Pre-treatment and in-vivo dosimetry of Helical Tomotherapy treatment plans using the Dosimetry Check system

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ABSTRACT: Dosimetry Check software is the world's first commercially available that provides patient-specific pre-treatment (PTD) and in-vivo transit (IVD) dose quality assurance of static and rotational intensity-modulated radiotherapy treatments. To investigate the feasibility of replacing pre-treatment verification with in vivo dosimetry for Helical Tomotherapy (HT), the commissioning and the application of the DC software was realised. Dose distributions were reconstructed from Mega Voltage Computed Tomography detectors, inside the phantoms or the patients for a total number of 6 treatment plans. Planned, reconstructed MV-CT dose and measurements using ionisation chambers and a matrix detector inserted in cylindrical and octagonal phantoms, respectively, were compared at the isocenter and in two dimensions using the γ_{2D} and γ_{10}-index (3%/3 mm). The dose reconstruction PTD and IVD methods of DC software provided, compared to detector measurements and for the 3 QA plans, similar point dose deviations and γ_{2D}-index passing rates: (0.41 ± 0.08)% vs. (-1.41±1.59)%, and (96.82 ± 0.94)% vs. (98.93 ± 0.63)%, respectively. In terms of γ_{10}-index passing rate, PTD and IVD modalities reached mean values of (99.37 ± 0.07)% and (97.21 ± 1.91)%, respectively. Also for the remaining 3 clinical plans, similar results were reached for IVD with γ_{10}-index passing rate reaching mean values of (95.94 ± 3.38)%. Therefore, either the PTD and the IVD verification modalities proved to be a very promising tool for the patient-specific QA of HT Plans.

KEYWORDS: -treatment dosimetry; in-vivo dosimetry; Helical Tomotherapy.

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Contents

1. Introduction

The complexity achieved by the most recent radiotherapy techniques necessitates dedicated quality assurance (QA) programs to ensure the quality of treatment and safety of patients. This is particularly true for Helical Tomotherapy (HT)[1], which represents one of the most advanced intensity-modulated radiation therapy (IMRT) modalities. To its periodic machine QA program has been added a patient-specific delivery quality assurance (DQA) program to ensure the quality of each individual patient treatment plan[2]. The DQA procedure consists of comparing measured versus calculated doses in a phantom by means of many single-point and array detectors. The differences between the measured dose distributions and their calculated counterparts are frequently compared using gamma (γ) analysis[3]. High values (≥ 95%) of γ passing rates are currently used as a key feature to define plans that are acceptable for treatment, although the correlation between such a metric and clinically important patient dose-volume histogram (DVH) errors has proved to be extremely weak[4]. Although the conventional γ–based metric does not seem sufficiently safe or effective, it nevertheless represents the gold standard in the evaluation methods. However, the action levels for considering a treatment plan acceptable should be based on metrics that directly reflect the impacts on the dose delivered to the patient[5]. Therefore, systems that are able to predict and visualize the delivered dose distributions, not on a phantom, but directly on the patient computerized tomography (CT) images, together with their relative target and organs at risk DVHs, would represent a significant improvement.

The verification process could be pre-treatment dosimetry (PTD)[6] or in-vivo dosimetry (IVD)[7], depending on when it is carried out. In the former case, plan verification is performed

on a phantom before patient treatment, while in the latter the verification is carried out directly on the patient during treatment.
Recently, the Dosimetry Check (or DC, Math Resolutions, LLC, Maryland, USA) system was introduced on the market. It is able to reconstruct the dose delivered during HT treatment on patient CT data, without using a phantom and by processing the transit dose in the therapy phase. In both cases, the signal processed by the DC software is acquired by the MVCT HT detectors. The main advantage of the IVD compared to the PTD modality, or to other on-line dose verification techniques[8], is its ability to reconstruct the dose without any pre-therapy measurements so as to be able to consider the real impact of the delivery on the patient's actual anatomy.
The aim of the study consists therefore in commissioning and evaluating the DC software in pre-therapy and in-vivo dosimetry mode by using the γ base metrics, and to verify some clinical plans in terms of IVD method.

