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A Dosimetric study of Ray Tracing and Monte Carlo calculated Treatment Plans using ICRU91 Dose Reporting for Cyberknife Stereotactic Pituitary Adenoma.

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Abstract

Purpose: To compare the dose distributions of Cyberknife Stereotactic Pituitary treatment plans when using the Ray Tracing (RT) vs the Monte Carlo (MC) Dose Calculation Algorithm. Methods: 37 SRS Pituitary treatment plans were selected for retrospective analysis. Plans were recalculated so that both an RT and MC calculated plan was available for each patient. The ICRU 91 metrics Dnearmin, Dnearmax, D50 were recorded and compared between the MC and RT calculated plans while maintaining the same Monitor Units (MU), Organs at Risk (OAR) doses were also compared using the TG101[7] convention. Results: There was a mean difference in Dnearmin of 4.4% SD ±3.5% between the MC and RT calculated plans (max difference 12.3%) .The D50 showed a mean difference of 1.4% SD ±1.2%. The Volume Receiving the Prescription Dose "VRx" was on average 3.9% lower SD ±3.9 in the MC plans (max difference 15.3%) . OAR Dnearmax doses increased with the MC calculation by 2% to 3.7% depending on the OAR. Conclusion: When calculating with RT, the Dnearmin was artificially high for smaller targets <6cc and with increasing air in the target. In these cases MC is recommended to avoid target underdose. The D50 metric showed no significant variation between MC and RT calculated plans. There was no significant difference in Dnearmax between the MC and RT calculated plans. There is no need to rescale the prescription of an MC calculated Pituitary plan.
Keywords: *Cyberknife, Radiosurgery, Calculation Algorithms, Monte Carlo, Ray Tracing, Pituitary.*

1. Introduction

The increase in computing power over the last decade has led to the computationally intensive Monte Carlo (MC) dose calculation algorithms becoming a realistic daily clinical option in Treatment Planning Systems (TPS) [1]. This brings great benefits in terms of dose calculation accuracy with MC being the most accurate calculation algorithm, however it also brings great challenges given that the bulk of evidence on the clinical outcome of dose prescriptions is based on older Equivalent Path Length (EPL) algorithms [2-3].

The Cyberknife Multiplan treatment planning system has both MC and Ray Tracing (RT) algorithms available for Stereotactic Treatment planning. For most cranial tumors, the RT algorithm is sufficient given the homogenous nature of brain tissue, however in certain cases such as Pituitary Adenoma, bone, sphenoid sinus air and normal tissue all combine to form a heterogeneous region which is too complex to be accurately calculated by the RT algorithm.

In these cases, the RT algorithm corrects for the density variation along the ray line but does not account for lateral scatter due the increased range of charged particles in less dense media leading to an overestimation of the absorbed dose to the target [2,4]. It has also been shown that lateral electronic disequilibrium and steep dose gradients exist in larger portions of the smaller field sizes used in

radiosurgery and this makes the calculation of dose more difficult, especially in a heterogeneous medium [5].

In these cases, the RT algorithm will not be sufficiently accurate. This is in contrast to the MC algorithm which models all interactions of primary secondary and tertiary particles using probability models to determine the dose depositions of all particles [4] giving an accurate dose calculation. However, this is dependent on the treatment head and resulting energy spectrum being modelled correctly.

The recent introduction of ICRU 91 [6] has given us new tools for reporting doses to targets and OARs in Stereotactic Radiotherapy and will be used to compare the dosimetry of the RT and MC based Pituitary plans for this study. Additional parameters such as target size, target air overlap, sphenoid sinus volume and cone size will also be used to see what affect if any there is on the dosimetry and in particular how the MC and RT algorithms cope with varying target sizes and heterogeneities. Finally, the prescription will be examined given that EPL based prescriptions have been proven to be effective with empirical evidence based on clinical outcome [3] so the question is -should MC prescriptions be scaled down to match the actual dose for an equivalent prescription in EPL?

2. Materials and Methods

2.1 Equipment

The Multiplan TPS (Accuray Sunnyvale CA version 4.6) was used in this study. The TPS has two treatment planning algorithm options, RT and MC. All Pituitary patients had been previously treated using the Cyberknife (Accuray Sunnyvale CA version 9.5) system at Hermitage Medical Clinic in Dublin.

