1.043	0.0002	0.014	1.004	1.000	1.001	1.013	0.0000	0.006
Energy=15 MV, field size=15 cm×15 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
10	4.762	4.627	4.762	4.858	0.0074	0.086	5.167	5.081	5.167	5.252	0.0054	0.074	5.006	4.850	5.006	5.152	0.0132	0.115
12	2.959	2.895	2.959	3.020	0.0026	0.051	3.193	3.109	3.193	3.291	0.0063	0.080	3.126	3.071	3.126	3.205	0.0030	0.054

Contd...

Table 1d: Contd...

Off-axis distance (cm)	Energy=15 MV, field size=15 cm×15 cm																	
	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
14	1.891	1.858	1.891	1.929	0.0011	0.033	2.113	2.066	2.113	2.151	0.0012	0.035	2.068	2.007	2.068	2.121	0.0027	0.052
16	1.204	1.166	1.204	1.241	0.0012	0.035	1.511	1.465	1.511	1.555	0.0017	0.041	1.463	1.426	1.463	1.500	0.0010	0.032
18	0.693	0.676	0.693	0.714	0.0003	0.017	1.180	1.153	1.180	1.202	0.0004	0.020	1.142	1.124	1.142	1.164	0.0003	0.018
20	0.368	0.363	0.368	0.374	0.0000	0.005	0.960	0.933	0.960	0.990	0.0006	0.024	0.930	0.899	0.930	0.956	0.0006	0.025

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, FFF: Flattening filter free

There is a checkbox option in the VirtuaLinac to enable the head shielding called "simulate head shielding." For head leakage simulation, this option was enabled for more accuracy. If checked, the TB head shielding away from the treatment beam was enabled. This includes the shielding for backscatter from the target, shielding around the jaws, and the covers. Shielding adjacent to the treatment beam (e.g., primary collimator and shielding between jaws) was always enabled. Enabling "simulate head shielding" will make the simulation time longer. The PS files were generated for the field sizes 2 cm × 2 cm, 4 cm × 4 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm (five field sizes) for 6 MV, 6 MV flattening filter free (FFF), 10 MV, and 15 MV beams (four energies). The machine model parameters used to generate the PS files for 6 MV were as follows: the mean energy of the incident electron beam, energy (E) = 6.18 MeV; Gaussian energy spread, dE = 0.053 MeV; Gaussian spacial spread in the "X" direction (FWHM), Spot X (σ_x) = 0.6866 mm; Gaussian special spread in "Y" direction (FWHM), Spot X (σ_y) =0.7615 mm; source beam divergences, Beam div (σ_{px} and σ_{py}) =0.0573°. Table 3 lists these parameters used for other energies also.

The number of particles contained in each PS file was approximately 5 × 10^9. The PS files were tallied on a sphere of radius 70 cm from the target, which was 100 cm upstream of the isocenter.

Multileaf collimator bank was placed in a fully retracted state.

Out-of-field dose simulation using PRIMO

The PS files generated by Varian's VirtuaLinac was used as an input source for out-of-field dose simulation. MC program used here is called PRIMO,[9] a PENELOPE-based code.

The PRIMO program was installed in a Windows server class machine deployed in Amazon Cloud (AWS, Inc., Seattle, WA). The server's hardware specifications used for this study were as follows: family – computer optimized; type – C5d. 18x large; vCPUs – 72; memory – 144 GB; internal storage – 2 × 90 GB (SSD); network performance – 25 GB.

The main program used to drive the PENELOPE code was "PENEASY."[9] The input files for the PENELOPE/PENEASY system to function were created during run time by PENEASYLINAC.[9,10] Depending on the choice of the linac model and the mode (photon/electron) and energy used, PENEASYLINAC created a configuration file, geometry file, and a set of materials' file. The configuration file defines the primary beam parameters and the tallied characteristics to be used. A wide variety of dedicated variance-reduction techniques developed for the simulation of the linac were applied.[9,10] The PRIMO program consists of PENELOPE/PENEASY/PENEASYLINAC system along with an easy-to-use graphical user interface which makes the program self-explanatory and straightforward for the users to perform the simulation and analysis of the results. The PS files handled (imported and exported) by the PRIMO were coded as per the International Atomic Energy Agency format.[11] Even

Table 1e: Statistical analysis of treatment planning system-calculated, Monte Carlo-simulated, and measured out-of-field dose for field size of 20 cm×20 cm for different energies

Energy=6 MV, field size=20 cm×20 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
12	8.284	8.093	8.284	8.503	0.033	0.182	8.853	8.731	8.853	8.982	0.0139	0.118	8.711	8.562	8.711	8.884	0.0177	0.133
14	5.359	5.232	5.359	5.475	0.011	0.107	5.908	5.798	5.908	5.991	0.0066	0.082	5.752	5.656	5.752	5.845	0.0073	0.085
16	3.688	3.602	3.688	3.770	0.005	0.074	4.127	4.061	4.127	4.202	0.0034	0.058	3.991	3.900	3.991	4.135	0.0092	0.096
18	2.671	2.631	2.671	2.717	0.001	0.037	2.757	2.709	2.757	2.796	0.0012	0.035	2.726	2.653	2.726	2.793	0.0040	0.063
20	1.771	1.725	1.771	1.818	0.001	0.038	2.012	1.950	2.022	2.047	0.0013	0.037	1.982	1.948	1.982	2.010	0.0006	0.025
22	1.116	1.091	1.116	1.138	0.000	0.020	1.431	1.404	1.431	1.454	0.0004	0.019	1.410	1.383	1.410	1.435	0.0004	0.021
Energy=6 MV FFF, field size=20 cm×20 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
12	4.507	4.393	4.507	4.625	0.0128	0.113	5.425	5.364	5.425	5.496	0.0028	0.053	5.309	5.243	5.309	5.388	0.00390	0.062
14	2.735	2.660	2.747	2.774	0.0019	0.044	3.357	3.306	3.357	3.412	0.0022	0.047	3.285	3.249	3.285	3.320	0.00101	0.032
16	1.793	1.749	1.793	1.828	0.0010	0.032	2.336	2.303	2.336	2.374	0.0011	0.033	2.261	2.236	2.261	2.296	0.00066	0.026
18	1.201	1.172	1.201	1.226	0.0006	0.024	1.732	1.697	1.732	1.763	0.0010	0.031	1.710	1.687	1.710	1.741	0.00041	0.020
20	0.827	0.808	0.827	0.847	0.0002	0.016	1.327	1.295	1.327	1.363	0.0007	0.027	1.285	1.259	1.285	1.313	0.00055	0.023
22	0.695	0.677	0.697	0.703	0.0001	0.010	1.120	1.096	1.120	1.152	0.0005	0.023	1.073	1.060	1.073	1.084	0.00010	0.010
24	0.588	0.576	0.588	0.599	0.0001	0.011	0.973	0.957	0.973	0.987	0.0001	0.012	0.949	0.935	0.949	0.962	0.00016	0.012
Energy=10 MV, field size=20 cm×20 cm																		
Off-axis distance (cm)	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
12	6.400	6.310	6.400	6.506	0.0068	0.082	7.881	7.788	7.881	7.988	0.0087	0.093	7.791	7.708	7.791	7.877	0.0055	0.074
14	4.026	3.963	4.026	4.078	0.0021	0.046	5.098	5.020	5.098	5.210	0.0061	0.078	4.992	4.949	4.992	5.052	0.0018	0.043
16	2.666	2.636	2.666	2.697	0.0007	0.026	3.458	3.425	3.458	3.496	0.0011	0.033	3.398	3.334	3.398	3.454	0.0021	0.045
18	1.630	1.596	1.630	1.663	0.0008	0.028	2.461	2.436	2.461	2.486	0.0004	0.021	2.395	2.334	2.395	2.454	0.0020	0.044
20	0.967	0.955	0.967	0.987	0.0002	0.013	1.831	1.807	1.831	1.853	0.0003	0.018	1.793	1.758	1.793	1.828	0.0010	0.031
22	0.752	0.736	0.752	0.768	0.0002	0.014	1.481	1.454	1.481	1.515	0.0007	0.027	1.440	1.414	1.440	1.468	0.0005	0.022
24	0.589	0.582	0.589	0.596	0.0000	0.005	1.262	1.246	1.260	1.286	0.0002	0.015	1.251	1.235	1.251	1.267	0.0002	0.014

Contd...

Table 1e: Contd...

