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PRIMO Monte Carlo software as a tool for commissioning of an external beam radiotherapy treatment planning system

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ABSTRACT

Background: The purpose was to validate the PRIMO Monte Carlo software to be used during the commissioning of a treatment planning system (TPS).

Materials and methods: The Acuros XB v. 16.1 algorithm of the Eclipse was configured for 6 MV and 6 MV flattening-filter-free (FFF) photon beams, from a TrueBeam linac equipped with a high-definition 120-leaf multileaf collimator (MLC). PRIMO v. 0.3.64.1814 software was used with the phase space files provided by Varian and benchmarked against the reference dosimetry dataset published by the Imaging and Radiation Oncology Core–Houston (IROC-H). Thirty Eclipse clinical intensity-modulated radiation therapy (IMRT)/volumetric modulated arc therapy (VMAT) plans were verified in three ways: 1) using the PTW Octavius 4D (O4D) system; 2) the Varian Portal Dosimetry system and 3) the PRIMO software. Clinical validation of PRIMO was completed by comparing the simulated dose distributions on the O4D phantom against dose measurements for these 30 clinical plans. Agreement evaluations were performed using a 3% global/2 mm gamma index analysis.

Results: PRIMO simulations agreed with the benchmark IROC-H data within 2.0% for both energies. Gamma passing rates (GPRs) from the 30 clinical plan verifications were (6 MV/6MV FFF): 99.4% ± 0.5%/99.9% ± 0.1%, 99.8% ± 0.4% /98.9% ± 1.4%, 99.7% ± 0.4%/99.7% ± 0.4%, for the 1), 2) and 3) verification methods, respectively. Agreement between PRIMO simulations on the O4D phantom and 3D dose measurements resulted in GPRs of 97.9% ± 2.4%/ 99.7% ± 0.4%.

Conclusion: The PRIMO software is a valuable tool for dosimetric verification of clinical plans during the commissioning of the primary TPS.

Key words: PRIMO; Monte Carlo; commissioning; HD120 MLC

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Introduction

The American Association of Physicists in Medicine (AAPM) Task Group (TG) 219 recommends using a secondary dose calculation algorithm to check the dose distribution of a clinical calculation algorithm [1], as part of the patient-specific quality assurance (PSQA) in radiotherapy modulated plans. An overall accuracy of ±5% is recommended for radiotherapy treatment planning of patient treatments [2]. To achieve this goal, an accurate dose calculation algorithm is required, especially when low-density and inhomogeneity areas such as lungs and air-bone interfaces are present. The Monte Carlo (MC) simulation of radiation transport in matter is considered the gold

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standard of dose calculation algorithms for radiotherapy applications. MC simulations have been proposed by the International Commission on Radiation Units and Measurements (ICRU) for independent dose verification, especially when heterogeneous tissues are present [3]. Several researchers have argued that MC simulations are very appropriate to test the accuracy of dose calculations given by a treatment planning system (TPS), especially in those situations where measurements are rather difficult as in the case of small fields due to the conditions of non-equilibrium radiation [4–8]. Several works have reported the use of both commercial and open-source MC simulation systems to perform verification of radiotherapy plans [9–13]. In particular, Hermida-López et al. explored the accuracy of the freely available PRIMO MC simulation software [14, 15] and they pointed out the possibility of using PRIMO as an independent verification system of radiotherapy plans computed by a TPS [16].

The AAPM Medical Physics Practice Guideline (MPPG) 5.a recommends checking the dose calculation accuracy of clinical plans during the commissioning of a TPS [17]. Although this recommendation refers to delivering the plan to a phantom with appropriate dosimeters enabling the user to compare planned and delivered dose distributions, a validated MC simulation system allows the dose to be accurately computed in the full three-dimensional (3D) patient geometry. Therefore, MC simulations offer a good complement to these phantom-based measurements during the commissioning of a TPS [18].

Recently, the PRIMO MC software was validated by Calvo-Ortega et al. as a tool for independent dose verification of HyperArc radiosurgery plans [19]. In that work, the phase-space files (PSFs) provided by Varian for 6 MV flattening-filter-free (FFF) photon beams from a Varian TrueBeam linear accelerator (linac) were used. The authors concluded that the PRIMO Monte Carlo software can be used as secondary dose calculation software to check stereotactic radiosurgery plans from Eclipse using the HyperArc technique.

As a complement to the above study, the purpose of this article is to describe the feasibility of using the PRIMO MC software for an independent check of clinical plans for a variety of sites computed by the Varian Eclipse TPS during the commissioning of a TPS, in addition to during the clinical routine. This work focused on intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) plans with 6 MV and 6 MV FFF photon beams from a Varian TrueBeam linac equipped with a high-definition 120-leaf multileaf collimator (HD120 MLC). PRIMO-based independent verifications of clinical plans were performed and the results were compared to those obtained by using an ionization chamber array and portal dosimetry measurements. As a novelty, this study is the first one describing the use of PRIMO in conjunction with the Varian PSFs for 6 MV and 6MV FFF beams and the HD MLC.

