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Original paper

Preliminary evaluation of a novel secondary check tool for intensity modulated radiotherapy treatment planning

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ABSTRACT

Purpose: To evaluate the dosimetric accuracy of the Delta4 Insight (DI) secondary-check dosimetry system.
Methods: Absolute dosimetry in reference conditions, output factors, percent depth doses normalized and off-axis dose profiles for different field sizes calculated by DI were compared with measurements. Dose calculations for 20 clinical IMRT/VMAT plans generated in the TPS using both AAA or AcurosXB algorithms were compared with measurements. The average difference between calculated and measured point dose in high-dose region was calculated for all cases. 3D dose measurements were performed in Delta4 Phantom+ and a comparison between calculated and measured dose distributions was performed by means of the gamma analysis with 3 %/2 mm criteria. The dose distributions calculated by DI for 20 IMRT/VMAT plans were compared with those calculated by the TPS.
Results: The absolute dosimetry computed by DI showed dose value in agreement with the measured one within 0.3 %. The average differences between measured and calculated output factors were less than 2.5 %. The average PDD differences were less than 0.6 %. An excellent agreement between calculations and off-axis measurements is found. The point doses calculated for the 20 recalculated plan showed good agreement with measurements with average differences less than 0.5 %. The average gamma pass rate values for the Delta4 Phantom + 3D dose analysis was greater than 97.%. The comparison of DI with theTPS showed good agreement for the used metrics.
Conclusions: Delta4 Insight may provide a useful independent secondary dose verification system for IMRT/VMAT plans, complementing the traditional global QA protocols.

Introduction

Intensity modulated radiation therapy (IMRT) and Volumetric modulated arc therapy (VMAT) have become the predominant radiotherapy techniques for a variety of treatment sites. The steep dose gradients generated by means of dynamical modulation of multileaf collimator motion, gantry rotation speed and dose rate have increased type and frequency of potential errors. Consequently, extensive pre-treatment quality assurance program (QA) is needed for the dosimetric verification of the plan in order to ensure the accuracy and safety of the treatment.

In most of the radiation oncology departments, QA program consists of two components: a machine QA, generally performed accordingly with AAPM TG-100 [1] and AAPM TG-142 [2] methodology, that ensures that each component of the delivery system is working within tolerance and a patient-specific pre-treatment IMRT QA [3], that verifies the accuracy of IMRT plan dose calculation and detects relevant errors in the radiation delivery. The patient-specific pre-treatment QA consists in the verification of the primary dose calculation algorithm for each plan using measurement-based techniques and/or an independent secondary check calculation, as suggested by the Report 83 of the International Commission on Radiation Units and Measurements (ICRU) [4].

The independent dose calculation method [5,6] shows many advantages: it is far less time consuming than experimental methods for patient-specific QA; it does not require machine time or additional efforts to perform the measurements; it is performed in the individual patient geometry including heterogeneities; it has more calculation comprehensiveness, in terms of 3D dose calculations based on the

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patient's CT dataset, with analysis tools, such as DVH verification [7].

A new generation of calculation-based QA tools are coming into clinical practice that are based on more advanced dose calculation algorithms [8–10]. In the ICRU Report 83, Monte Carlo (MC) algorithms [11] are indicated as acceptable independent dose calculation methods, especially for determining the absorbed dose in heterogeneous tissues.

Recently, a new commercial secondary check tool based on a Monte Carlo dose engine has been developed Delta4 Insight (DI) (ScandiDos, Uppsala, Sweden). Clinical validation of the system was not heretofore reported. The purpose of this work is to evaluate the dosimetric accuracy of the system for clinical use by comparing output factors (OF), percentage depth doses (PDD), profiles, point dose values and dose distributions independently calculated with measured ones in phantom geometries. Finally, dose calculated for IMRT and VMAT plans by the Delta4 Insight was compared to that calculated by the Eclipse Treatment Planning System (TPS) (Version 15.6, a Siemens Healthineers Company, Palo Alto, CA, USA).

Materials and methods

Delta4 Insight software

Delta4 Insight (DI) is a secondary-check dosimetry system that performs a full recalculation of dose on the patient CT-dataset using treatment parameters exported from the primary treatment planning system and an independent Monte Carlo calculation algorithm. Delta4 Insight MC algorithm uses MC simulator Geant4 [12,13] to generate particle tracks in single-material phantoms; then, the events are post-processed and a random subset is selected as representative of a specific particle behavior.