Off-axis distance (cm)	Energy=15 MV, field size=20 cm×20 cm																	
	Relative dose (%)																	
	TPS calculation						MC simulation						Measurements					
	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD	Mean	Minimum	Median	Maximum	Variance	SD
12	6.677	6.557	6.677	6.757	0.0067	0.082	7.129	7.021	7.129	7.202	0.0059	0.077	7.018	6.900	7.018	7.152	0.0122	0.111
14	4.076	4.004	4.076	4.156	0.0039	0.062	4.589	4.519	4.589	4.676	0.0042	0.065	4.412	4.354	4.412	4.456	0.0020	0.044
16	2.850	2.825	2.850	2.876	0.0004	0.020	3.112	3.091	3.112	3.130	0.0002	0.015	3.080	3.036	3.080	3.121	0.0011	0.033
18	1.782	1.758	1.782	1.808	0.0004	0.021	2.227	2.172	2.227	2.278	0.0019	0.044	2.175	2.127	2.187	2.197	0.0008	0.028
20	1.085	1.073	1.085	1.097	0.0001	0.012	1.664	1.636	1.664	1.688	0.0005	0.023	1.621	1.602	1.621	1.642	0.0002	0.016
22	0.840	0.824	0.840	0.854	0.0001	0.011	1.339	1.314	1.339	1.364	0.0004	0.020	1.291	1.279	1.291	1.302	0.0001	0.011
24	0.644	0.635	0.644	0.654	0.0001	0.007	1.149	1.120	1.149	1.175	0.0005	0.022	1.125	1.108	1.125	1.138	0.0001	0.011

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, FFF: Flattening filter free

though PRIMO is a comparatively new program, the MC code, the variance-reduction techniques applied, and the geometry files used in it have a long history and have been tested extensively and benchmarked by numerous researchers.[12-14]

Simulations of 6 MV, 6 MV FFF, 10 MV, and 15 MV were performed for the above-mentioned five field sizes with (2 mm × 2 mm × 2 mm) voxels. As a next step, these particles were transported downstream to the water phantom, and the absorbed dose was estimated. The depth considered in this study was 5 cm, and the SSD was 95 cm.

Simulations were performed in two segments: in the first segment, particles were transported from the PS files downstream to a plane located on the surface of the water phantom. In this section, by default, the variance-reduction technique of movable skins[10] was applied for the simulation of the patient-dependent geometry (i.e., the movable jaws). In the second segment, the particles were transported downstream into the water phantom. Particle splitting was applied here. The splitting factor was decided depending on the field size. For a small field size, a larger splitting factor was applied. In this study, the splitting factor selected was large enough to ensure that the statistical variance was close to the latent variance[15] of PS files.

As per PRIMO user manual[16] recommendation, the machine selected in PRIMO program for TrueBeam® simulation was Varian Clinac 2100. The phantom used for the simulation was created as a slab phantom in PRIMO program. The geometry of the phantom is shown in Figure 1.

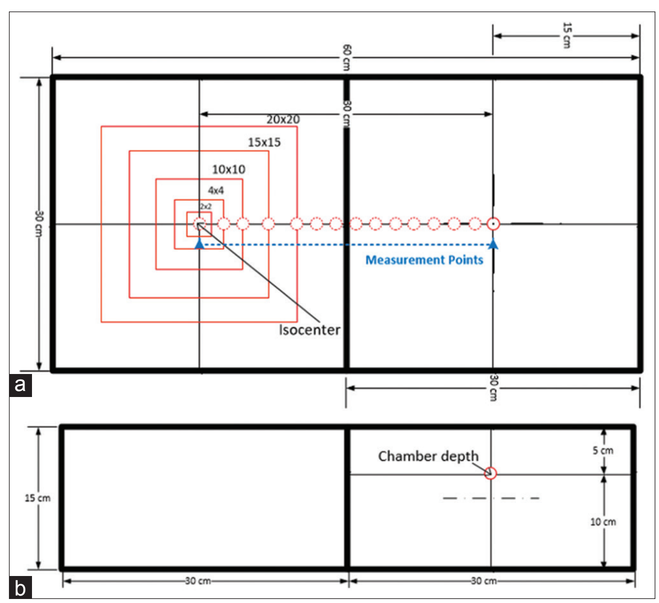

Figure 1: The geometry of the phantom: Coronal (a) and sagittal (b) views. Two 30 cm × 30 cm phantom sets are stacked together. Source-to-surface distance was 95 cm, and the chamber was placed at a depth of 5 cm. 10-cm phantom was kept below the measurement point for providing sufficient backscatter. 10 cm × 10 cm was taken as a reference field. A monitor unit of 100 MU was given as a reference MU

Table 2a: Percentage dose difference (%): Comparison between out-of-field dose for treatment planning system-calculated, Monte Carlo-simulated, and measured values for all the four energies and the field size of 2 cm×2 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
Energy=6 MV, field size=2 cm×2 cm												
5	0.210	0.003	0.393	0.000	0.390	0.001	46.52	0.75	46.13	0.79	0.73	0.26
7.5	0.081	0.000	0.269	0.000	0.266	0.001	69.96	0.10	69.69	0.24	0.89	0.49
10	0.036	0.000	0.225	0.000	0.223	0.002	83.78	0.18	83.64	0.17	0.83	0.95
12	0.021	0.000	0.204	0.002	0.203	0.001	89.56	0.16	89.49	0.23	0.67	0.74
Energy=6 MV FFF, field size=2 cm×2 cm												
5	0.199	0.001	0.334	0.002	0.327	0.003	40.27	0.18	38.96	0.40	2.15	0.53
7.5	0.091	0.000	0.216	0.003	0.209	0.001	57.88	0.61	56.52	0.28	3.12	1.75
10	0.044	0.000	0.163	0.002	0.159	0.001	73.09	0.29	72.50	0.16	2.15	0.71
12	0.027	0.000	0.138	0.002	0.136	0.003	80.32	0.23	80.00	0.39	1.58	2.75
Energy=10 MV, field size=2 cm×2 cm												
5	0.138	0.001	0.405	0.003	0.396	0.003	65.81	0.07	65.06	0.52	2.15	1.39
7.5	0.054	0.000	0.279	0.001	0.273	0.002	80.75	0.15	80.30	0.16	2.32	1.15
10	0.024	0.000	0.239	0.002	0.234	0.004	90.07	0.22	89.84	0.16	2.21	1.53
12	0.014	0.000	0.223	0.002	0.216	0.004	93.74	0.07	93.53	0.10	3.21	1.69
Energy=15 MV, field size=2 cm×2 cm												
5	0.136	0.003	0.384	0.003	0.376	0.005	64.69	0.34	63.92	1.13	2.12	2.11
7.5	0.051	0.000	0.270	0.003	0.264	0.003	81.06	0.25	80.65	0.23	2.12	0.63
10	0.023	0.001	0.254	0.002	0.251	0.001	90.77	0.26	90.68	0.21	0.98	0.78
12	0.013	0.000	0.224	0.001	0.222	0.002	94.11	0.05	94.06	0.07	0.87	0.87

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, % Diff: Percentage dose difference, FFF: Flattening filter free

The slab phantom definition dialog allows establishing the dimensions, the voxel size of the phantom, and the selection of phantom material. In this study, Lucite (poly methyl methacrylate [PMMA]), with a density of 1.19 g/cm^3, was used as the phantom material.

Figure 2 shows the three primary workspaces of the PRIMO program, namely, "simulation setup," "plan and dose," and "dose evaluation." It also shows the windows for "simulation configuration" as well as "field edit" window.

Out-of-field dose calculation – Eclipse™ treatment planning system

Eclipse™ TPS version 13.7 (Varian Medical Systems, Inc., Palo Alto, CA, USA) was used to calculate the out-of-field dose for the above-mentioned five field sizes for energies 6 MV, 6 MV FFF, 10 MV, and 15 MV for a depth of 5 cm in plastic phantom, with a backscatter thickness of 10 cm. The phantom geometry is illustrated in Figure 1. The algorithm used for calculation was analytic anisotropic algorithm (AAA) 13.7 with a grid size of 2.5 mm and International Electrotechnical Commission (IEC) 61217.