Materials and methods

Clinical plans

Thirty clinical cases (see Tab. 1), previously treated at the Hospital Quirónsalud Barcelona (Site 1), were used during the setting up of a new radiation therapy department of the Hospital Quirónsalud *Málaga* (Site 2). Both sites belong to the same institution and share the same radiotherapy database. The dosimetric DICOM data (CT images, targets, and organs-at-risk structures) were anonymized to be used during the commissioning of the Eclipse TPS configured for a TrueBeam linac (Varian Medical Systems, Palo Alto, CA) installed at the Site 2. This study was limited to 6 MV and 6 MV FFF beams.

The planning CT images of all cases were acquired with 1.25 mm slice thickness. Clinically acceptable IMRT/VMAT plans were calculated using with the Acuros XB algorithm v. 16.10 (dose to medium) of the Eclipse TPS. Plans were planned using 6 MV (15 cases) and 6 MV FFF (15 cases) photon beams from the TrueBeam linac of the SITE 2, equipped with a HD120 MLC. A 2.5 mm dose calculation grid size was used in all plans, except for the stereotactic cases that were calculated with 2 mm resolution, a choice compatible with the recommendation of the Report of AAPM TG-101 [20]. The configured values in Eclipse for the MLC dosimetric leaf gap (DLG), MLC transmission, and effective spot size were 0.950 mm, 0.012 and 1.350 mm for 6 MV, and 1.250 mm, 0.010 and 1.000 mm for 6 MV FFF, respectively. These values were established during Eclipse commissioning.

Each plan was verified with three independent methods: 1) using the Octavius 4D system

Table 1. Clinical cases included in this study

Case ID	Site	Prescription dose	Energy	Technique
1	Breast plus nodes	15 × 2.67 Gy	6 MV	VMAT
2	Breast (simple)	5 × 5.2 Gy		IMRT
3	Breast plus nodes	15 × 2.67 Gy/ 3.2 Gy		IMRT
4	Breast plus nodes	15 × 2.67 Gy/ 3.2 Gy		IMRT
5	Gynecologic	25 × 1.8 Gy		VMAT
6	Lung	30 × 2 Gy		VMAT
7	Prostate plus pelvic nodes	20 × 3 Gy/ 2 Gy		VMAT
8	Rectum	5 × 5 Gy		VMAT
9	Anal canal	30 × 1.8 Gy		VMAT
10	Breast (simple)	5 × 5.2 Gy		IMRT
11	Breast (simple)	5 × 5.2 Gy		IMRT
12	Breast plus nodes	15 × 2.67 Gy/3.2 Gy		IMRT
13	Breast plus nodes	15 × 2.67 Gy/3.2 Gy		VMAT
14	Breast plus nodes	15 × 2.67 Gy		VMAT
15	Head and neck	33 × 1.64 Gy/1.8 Gy/2.12 Gy		VMAT
16	Vertebrae	2 × 12 Gy	6 MV FFF	VMAT
17	Vertebrae	5 × 6 Gy		
18	Lung	3 × 18 Gy		
19	Lung	5 × 10 Gy		
20	Lung	8 × 4 Gy		
21	Lung	1 × 28 Gy		
22	Lung	5 × 10 Gy		
23	Panchreas	6 × 7.5 Gy		
24	Prostate	5 × 7.25 Gy		
25	Prostate	5 × 7.25 Gy		
26	Brain	3 × 9 Gy		
27	Brain	1 × 18 Gy		
28	Head and neck	33 × 1.64 Gy/1.8 Gy/2.12 Gy		
29	Prostate	20 × 3 Gy		
30	Lung	5 × 10 Gy		

FFF— flattening filter-free; IMRT — intensity-modulated radiation therapy; VMAT — volumetric modulated arc therapy

(O4D, PTW, Freiburg, Germany), equipped with the PTW 1600 SRS two-dimensional (2D) array; 2) the Varian Portal Dosimetry system (v. 16.10) and 3) Monte Carlo PRIMO software (v. 0.3.64.1814). The first two methods do not take into account the real anatomy of the patient, while the PRIMO-based verification does not include the plan delivery.

The PTW 1600 SRS detector has an active detection area of 15 × 15 cm^2. For measurements, the array was inserted into the motorized O4D modular phantom together with the Octavius Top SRS plus, resulting in an effective homogeneous cylinder geometry (21 cm diameter and 26 cm length). Measurement acquisition was controlled by the PTW Verisoft software v. 8.1, which reconstructs the 3D dose in the cylindrical phantom. Due to the array detection size, 3D dose reconstruction is possible only in a cylindrical volume of 15 cm diameter and length.

The Portal Dosimetry software was used with the portal dose image prediction (PDIP) algorithm.