The convergence criteria in the Monte Carlo calculation can be selected by the user; in such a way, a trade-off between calculation time and relative error can be attained in the way best suited for user's workflow. A convergence criteria of 1 % was used in the study.

The Delta4 Insight MC algorithm relies on specific material definitions to model the patient. The dose calculator maps input Hounsfield Unit data to materials on a voxel-by-voxel basis. This mapping is based on a user-defined Hounsfield Unit to mass density table specified in the software.

DI operates on DICOM objects (CT images, RT Dose, RT Structure, and RT Plan) exported from the TPS. The necessary treatment field information is extracted from the RT plan file and then passed to the MC algorithm for the calculation of the three-dimensional dose distribution, dose-to-water or dose-to-medium, within the CT dataset associated with the plan.

The dose calculated by the software is then automatically compared with the dose calculated by the TPS performing a global 3D gamma [14] and Dose-Volume Histogram (DVH) analysis against defined levels to ensure doses to both the target and organs at risk are within criteria.

DI has a pre-defined list of Target Plan Objectives that can be edited and enabled/disabled. For the organ at risks, the RTOG protocols dose limits are implemented and a list of organ at risk objectives will be selected based on the number of planned fractions in the DICOM RT plan. Lists exists for treatments with 1, 3, 4, 5 and $\geq$ 15 fractions. DVHs calculated by DI and TPS are automatically checked against the relative DVH limits.

DI can utilize either a reference "golden" beam model (GM), using accelerator-specific universal beam data, or a customized model (CM) using a subset of site-specific depth-dose values, output factors and off-axis ratios.

The study was performed using the beta version 1.0 of the software.

Pre-clinical validation

The accuracy verification of the Delta4 Insight system was done in several steps. To begin, the absolute dosimetry, output factors, percent depth doses and profiles calculated by the software were compared with data measured on a TrueBeam (Varian, a Siemens Healthineers Company, Palo Alto, CA, USA) equipped with a standard Millennium 120 multileaf collimator and clinically commissioned energies of 6 MV FF and 6 MV FFF. The absolute dosimetry mesurement was executed in reference conditions (10 $\times$ 10 cm^2, SSD 100 cm, depth 10 cm) using a PTW 30013 farmer type Ionization Chamber (IC). The measure was performed following IAEA TSR398 indications [15]. For relative dosimetry field sizes ranging from 2 $\times$ 2 cm^2 to 20 $\times$ 20 cm^2 were acquired using IBA CC13 and CC01 IC. Output Factors were obtained at a depth of 10 cm. Profiles were extracted at depth of d_{max}, 5 cm, 10 cm and 20 cm. Percentage depth dose (PDD) curves were normalized to d_{max}; then, the difference between DI calculated values and measured data was computed for each data point from d_{max} to a depth of 25 cm and the average difference was computed for each field size. Dose profiles were normalized to the central axis and then a gamma analysis was performed with 2 %/2mm and 1 %/1mm as passing criteria.

Table 1
Treatment site, beam energy and calculation algorithm of the IMRT/VMAT plans used in the study.

Treatment site	Energy	Algorithm
Lung SBRT	6 MV FFF	AXB
Lung	6 MV	AXB
Prostate	6 MV	AAA
H&N	6 MV	AAA
Brain	6 MV	AAA

In the next step, the accuracy of Delta4 Insight system was evaluated by comparing dose calculations for 20 clinical IMRT/VMAT plans (4 for each of the main treatment site) with measurements. For each of the selected treatment plans, whose characteristics can be found in Table 1, two verification plans were generated in the Eclipse Treatment Planning System on RW3 solid water phantom (PTW Freiburg) and Delta4 Phantom+ (ScandiDos, Uppsala, Sweden) [16,17] in order to obtain point dose and 3D dose verification respectively. As reported in Table 1, AAA or AcurosXB (dose to medium) algorithm were used for dose calculation depending on the treatment site. The plans incorporated tracking of the primary jaws to minimize MLC leakage.

Then the 40 RT plans were individually exported from Eclipse to the DI system for the secondary dose calculation performed with both the GM and CM model.

Point dose in high-dose region was extracted from each of the Delta4 Insight plans and compared to point dose measured in the RW3 phantom by means of a 31016 Ion Chamber (PTW Freiburg). The point dose was determined in DI by placing a region of interest with the same geometry as ion chamber sensitive volume and recording the average dose to the ROI. The average difference between calculated and measured dose was calculated for all cases. As reported in ESTRO Booklet 9 [18] and AAPM TG 218 [3] report tolerance limits of 3 % for ion chamber measurements in target areas and action limits of 5 % for point dose verification were used.

