Original Article

Dose Calculation Comparisons between Three Modern Treatment Planning Systems

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Abstract

Purpose: Monaco treatment planning system (TPS) version 5.1 uses a Monte-Carlo (MC)-based dose calculation engine. The aim of this study is to verify and compare the Monaco-based dose calculations with both Pinnacle[3] collapsed cone convolution superposition (CCCS) and Eclipse anisotropic analytical algorithm (AAA) calculations. **Materials and Methods:** For this study, 18 previously treated lung and head-and-neck (HN) cancer patients were chosen to compare the dose calculations between Pinnacle, Monaco, and Eclipse. Plans were chosen from those that had been treated using the Elekta VersaHD or a Novalis Tx linac. All of the treated volumetric-modulated arc therapy plans used 6 MV or 10 MV photon beams. The original plans calculated with CCCS or AAA along with the recalculated ones using MC from the three TPS were exported into Velocity software for intercomparison. **Results:** To compare the dose calculations, Planning target volume (PTV) heterogeneity indexes and conformity indexes were calculated from the dose volume histograms (DVH) of all plans. While mean lung dose (MLD), lung V5 and V20 values were recorded for lung plans, the computed dose to parotids, brainstem, and mandible were documented for HN plans. In plan evaluation, percent differences of the above dosimetric values in Monaco computation were compared against each of the other TPS computations. **Conclusion:** It could be concluded through this research that there can be differences in the calculation of dose across different TPSs. Although relatively small, these differences could become apparent when compared using DVH. These differences most likely arise from the different dose calculation algorithms used in each TPS. Monaco employs the MC allowing it to have much more detailed calculations that result in it being seen as the most accurate and the gold standard.

Keywords: Radiation dose comparison, radiotherapy plan similarity, treatment planning system comparison

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Introduction

A radiation treatment plan with accurate and reliable dose calculation is designed to be an important evaluation tool for any radiation therapy treatment clinic. The plan is dependent on the type of the dose calculation algorithm used by the treatment planning system (TPS). Since the dose delivered is independent of the dose calculation algorithm, the predicted dose from various TPS needs to be accurate and reliable across different TPSs. However, differences in the computed dose exist between various TPS even when using the identical beam shaping techniques (gantry, collimator, couch orientation, field shapes, and monitor units among others). Such differences are observed in the resulting isodose distributions and on dose volume histograms (DVH). Although the beam models between various TPS have negligible differences in homogeneous media when using open fields, larger differences were observed between the various TPS in other scenarios including at the tissue-inhomogeneity interface. Although the algorithms used in most modern TPS are considered accurate, it has been widely accepted that the Monte-Carlo (MC) algorithm is able to simulate the most close to actual dose calculations.[1] The MC technique is a statistical method for performing numerical integrations based on the random

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sampling. The radiation transport problem is simulated with the tracks of individual particles using probability distributions governing the physical processes and machine-generated random numbers. Extensive efforts were made to improve the MC dose calculation algorithms used in TPS to reproduce beam geometries, beam modification devices (including wedges), and heterogeneities in the patient geometry.[2] MC takes into account the radiological differences in tissues such as the lung and bone to achieve true dose computation. The American Association of Physicists in Medicine report 85 states that a 5% change in dose may result in the significant change in tumor control and normal tissue complication probabilities.[3] Because of this, the Monaco-based MC dose calculations were used in this study as the gold standard for comparison purposes.

The aim of this study is to verify and compare Elekta's Monaco MC-based dose calculations with Philips Radiation Oncology's Pinnacle^3 collapsed cone convolution superposition (CCCS) and Varian's Eclipse anisotropic analytical algorithm (AAA) calculations and to quantify the differences in the overall dose computation in various treatment scenarios.

Materials and Methods

Patient population

For this study, 18 previously treated patients with lung and head-and-neck (HN) cancer were chosen to compare the dose calculations between Pinnacle CCCS version 9.8, Monaco version 5.1, and Eclipse AAA ver 8.9. The plans were intended for delivery using the Elekta VersaHD (Elekta, Crawley, UK) or a Varian Novalis Tx (Varian Medical Systems, Palo Alto, CA) linear accelerators. All these 18 patients were planned with volumetric-modulated arc therapy (VMAT) technique for both 6 and 10 MV photon beams and had highly conformal dose distribution. All plans were calculated using CCCS, AAA, and then recalculated using MC before they were exported into Velocity (Varian Medical Systems, Palo Alto, CA) software for inter-TPS comparison.