PDIP was configured for 6 MV beams using the van Esch package [21]. For 6 MV FFF energy, the analytical anisotropic algorithm (AAA) was used for the prediction of the portal dose image.

For methods 1) and 3), evaluation of the Eclipse dose calculations was performed using a 3D gamma index analysis. For the portal dosimetry verification, a 2D gamma index analysis was done. The 3% global/2 mm (dose threshold of 10%) criteria recommended by the AAPM TG-218 report was used with the three verification methods [22]. For the PRIMO verification, gamma passing rates (GPRs) for the whole patient ("body") and the planning target volume (PTV) were calculated.

PRIMO simulations

PRIMO is a freely available software (www.primoproject.net) that allows Monte Carlo simulations of radiotherapy linacs, estimating absorbed dose distributions in phantoms and computed tomography datasets. It is based on the general-purpose radiation transport MC code PENELOPE.[23] The fast MC algorithm Dose Planning Method (DPM), tailored for radiotherapy applications, is also incorporated in PRIMO [24, 25].

PRIMO v. 0.3.64.1816 was used in this study. All the simulations were run with the DPM algorithm. The MC PSFs (v. 2, Feb. 27, 2013) provided by Varian for the 6 MV and 6 MV FFF photon beams from a TrueBeam linac were used as sources of particles. The full PSFs were used in the simulations, corresponding to 4.95×10^{10} particles. PRIMO automatically distributes the particles available in the PSF among all the control points of the plan, according to the control point weight.

The simple splitting variance-reduction technique was applied to the particles entering the phantom or patient CT. This technique is a kind of geometry-based splitting method, which tries to favor particles entering "interesting" regions of the simulation geometry, that is, regions in which the particle interactions will contribute to the scored quantities such as the absorbed dose, thus spending less time to simulate particles that will not contribute appreciably to the scores. In the simple splitting implemented in PRIMO, a particle entering the CT is split into a number of clones given by the splitting factor S, and each of them is simulated sequentially. To avoid introducing a bias in the tallied quantity, the statistical weight of each cloned particle is multiplied by 1/S. An empirically determined splitting factor S = 150 was applied to all the simulations of this work, ensuring PRIMO statistical uncertainties smaller than 2% (k = 2) with the PSF used.

PRIMO reports inherently dose results in units of eV/g per simulated history. Hence, a calibration factor is needed in PRIMO to convert these dose values per history to absorbed dose values in Gy. To do this, the dose measured at a point in reference conditions (e.g., source-to-surface distance of 90 cm, a 10×10 cm^2 field size, and depth of 10 cm) in a water phantom has to be compared with the corresponding dose value obtained from the simulation using the same setup. Then, the calibration factor (f) for a given treatment plan is obtained as:

Where is the number of fractions of the plan, is the dose measured in reference conditions, is the dose estimated by a PRIMO simulation in the reference conditions, are the reference monitor units (MUs) used to obtain the measured reference dose, and MU are the MUs per fraction of the treatment plan.

The simulations were performed in a computer with two Intel(R) Xeon(R) CPU E5-2640 v4 @ 2.40 GHz processors, with 64 GB of RAM and using the 20 CPU cores simultaneously.

According to the AAPM TG-114 report [26], two general requirements must be fulfilled by a software to be used as a true independent calculation system: a different dose calculation algorithm and different beam data from the TPS should be used. PRIMO fulfills the AAPM TG-114 requirements, as the implemented MC algorithms are not used by our primary TPS. The second one is also met as the Varian PSFs for a TrueBeam linac have been used, instead of tuning PRIMO to match the specific linac. In this way the propagation of possible flaws in the data used to commission the TPS to the simulation results are avoided.

For the simulation of clinical plans, PRIMO used the same Hounsfield units to mass-density calibration curve as the one used by Acuros in Eclipse. The default material table of PRIMO including six materials (air, lung ICRP, adipose tissue, muscle skeletal, cartilage, and compact bone) was used to assign the material to each patient CT voxel. Although Acuros allows an overlapping HU range for adjacent materials, PRIMO assigns a materi-

al to each voxel based on a predefined HU range. The default material assignments used by PRIMO and Acuros are similar, but not exactly the same. For breast plans, Fogliata et al. found a dose difference of about 0.1% between using the PRIMO default material table and the Acuros values [27]. Similar differences should be expected for other sites. Based on this information, the PRIMO default material table was used in this study.

A set of scripts written in Python 3.7 were used to automate the simulation setup process [28]. The scripts run in background monitoring a specified folder, in which plan DICOM files can be exported from the TPS. When the DICOM files are detected, the scripts extract relevant parameters from the DICOM files, and create the PRIMO files needed to set up the simulation and the gamma index analyses. Then, the scripts start PRIMO and the simulation begins. The automation of the simulation setup facilitates introducing PRIMO as a system for routine independent calculation, with a minimal workload for the clinical dosimetry team.