3D dose measurements were performed in Delta4 Phantom+. A dose distribution was extracted from the Delta4 Insight plans in the same geometry as the phantom, then a comparison between calculated and measured 3D dose distribution was performed and a gamma analysis was performed using the Delta4 software to determine the gamma passing rate (GPR) at the 3 %/2 mm criteria. An overall average was then computed for all the 3D dose distribution analysis. Tolerance and action levels suggested by AAPM TG 218 [3] were used. Using global normalization in absolute dose and a 10 % dose threshold, the GPR should be $\geq$ 95 % and $\geq$ 90 %, for tolerance and action limits, respectively.

Finally, the accuracy of the Delta4 Insight system was evaluated by comparing dose calculations for IMRT/VMAT plans in actual patient data with those calculated by the TPS. For each of the 20 selected

Table 2
Average difference ± standard deviation between measured and calculated output factors.

DI Model	6 MV	6 MV FFF
Customized	0.1 %±0.3 %	−0.2 %±0.1 %
Golden	−0.3 %±0.4 %	0.2 %±1.3 %

treatment plans, the dose distributions calculated by the DI system were compared with those from the TPS using the following metrics: target D95% percent difference, homogeneity index (HI) defined as (D2%-D98%)/D50% [4], and global 3D gamma pass rate (GPR) over the entire dataset. A gamma criterion of 3 %, 2 mm was used for this pre-clinical gamma analysis.

For DI based on MC algorithm, the dose has been reported as dose-to-medium and a statistical uncertainty of 1 % has been selected.

Results

The absolute dosimetry computed by DI system in reference conditions showed a dose value in agreement with the measured one within 0.3 % for both energies and beam models.

The average differences (±standard deviation) between measured and calculated square fields output factors for the two energies and beam models are reported in Table 2. The lowest agreement of 2.4 % was found for the GM model, 6MV FFF and 2x2 cm^2 field size.

The average PDD differences are less than 0.3 % and 0.6 % for 6MV and 6MV FFF respectively for both the golden and customized models. A maximum value of about 1 % is obtained for field size 20x20 cm^2 and 6MV FFF energy (Fig. 1).

An excellent agreement between Delta4 Insight calculations and off-axis measurements is found, with a gamma passing rate of 100 % and ≥ 90 % at the 2 %/2 mm and 1 %/1 mm criteria respectively, for both the energies and models. Gamma only failed in small regions at the boundaries of the beam profile with high-dose gradients.

The DI point doses calculated for the 20 recalculated plan in RW3 phantom by DI system show good agreement with ionization chamber point dose measurements with average differences of −0.5 %±1.4 % and 0.4 %±1.1 %, for GM and CM models respectively, with dose differences within the chosen clinical action threshold of 5 % and a maximum value of 3 %. Neither treatment sites, nor beam energy or treatment technique had a significant effect on the differences between DI calculations and measurements. The lower agreement was found in SBRT lung treatments for GM model.

The average and the standard deviation of gamma pass rate values for the full dataset of Delta4 Phantom+ 3D dose analysis is 97.9 %±2.8 % and 97.3 %±3.3 %, for GM and CM models respectively. The GPR average values are all above the chosen clinical tolerance threshold of 95 % and all the values were found to be above the action level of 90 % although values close to the action level was found in SBRT lung treatments for GM model.

In Fig. 2, as example, the comparison of the DVHs calculated by TPS and DI system on the patient CT-dataset is shown for a head and neck treatment site. In general, DI tended to report a less homogeneous dose to the target compared to TPS. A more rounded shoulder and an higher maximum point dose were observed for the DI calculation.

The results of the comparison of Delta4 Insight system with the Eclipse TPS are reported in Table 3, where average, standard deviation, maximum and minimum values of the target D95% percentage difference, 3D global gamma pass rate and HI difference are reported. A positive percent difference indicates that DI calculated a higher value for a given statistic.

The GM model showed a lower target D95% than TPS for both the algorithm, with a target D95% difference ranged from −3.2 to 1 %, while the CM model resulted in a broader distribution.

The gamma analysis of the 3D dose distributions showed a good agreement between DI and TPS with average GPR values above the clinical tolerance threshold of 95 %. The worst agreement was observed in lung cases, where the presence of tissue inhomogeneity and the corresponding complex dose distributions presumably yield to lower GPR values.