2. Materials and methods

2.1 Helical Tomotherapy unit

The HT system is a rotational intensity-modulated radiotherapy unit which combines a mega-voltage (MV) CT scanner and a conventional 6MV linear accelerator coupled with a pneumatic multi-leaf collimator (MLC) served by a common treatment couch. The treatment arcs are delivered in a spiral, or helical, manner in the fashion now familiar on spiral CT. Treatments planned on this system use 51 equispaced beam directions per gantry rotation, and the jaws can be opened so as to form a 1.0 cm, a 2.5 cm or a 5 cm wide fan beam (indicated as FW in the text).
HT has its own completely integrated treatment planning system (TPS), which implements a parallel processing architecture for the plan calculation. The process is split into a pre-calculation and the optimization stage, where the final plan calculation is performed with a collapse-cone convolution algorithm.

2.2 Dosimetry devices

For routine DQA of HT plans, cylindrical solid water phantom (or cheese phantom[9]) with multiple ionization chambers is commonly used. The cheese is a cylinder of 15 cm in radius and 15 cm in length, with a linear series of holes that extends on one face of the phantom for ionization chamber measurements. To perform the commissioning of the DC software with the cheese phantom, the point doses were measured using 0.057 cm^3 Exradin A1SL ion chambers (Standard Imaging, Inc., Middleton, WI).
A 2D array vented ion chamber matrix (seven29, PTW, Freiburg, Germany) equipped with 729 ionization chambers uniformly arranged in a 27×27 matrix with an active area of 26×26 cm^2 was used for the study[8]. An octagon-shaped phantom (Octavius II Phantom, PTW, Freiburg, Germany) with a central cavity is used to insert the 2D ion chamber array. The combination of the 2D array with the Octavius phantom proved to be a fast and reliable method for pretreatment verification of rotational treatments[10], and is the system that our center uses for treatment plans verification. In this study, it was considered as the reference dosimeter to carry out the dosimetric tests and is indicated as the Octavius.
The detector used in the HT system is an integrated arc-shaped CT xenon detector (MVCT), consisting of 738 detector cells. Each cell is comprised of two gas cavities that are divided by a thin tungsten septal plate. The distance between the two plates defines the size of a single gas

cavity. The separation is 0.32 mm, which is also the thickness of the plates. The septal plates are 2.54 cm long in the beam direction. A potential of 1300 V is applied across every odd plate, and the even plates act as charge collection electrodes for the charge produced in the gas cavities. The gas cavities are filled with xenon gas under high pressure. The detector focus point is in front of the detector, 25.6 cm away from the photon source, toward the isocenter. The front face of the detector is placed 132.3 cm away from the photon source. The HT detector array collects and stores exit dosimetry data during treatment delivery in the form of sinograms. These sinograms contain a record of the radiation exiting the MLC and passing through the patient during the treatment delivery and constitute the basis from which it is possible, in theory, to reconstruct the dose delivered to the patient.

2.3 Dosimetry Check

The DC software is a commercially available system that provides patient-specific PTD and IVD QA. The software package (version 4 release 1, Math Resolution LLC, Maryland, USA) was used to reconstruct in 2D and 3D the dose of the treatment plans delivered to the phantoms and to the patients, using both methods of dose reconstruction the system has.

The PTD verification mode is performed without any QA phantom or additional detector system, with the HT couch outside the unit bore during the MVCT detector acquisition. The recorded fluence is compared to that planned and used to reconstruct the 3D dose distribution by considering the CT image set of the patient. The IVD verification mode uses the sinogram, exiting from the patient during the treatment. This exit sinogram is deconvolved by a kernel specifically fitted to the MVCT detector to obtain the corresponding primary treatment fluence map (i.e., the entrance sinogram). The dose is then computed using this fluence map with a pencil beam dose algorithm in the phantom's and patient's planning CT[11]. Either the planning CT or the MVCT imaging data can be used to reconstruct the patient's anatomy.