The above-defined phantom was scanned with Trueflight positron emission tomography-CT scanner by Phillips (Philips Healthcare, Best, The Netherlands). The CT study sets were imported into Eclipse™. The origin was fixed on the reference point of the ion chamber, whereas fields were placed at 30 cm away longitudinally out from this origin (i.e., ion chamber was placed at the farthest point of measurement from the isocenter). Dose calculation was performed giving 100 MU for each field and energy using AAA 13.7 algorithm with a

Table 2b: Percentage dose difference (%): Comparison between out-of-field dose for treatment planning system-calculated, Monte Carlo–simulated, and measured values for all the four energies and the field size of 4 cm×4 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
Energy=6 MV, field size=4 cm×4 cm												
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
5	1.155	0.018	1.400	0.033	1.389	0.019	17.49	3.13	16.88	1.88	0.73	2.77
7.5	0.495	0.005	0.696	0.006	0.691	0.017	28.88	0.67	28.32	2.00	0.78	2.89
10	0.219	0.003	0.477	0.008	0.472	0.005	54.17	0.26	53.66	0.72	1.10	1.91
12	0.116	0.001	0.398	0.006	0.386	0.006	70.93	0.33	70.00	0.48	3.10	1.91
14	0.067	0.001	0.348	0.002	0.343	0.020	80.80	0.15	80.61	0.26	0.98	0.72
Energy=6 MV FFF, field size=4 cm×4 cm												
Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
5	0.879	0.012	1.127	0.027	1.104	0.009	21.94	2.21	20.36	1.65	1.99	2.74
7.5	0.382	0.006	0.557	0.003	0.541	0.004	31.45	1.39	29.34	0.88	2.99	1.18
10	0.193	0.003	0.372	0.003	0.365	0.009	48.19	0.85	47.14	1.48	1.99	3.05
12	0.118	0.001	0.299	0.009	0.293	0.005	60.44	1.60	59.56	0.57	2.16	4.37
14	0.077	0.001	0.244	0.004	0.238	0.005	68.37	0.77	67.50	0.92	2.65	1.11
Energy=10 MV, field size=4 cm×4 cm												
Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
5	0.809	0.012	1.415	0.019	1.372	0.007	42.84	1.57	41.06	1.01	3.02	1.04
7.5	0.334	0.009	0.727	0.004	0.715	0.008	54.12	1.35	53.38	0.87	1.58	1.54
10	0.142	0.002	0.493	0.002	0.482	0.006	71.13	0.36	70.44	0.45	2.35	0.95
12	0.073	0.001	0.419	0.006	0.410	0.008	82.46	0.27	82.08	0.50	2.12	1.94
14	0.043	0.001	0.370	0.006	0.362	0.004	88.36	0.20	88.10	0.31	2.15	2.46
Energy=15 MV, field size=4 cm×4 cm												
Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
5	0.815	0.007	1.338	0.009	1.296	0.011	39.09	0.51	37.12	0.94	3.12	0.76
7.5	0.332	0.002	0.692	0.013	0.677	0.017	52.05	0.75	51.00	1.29	2.15	3.08
10	0.145	0.001	0.467	0.003	0.462	0.005	69.06	0.23	68.71	0.23	1.14	0.67
12	0.075	0.001	0.407	0.005	0.398	0.005	81.56	0.34	81.16	0.08	2.12	1.44
14	0.042	0.000	0.367	0.003	0.363	0.005	88.54	0.11	88.42	0.17	0.99	1.89

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, % Diff: Percentage dose difference, FFF: Flattening filter free

grid size of 2.5 mm following the conventions of IEC 61217. Once calculated, dose profiles at 5 cm depth in the longitudinal direction from the isocenter were taken with the profile tool available in Eclipse™. The profiles were then exported in CSV format for analysis. Figure 3 illustrates Eclipse™-calculated dose distribution in all the three planes (transverse, sagittal, and coronal) and the three-dimensional view on the phantom.

Out-of-field dose measurements

Out-of-field dose measurements were performed to compare it with the MC-simulated values. Farmer type FC65-G chamber with IBM Dose 1 Electrometer was used for the measurements. Reference reading was taken using a SSD 95 cm for a 10 cm × 10 cm field size by delivering 100 MU.

The plastic phantom made of PMMA, at a density of 1.19 g/cm^3, used for measurement had the dimensions of 30 W × 60 L × 15 H cm^3, with an adaptor plate for FC65-G ionization chamber kept at 5-cm depth. The ion chamber was placed perpendicular to the length of phantom, whereas the length of the phantom was placed along the longitudinal direction of movement on the machine [Figure 4]. This

Table 2c: Percentage dose difference (%): Comparison between out-of-field dose for treatment planning system-calculated, Monte Carlo-simulated, and measured values for all the four energies and the field size of 10 cm×10 cm

Energy=6 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
7.5	3.749	0.042	4.437	0.040	4.350	0.039	15.49	0.20	13.81	0.29	1.95	0.22
10	1.950	0.037	2.323	0.034	2.236	0.032	16.03	0.54	12.79	0.90	3.72	1.16
12	1.251	0.019	1.499	0.002	1.477	0.021	16.54	1.34	15.33	2.47	1.43	1.29
14	0.900	0.010	1.092	0.011	1.081	0.021	17.58	1.67	16.76	0.76	0.99	2.87
16	0.595	0.008	0.842	0.015	0.830	0.014	29.31	2.27	28.30	2.14	1.40	1.42

Energy=6 MV FFF, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
7.5	2.816	0.013	3.257	0.018	3.155	0.007	13.54	0.75	10.75	0.34	3.12	0.72
10	1.393	0.010	1.648	0.015	1.627	0.009	15.49	1.30	14.41	0.99	1.25	0.93
12	0.849	0.014	1.125	0.004	1.101	0.003	24.58	1.17	22.93	1.11	2.15	0.39
14	0.543	0.016	0.830	0.013	0.812	0.007	34.52	2.63	33.10	2.00	2.12	2.15
16	0.360	0.014	0.641	0.012	0.628	0.004	43.84	3.19	42.70	2.51	1.99	1.66

Energy=10 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
7.5	3.312	0.007	4.312	0.010	4.263	0.019	23.18	0.15	22.31	0.28	1.12	0.21
10	1.700	0.039	2.221	0.013	2.190	0.023	23.47	1.39	22.41	1.02	1.37	0.70
12	0.980	0.013	1.441	0.008	1.422	0.012	32.03	0.67	31.09	1.19	1.36	1.22
14	0.536	0.009	1.027	0.014	0.995	0.005	47.77	1.28	46.09	0.76	3.13	1.53
16	0.298	0.011	0.796	0.013	0.777	0.013	62.51	1.88	61.60	1.22	2.37	3.05

Energy=15 MV, field size=10 cm×10 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
7.5	3.449	0.039	3.962	0.023	3.910	0.042	12.96	0.81	11.80	0.14	1.32	0.95
10	1.789	0.024	2.043	0.031	2.001	0.042	12.41	0.41	10.58	0.78	2.05	0.60
12	1.099	0.020	1.324	0.025	1.305	0.020	16.97	3.00	15.77	2.68	1.42	0.48
14	0.636	0.014	0.959	0.013	0.935	0.020	33.73	1.66	32.03	0.38	2.51	2.69
16	0.367	0.005	0.760	0.009	0.756	0.016	51.68	0.34	51.44	1.69	0.51	3.20

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, % Diff: Percentage dose difference, FFF: Flattening filter free

geometry was preferred to minimize the length of ion chamber's cable exposed when the phantom was moved longitudinally during measurement. Cable exposed to radiation can induce extra-cameral effects, affecting the charge collected by the ion chamber.[17,18]

While setting up the phantom on the machine, first, the phantom was assembled in the same manner as scanned and then positioned with the adaptor plate lines grooved on it. The farthest measurement point was at 30 cm longitudinally toward the gantry from the isocenter [Figure 1a]. In the TPS simulation of the measurement setup, the isocenter, as well as the field borders, was fixed with respect to the phantom. However, during measurements, the phantom was moved longitudinally outward (away from the gantry) to reduce the distance between the field edge and ion chamber, making measurements at decreasing distance from the isocenter at an interval of 2 cm. Here, it was assumed that the change in the geometry when the phantom was moved longitudinally results in negligible scatter contribution and hence minimal effect on the out-of-field dose.