2.2 Patient Selection

Thirty-seven Cyberknife Pituitary patient treatment plans were selected for retrospective analysis from cases previously treated at HMC. The plans were selected so that a wide range of target sizes and target air volumes were available. The plans were recalculated so that both an RT and MC calculated plan were available for each patient. 24 patients had a tumor more than 2 cc in volume, while 13 patients had a tumor of less than 2 cc volume. For consistency, the Sinus air volume anterior to the tumor was retrospectively automatically volumed in each case using the W=500, L=1000 window setting for all slices.

2.3 Treatment Planning

According to the HMC CT Scanning Protocol, a planning CT with a 1 mm slice thickness is taken of the patient’s head. In addition, a 1mm T1 MRI with contrast and a T2 weighted MRI are fused to the CT prior to delineation.

Table1: ICRU-91 Dose Metrics, OAR Metrics and additional analytical Parameters of interest.

		Min Dose 'cGy'	Target Coverage '%'	Max Dose 'cGy'
Target	Tumors < 2 cc	$D_{PTVVol-35mm^3}$	$D_{50\%vol}$ & V_{Rx}	D_{35mm^3}
	Tumors > 2 cc	$D_{98\%vol}$	$D_{50\%vol}$ & V_{Rx}	$D_{2\%vol}$
Organ at Risk		Vol Dose cc	Point Dose	
	Optic Chiasm	D_{200mm^3}	D_{35mm^3}	
	Optic Nerves	D_{200mm^3}	D_{35mm^3}	
	BrainStem	D_{200mm^3}	D_{35mm^3}	
Additional Parameters		Target Volume		
		Number of Beams		
		Cone Size		
		Tumor Air Overlap Volume		
		Sphenoid Sinus Volume		

The target and OARs are then outlined by a Neurosurgeon and a Radiation Oncologist. A 1mm margin is added to the GTV to form the PTV. The Radiation Oncologist prescribes the target dose as per department protocol with a standard dose of 13 to 15 Gy in a single fraction being the preferred choice. However, for larger targets close to the Optic Nerves and Optic Chiasm, the protocol mandates a fractionated regime of 6 to 8 Gy in 3 fractions. In addition, for secreting tumors a higher dose of 18 to 24Gy in 1# is preferred. The OAR'S contoured included the Eyes, Optic Chiasm, Optic Nerves and Brainstem.

The treatments were planned so as to cover the target surface with an isodose line of between 70% and 85% while at the same time minimizing the dose to the OARs so that they were within published tolerances as set out in TG101[7]. The treatment plans were retrospectively recalculated maintaining the same MU so that a RT and MC plan was available for each patient. All plans were originally optimized in Ray tracing as per our department protocol for cranial patients. For final calculation, the RT algorithm was calculated using a high resolution while the MC algorithm utilised a 1% uncertainty value.

2.4 Plan Analysis RT vs MC

As shown in Table (1), for plan evaluation, the recalculated RT and MC Pituitary plans were analysed and data was collected using the ICRU 91 METRICS: D50, Dnearmin, Dnearmax and also the percentage volume receiving prescription dose (VRx). The D50, Dnearmin and Dnearmax were reported as a percentage of the prescription dose due to the different prescriptions in use. The OAR doses were evaluated according to the TG101 dose tolerances. Additional useful parameters of interest were also collected to characterize each plan as shown in table 1. The target air overlap was contoured as the sphenoid sinus volume which intersected the target volume. This volume was plotted against the

Dnearmin and D50 for both the RT and MC plans, in order to quantify how both algorithms cope with increasing amounts of air in the target.

The plans were then ordered by target size and the minimum dose and D50 were examined to see how the target coverage was affected by target size for both the RT and MC calculated plans. The sphenoid sinus volume anterior to the pituitary was also collected for each patient. Patients were ordered by this sinus volume and the minimum dose and D50 were plotted to see how the sinus volume affected the target dosimetry. Additional Parameters such as the Conformity Index (CI) and Heterogeneity index (HI) were also recorded for each patient. The CI and HI were taken from the Multiplan TPS calculation, which uses the following formulae:

$$CI = \frac{V_{Rx}}{V_{PTV}(Rx)} \qquad (1)$$

$$HI = \frac{Dmax}{Rx} \qquad (2)$$

where the VRX is the volume receiving the prescribed dose (RX) and VPTV(RX) is the PTV volume that received the prescribed dose. The Organs at Risk (OAR) doses were also quantified, namely the volume dose and the point dose as prescribed by TG101 for both the MC and RT calculated plans. The Cone sizes used for each plan were recorded and the minimum dose was compared for plans of increasing cone size. As the RT algorithm can overestimate the dose in heterogeneous regions [2,4], it was necessary to pay more attention to the target coverage. The Dnearmin D50 and VR(x) were recorded and compared for both the RT and MC calculated plans.