2.4 Commissioning of the Dosimetry Check software

We configured and optimized the dose reconstructor of the DC, a process that requires a fine-tuning between its calculation algorithm and the dosimetric data of the HT unit. The beam data acquired during the Tomotherapy acceptance test (ATP) procedure were used for this purpose.

The absolute calibration of HT unit was performed using a helical plan, one for each FW, which delivers a homogeneous dose of 200 cGy to a 6 cm diameter by 6 cm length cylindrical target in the cheese phantom. These plans were referred as QA plans and calculated with a dose grid size of 2x2x2 mm^3

The correct configuration of the system was verified by comparing some measured and simulated depth dose and profiles data in its analysis environment, and by testing the dosimetric agreement of some measured and reconstructed QA plans. Three ionization chambers, 1cm equispaced, were inserted on the cheese phantom, in the center of the target volume irradiated with the QA plans. The reconstructed doses to the ionization chambers were estimated, and the output difference was thus determined by comparing the measurements with the recalculated doses. During these tests, the reconstructed doses calculated by DC software for the PTD and IVD modalities were verified. In all cases, an average of 3 measurements was calculated.

Different dose grids in DC were tested from 2 to 8 mm, in order to reach a good compromise in terms of acceptable calculation times and high level of accuracy in the reconstructed dose. The QA plans simulated and measured on the cheese phantom were also used to conduct these tests.

Our current hardware setup for DC is a workstation with Intel dual core CPUs (2.2GHz), 3 GB of RAM and Windows XP 32-bit.

2.5 Phantom and patient treatment plans

The verification of the dose was performed on the 2D array detector, recomputing the same QA plans in the Octavius and comparing them with the DC software (both in PTD and the IVD working modalities).
For the IVD mode on patients, the analysis was performed on three different clinical treatment plans selected randomly: a brain, a prostate and a head and neck cancer patient. The prescribed dose for the plans were 30 Gy, 72.8 Gy and 60 Gy, delivered in 3, 28 and 30 treatment fractions, respectively. All plans were calculated by TPS on the preplanning CT data with a calculation dose grid of 2x2x2 mm^3. The treatment planning parameters were: FW=1.0 cm for the first case and FW=2.5 cm for the remaining cases, with Modulation Factor (MF) equal to 1.7 for the brain and head and neck cases, and 2.8 for the prostate. The pitch was set equal to 0.215 in all cases.

2.6 Metrics for the dose evaluation

To quantify the differences between calculated and measured doses, we introduced 2D and 3D γ based quantities, γ_{2D} and γ_{10}[12]. The well accepted 3%(global)/3mm, 10% threshold criteria was used for the 2D γ-analysis . The 3D γ pass rates (the percentage of voxels with $\gamma \leq 1.0$) within the $V_{10\%}$ volume was used instead, where $V_{10\%}$ refers to the 3D volume within phantom or patient body that is enclosed by the 10% isodose surface, normalized to the maximum dose in the plan[12]. The γ pass rates of 3%/3mm was adopted in this case as well. The criteria of the AAPM Task Group 119[13] were adopted to consider a treatment plan acceptable and deliverable when its measurement is performed and compared with its calculated data. Following the TG formalism, we considered a plan acceptable when its 2D (γ_{2D}) or 3D (γ_{10}) γ passing rates was greater than or equal to 95%.
By means of software specifically developed for the γ-analysis evaluation (Verisoft, v4, PTW, Freiburg, Germany) and with DC dose evaluation tools, γ-index and dose profile comparisons were created to compare (in 2D with the 2D array and in 3D with the MVCT detectors) the two different PTD and IVD reconstruction dose methods with the Octavius.