Table 2d: Percentage dose difference (%): Comparison between out-of-field dose for treatment planning system-calculated, Monte Carlo-simulated, and measured values for all the four energies and the field size of 15 cm×15 cm

Energy=6 MV, field size=15 cm×15 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
10	5.821	0.061	6.584	0.094	6.455	0.147	11.59	2.08	9.83	2.96	1.95	1.10
12	3.688	0.052	4.299	0.054	4.206	0.069	14.21	0.21	12.31	2.67	2.17	2.79
14	2.276	0.031	2.828	0.047	2.766	0.026	19.54	0.60	17.74	0.49	2.18	0.76
16	1.285	0.033	1.801	0.038	1.788	0.036	28.68	3.29	28.15	0.54	0.74	4.05
18	0.911	0.018	1.385	0.030	1.373	0.021	34.22	2.70	33.64	1.62	0.88	2.88
20	0.657	0.010	1.108	0.018	1.091	0.013	40.71	1.30	39.76	0.84	1.58	2.39

Energy=6 MV FFF, field size=15 cm×15 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
10	3.562	0.047	4.140	0.056	4.042	0.098	13.95	2.26	11.87	3.24	2.36	1.40
12	2.128	0.031	2.512	0.019	2.475	0.048	15.27	1.49	14.02	2.18	1.46	1.54
14	1.348	0.020	1.735	0.017	1.700	0.021	22.31	1.23	20.74	1.37	1.99	2.08
16	0.899	0.020	1.287	0.040	1.257	0.026	30.18	1.23	28.49	2.58	2.37	4.75
18	0.608	0.018	0.993	0.021	0.984	0.031	38.70	1.21	38.16	3.76	0.87	5.20

Energy=10 MV, field size=15 cm×15 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
10	4.601	0.061	5.708	0.085	5.612	0.131	19.40	0.59	18.03	1.94	1.68	2.84
12	2.833	0.044	3.530	0.048	3.435	0.056	19.74	0.21	17.53	0.37	2.68	0.36
14	1.723	0.034	2.331	0.037	2.301	0.043	26.10	1.86	25.15	0.39	1.27	2.37
16	1.027	0.016	1.660	0.030	1.641	0.032	38.15	1.95	37.45	2.08	1.12	0.22
18	0.597	0.007	1.271	0.014	1.246	0.021	53.08	0.84	52.11	0.39	2.02	1.83
20	0.275	0.002	1.022	0.014	1.004	0.006	73.08	0.23	72.60	0.08	1.75	0.89

Energy=15 MV, field size=15 cm×15 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
10	4.762	0.086	5.167	0.074	5.006	0.115	7.84	2.71	4.86	3.40	3.12	1.17
12	2.959	0.051	3.193	0.080	3.126	0.054	7.32	3.86	5.32	3.22	2.10	0.85
14	1.891	0.033	2.113	0.035	2.068	0.052	10.53	3.05	8.57	2.82	2.14	3.06
16	1.204	0.035	1.511	0.041	1.463	0.032	20.26	3.18	17.67	4.17	3.14	3.57
18	0.693	0.017	1.180	0.020	1.142	0.018	41.26	2.44	39.29	2.43	3.24	0.48
20	0.368	0.005	0.960	0.024	0.930	0.025	61.64	1.04	60.40	0.52	3.14	3.25

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, % Diff: Percentage dose difference, FFF: Flattening filter free

Results

The statistical analysis on the TPS-calculated, MC-simulated, and the measured values of out-of-field dose obtained for all the five field sizes and four energies for a TrueBeam® machine is shown in Table 1a-e. The standard deviation was used to assess the spread of the data rather than estimating the uncertainty in the data. The absolute values (μGy/MU) of out-of-field dose from MC simulation for different field sizes and energy are represented in Figure 5a-d for energies 6 MV, 6 MV FFF, 10 MV, and 15 MV. For a specific off-axis distance of 12 cm, at a field size of 20 cm × 20 cm, a maximum value of out-of-field dose, 802 μGy/MU, was found for 10 MV beam and a minimum value of 510 μGy/MU was found for 6 MV FFF beam.

Table 2e: Percentage dose difference (%): Comparison between out-of-field dose for treatment planning system-calculated, Monte Carlo-simulated, and measured values for all the four energies and the field size of 20 cm×20 cm

Off-axis distance (cm)	Relative dose (%)						TPS versus MC		TPS versus measurement		MC versus measurement	
	TPS calculation		MC simulation		Measurements							
	Mean	SD	Mean	SD	Mean	SD	% Diff	SD	% Diff	SD	% Diff	SD
Energy=6 MV, field size=20 cm×20 cm												
12	8.284	0.182	8.853	0.118	8.711	0.133	6.43	0.89	4.90	0.67	1.61	0.50
14	5.359	0.107	5.908	0.082	5.752	0.085	9.29	3.05	6.83	3.23	2.64	0.53
16	3.688	0.074	4.127	0.058	3.991	0.096	10.62	3.05	7.58	0.83	3.29	3.62
18	2.671	0.037	2.757	0.035	2.726	0.063	3.11	2.58	2.02	3.58	1.12	1.25
20	1.771	0.038	2.012	0.037	1.982	0.025	11.95	1.43	10.64	2.94	1.46	2.89
22	1.116	0.020	1.431	0.019	1.410	0.021	21.99	0.44	20.82	0.36	1.49	0.50
Energy=6 MV FFF, field size=20 cm×20 cm												
12	4.507	0.113	5.425	0.053	5.309	0.062	16.94	2.88	15.11	3.12	2.15	0.22
14	2.735	0.044	3.357	0.047	3.285	0.032	18.53	2.12	16.74	1.78	2.15	0.53
16	1.793	0.032	2.336	0.033	2.261	0.026	23.24	0.46	20.69	2.29	3.21	2.44
18	1.201	0.024	1.732	0.031	1.710	0.020	30.68	0.20	29.80	0.90	1.25	1.01
20	0.827	0.016	1.327	0.027	1.285	0.023	37.68	0.74	35.66	2.36	3.15	3.70
22	0.695	0.010	1.120	0.023	1.073	0.010	37.93	1.15	35.17	1.38	4.25	2.82
24	0.588	0.011	0.973	0.012	0.949	0.012	39.53	0.48	38.04	1.47	2.40	2.10
Energy=10 MV, field size=20 cm×20 cm												
12	6.400	0.082	7.881	0.093	7.791	0.074	18.80	0.34	17.86	0.29	1.14	0.34
14	4.026	0.046	5.098	0.078	4.992	0.043	21.03	0.66	19.36	1.59	2.08	2.28
16	2.666	0.026	3.458	0.033	3.398	0.045	22.91	1.49	21.56	0.52	1.71	2.16
18	1.630	0.028	2.461	0.021	2.395	0.044	33.76	0.63	31.92	0.34	2.71	1.17
20	0.967	0.013	1.831	0.018	1.793	0.031	47.17	0.82	46.07	0.83	2.04	0.92
22	0.752	0.014	1.481	0.027	1.440	0.022	49.20	0.32	47.75	1.74	2.78	3.19
24	0.589	0.005	1.262	0.015	1.251	0.014	53.31	0.95	52.90	0.57	0.88	1.88
Energy=15 MV, field size=20 cm×20 cm												
12	6.677	0.082	7.129	0.077	7.018	0.111	6.34	2.10	4.86	2.56	1.56	0.72
14	4.076	0.062	4.589	0.065	4.412	0.044	11.17	0.66	7.61	0.57	3.85	0.51
16	2.850	0.020	3.112	0.015	3.080	0.033	8.43	0.73	7.47	1.14	1.04	1.44
18	1.782	0.021	2.227	0.044	2.175	0.028	20.01	2.54	18.06	0.85	2.37	2.92
20	1.085	0.012	1.664	0.023	1.621	0.016	34.79	0.24	33.04	1.34	2.61	2.28
22	0.840	0.011	1.339	0.020	1.291	0.011	37.25	0.62	34.94	1.37	3.55	2.26
24	0.644	0.007	1.149	0.022	1.125	0.011	43.95	1.69	42.78	0.59	2.04	2.46

TPS: Treatment planning system, SD: Standard deviation, MC: Monte Carlo, % Diff: Percentage dose difference, FFF: Flattening filter free

It was found that, in a range of 5–24 cm off-axis distance, the % diff between TPS-calculated and MC-simulated dose is around 45%. As the distance from the treatment field increases, an increase in the magnitude of the % diff of the TPS compared to MC simulation was noticed. Measurements were performed with the same geometry to compare the accuracy of MC-simulated values of out-of-field dose.