3. Results and Discussion

It is vitally important that a suitable dose calculation algorithm is used when calculating the dose to targets in the presence of heterogeneities [7]. Using an unsuitable algorithm in heterogeneous tissue could lead to under dosage, leading to a loss of target local control. While this effect has been well documented for lung cases [3, 4] it has to the best of our knowledge not been examined for the specific case of pituitary tumors.

The presence of sphenoid sinus, tissue, bone and air provide a unique challenge for this tumor site. In particular when modelling dose distributions in areas of high tissue heterogeneity, the RT methodology is unable to account for changes in the lateral range, scatter and final dose deposition of liberated electrons resulting in an overestimation of the deposited dose [9]. For this study the ICRU91 Stereotactic dose reporting metrics were used to compare the dosimetry of the RT and MC calculated plans.

3.1 D_{50} ‘Median Dose’

Firstly, the D50 or median dose was analysed to see if there was a difference between the algorithms. It was found that the target in each plan had a largely similar D50 value when calculated with the MC and RT algorithms as per Figure 1.

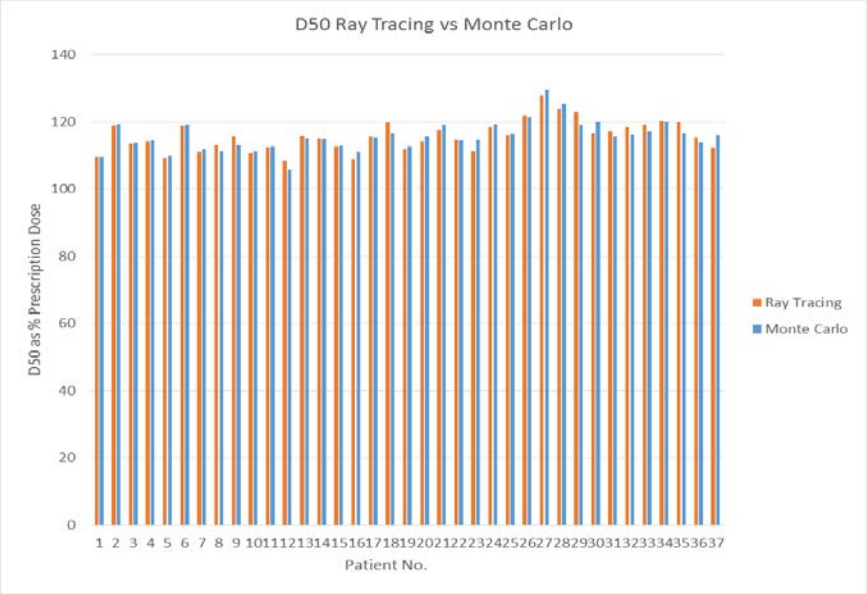

Fig. 1 Target D50 RT vs MC algorithm

3.2 Dnearmin "Minimum Dose"

Secondly the minimum Dose to the target was compared between the RT and MC calculated plans. ICRU 91 defines the minimum dose as DPTVvol-35mm for tumors less than 2cc and D98 for tumors greater than 2cc.In this study the minimum dose showed a large variation between RT and MC calculated plans with an average difference of -4.4% between RT and MC and a maximum difference of -12.3%.This can be seen in figure2.Given that the D50 was almost identical between RT and MC plans, it is important to be aware of the minimum dose when evaluating a treatment plan as the D50 coverage value will mask local minima ,for this reason both the D50 and Minimum dose should be used when evaluating a treatment plan.