3. Results and discussions

3.1 Dosimetry Check evaluation

A poly-energetic kernel dose was obtained in the DC system for each commissioned fan beam, based on the producer's procedure for the MVCT detector calibration[14]. For each FW, a comparison was performed between the depth dose and profile curves simulated from the kernel of the DC algorithm in water with respect to the ATP data. Figure 1 shows the high level of dosimetric accuracy reached in the configuration of the DC software.
Using our hardware configuration, the time required by DC software to recalculate a simple HT plan on the phantom CT scans in both PTD and IVD modalities can be extremely long and varies from 0.75 to 21.2 hours. Table I reports the calculation grid size, together with the γ_{10} passing rates and the computation time for each FW in the PTD modality. These results are also representative of the IVD mode. The grid size of 5 mm was chosen as a best compromise of the

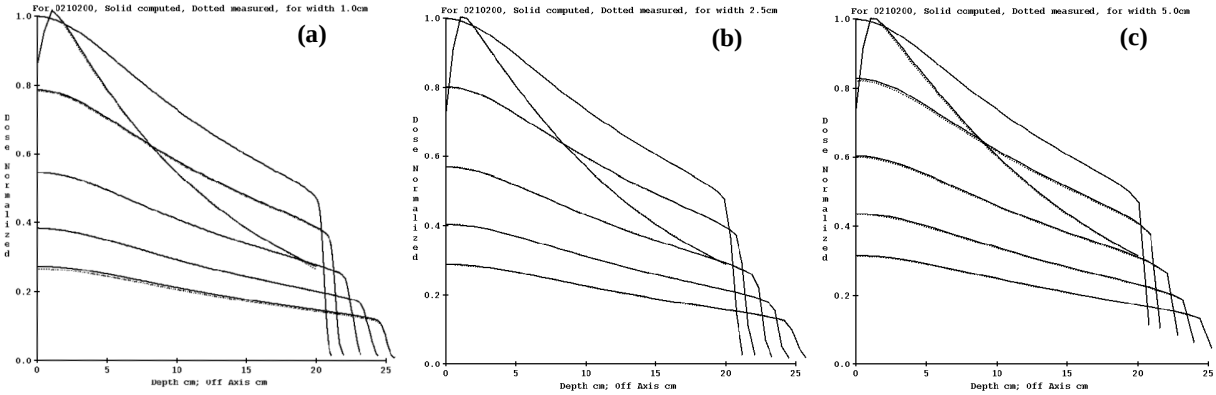

Figure 1. Comparison of the HT profiles between DC (solid lines) and ATP (dotted lines) for a) 1.0cm, b) 2.5cm and c) 5.0cm FW.

Table I. Results of the QA plan comparison, expressed as γ_{10} and computational times, between the TPS and PTD mode, for each FW, by varying the DC voxel sizes.

Voxel size (mm)	FW=1,0cm	FW=2.5cm	FW=5.0cm	Comp. time (h)
2	100.00%	100.00%	100.00%	21.25
3	99.20%	99.00%	99.90%	7.12
5	95.70%	95.90%	95.90%	2.25
8	90.10%	90.00%	90.05%	0.75

dose reconstruction in terms of calculation time (~2 hours) and level of the reachable dosimetric accuracy (γ_{10} passing rates > 95%).

Using the same QA plans, the delivered doses in the phantom calculated by the PTD and IVD modalities, considering the ionization chamber measurements as reference, provided average point dose deviations equal to (0.41 ± 0.08)% and (-1.41±1.59)%, respectively.

The transversal and sagittal dose profile comparisons of the same QA planes, simulated by the TPS and reconstructed in both PTD and IVD modalities, are presented in figure 2. The figure shows the dose profiles passing through the target volume into the cheese phantom for each FW. In general, for the IVD the dosimetric agreement in comparison with the TPS calculation is slightly lower than that reached by the PTD mode. One of the main problems in IVD mode could be the set-up uncertainties of the phantom in the measurement phase, compared to the PTD mode where non phantoms are used. However, these dosimetric differences appear not very significant since the reconstructed dose profiles are very similar and in good agreement with each other.