As shown in Fig. 3, because of the fundamentally different method each algorithm uses to account for heterogeneities and re-build-up of dose, DI calculated a slightly higher absorbed dose in low-density lung tissue as compared with the TPS. Dose values showed significant point differences, due to the statistical behavior of MC calculation algorithm,

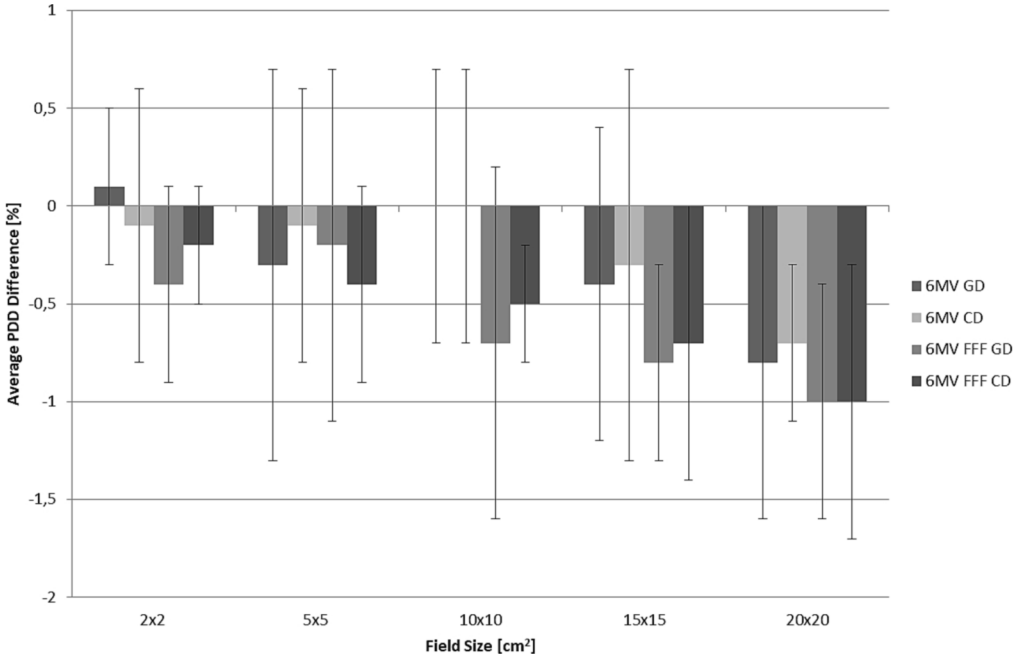

Fig. 1. Average PDD percentage differences for 6MV and 6MV FFF beams for both golden and customized models. Data are shown for different square field sizes. Error bars represent ± 1 standard deviation.