First, all plans were designed and optimized using Pinnacle TPS and the three-dimensional (3D) dose distributions were calculated using CCCS algorithm. Three (n = 3) lung and five (n = 5) HN were planned for the delivery on the Elekta VersaHD using Pinnacle TPS and five (n = 5) lung and five (n = 5) HN for delivery using the Novalis Tx linac using Eclipse TPS. The plans, including prescription, CT, structures, and total dose, were exported to other TPS using a DICOM server. Due to the fact that not all TPS had available models for both linear accelerators, we were able to recalculate only the plans for the VersaHD in Monaco due to nonavailability of VersaHD beam model in Eclipse. This implies that all 10 patient plans (5 lung and 5 HN) treated on NovalisTx were computed in Pinnacle, Eclipse, and Monaco TPS. However, the eight patient plans treated in VersaHD (3 lung and 5 HN) were computed in Pinnacle and Monaco TPS. All dose calculations were exported to Velocity for comparison.

Differences in planning approaches

Before attempting to perform a direct dose comparison for each dose calculation algorithm, there are a few considerations that should be addressed to standardize the data. Such considerations include homogenizing over all three planning techniques: couch structures, external contours, density overrides, whether calculating dose to water or dose to medium, beam model comparisons, and chosen statistical uncertainty.

Couch structures

When recalculating dose using VMAT plans, the couch cannot be overlooked. Dose differences between 2% and 5% can occur if the same couch is not used over all systems and up to 6% if the couch is ignored altogether.[4-7] Because of this error, the structures in each TPS should have equivalent geometry and density overrides. This study utilized two different couch structures, one for the VersaHD and one for the Novalis Tx, and for each couch the density of the structures were defined in the plan.

External contours

In Monaco TPS, the identification of patient's external contour was established before dose calculations. Auto contouring of the external body contour was applied to each plan, but it must be noted that the contour always needs to be evaluated and verified before calculation. The calculation accuracy of the patient dose, especially close to the skin, depends directly on the shape of the external contour.[8]

Volume rendering: In TPS, the 3D shape of a contour is derived from a set of 2D contours drawn on the CT image using a surface mesh. Classification of each voxel is based on the trapezoids used in the TPS for volume rendering.[9] The dose calculated in a voxel within the patient volume depends on the CT slice thickness or resolution of the images. Although it is possible to calculate DVH and dose array to finer resolutions if higher accuracy is needed, the dose grid resolution was kept at a uniform 1.25 mm across the TPS in this study. Differences in volume of contours were observed to be within 0.5%, except in the case of very small contours.

Density overrides

Density overrides must also be considered when imaging contrast has been used for enhanced imaging or in the case of metal artifacts. While Eclipse and Monaco uses relative electron density in dose calculation algorithm, the Pinnacle uses physical density causing discrepancies to arise in the comparisons.[10,11] The density overrides can be defined in terms of physical density, CT number, or electron density and composition. In addition, the couch structures consisting of a foam inner core and an outer layer of carbon fiber were forced to a uniform density override stated in the manufacturer's reference manual.

Dose to water or dose to medium

Another difference between TPS that can cause additional error is the medium in which the TPS calculates dose. Most

TPS report dose to water while MC based TPS defaults to reporting dose to a medium. For comparing dose with other TPS, Monaco calculated dose to the medium is recalculated to a uniform water medium.[12,13]

Beam model comparison

It is important to make sure that the beam models are in agreement between the different TPS. To verify this, output factors, tongue and groove effect, and MLC leakage should be evaluated. A homogenous phantom was used for the verification of this data. Measurements taken at different depths in the phantom and calculated in each TPS can be compared for water, lung, or bone based on the density chosen for the phantom.

Statistical uncertainty

Statistical uncertainty chosen at the dose calculation can affect the isodose distribution and DVH. As the percent uncertainty is taken in reference to the maximum dose, lower dose regions will usually have a higher uncertainty. Statistical uncertainty of up to 2% may have negligible effect, but anything higher will impact the shape of the DVH and the isodose distribution. Our MC calculations were performed with a maximum 1% uncertainty.