PRIMO validation

PRIMO, in conjunction with the Varian PSFs, was validated by comparing the dosimetric parameters obtained from PRIMO simulations against the dosimetric dataset published by the Imaging and Radiation Oncology Core–Houston (IROC-H), based on measurements on a series of TrueBeam linacs [29]. Tables 2 and 3 show the dosimetric parameters determined by IROC–H for 15 TrueBeam linacs, as well as the point locations where they are specified: percentage depth–doses (PDD), off-axis

Table 2. Values derived by PRIMO for the dosimetric parameters reported by Imaging and Radiation Oncology Core–Houston (IROC-H) for 6 MV beams from the TrueBeam linac model used in this study

Field size [cm^2]	Parameter	IROC Median	IROC 2 × SD	PRIMO	PRIMO 2 × SD	PRIMO-IROC (%)
10 × 10	PDD at Dmax depth	1.508	0.010	1.502	0.016	–0.4
	PDD at 5 cm depth	1.300	0.004	1.300	0.014	0.0
	PDD at 15 cm depth	0.759	0.004	0.757	0.009	–0.3
	PDD at 20 cm depth	0.572	0.004	0.572	0.007	0.0
6 x 6	PDD at 5 cm depth	1.332	0.008	1.325	0.014	–0.5
	PDD at 15 cm depth	0.742	0.002	0.746	0.009	0.5
	PDD at 20 cm depth	0.551	0.004	0.553	0.007	0.4
20 x 20	PDD at 5 cm depth	1.258	0.004	1.257	0.012	–0.1
	PDD at 15 cm depth	0.781	0.002	0.776	0.008	–0.6
	PDD at 20 cm depth	0.604	0.002	0.607	0.007	0.5
6 × 6		0.962	0.006	0.961	0.010	–0.1
15 × 15	OF at Dmax depth	1.030	0.006	1.029	0.010	-0.1
20 × 20		1.052	0.006	1.051	0.010	-0.1
30 × 30		1.074	0.010	1.074	0.011	0.0
40 × 40	OAR at 5 cm left	1.024	0.008	1.022	0.010	-0.2
	OAR at 10 cm avg	1.042	0.008	1.041	0.010	-0.1
	OAR at 15 cm left	1.054	0.010	1.053	0.010	-0.1
2 × 2		0.804	0.016	0.819	0.009	1.9
3 × 3	IMRT-style MLC OF at 10 cm depth	0.849	0.014	0.864	0.009	1.8
4 × 4		0.885	0.012	0.901	0.010	1.8
6 × 6		0.937	0.010	0.945	0.010	0.9
2 × 2		0.781	0.014	0.797	0.009	2.0
3 × 3	SBRT-style MLC OF at 10 cm depth	0.825	0.012	0.834	0.009	1.1
4 × 4		0.856	0.014	0.864	0.010	0.9
6 × 6		0.914	0.008	0.920	0.010	0.7

SD — standard deviation; PRIMO-IROC is the percent difference related to the IROC value; PDD — percentage depth–doses; OF — outfoot factor; OAR — organ at risk; IMRT — intensity-modulated radiotherapy; MLC — multileaf collimator; SBRT — stereotactic body radiotherapy .

Table 3. Values derived by PRIMO for the dosimetric parameters reported by Imaging and Radiation Oncology Core–Houston (IROC-H) for 6 MV flattening-filter-free (FFF) beams from the TrueBeam linac model used in this study

Field size [cm^2]	Parameter	IROC Median	IROC 2 × SD	PRIMO	PRIMO 2 × SD	PRIMO-IROC (%)††
10 × 10	PDD at Dmax depth	1.571	0.004	1.590	0.013	1.2
	PDD at 5 cm depth	1.334	0.003	1,339	0.009	0.4
	PDD at 15 cm depth	0.738	0.003	0.734	0.007	–0.5
	PDD at 20 cm depth	0.543	0.002	0.539	0.005	–0.7
6 x 6	PDD at 5 cm depth	1.370	0.005	1.381	0.012	0.8
	PDD at 15 cm depth	0.722	0.001	0.717	0.007	–0.7
	PDD at 20 cm depth	0.525	0.002	0.519	0.005	–1.1
20 x 20	PDD at 5 cm depth	1,293	0.002	1.299	0.010	0.5
	PDD at 15 cm depth	0.759	0.001	0.760	0.007	0.1
	PDD at 20 cm depth	0.571	0.001	0.565	0.005	–1.1
6 × 6		0.976	0.003	0.975	0.007	–0.1
15 × 15	OF at Dmax depth	1,017	0.003	1.014	0.008	–0.3
20 × 20		1,029	0.003	1.025	0.008	–0.4
30 × 30		1,041	0.005	1.038	0.008	–0.3
40 × 40	OAR at 5 cm left	0.909	0.003	0.904	0.008	–0.6
	OAR at 10 cm avg	0.766	0.001	0.760	0.007	–0.8
	OAR at 15 cm left	0.642	0.003	0.638	0.006	–0.6
2 × 2		0.802	0.006	0.817	0.008	1.9
3 × 3	IMRT-style MLC OF at 10 cm depth	0.842	0.004	0.858	0.008	1.9
4 × 4		0.875	0.003	0.887	0.008	1.4
6 × 6		0.928	0.004	0.937	0.008	1.0
2 × 2		0.786	0.003	0.808	0.008	2.8
3 × 3	SBRT-style MLC OF at 10 cm depth	0.827	0.005	0.843	0.008	1.9
4 × 4		0.861	0.004	0.875	0.008	1.6
6 × 6		0.920	0.003	0.929	0.008	1.0