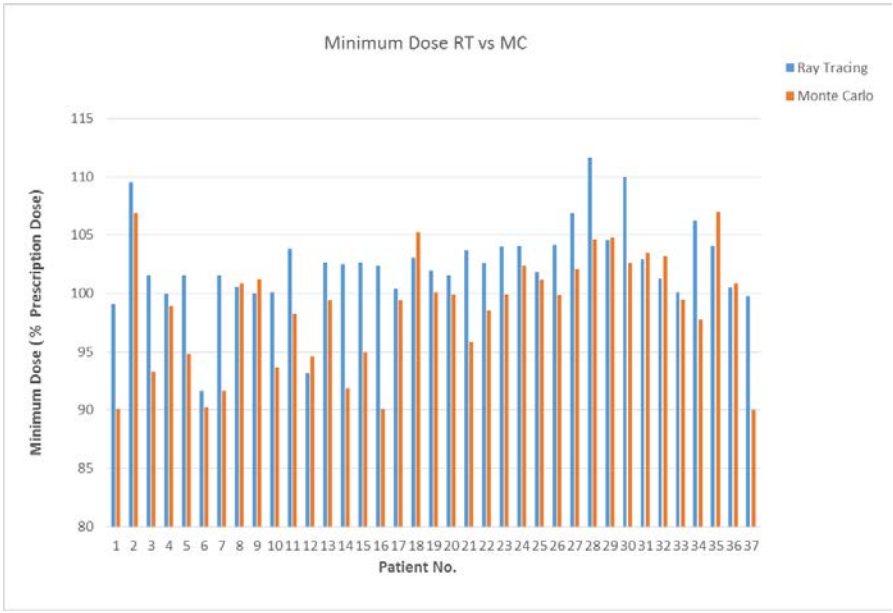

Fig.2 Target Min dose RT vs MC Algorithm

3.3 Dnearmax ‘Maximum Dose’

The ICRU 91 maximum dose metric D35mm3 was also analysed. The maximum dose showed good agreement between the RT and MC calculated plans with an average difference of 1.72% for the targets. This can be seen in Table 2. In the case of a Cyberknife plan which is typically prescribed to the 70 to 80% prescription isodose line (PIDL), the maximum dose is typically at the center of the target and thus away from heterogeneities leading to similar values for the RT and MC calculated plans. In the presence of air after the radiation enters the tumor the depth doses profile decreases further using RT while MC produces a re -buildup effect. Thus, the deviation of maxima in the target between RT and MC calculated plans are lower than the deviations in minima [4]. The re-buildup of depth dose for beams that have traversed the sphenoid sinus causes a loss of coverage around the GTV circumference and as such, affects the minimum dose to a greater extent than the maximum dose. The difference between the two algorithms is higher on the edge of the target because the dose in this area is dependent on a lack of electronic equilibrium [10].

3.4 V(Rx) ‘Coverage’

In addition to the ICRU91 metrics, the Multiplan reported PTV coverage value also known as the volume receiving the prescription dose V(Rx) was compared between the RT and MC calculated plans. The RT plans showed an average increase in coverage of 3.9% ±3.9 % over the MC plans. This is likely caused by the RT algorithm overestimating the coverage to the target in the presence of heterogeneities, with MC being more reflective of the actual dose to the target.

Table 2: ICRU91 Metrics RT Vs MC calculation

Algorithm	**$D_{50\ (\%)}$**	**$V_{(Rx)\ (\%)}$**	**$D_{nearmin(\%)}$**	**$D_{nearmax(\%}$**
RT Avg	115.73	99.36	102.39	124.77
MC Avg	115.76	95.45	98.62	125.86
Max Diff per plan	3.8	15.3	12.3	5.3
Avg Diff per plan	1.4 SD±1.2.	3.9 SD±1.9.	4.4 SD±3.5	1.7 SD±1.3.

3.5 Target and Sinus Air Overlap

The target air overlap and bone, air, tissue interfaces (figure 3 above), are useful to test the algorithms ability to cope with heterogeneities. The MC algorithm shows a significant decrease in minimum dose with air in the target with a statistically significant Pearson correlation of -0.33(Fig 4). With increasing air in the target the RT algorithm shows an increase in the minimum dose (Fig 4). It is clear from figure 4 that the RT algorithm is overestimating the dose to the target with increasing target air overlap present.