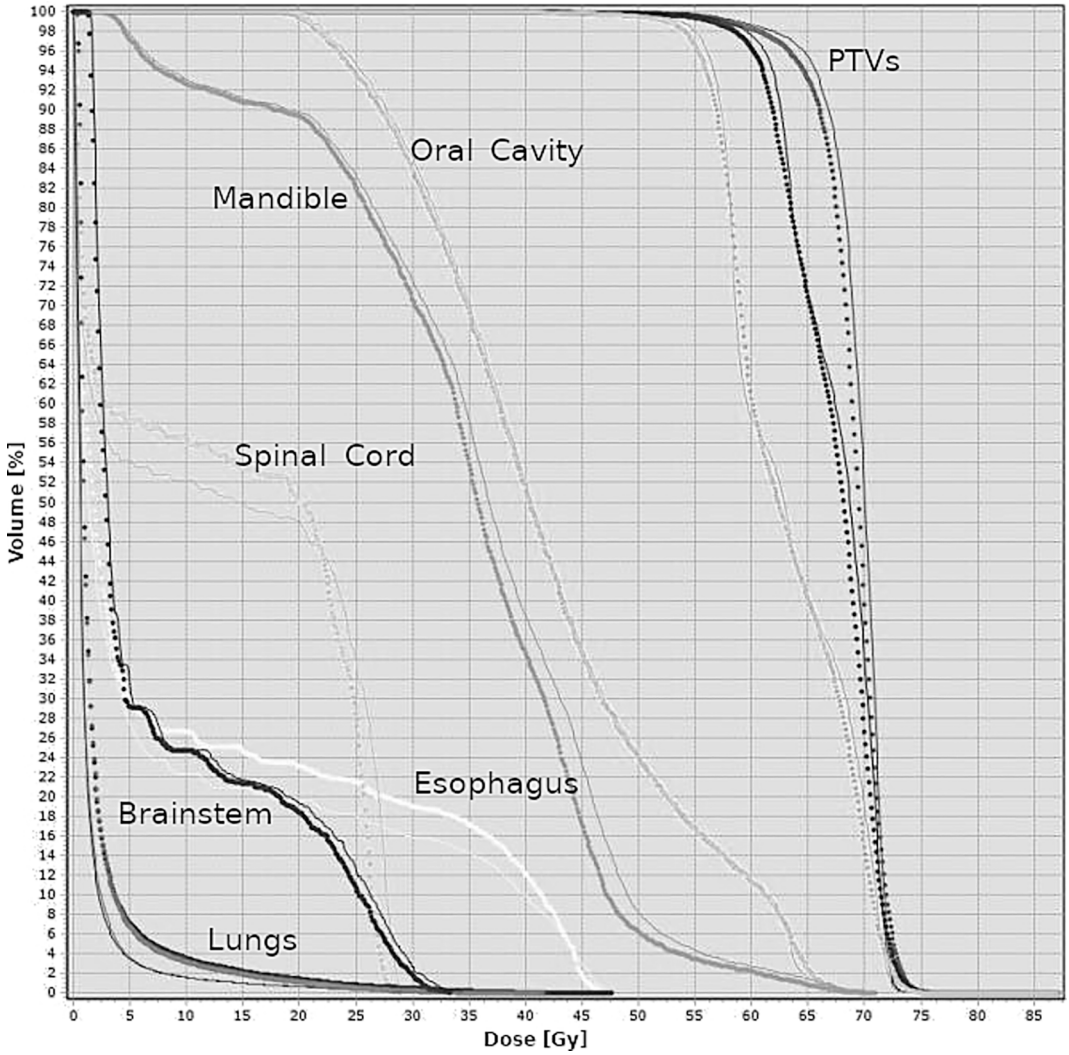

Fig. 2. DVHs calculated by TPS (solid) and DI (dashed) system on the patient CT-dataset for a head and neck treatment site.

Table 3
Comparison of Delta4 Insight system with the Eclipse TPS for different statistics.

	Target D95% percentage difference (%)		3D global gamma pass rate (%)		Homogeneity Index difference	
	CM	GM	CM	GM	CM	GM
Average	−0.1	−0.4	98.1	98.4	0.04	0.04
Standard Deviation	1.7	1.2	1.3	1	0.01	0.02
Maximum	2.5	1	99.5	99.6	0.06	0.07
Minimum	−3	−3.2	94.8	96.1	0.02	0.02

but the average dose difference of about 2 % is adequate.

HI differences always showed positive values compatible with higher inhomogeneity distribution in Monte Carlo calculation. However, the average value is less than 0.05.

The agreement between organ at risk objectives was very good; the maximum difference was obtained for anatomical regions located in high-dose gradients which contain significant density inhomogeneity (Fig. 2).

Discussion

In this study, we have presented the preliminary steps needed to commission a system that will be used as a secondary verification tool of a clinical TPS using a fully automated computer system.

Point and planar doses calculated by the software showed an excellent agreement with the measured data.

The validation measurements performed using the phantom yielded very good results for DI. Point dose difference was below the action level of 5 % for the full dataset. A global average GPR value greater than 97 % was found by running the Delta4 gamma analysis over all 20 plans for both the DI beam models. The observed values showed a narrow distribution with a global standard deviation of about ± 3 % for both models. The cases below the 95 % threshold or close to the 90 % lower limit were studied in more details: the largest deviation was observed in high complexity SBRT treatments where DI tends to overestimate dose respect to measurements.

DI agrees very well with the considered primary TPS over a large variety of treatment sites. No clinical cases showing a difference for target D95% and 3D global gamma pass rate greater and lower respectively than our clinical tolerances of 5 % or 95 % were found. The dose differences reported by DI are likely due to dissimilarities between the dose calculation algorithms. The largest deviations observed in the low-density regions is due to the differences in the way each algorithm handles heterogeneous materials [19].