SD — standard deviation; PRIMO-IROC is the percent difference related to the IROC value; PDD — percentage depth–doses; OF — outfoot factor; OAR — organ at risk; IMRT — intensity-modulated radiotherapy; MLC — multileaf collimator; SBRT — stereotactic body radiotherapy

ratios (only for a 40 × 40 cm^2 field size), open–field (i.e., with the MLC fully retracted) output factors (OF) at the depth of the maximum dose (dmax), and OF for IMRT–style and SBRT–style fields, both determined at a depth of 10 cm. A source-to-surface distance of 100 cm was used in all cases. In the IMRT–style fields, the jaws were fixed at 10 × 10 cm^2 and the field sizes were defined by the static MLCs, while in the SBRT–style fields both jaws and MLCs moved to the given field sizes. These fields represent approximate typical segments of IMRT and SBRT fields.

The IROC-H dosimetric parameters were measured and simulated with PRIMO in our facility. Measurements were performed with a PTW BeamScan water phantom. A Semiflex 3D ion chamber, type PTW 31021 (sensitive volume of 0.07 cm^3), was used for all fields, except for the SBRT– and IMRT–style fields, for which the chosen detector was a microDiamond detector, type PTW 60019 (sensitive volume of 0.004 mm^3). Measurements were simulated in PRIMO using a voxel size of the water phantom of 2 × 2 × 2 mm^3. The values derived for each IROC-H parameter from simulations and measurements were compared to the median values reported by IROC–H.

Three of the AAPM TG-119 report [30] mock cases (C-Shape, Head and Neck, and Prostate) were used to test/validate the entire linac/MLC model in PRIMO to be used as a patient-specific verification tool. For each case, a VMAT plan was designed in Eclipse onto the O4D phantom. The volumes (tar-

gets and organs-at-risk) provided by the TG-119 report for each structure were transferred to the image set of the O4D phantom. Then, isocenter placement and plan goals described in the TG-119 document were followed for the planning of each case. The TG-119 plans calculated by Eclipse were then simulated in the PRIMO system, and also delivered to the O4D phantom, loaded with the PTW 1600 SRS detector. The measurement-based 3D dose reconstruction in the O4D phantom was performed using a 2 × 2 × 2 mm^3 resolution [31]. A voxelized geometry of 1.2 × 1.2 × 1.0 mm^3 was used in PRIMO for the O4D phantom. Water material was assigned to the O4D phantom both in PRIMO and in the Verisoft software. For each TG-119 plan, the simulated 3D dose distribution in the O4D phantom was compared with the respective 3D dose reconstruction performed by Verisoft. The comparison was done using the 3D gamma index analysis tool available in PRIMO. The 3%(G)/2 mm criteria with a threshold of 10% of the MC maximum dose were used, as recommended by the TG-218 report. Following the methodology described in the TG-119 report, the local dose difference at the isocenter was also calculated for the three mock plans, and for the point located at 2.5 cm anterior to the isocenter for the C-Shape case.

In addition to the TG-119 cases for PRIMO validation, the O4D-based verifications performed for the 30 clinical plans were also simulated. For each case, the 3D dose reported by Verisoft was compared to the simulated dose distribution using the 3%(G)/2 mm criteria and a 10% dose threshold, as recommended by the TG-218 report. Local dose differences at the isocenter were registered.

Results

Tables 2 and 3 show the comparison between the PRIMO results and the IROC–H data for 6 MV and 6 MV FFF beams from the TrueBeam linac used in this study. The differences found in all parameters for 6 MV are appreciably lower than for 6MV FFF. Excluding the OFs of the IMRT and SBRT-style fields, differences in all parameters were within 1.0% and 1.5% for 6 MV and 6 MV FFF beams, respectively. For each energy, the maximum discrepancies were found for the OFs of the 2 × 2 cm^2 SBRT-style fields, with differences of 2.0% for 6 MV and 2.8% for 6 MV FFF photons.