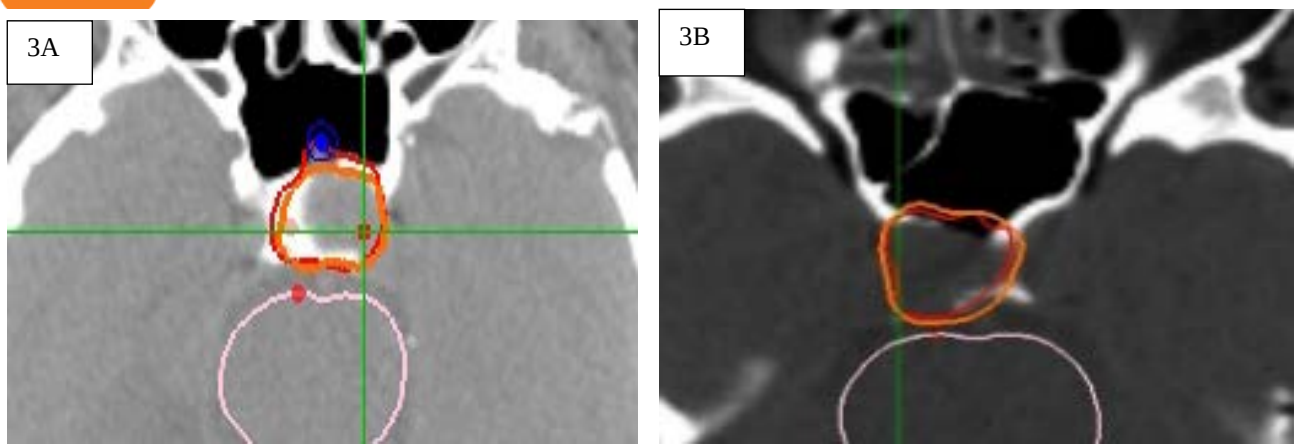

Fig. 3A: Monte Carlo Recalculated Plan shows loss of coverage near the Sphenoid Sinus. Figure 3B: Ray Tracing overestimates the coverage in the presence of bone, air (Sphenoid sinus) and tissue heterogeneities.

There was no statistically significant correlation between the D50 and increasing target air overlap as can be seen in Figure 5. The minimum dose to the target showed a strong positive Pearson correlation (+0.49) with increasing Sinus Volume in the RT calculated plans. However, for the MC calculated plans, there was no significant correlation (Pearson -0.06) between the sinus air volume and minimum dose, however the minimum dose was consistently lower than that of the RT calculation (Fig. 6). The RT algorithm cannot model the re –buildup of dose after the air cavity which from measurement studies using a diamond detector should show a loss of coverage. [11,12] however this is correctly modelled by the MC algorithm where the loss of coverage posterior to the air cavity can be seen (Fig. 3A).