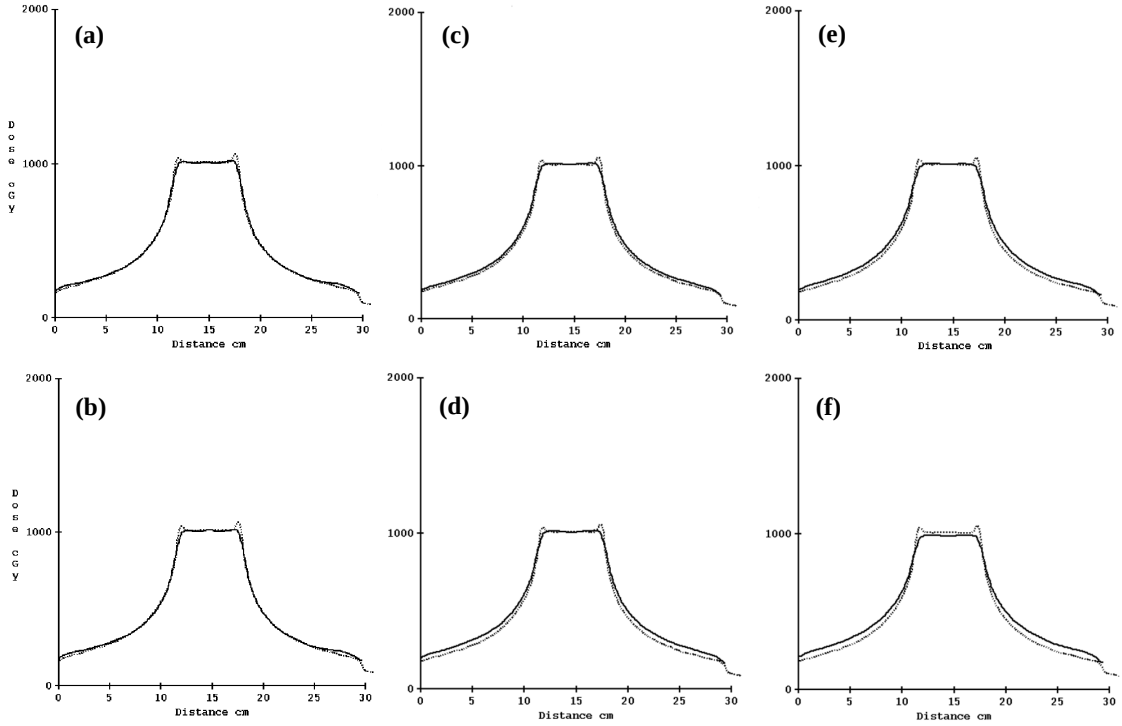

Figure 2. Dose profile comparisons of QA plans for 1.0cm (a, b), 2.5cm (c, d) and 5.0cm (e, f) FW between TPS (dotted line) and DC reconstruction modes (solid line): PTD (a, c, e) and IVD (b, d, f).

3.2 Phantom plans dose QA

Table II shows both the γ_{2D} agreement between Octavius vs. TPS and DC vs. TPS in PTD mode for the same QA plans considered previously. In this 2D analysis, we chosen in the DC recostructed dose the plane corresponding to the Octavius detector active area. The results for both systems are very similar, exceeding in all cases 95% passing rates. In light of these data and of the good correspondence obtained between the two dosimetric systems, the DC software in its PTD reconstruction mode seems to be a reliable tool for the dosimetry verification of these artificial HT plans.

Table II. QA plan verifications in terms of 2D γ-analysis, considering the TPS as reference, between the Octavius measurements and PTD dose reconstructions.

FW (cm)	OCTAVIUS vs TPS	PTD vs TPS
1.0	98.92%	97.83%
2.5	99.57%	96.65%
5.0	98.31%	95.97%

In order to compare the dose distributions reconstructed in 3D from the DC software in PTD and IVD modes, the QA plans were delivered and acquired for both modalities. In this case, the dose reconstruction was done on the Octavius. Table III shows the results in terms of 3D γ-index. Applying the γ_{10} passing rate by varying the HT fan beams, the PTD and IVD modalities

reached very similar results, providing mean values of (99.32 ± 0.02)% and (97.40 ± 2.09)%, respectively.