The PRIMO 3D dose distributions for the three AAPM TG-119 cases directly designed onto the O4D phantom, as well as for the 30 clinical plans mapped to this phantom, were compared to the corresponding 3D dose distributions reconstructed from O4D measurements (Figure 1 shows the C-Shape case). As Table 4 shows, excellent 3D GPR (3% global/ 2mm) values were obtained: 97.9% ± 2.4% and 99.7% ± 0.4% for 6 MV and 6 MV FFF plans, respectively. Point local differences (PRIMO *vs.* measured) were 0.5% ± 1.5% and –1.3% ± 1.2% for 6 MV and 6 MV FFF plans. A maximum local dose deviation of –3.5% was found over all plans. The absolute point local difference was significantly greater than the statistical PRIMO uncertainty (1.4% *vs.* 0.9%, $p < 0.05$), as revealed by a two-tailed t-test.

The O4D verification carried out for each clinical plan showed a good agreement between the measured and the 3D dose distributions calculated by Eclipse within the cylindrical O4D phantom (Tab. 5). Average GPRs (3% global/ 2 mm) of 99.4% ± 0.5% and 99.8% ± 0.4% were obtained for 6 MV and 6 MV FFF plans, respectively. Local dose differences at the isocenter were –0.8% ± 0.7% and 0.3% ± 1.2%, respectively. Portal dosimetry verifications performed for the individual fields/arcs of the clinical plans resulted also in high GPR values (3% global/2 mm): 99.9% ± 0.1% and 98.9% ± 1.4%, for 6 MV and 6 MV FFF plans, respectively.

Regarding the comparison of the Eclipse clinical plans against the corresponding plans simulated with PRIMO, 3D GPRs (3% global/ 2 mm) greater or equal to 90% were always observed both in the case of the body and PTV structures (Tab. 5). Statistical uncertainties ($k = 2$) of the simulations were below 1.2%. GPR values of 99.7% ± 0.4% and 99.7% ± 0.5% were respectively found for the body structure and PTV over the 6 MV plans, while 99.7% ± 0.4% and 98.7% ± 2.1% were registered for the cases planned using 6 MV FFF energy.

Discussion

In this study, we have illustrated the use of the PRIMO software during the commissioning of the Acuros algorithm for 6 MV and 6 MV FFF photons beams from a Truebeam linac. Com-

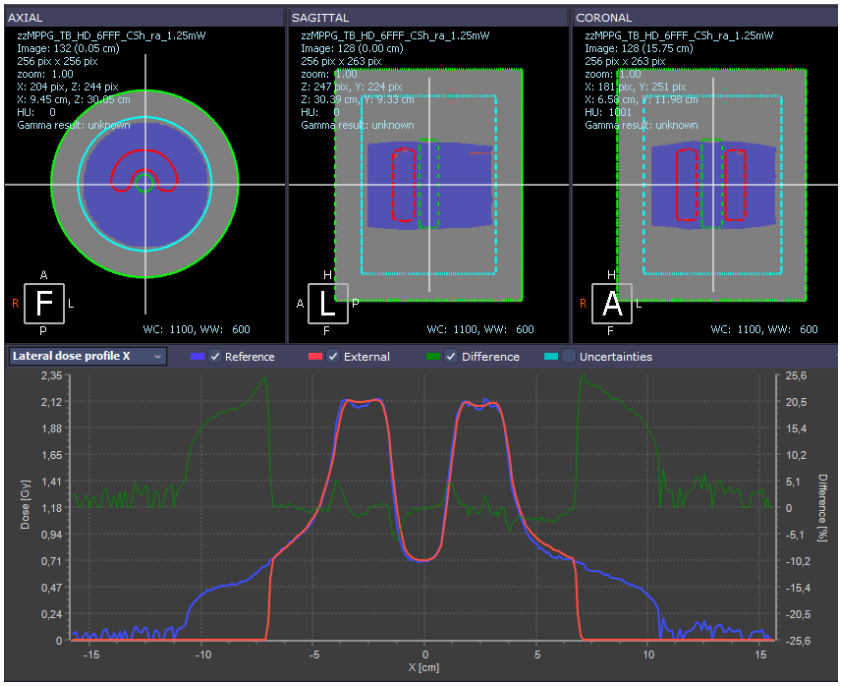

Figure 1. TG-119 C-Shape case planned on the O4D phantom: PRIMO simulation *vs*. O4D measurement. Contours on the phantom images are: the blue circle is the 15 cm diameter dose reconstruction performed by Verisoft, the red contour is the C-Shape target, dark green contour is the spinal cord. Lateral profiles taken through the cord middle plane are compared: reference (blue curve) is the PRIMO calculation, external (red curve) is the O4D measurement; the difference (green curve) is the local dose difference. In the upper row of the figure, the blue washes indicate values < 1 of the gamma index (3%/2 mm) over the axial, sagittal and coronal views of the O4D phantom

missioning was performed following the tests described in the MPPG 5.a. guideline [17]. As part of the VMAT/IMRT recommended tests, this guideline advises planning, measuring, and comparing plans for both the Head and Neck and C-Shape mock cases of the TG-119 report, as well as performing the PSQA for at least two relevant clinical cases. Such recommendations were followed in our study. The PSQA typically consists in mapping the clinical case onto a phantom containing a detector and comparing the planned dose distribution against the measured one, but no real patient anatomy is considered in this approach. To include the patient anatomy during the commissioning of the TPS for VMAT/IMRT plans, we have added the comparison of calculated-simulated dose distributions over the patient CT images. For that task, the DPM algorithm of the PRIMO simulation software was used with the PSFs provided by Varian for TrueBeam 6 MV and 6 MV FFF beams.