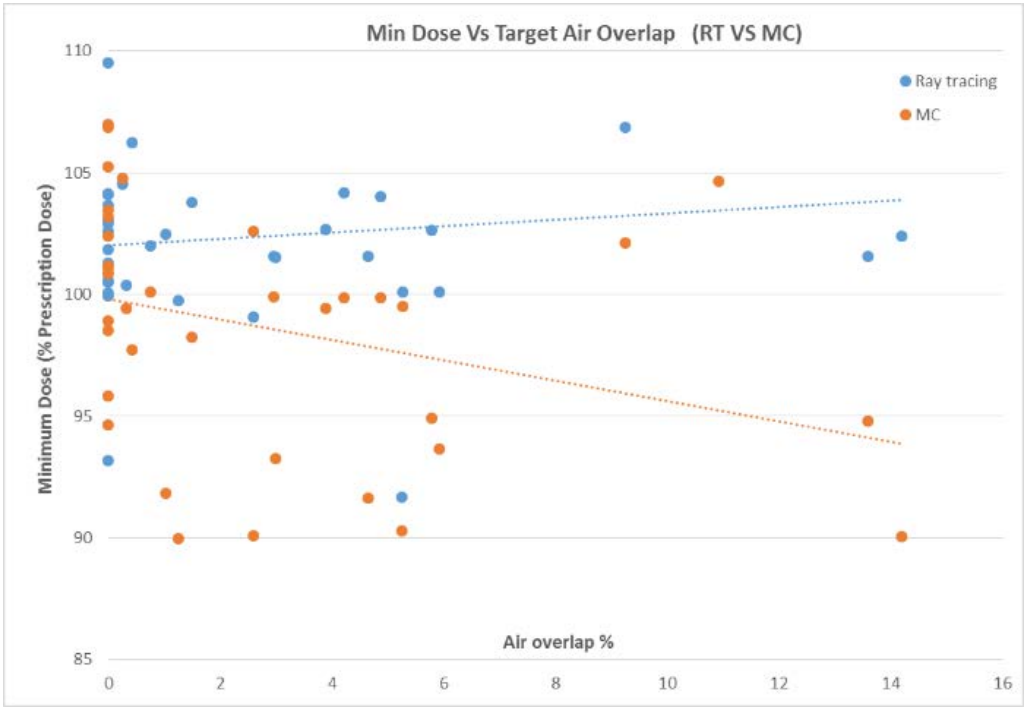

Fig. 4 Min Dose with Increasing Target Air Overlap - Ray Tracing vs Monte Carlo

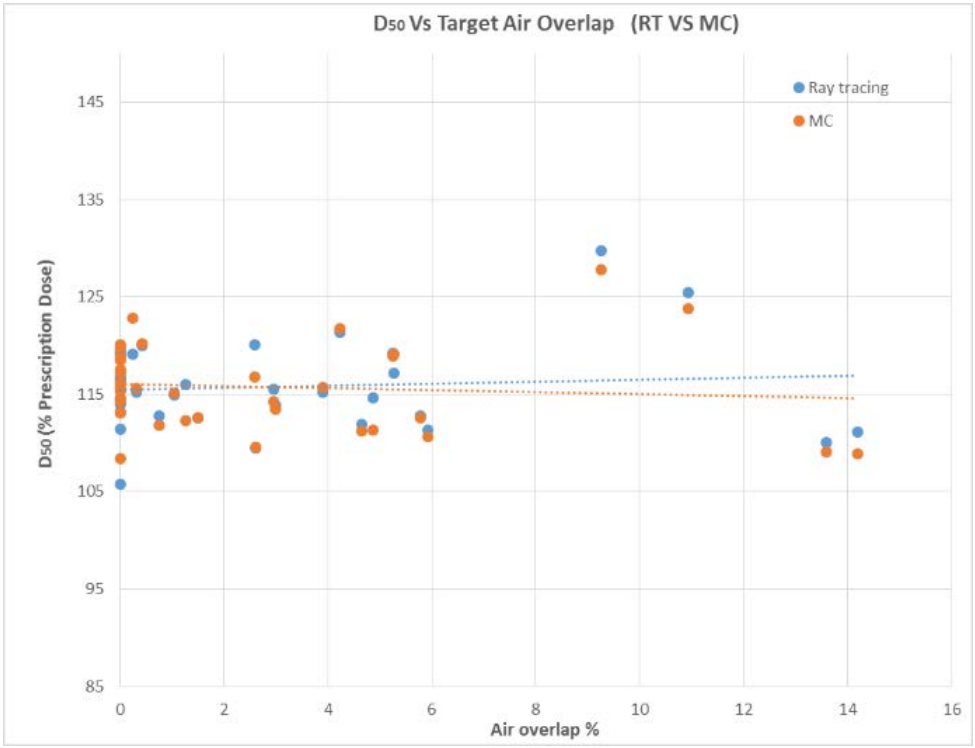

Fig. 5 D50 with Increasing Air Overlap - Ray Tracing vs Monte Carlo

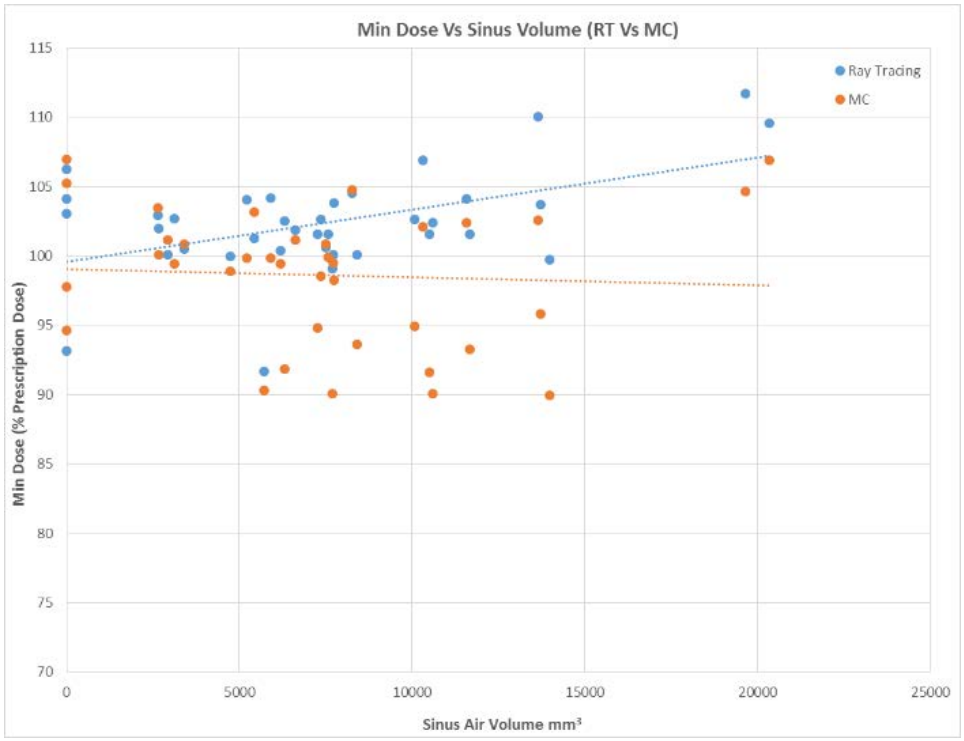

Fig. 6 Min Dose with increasing adjacent Sinus Air Volume - Ray Tracing vs Monte Carlo