	Plan analyzed	FW (cm)	TPS dose (Gy)	DC dose (Gy)	Dose difference (%)	Dose mode	γ_{10}
a)	QA plan	1.0	10.17	10.20	0.34%	PTD	99.45
	QA plan	1.0	10.17	10.21	0.42%	IVD	98.34
	QA plan	2.5	10.12	10.16	0.39%	PTD	99.33
	QA plan	2.5	10.12	9.90	-2.24%	IVD	98.29
	QA plan	5.0	10.11	10.16	0.49%	PTD	99.33
	QA plan	5.0	10.11	9.86	-2.42%	IVD	95.01
b)	Brain	1.0	26.35	26.50	0.60%	IVD	99.47
	Prostate	2.5	73.20	72.98	-0.31%	IVD	95.61
	Head and neck	2.5	61.61	62.24	1.03%	IVD	92.73

Table III. a) Comparison of QA plan verifications between PTD and IVD mode in terms of point dose differences and 3D γ-analysis estimated on the full treatment. b) Results of patient plan verifications by using only the IVD mode.

The values of the reference point doses (relative to the target centroids) also provide dose percentage differences not exceeding 2.5%. The lower levels of agreement obtained for the IVD compared to the PTD modes are correlated to phantom set-up errors that may have occurred during the measurement phases.

3.3 Patient-specific dose QA

The results concerning the DC-IVD mode on HT patient treatments are reported in Table III in terms of γ_{10} passing rates relative to the body volume and dose difference in the high dose regions. All plans provide reference point doses with discrepancies that slightly exceed 1%, and values of γ_{10} pass rates that remain well above 90%. Figure 3 illustrates the 2D isodose overlay on the axial and sagittal planes, passing through the centres of the target volumes, together with selected dose profiles for the same clinical plans. Looking at the figure, the recalculated isodose lines (in green) show a very good agreement with those (in magenta) calculated by the TPS. In particular, the selected profiles, corresponding to the yellow dashed lines, confirm the high level of agreement reached for the brain tumour case. A very good agreement is also visible in the prostate case, where the mismatch in the two edges of the peak and the slight variation in the shape of the profile tails have been ascribed to the existence of set-up errors and regions of inhomogeneity. Larger deviations, definitely related to the same reasons (the presence of trachea and oesophagus) and due to greater anatomy deformations, are visible in the head and neck case. In the same figures 3, DVHs of the planned (dotted line) and reconstructed (continuous line) dose distributions are reported where the target volumes and the principal organs at risk are shown. While lower values of mean doses are in general received by the targets, if the data are compared with the corresponding planned values, for the organs at risk, instead, the effect is generally the opposite, where the doses that they receive are on average higher.