Validation of measurements

For purposes of the beam model comparison, doses were calculated on a uniform phantom of water, lung, and bone medium with dimensions 30 cm × 30 cm × 40 cm. Point doses measured at depths of 5 cm, 10 cm, and 20 cm for a 10 cm × 10 cm open beam were cross-compared across the three TPS.

In addition, an independent validation was performed by the irradiation of the RTOG thorax-lung phantom provided by IROC Houston. The phantom represents a heterogeneous moving lung and includes a centrally located target. In addition to the two thermo-luminescent dosimeters (TLD) located at a superior and an inferior location inside the target, three radiochromic films are used to analyze the accuracy of treatment delivery.[14]

Plan comparison

In Velocity, Monaco was chosen as the reference TPS. The organs at risk (OAR) chosen for comparison were total lung and PTV for the lung patients; and right and left parotid, mandible, brainstem, and PTV for the HN patients. Isodose curves and DVH were generated comparing the plans. Tolerance tables were set up to suit the study's purposes including the dose at 98%, 50%, and 2% volumes of the PTV, and doses at 20% and 5% volumes of the total lung. These numbers along with the max doses and mean doses for all OARs were recorded. The absolute percent difference of these metrics between Monaco and either CCCS or AAA computed doses were averaged over all patients.

$$\%\text{difference} = \text{Absolute}\left(\frac{\text{Mvalue} - \text{Pvalue}}{\text{Mvalue}}\right) * 100$$

The homogeneity index (HI) and the conformity index (CI) were also calculated for the PTVs.

$$\text{HI} = \frac{(\text{D2} - \text{D98})}{\text{D50}}$$

$$\text{CI} = \frac{\text{V100}}{\text{PTV}_{\text{vol}}}$$

Statistical analysis

Test for normal distribution was performed using a Shapiro–Wilk test in the R statistical package (R Foundation for Statistical Computing, Vienna, Austria).[15]

For normally distributed data, statistical significance was tested using a paired two-tailed Student's *t*-test. For a distribution showing larger deviation from a normal distribution, a Wilcoxon signed-rank test was utilized. Statistical significance was compared against a threshold *P* value of 0.05.

Results

Dosimetric validation

In the beam model comparison across the TPS, open-beam dose computations at 5 cm, 10 cm, and 20 cm depths in uniform water and lung phantoms agree with one another to within 1%. In a uniform bone-density medium, dose differences of up to 3% were observed in Pinnacle^3, AAA, and Monaco calculations.

In the RTOG lung phantom irradiation using 6X beams in a NovalisTx linac, measurements of the two TLDs (stated in the report from IROC Houston) were compared against the TPS calculated dose. Note that Table 1 tabulates the percent difference in measured and computed dose to water in all TPS as well as to dose to the medium in Monaco.

Patient plan comparison

Tables 2 and 3 tabulate the mean and range of absolute percent differences in these dosimetric parameters of CCCS and AAA plans from the corresponding Monaco plan. While Table 2 deals with 6MV and 10 MV photon beam plans of lung tumor patients, respectively, Table 3 tabulates 6 MV and 10 MV plans of HN tumor cases, respectively. It shall be noted that Eclipse TPS has beam model only for Novalis Tx linac.

Values tabulated in Tables 2 and 3 ascertain that the HI values had consistently large total percent differences for all energies

Table 1: Percent difference in measured and calculated dose to water in collapsed cone convolution superposition, analytical anisotropic algorithm, and Monaco as well as dose to medium in Monaco

TLD location	CCCS (%)	AAA (%)	Monaco (water) (%)	Monaco (medium) (%)
Inferior	3.23	3.51	−1.78	−1.78
Superior	4.92	4.92	−0.45	−0.45

CCCS: Collapsed cone convolution superposition, AAA: Analytical anisotropic algorithm, TLD: Thermo-luminescent dosimeter

Table 2: Absolute differences of mean (range) percent values of Monaco calculated plans from collapsed cone convolution superposition and analytical anisotropic algorithm for all lung patient plans using 6X and 10X photon beams