3.5.1 Target Air overlap and Maximum Dose

There was a moderately significant positive correlation (Pearson +0.3) between the % air overlap in the target and the maximum dose when calculated using the RT algorithm. (Fig. 7)

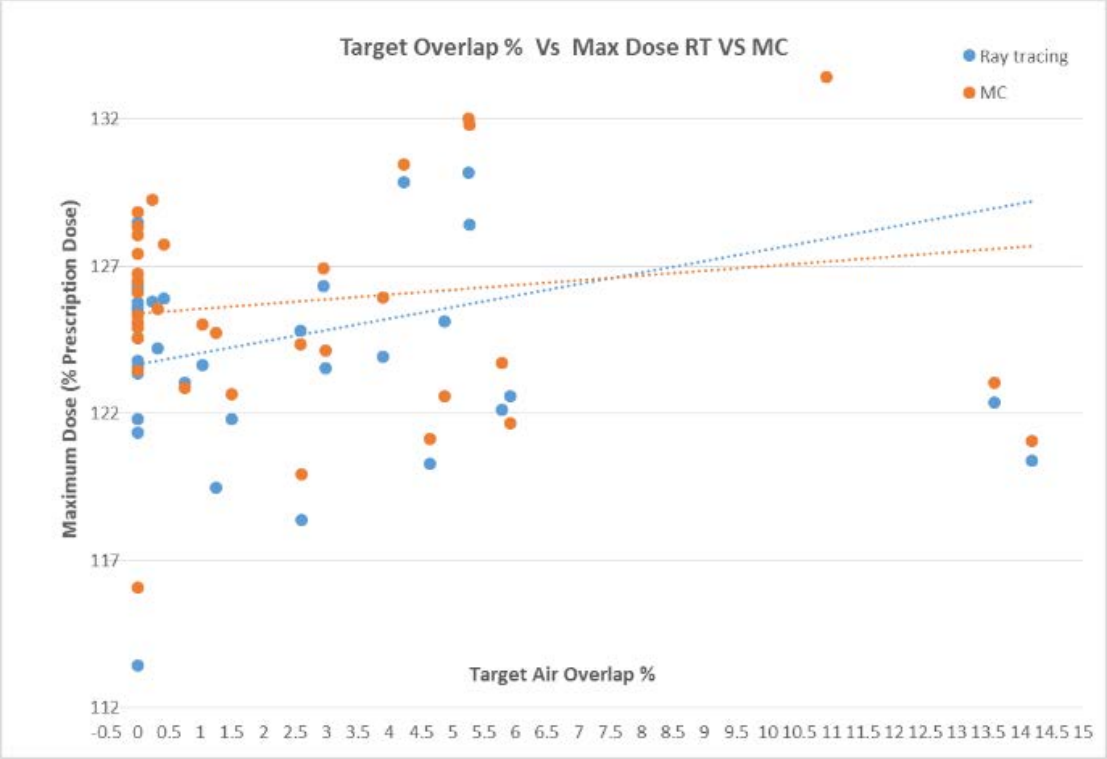

Fig. 7 Target Air overlap % vs Max Dose (RT and MC)