Table 3: Model parameters used to generate the phase-space files

Beam energy	Energy (MeV)	dE (MeV)	Spot X (mm)	Spot Y (mm)	Beam div (deg)
6 MV	6.18	0.0530	0.6866	0.7615	0.0573
6 MV FFF	5.90	0.0510	0.6645	0.7274	0.0573
10 MV	10.70	0.0909	0.8345	0.8710	0.0573
15 MV	13.50	0.1150	0.6415	0.5768	0.0573

All these values, except the spot size, were determined by tuning them to match measured dose distributions. Spot sizes were the measured values from the manufacturer. Energy=Mean energy of incident electron beam, dE=Sigma of the Gaussian distribution, Spot X and Spot Y are the sigmas of the Gaussian distributions of the lateral directions of the incident beam, Beam div=Sigma of Gaussian describing the initial momentum of the electrons, FFF: Flattening filter free

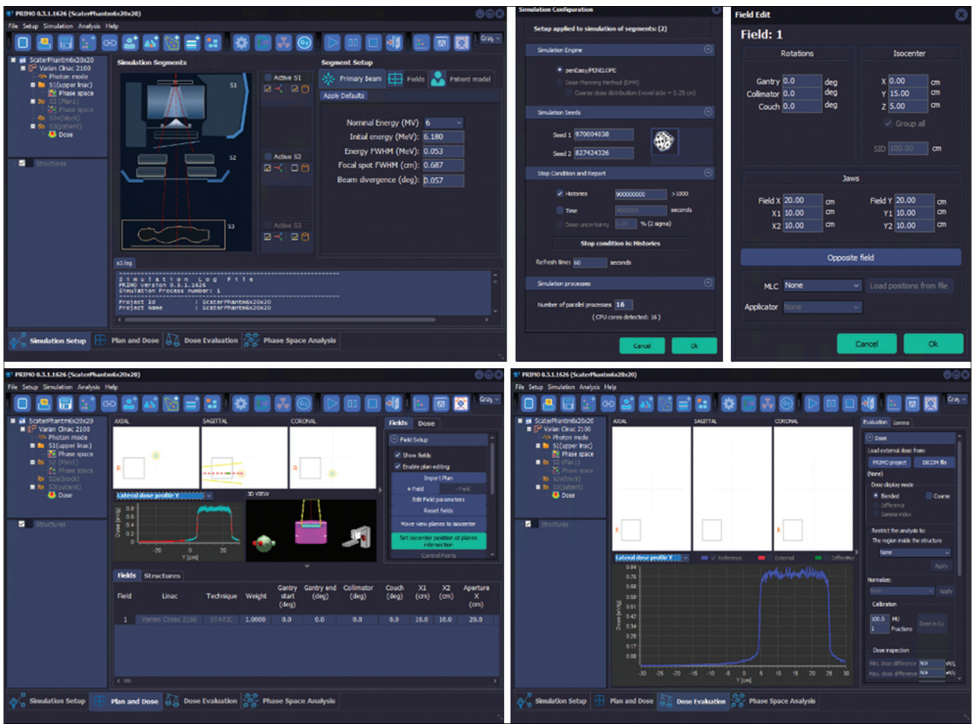

Figure 2: PRIMO: Workspaces and Configuration windows. PRIMO is a Monte Carlo dose calculation software that simulates radiotherapy linacs. Absorbed dose in water/slab phantom and computed tomography sets can be estimated with the help of PRIMO. It has a self-explanatory, easy-to-use graphical user interface, already-configured specific linac models and their multileaf collimators, and a calculation engine based out of Monte Carlo-based PENELOPE code

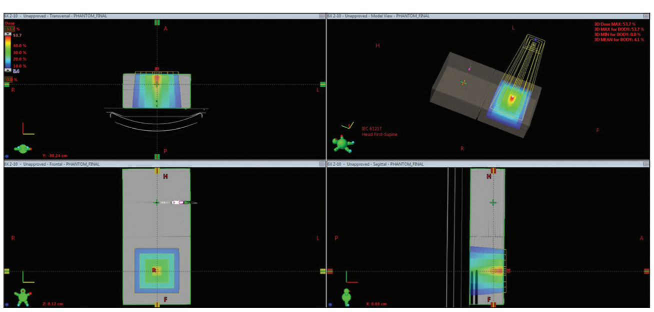

Figure 3: Eclipse™ treatment planning system: Dose distribution on the phantom. Calculated dose distribution in transverse, sagittal, and coronal planes and the three-dimensional view on the phantom are shown here. Eclipse v13.7 was used in this study

The comparison among relative out-of-field dose for TPS-calculated, MC-simulated, and measurements is shown in Figure 6a-d for energies 6 MV, 6 MV FFF, 10 MV, and 15 MV. The comparison between out-of-field dose obtained by MC simulation and measurements is shown in Figure 7a-d for 6 MV, 6 MV FFF, 10 MV, and 15 MV. Data were obtained up to an off-axis distance of 24 cm. Percentage dose difference (% diff) between MC simulation and TPS, MC simulation and measurement, and TPS and measurement is represented in Figures 8-10. In all these three comparison charts, a particular marker shape represents each field size. Table 2a-e shows the mean relative dose and standard deviation of TPS-calculated, MC-simulated, and measured values for all the four energies and five field sizes at various off-axis distance points ranging from 5 to 24 cm. This table also shows the percentage dose comparison between out-of-field dose for TPS-calculated, MC-simulated, and measured values, represented as % diff, for all the four energies and five field sizes at various off-axis distance points ranging from 5 to 24 cm.

Treatment planning system calculation versus Monte Carlo simulation

The maximum value of % diff between TPS-calculated and MC-simulated values was 94.11% and was observed for the 15 MV beam for a field size of 2 cm × 2 cm at an off-axis distance of 12 cm. Similarly, a minimum of 3.11% was observed for the 6 MV beam for a field size of 20 cm × 20 cm at an off-axis distance of 18 cm.

Treatment planning system calculation versus measurement

The maximum value of % diff between TPS-calculated and measured values was 94.06% and was observed for the 15 MV beam for a field size of 2 cm × 2 cm at an off-axis distance of 18 cm. Similarly, a minimum of 2.02% was observed for the 6 MV beam for a field size of 20 cm × 20 cm at an off-axis distance of 18 cm.

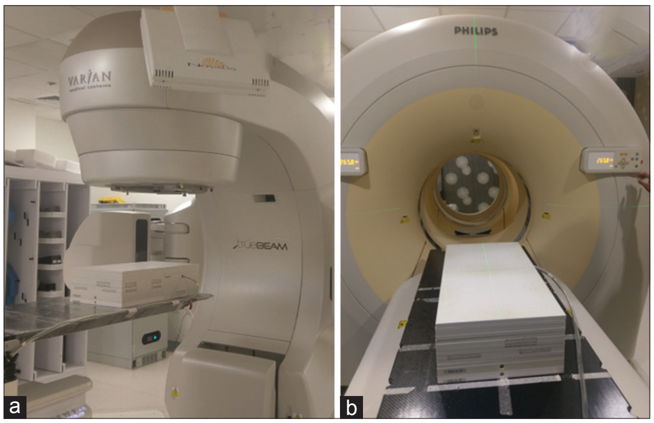

Figure 4: TrueBeam® – Measurement setup (a) and computed tomography scanning setup (b). Farmer type FC65-G chamber with IBM dose 1 Electrometer was used for the measurements. Reference reading was taken using a SSD 95 cm for a 10 cm × 10 cm field size by delivering 100 MU. The plastic phantom made of poly methyl methacrylate, at a density of 1.19 g/cm^3, used for measurement had the dimensions of 30 W × 60 L × 15 H cm^3, with an adaptor plate for FC65-G ionization chamber kept at 5-cm depth

Monte Carlo simulation versus measurement

The maximum value of % diff between MC simulated and measurement was 4.25% and was observed for 6 MV FFF beam for a field size of 20 cm × 20 cm at an off-axis distance of 22 cm. Similarly, a minimum value of 0.51% was observed for the 15 MV beam for a field size of 10 cm × 10 cm at an off-axis distance of 16 cm. If the estimation is extended up to an off-axis distance of 30 cm, then the maximum value increases up to around 6%.