To validate the use of PRIMO for dose calculations, two kinds of verifications were performed. First, PRIMO was benchmarked against the reference dosimetry dataset published by the IROC-H. Excellent agreement was found in the analyzed metrics with differences in general within 2% (Tab. 2 and 3). The second type of verifications included three TG-119 mock VMAT plans and 15 clinical VMAT/IMRT plans for each energy. The use of clinical plans to test MC software as a patient-specific verification tool was described previously in the literature [32]. While the TG-119 plans were designed directly on the O4D phantom, the patient plans were transferred to that phantom for a PSQA check. Three-dimensional dose distributions calculated by PRIMO of all these 36 plans were verified successfully. Table 4 shows that all PRIMO-calculated plans, except two, met the 95% passing rate with criteria 3% global/2 mm and 10% dose threshold (as recommended by the TG-218 report) in the condition of true composite measurement. However, these two plans did not exceed the 90% passing rate established by the TG-218 report as the universal action level. Local dose differences (PRIMO *vs*. measured) found in the point checks shown in Table 3 were mostly within ±2%. In general, a systematic underestimation was observed for the plans using 6 MV FFF energy. We

Table 4. Verification of the PRIMO simulated TG-119 mock and clinical cases *vs*. measurements with the Octavius 4D (O4D)

Energy	Plan ID[1]	3D GPR (%)[2]	Point[3]	Point Diff[4]	U (k = 2)[5]
6 MV	TG-119-Prostate	100	Isocenter	–0.3	0.9
	TG-119-Head and neck	99.4	Isocenter	–0.8	1.0
	TG-119-Cshape (easier)	99.9	2.5 cm off	–0.7	1.0
			Isocenter	0.0	
	1	94.3	Isocenter	0.8	1.3
	2	99.5		–0.6	1.0
	3	99.5		3.3	0.9
	4	98.0		1.9	1.0
	5	100		2.5	0.7
	6	98.2		–2.1	1.0
	7	99.8		0.7	1.0
	8	97.9		–0.3	0.9
	9	95.9		2.4	0.9
	10	98.0		2.0	0.8
	11	99.8		0.2	0.8
	12	96.8		1.6	1.0
	13	92.5		–0.2	1.3
	14	93.1		–2.1	1.1
	15	98.7		1.0	1.2
6 MV FFF	TG-119-Prostate	99.9	Isocenter	–1.2	0.7
	TG-119-Head and neck	99.0	Isocenter	–0.2	0.9
	TG-119-Cshape (easier)	99.7	2.5 cm off	–2.1	0.9
			Isocenter	–1.3	
	16	99.3	Isocenter	–3.5	0.9
	17	99.7		0.9	0.9
	18	100		–0.5	0.7
	19	99.6		–1.8	0.8
	20	99.9		–1.4	0.8
	21	100		–1.9	0.7
	22	100		–1.6	0.8
	23	99.9		–1.9	0.8
	24	100		1.9	0.7
	25	100		–0.8	0.7
	26	99.9		–2.2	0.8
	27	100		–2.7	0.8
	28	98.9		–0.6	0.9
	29	99.5		–1.9	0.8
	30	99.9		–1.4	0.8

[1]Details of the clinical plans are shown in Table 1; [2]GPR: gamma passing rate using global 3%/2 mm/10% dose threshold criteria; [3]Point selected for local dose difference calculation. 2.5 cm off means point located 2.5 cm anteriorly in respect to the isocenter; [4]Local dose difference (PRIMO vs. measured with O4D); [5]Simulation statistical uncertainty (k = 2)

suspect that this issue might be attributed to a slightly inexact modeling in PRIMO of the actual HD120 MLC, resulting in small differences in transmission and leakage, as we pointed out for 6 MV FFF beams from a TrueBeam equipped with a Millennium 120 MLC [19].