Organ	Metric	CCCS - Monaco	AAA - Monaco	CCCS - Monaco	AAA - Monaco
		6X lung plans		10X lung plans	
PTV	D98	2.36 (0.2-5.7)	2.66 (0.7-4.7)*	2.85 (0.3-8.8)	2.32 (0.1-3.9)
PTV	D2	2.53 (0.6-4.1)	2.28 (0.1-5.7)	2.7 (1.3-4.6)	2.67 (0.1-5.6)
PTV	D50	2.0 (0.3-3.8)	2.1 (0.4-3.7)	1.96 (0.3-4.7)	8.5 (7.1-10.1)*
PTV	V100	5.51 (1.5-9.0)*	4.5 (1.2-7.6)*	5.2 (0-16.2)	10.5 (5.1-15.3)*
PTV	CI	5.51 (1.5-9.0)	4.51 (1.3-7.6)	5.22 (0.0-16.2)	10.51 (5.1-15.3)
PTV	HI	23.3 (0.7-47.2)*	10.2 (5.8-16.6)	15.98 (2.9-36.5)*	21.42 (4.8-36.4)*
Total lung	V20	2.89 (1.3-7.4)	2.77 (0.5-5.0)	2.63 (1.1-5.1)	2.66 (0.2-7.0)
Total lung	V5	2.72 (0.1-11.9)	1.57 (0.2-3.8)	1.41 (0.4-2.8)	1.76 (0.6-2.9)

*Statistically significant difference of the plan parameter against Monaco computed plan. CCCS: Collapsed cone convolution superposition, AAA: Analytical anisotropic algorithm, CI: Conformity index, HI: Heterogeneity index

Table 3: Absolute differences of mean (range) percent values of Monaco calculated plans from collapsed cone convolution superposition and analytical anisotropic algorithm for all head-and-neck patient plans using 6X and 10X photon beams

Organ	Parameter	CCCS - Monaco	AAA - Monaco	CCCS - Monaco	AAA - Monaco
		6X head and neck plans		10X head and neck plans	
PTV	D98	2.1 (0.6-5.0)*	2.7 (2.0-3.9)*	3.0 (0.6-5.0)	3.3 (0.4-10.7)
PTV	D2	2.2 (0.2-5.1)*	0.9 (0.2-2.4)	2.2 (0.1-4.7)*	4.2 (1.0-9.9)
PTV	D50	1.4 (0.2-3.2)	1.9 (0.5-5.2)	1.7 (0.5-2.8)	3.3 (0.4-10.7)*
PTV	V100	4.1 (0.1-10.7)*	5.0 (2.6-6.7)*	6.6 (1.6-21.5)*	4.2 (1.0-9.9)*
PTV	CI	4.1 (0.5-9.0)	5.0 (2.7-6.8)*	6.6 (1.6-21.5)	12.5 (6.0-14.2)
PTV	HI	36.4 (22.1-68.0)*	13.8 (8.9-21.7)*	29.9 (1.8-45.7)*	13.0 (3.5-22.3)
Mandible	Max dose	4.2 (0.4-9.1)*	1.2 (0.2-2.8)	3.5 (0.1-8.3)*	2.8 (0.8-4.2)
Brainstem	Max dose	2.3 (0.1-5.3)	4.2 (0.8-10.7)	2.5 (0.1-4.9)	5.0 (3.5-8.9)
Right parotid	Mean dose	13.8 (1.4-34.2)*	9.1 (3.5-23.3)*	8.1 (0.4-26.8)	5.7 (0.9-11.0)
Left parotid	Mean dose	8.3 (3.1-24.0)*	5.6 (3.4-8.2)*	4.3 (0.8-22.4)	3.8 (0.7-10.9)

*Statistically significant difference of the plan parameter against Monaco computed plan. CCCS: Collapsed cone convolution superposition, AAA: Analytical anisotropic algorithm, CI: Conformity index, HI: Heterogeneity index

and all sites. The significantly lower HI values in CCCS plans indicate homogeneous dose distribution than in Monaco.

The percent difference in dose values for all the OAR were within 5%, with parotid glands being a notable exception in the HN plans. The mean dose to either parotids is significantly lower in Monaco plans than CCCS or AAA plans that uses 6X beam. Although the same tendency was apparent in 10X beams, the differences are not significant enough.