In Figures 5 and 7, there was a sudden fall off from the off-axis distance of 20–22 cm mostly predominant in small field sizes such as 2 cm × 2 cm and 4 cm × 4 cm. This was because of the leakage passing beyond the limits of the primary collimator into the secondary collimator region. The primary collimators open to a field size of 40 cm × 40 cm, i.e., 20 cm from the central axis to the field edge. Even though a field was defined by the secondary collimators, there will be an additional leakage component which passes through the secondary collimator from the primary collimator till 40 cm × 40 cm. This additional leakage contribution from the primary will be predominant and much appreciable for small field sizes (2 cm × 2 cm, 4 cm × 4 cm); this was manifested as a sudden dose fall soon after the primary collimator's maximum field size (off-axis distance of 20 cm). However, once we move to higher field sizes, the scatter contribution from the wide-open field will be more predominant even outside the 40 cm × 40 cm. This additional scatter component

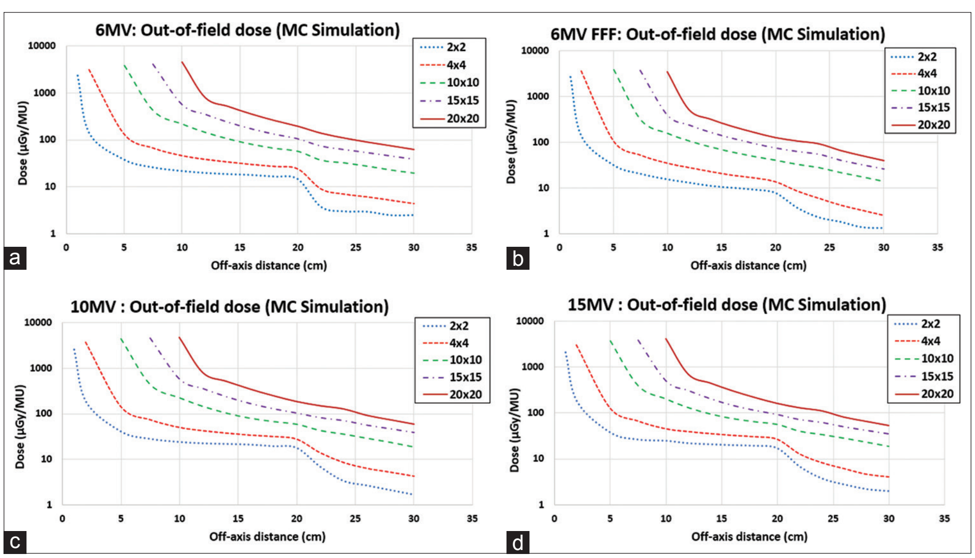

Figure 5: Out-of-field dose in-plane – Monte Carlo simulation values in absolute scale: Y-axis is represented by the out-of-field dose per MU (µGy/MU), and the X-axis is represented by the off-axis distance (cm). A logarithmic scale was used on the Y-axis to represent the entire range of values. Four energies (6 MV, 6 MV flattening filter free, 10 MV, and 15 MV) are represented in sections a, b, c, and d, respectively, and five field sizes are represented by different styles of dotted and solid lines

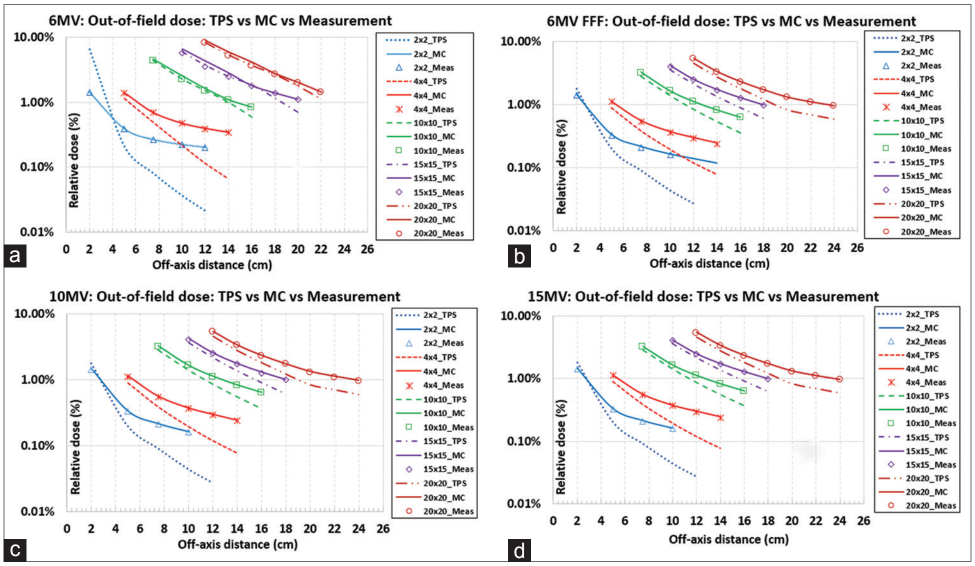

Figure 6: Out-of-field dose in-plane – treatment planning system versus Monte Carlo versus measurement: Y-axis is represented by a relative dose (%), and the X-axis is represented by the off-axis distance (cm). Four energies (6 MV, 6 MV flattening filter free, 10 MV, and 15 MV) are represented in sections a, b, c, and d, respectively, and five field sizes are represented by different styles of dotted and solid lines. The treatment planning system used was Varian Eclipse v13.7, and MC simulation was performed using PRIMO and Geant 4. Measurements were made reproducing the same geometry using FC65G Farmer-type chamber on water-equivalent phantoms

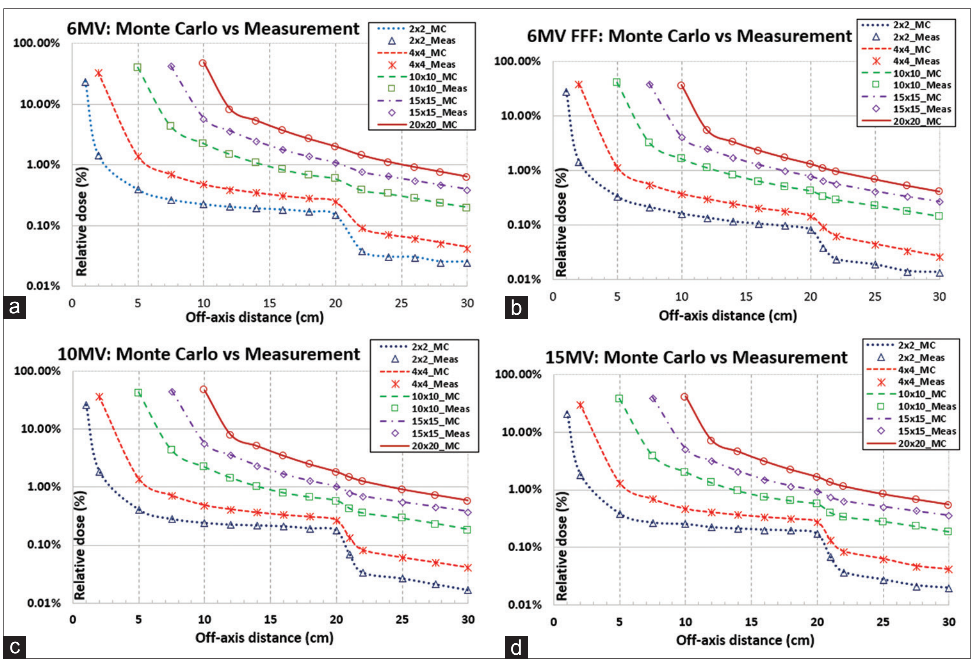

Figure 7: Out-of-field dose Monte Carlo versus measurement: Y-axis is represented by a relative dose (%), and the X-axis is represented by the off-axis distance (cm). A logarithmic scale was used on the Y-axis to represent the entire range of values. Four energies (6 MV, 6 MV flattening filter free, 10 MV and 15 MV) represented in sections a, b, c and d respectively, and five field sizes represented by different styles of dotted and solid lines. Monte Carlo Simulation was performed using Geant 4 and PRIMO programs. Measurements were made using FC65G farmer-type chamber on water-equivalent phantoms

compensates for the lack of dose and in effect nullifies the dose fall at this region.

Discussion

Through this study, the accuracy of the out-of-field dose calculated by the Eclipse™ TPS for a TrueBeam® machine was estimated. As per the results in comparison with MC simulations, the planning system underestimated the dose by around 45% [Table 1a-e] on an average for the off-axis-distance range considered in this study. As the off-axis distance increased, the underestimation of the dose value also increased [Figures 6, 8 and 10].