Table 5. Verifications of clinical plans calculated by Eclipse against Octavius and portal dosimetry measurements and PRIMO simulations

Plan ID[1]	Energy	Eclipse *vs* measurement			Eclipse *vs* PRIMO (over patient CT scan)	
		Octavius 4D		Portal Dosimetry	3D GPR (%)[5]	
		3D GPR (%)[2]	Point Diff (%)[3]	2D GPR (%)[4]	Body	PTV
1	6 MV	99.9	0.4	(100, 100)	99.7	99.8
2		99.1	–0.4	(99.9, 100)	99.9	100
3		99.7	–0.6	(99.6, 100)	99.9	(100, 100)
4		99.0	–1.0	(100, 100)	99.1	(99.7, 99.9)
5		100	–0.2	(100, 100)	99.8	99.5
6		98.8	–1.3	(99.8, 100)	99.2	98.4
7		100	–2.0	(100, 100)	100	(100, 100)
8		99.5	0.2	100	99.9	100
9		100	–0.6	(100, 100)	100	100
10		99.8	–0.7	(100, 100)	99.8	100
11		99.7	–0.5	(100, 100)	99.7	100
12		98.9	–1.2	(99.9, 100)	100	(100, 100)
13		99.1	–0.2	(99.7, 100)	99.7	(99.8, 99.8)
14		99.1	–2.2	(100, 100)	98.9	99.3
15		99.0	–1.5	(99.6, 99.8)	99.2	(99.1, 99.9, 100)
16	6 MV FFF	100	–1.9	(98.2, 99.7)	99.6	98.4
17		100	2.5	(98.4, 98.5)	98.9	95.4
18		100	1.9	(100, 100)	99.1	92.9
19		99.6	0.7	(96.8, 97.9)	99.8	99.9
20		99.6	–0.6	99.2	99.9	97.3
21		100	–0.3	(98.5, 100)	99.9	100
22		99.9	–0.7	(99.9, 100)	99.6	98.4
23		98.4	–0.9	(98.4, 99.2)	100	99.9
24		100	0.4	100	100	99.9
25		100	0.9	100	99.9	98.8
26		100	0.1	(99.0, 100)	99.4	99.7
27		100	1.5	(95.0, 96.7)	100	100
28		99.9	–0.1	(99.9, 99.9)	99.3	(100, 99.6, 99.3)
29		99.9	1.0	100	100	100
30		100	0.1	(97.5, 99.7)	99.9	100

[1]Details of the clinical plans are shown in Table 1; [2]3D GPR — gamma passing rate using global 3%/2 mm/10% dose threshold criteria; [3]Local dose difference (measured vs. Eclipse); [4]2D GPR — gamma passing rate using global 3%/2 mm/10% dose threshold criteria. Range of the GPR values obtained for all fields of each plan is given in parentheses; [5]3D GPR — gamma passing rate using global 3%/2 mm/10% dose threshold criteria, and analysis restricted to the Body and PTV structures. GPR values obtained for plans including several PTVs are given in parentheses

From these results, it seems reasonable to use PRIMO to check the Eclipse dose calculation of clinical plans with an accuracy within 3%/2 mm. As described in this study, PRIMO is also a valuable tool to be used during the commissioning of a TPS, to complement the checks based on measurements of clinical cases, as described in the TG-218 report (Tab. 5). However, the use of the criterion of 3% for the dose difference presumes that the accuracy of PRIMO itself is significantly less than this value. Therefore, we believe it is appropriate to expand the 3% gamma dose criterion to 5% to account for the ~3% accuracy found in this study for the dose distributions cal-

culated by PRIMO. For instance, this 5% criterion has been established for secondary dose calculation in the AAPM MPPG 11.a [33].

Several authors have described the use of MC software for dose calculation independent check of clinical plans designed using the HD120 MLC of a Varian TrueBeam linac. Bergman et al. [32] validated the BEAMnrc/DOSXYZnrc MC code with the Varian phase-space files for verification of 6 MV and 6 MV FFF VMAT treatment plans. They validate this MC code for patient-specific 3D verification of clinical VMAT plans. Paganini et al. described the suitability of using PRIMO to check clinical plans computed with the Acuros algorithm [34]. However, they focused on 10 MV FFF beams and the Varian phase space files were not used as particle sources for the PRIMO simulations.

As a limitation, our study has not included verification of single-isocenter stereotactic radiosurgery plans for multiple brain metastases. This topic was previously investigated for 6 MV FFF beams and a Millennium 120 MLC, concluding that PRIMO can be used as secondary dose calculation software to check stereotactic radiosurgery plans from Eclipse [19]. Similar behavior should be expected for PRIMO and the HD120 MLC model.

As far as we know, this study is the first evaluation/validation of the PRIMO software to simulate IMRT/VMAT plans using 6 MV and 6 MV FFF beams, the HD120 MLC model, and modeling PRIMO with the Varian phase space files.

Conclusion

PRIMO Monte Carlo software, in conjunction with the 6 MV and 6 MV FFF Varian phase-space files, has been validated for patient-specific 3D dose verification of 6 MV and 6 MV FFF treatment plans, designed with the HD120 MLC of a TrueBeam linac. The pretreatment PSQA checks showed dosimetrically acceptable/excellent agreement between the Acuros XB and measurements and between Acuros XB and PRIMO for the IMRT/VMAT plans.

Conflict of interest

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