Although all Monaco plans have lower CI than either CCCS or AAA plans, the differences are not significant. 10X photon plans have higher CI values than the corresponding 6X photon plans in all TPS, which can be explained from larger V100 (volume of 100% isodose curve) values in 10X photon beams due to higher lateral electronic scatter. A representative example of a lung tumor patient DVH using Monaco, CCCS, and AAA are shown in Figure 1.

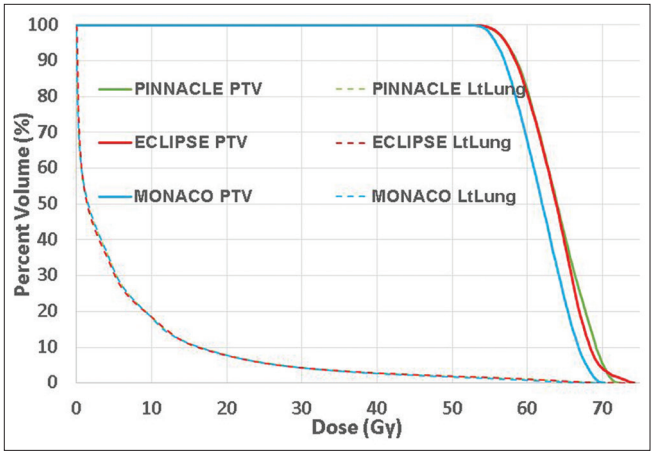

Figure 1: Dose volume histogram of a representative lung tumor plan comparing analytical anisotropic algorithm, collapsed cone-convolution superposition and Monaco algorithms on Novalis Tx

Discussion

By investigating the DVHs comparing Monaco to both AAA and CCCS, it is assumed that if Monaco is used as the gold standard, AAA tends to overestimate the PTV dose for all the cases that can be verified from the values of D2, D50, D98, and V100. As you can see in the Tables 2 and 3 for the lung

plans, the average percent dose difference for the PTV and lung OARs was under 3% in both CCCS and AAA. For HN plans that are known to have high modulation of intensity, the largest dose differences between the plans is observed in the right and left parotids. For all plan types with either energies, significantly large differences occurred HI calculations. This is shown prevalently in the differences at the shoulder in the DVH of PTV in Figure 1.

Chen *et al*. review of the impact of the dose calculation algorithm used on radiation therapy recounts similar results.[16] Knoos *et al*. had studied performance of different algorithms' divided into two groups based on the electron transport model on four common disease sites.[17] Knoos found that more accurate dose calculations in heterogeneous media can be obtained in algorithms that accounted for the changes in electron transport and volume scatter. Similarly, in our study, it was found that for all plans, CCCS and AAA calculated higher PTV coverage, though CCCS underestimated the maximum dose while AAA overestimated for both lung and HN plans.

Hasenbalg *et al*. completed a similar comparison as our study using pencil-beam convolution as his comparison tool.[18] They also found that the AAA and CCC algorithms performed well when compared to their Monte Carlo version VMC while the pencil beam tended to overestimate the dose coverage, especially in high heterogeneity regions. The DVHs from Hasenbalg's study show the AAA overestimating PTV coverage while the CCC more evenly matched the VMC.

In a stereotactic lung plan comparison study by Ojala *et al*., dose distributions showed high levels of agreement between Acuros XB and MC using DVH and gamma analysis, but larger discrepancies were reported for PTV smaller than 20–25 cc.[19] However, we could not establish a tendency of large dose differences in smaller PTVs due to a small cohort.

Conclusion

We are able to be conclude through this study that there can be differences in the calculation of dose across different TPSs. These differences may be relatively small but when compared using DVHs, it becomes apparent. These differences most likely arise from the inherent differences in the dose calculation algorithms used in TPS. Monaco employs the use of Monte Carlo allowing it to have much more detailed calculations that result in it being seen as the most accurate and the gold standard. However, since the differences in calculations between it and CCCS and AAA are not large, the faster calculation times make the latter two appealing in a clinical setting.

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Conflicts of interest

There are no conflicts of interest.

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