Studies can be found in literature based on the same acceptance criteria used in this work (3 %,2mm for global normalization). Nelson et al. [20] tested Mobius3D measurements with a solid water phantom. Over 12 VMAT plans they obtained a percentage dose difference (%D_{diff})

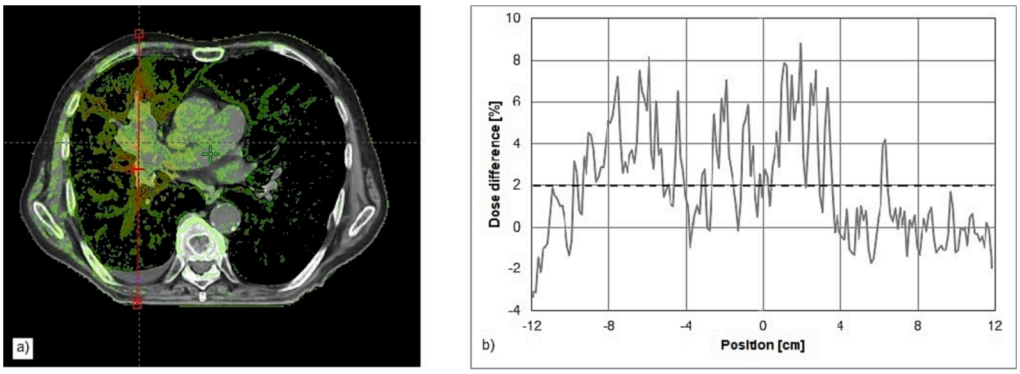

Fig. 3. Dose difference distribution (a) and relative profile of dose difference (b) between DI and TPS for golden model. Dose color wash range between 1% (green) and 10% (red). The dashed line represents the difference average value.

of 1.5 ± 1.0 % and GPR of 97.0 ± 5:6%. McDonald et al. [21] validated Mobius3D against phantom measurements. The results of the comparison with measurements were $\%D_{diff}$ of 0.2 ± 1.3 %. Similar results were also found by Piffer et al. [22]. In their study, they compared the dose distributions for 50 VMAT plans calculated with SciMoCa, a MC based software, against two TPS (Monaco and Pinnacle) and found good agreement with $\%D_{diff} \leq 0.7$ % and average GPR of 98 % ± 3.0 %.

Furthermore, Hoffmann et al. [23] compared SciMoCa and AcurosXB using a closer acceptance criteria (2 %,2mm). The comparison involved 25 patients, with different pathologies and treatment techniques. The results show good results, both in terms of gamma passing rate >97 % for all patient and percentage dose deviation <1 %, compatible with our results.

The results obtained in this work compared with literature ones indicate that the MC-based Delta4 Insight system for secondary check of IMRT/VMAT plans provides useful and accurate outcomes. However, it is important to notice here that not all aspects of QA can be checked with a software-based system like, for example, all the plan transfer and delivery steps as well as Linac hardware. Therefore, software-based QA must be complemented by an accurate, stringent, and robust protocol to ensure stable machine performances. However, software-based secondary dose check systems offer some important advantages. They allow recalculating independently the planned dose on patient images taking properly into account the complex tissue heterogeneity of the human body, which is inevitably simplified in the phantoms. In addition, given the affordable calculation times, software-based QA can be in principle applied on a per-plan basis.

The interface of DI software is user-friendly and, after the export of the DICOM RT from the TPS, the MC calculation of the dose distribution immediately starts and, once the calculation is completed, the results are showed. However, the implementation of some tools, like the visualization of dose and gamma distributions on the patient's CT scan and the possibility to customize the DVH metrics to better adapt the analysis to the workflow of the specific radiotherapy department, could further contribute to the user's dosimetric assessments.

MC simulations require a careful optimization of computing resources. While they are required to be robust and accurate, they necessarily involve tradeoffs between computing speed and precision. The dose calculation precision is largely determined by the number of simulated particles which is directly proportional to the CPU time needed for the calculation. Computing resources are also affected by the dose grid resolution, indicating that a careful optimization of these parameters is very important [11].

The behaviour of the two machine models, GM and CM, is similar. In the case of CM, to have an independent verification of Monitor Unit it is necessary to use different measures from those used for the commissioning of the TPS. The use of GM allows on the one hand to speed up the model implementation process, and on the other to intercept errors in the working method that otherwise could spread to all treatments.

Conclusions

A comparison of the Delta4 Insight Monte Carlo secondary dose check system with Eclipse TPS has been performed. Very good agreement between DI and the TPS has been observed for both the dose calculation algorithms, implemented in the TPS. The results of this work show that an MC-based software for patient-specific quality assurance may provide a useful independent secondary dose verification system for IMRT/VMAT plans, complementing the traditional global QA protocols.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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