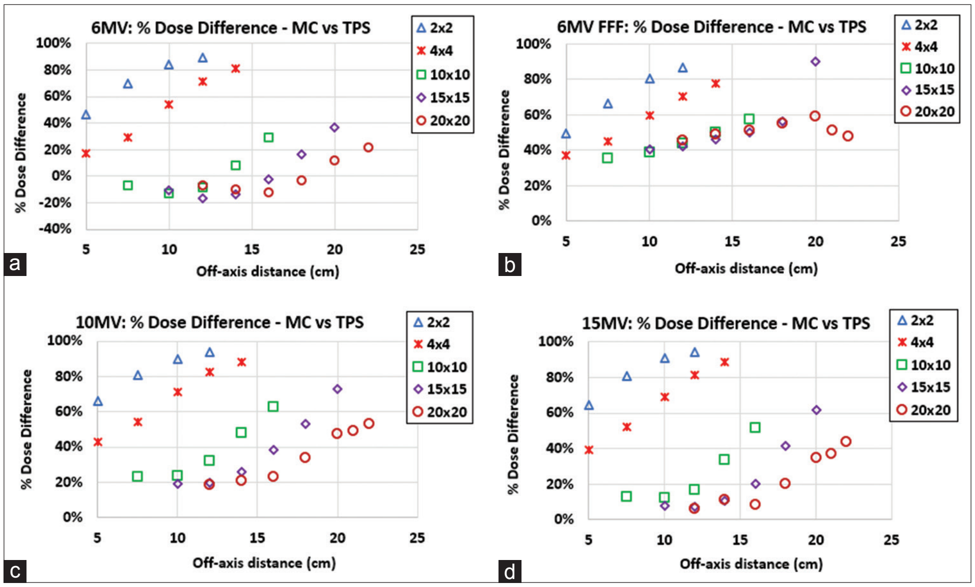

Figure 8: Percentage dose difference – Monte Carlo Simulation versus treatment planning system in-plane: Percentage dose difference was represented in the Y-axis, and off-axis distance (cm) was represented in the X-axis. Four energies (6 MV, 6 MV flattening filter free, 10 MV and 15 MV) represented in sections a, b, c and d respectively, and five field sizes represented by different marker shapes. Monte Carlo simulation was performed using PRIMO, and Geant 4 and treatment planning system used for dose calculation was Varian Eclipse v13.7

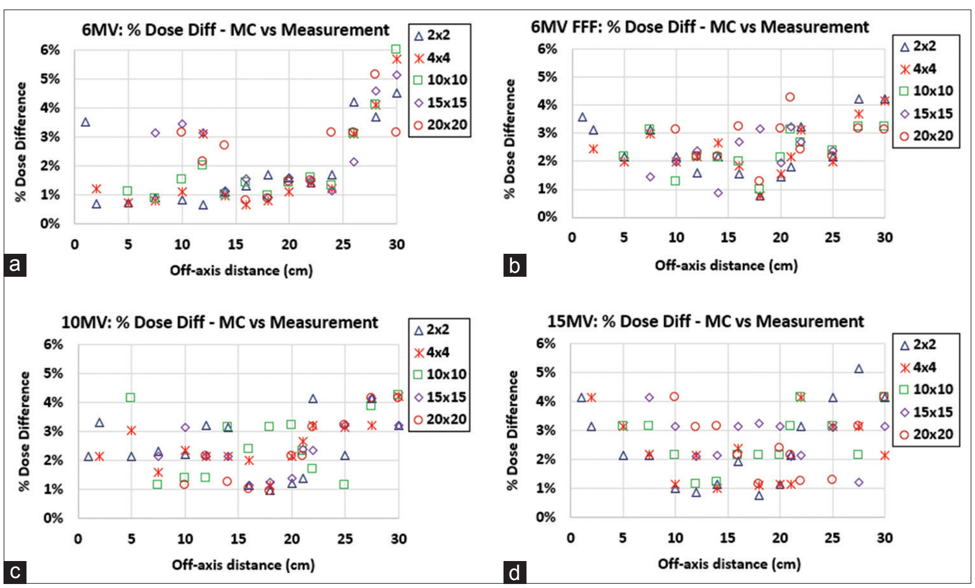

Figure 9: Percentage dose difference: Monte Carlo versus measurement: Four energies (6 MV, 6 MV flattening filter free, 10 MV, and 15 MV) are represented in sections a, b, c, and d, respectively, and five field sizes are represented by different marker shapes. Monte Carlo simulation was performed using PRIMO and Geant 4, and measurements were made using FC65G farmer-type chamber on water-equivalent phantoms

According to Howell *et al*.,[19] the Eclipse™ algorithm, AAA, calculates the out-of-field dose by applying a scaling function. As a result, the intensity of the out-of-field dose is decreased as a function of distance from the field edge. This tendency is possibly related to how the planning system models the out-of-field dose. The same trend is reported in the study performed by Stovall *et al*.[20] The AAA models all photons emitting from an outside target called extra-focal radiation utilizing a finite size virtual source. This virtual source is otherwise referred to as the "second source." The intensity distribution manifested by the second source is a Gaussian distribution. The Eclipse™ algorithm reference guide[21] clearly defines the second-source energy fluence and the parameters used to derive it at an arbitrary plane. The second-source fluence is computed by accumulating the individual contributions from each component of the second source for every pixel in the destination fluence array. For calculating the actual contribution, a scaling process takes place by the following factors: (1) Gaussian weight of the source element, (2) inverse square of the distance between

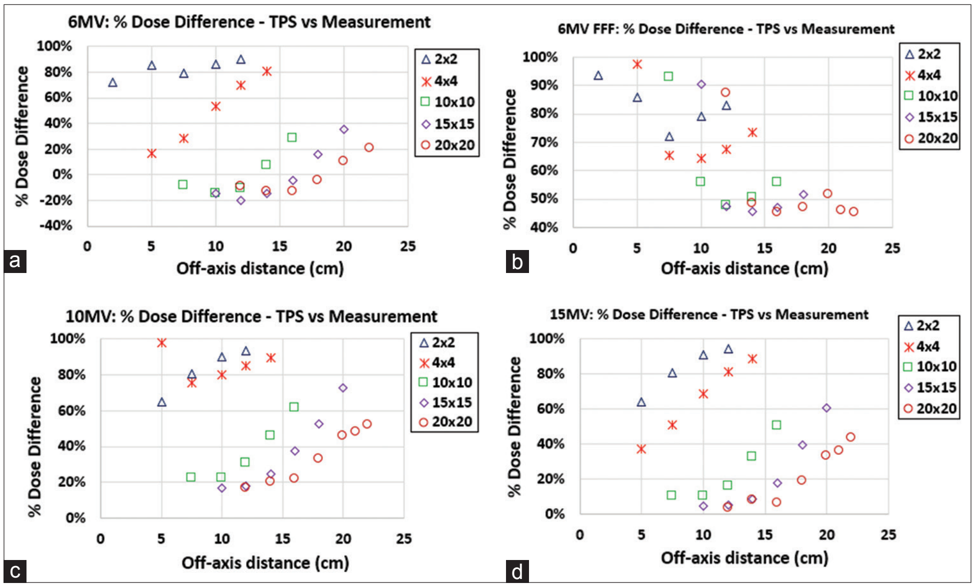

Figure 10: Percentage dose difference – Treatment planning system versus measurements: in-plane: Four energies (6 MV, 6 MV flattening filter free, 10 MV, and 15 MV) are represented in sections a, b, c, and d, respectively, and five field sizes are represented by different marker shapes. Treatment planning system used for dose calculation was Varian Eclipse v13.7, and the measurements were made using FC65G farmer-type chamber on water-equivalent phantoms

the elements at the destination and source planes, and (3) angle (cosine) of the ray.[19]

In this approach, TPS severely underestimates the collimator scatter and scatter from other components of the beam line. It also underestimates the patient scatter component and the leakage radiation from the accelerator head. This is the core reason behind the poor accuracy of TPS-calculated out-of-field dose.[22,23] The inaccuracy and underestimation increased as the distance from the field edge increased. This behavior matches the current study results.

This very severe inaccuracy is not due to poor beam modeling in the TPS but rather more fundamental origin. Even though the head leakage and the collimator scatter were better modeled in the planning system, the scatter component from the patient, which is the most predominant component near the field edge, will still be poorly estimated due to the underestimation of large angle scatter. This is considered a significant weakness of commercial implementation of the convolution/superposition dose calculation methods such as AAA.[22]

There are numerous studies which already demonstrated that the Eclipse™ algorithm (AAA) calculates the dose accurately inside the treatment field and within the penumbra region in water, water-equivalent materials, and heterogeneous media.[1,24-27] In general, the deviations reported in this article are for low-dose regions and at a large off-axis distance. Therefore, the impact of this study is highly significant and reserved for situations where very low doses are relevant. This work could be used for the evaluation of late radiation effects such as second cancer and also for the development of dose–response models addressing low-dose effects in radiotherapy. In these scenarios, the error reported in this study, which is around 50%, is of great significance. In one of their articles, Kry *et al*.[7] reported that a 50% discrepancy in low dose was suggested as sufficient to cause a striking difference in second cancer risk.