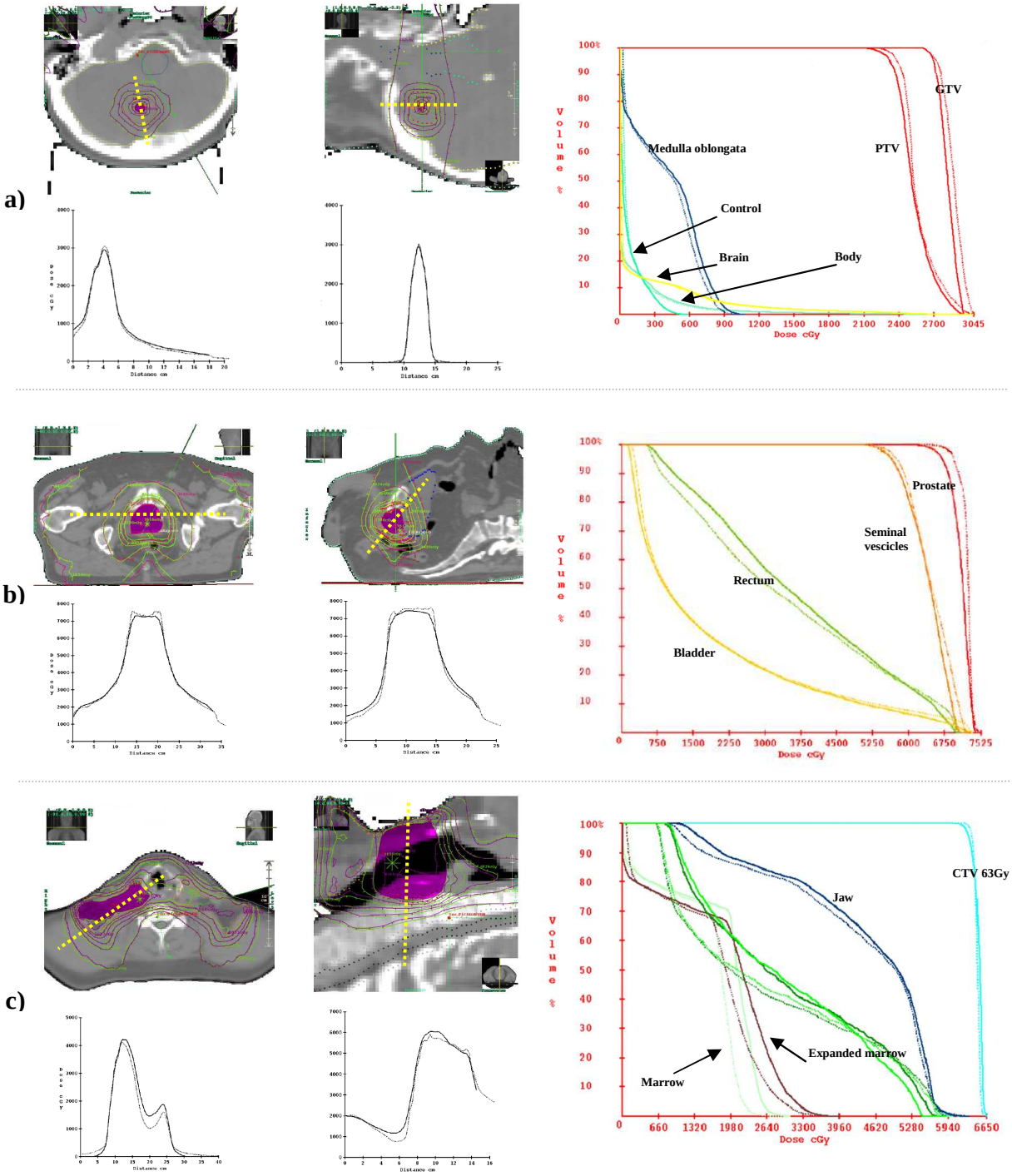

Figure 3. Patient-specific dose QA, performed with DC - IVD mode for the (a) brain, (b) prostate, and (c) head and neck plans. In the first two columns are reported the isodose lines, superimposed on the same patient CT slice, obtained with the IVD (green) and TPS (magenta). Below each CT slice, representing an axial (first column) and sagittal (second column) plane, the corresponding dose profiles, referring to the yellow dotted lines, are also shown. The corresponding target and organs at risk DVHs are also described in the third column (dotted lines - TPS, solid lines - IVD).

4. Conclusion

The Dosimetry Check system, using either the PTD or the IVD approach, has proved be a reliable system for the patient-specific dose QA of the Tomotherapy plans. The DC software is able to reconstruct in 3D the dose delivered to the patients with an high level of accuracy and reduces the HT time of the pre-therapy dose checks, either because the phantom set-up is not required (in PTD mode), or because the patient-specific dose QA is carried out during the patient treatment sessions (in IVD mode). On the other hand, using the pencil beam-based DC calculation algorithm, both the PTD and IVD verification methods represent an excellent tool for the plan dose reconstructions, particularly where the treated volumes are not too inhomogeneous. While the long calculation times are currently a strong limitation, the company is working to implement faster computation methods (GPU computing).

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