This study and the results were specific to the Eclipse™ TPS version 13.7 and Varian TrueBeam® linac. The exact value of the out-of-field dose depends on the planning system linac combination, and more precisely, it depends on the calculation algorithm as well as the beam data used for commissioning the planning system. Further extensive study is needed to understand the behavior of other commercially available planning systems and linac combination. Simple conventional fields were only considered in this study. To understand the complete spectra of out-of-field dose and its impact, a further extensive study by varying the beam angles and including different delivery techniques, for example, IMRT as well as VMAT, should be performed.

Further study is also needed for neutron contamination of the photon beam because the maximum photon energy used in this study was 15 MV which exceeds the photonuclear threshold energy in many of the materials. Even though photoneutron doses produced in the high-energy linear accelerators are a known fact, they are not considered in the currently available TPSs.[28] Therefore, characterization of photoneutrons around the treatment head could be considered as an extension of this study.

Conclusion

This study proves that the Eclipse™ TPS underestimates doses beyond the edges of treatment fields by an average of around 45% for a clinical treatment executed on a Varian

TrueBeam® machine. This value is in agreement with the study performed by Howell *et al*.[19] This concludes that the out-of-field dose from TPSs should only be used with a clear understanding of the inaccuracy of dose calculations beyond the edge of the treatment field. Clinical scenarios that require accurate out-of-field doses should use other more reliable dose calculation methods such as MC simulation or measurements. The details of these reliable alternate methods are explained thoroughly by studies performed by Stovall *et al*.[20] To estimate the accuracy of the MC simulation performed in this study, out-of-field dose measurements were conducted using the same geometry, and the overall results agreed within 3%.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Aspradakis MM, Morrison RH, Richmond ND, Steele A. Experimental verification of convolution/superposition photon dose calculations for radiotherapy treatment planning. Phys Med Biol 2003;48:2873-93.
2. Das IJ, Cheng CW, Watts RJ, Ahnesjö A, Gibbons J, Li XA, *et al.* Accelerator beam data commissioning equipment and procedures: Report of the TG-106 of the therapy physics committee of the AAPM. Med Phys 2008;35:4186-215.
3. Schneider U, Lomax A, Lombriser N. Comparative risk assessment of secondary cancer incidence after treatment of Hodgkin's disease with photon and proton radiation. Radiat Res 2000;154:382-8.
4. Kry SF, Salehpour M, Followill DS, Stovall M, Kuban DA, White RA, *et al.* The calculated risk of fatal secondary malignancies from intensity-modulated radiation therapy. Int J Radiat Oncol Biol Phys 2005;62:1195-203.
5. Howell RM, Hertel NE, Wang Z, Hutchinson J, Fullerton GD. Calculation of effective dose from measurements of secondary neutron spectra and scattered photon dose from dynamic MLC IMRT for 6 MV, 15 MV, and 18 MV beam energies. Med Phys 2006;33:360-8.
6. Fontenot JD, Lee AK, Newhauser WD. Risk of secondary malignant neoplasms from proton therapy and intensity-modulated x-ray therapy for early-stage prostate cancer. Int J Radiat Oncol Biol Phys 2009;74:616-22.
7. Kry SF, Followill D, White RA, Stovall M, Kuban DA, Salehpour M. Uncertainty of calculated risk estimates for secondary malignancies after radiotherapy. Int J Radiat Oncol Biol Phys 2007;68:1265-71.
8. Weber DC, Peguret N, Dipasquale G, Cozzi L. Involved-node and involved-field volumetric modulated arc vs. fixed beam intensity-modulated radiotherapy for female patients with early-stage supra-diaphragmatic Hodgkin lymphoma: A comparative planning study. Int J Radiat Oncol Biol Phys 2009;75:1578-86.
9. Sempau J, Badal A, Brualla L. A PENELOPE-based system for the automated Monte Carlo simulation of Clinacs and voxelized geometries-application to far-from-axis fields. Med Phys 2011;38:5887-95.
10. Brualla L, Salvat F, Palanco-Zamora R. Efficient Monte Carlo simulation of multileaf collimators using geometry-related variance-reduction techniques. Phys Med Biol 2009;54:4131-49.
11. Capote R, Jeraj R, Ma CM, Rogers DW, Sanchez-Doblado F, Sempau J, *et al*. Phase-Space Database for External Beam Radiotherapy. I.A. E. A., Nucl Data Sec. Report INDC (NDS)-0484; 2006.
12. Faddegon BA, Asai M, Perl J, Ross C, Sempau J, Tinslay J, *et al.* Benchmarking of Monte Carlo simulation of bremsstrahlung from thick targets at radiotherapy energies. Med Phys 2008;35:4308-17.
13. Faddegon BA, Kawrakow I, Kubyshin Y, Perl J, Sempau J, Urban L, *et al.* The accuracy of EGSnrc, geant4 and PENELOPE Monte Carlo systems for the simulation of electron scatter in external beam radiotherapy. Phys Med Biol 2009;54:6151-63.
14. Blazy L, Baltes D, Bordy JM, Cutarella D, Delaunay F, Gouriou J, *et al.* Comparison of PENELOPE Monte Carlo dose calculations with Fricke dosimeter and ionization chamber measurements in heterogeneous phantoms (18 meV electron and 12 MV photon beams). Phys Med Biol 2006;51:5951-65.
15. Sempau J, Sánchez-Reyes A, Salvat F, ben Tahar HO, Jiang SB, Fernández-Varea JM, *et al.* Monte Carlo simulation of electron beams from an accelerator head using PENELOPE. Phys Med Biol 2001;46:1163-86.
16. Brualla L, Rodriguez M, Sempau J. PRIMO User's Manual Version 0.3.1.1681; 2019. Available from: https://www.primoproject.net/primo/system/files/UserManual_0.3.1.1681.pdf. [Last accessed on 2019 Aug 25].
17. Boag JW, Currant J. Current collection and ionic recombination in small cylindrical ionization chambers exposed to pulsed radiation. Br J Radiol 1980;53:471-8.
18. Boag JW. The recombination correction for an ionisation chamber exposed to pulsed radiation in a 'swept beam' technique. I. Theory. Phys Med Biol 1982;27:201-11.
19. Howell RM, Scarboro SB, Kry SF, Yaldo DZ. Accuracy of out-of-field dose calculations by a commercial treatment planning system. Phys Med Biol 2010;55:6999-7008.
20. Stovall M, Weathers R, Kasper C, Smith SA, Travis L, Ron E, *et al.* Dose reconstruction for therapeutic and diagnostic radiation exposures: Use in epidemiological studies. Radiat Res 2006;166:141-57.
21. Varian Medical System Inc. Eclipse Photon and Electron Algorithms Reference Guide P1015026-001-A MyVarian; 2015. p. 40.
22. Huang JY, Followill DS, Wang XA, Kry SF. Accuracy and sources of error of out-of field dose calculations by a commercial treatment planning system for intensity-modulated radiation therapy treatments. J Appl Clin Med Phys 2013;14:4139.
23. Kry SF, Bednarz B, Howell RM, Dauer L, Followill D, Klein E, *et al.* AAPM TG 158: Measurement and calculation of doses outside the treated volume from external-beam radiation therapy. Med Phys 2017;44:e391-e429.
24. Fogliata A, Nicolini G, Vanetti E, Clivio A, Cozzi L. Dosimetric validation of the anisotropic analytical algorithm for photon dose calculation: Fundamental characterization in water. Phys Med Biol 2006;51:1421-38.
25. Fogliata A, Nicolini G, Vanetti E, Clivio A, Winkler P, Cozzi L. The impact of photon dose calculation algorithms on expected dose distributions in lungs under different respiratory phases. Phys Med Biol 2008;53:2375-90.
26. Huyskens D, Van Esch A, Pyykkonen J, Tenhunun M, Hannu Helminen H, Tillikainen L, *et al*. Improved photon dose calculation in the lung with the analytical anisotropic algorithm (AAA). Radiother Oncol 2006;81:S513.
27. Breitman K, Rathee S, Newcomb C, Murray B, Robinson D, Field C, *et al.* Experimental validation of the eclipse AAA algorithm. J Appl Clin Med Phys 2007;8:76-92.
28. Mohammadi N, Hakimabad HM, Motavlli LR, Akbari F, Abdollahi S. Neutron spectrometry and determination of neutron contamination around the 15 MV Siemens Primus LINAC. J Radioanal Nucl Chem 2015;304:1001-8.