There was no significant correlation between the air overlap in the target and the maximum dose when calculated using the Monte Carlo algorithm (Pearson +0.15). (Fig. 7)

3.6 Target size

3.6.1 Targets < 2cc

The relationship between the minimum dose and target size was studied for the smaller targets of less than 2cc in volume. ICRU 91 defines the minimum dose as DPTVvol-35mm which can be closer to D90 for very small targets due to the volume effect as opposed to the minimum dose for targets above 2cc which is always defined as D98.For this reason both the MC and RT minimum doses were high for DPTVvol-35mm particularly below 1cc (Fig. 8).

However, the D98 minimum dose differed significantly between the MC and RT plans for these small targets with RT overestimating the dose and MC showing a lower minimum dose to the target as can be seen in Figure 9. RT calculated plans showed a statistically significant decrease in D98 minimum dose with increasing target size (Pearson -0.67) while MC did not show any significant change in minimum dose with tumor size (Pearson -0.04).

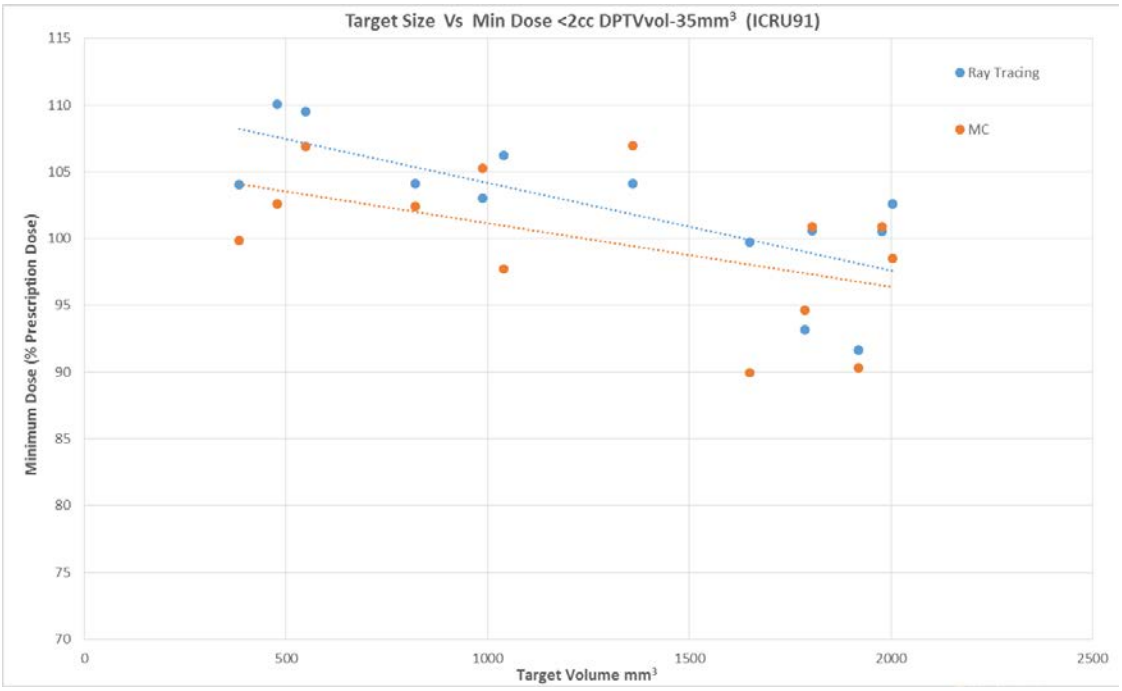

Fig. 8 Volume effect in tumors < 2cc on the Min Dose using ICRU 91 metrics

Fig. 9 Min Dose in tumors < 2cc volume

The D98 for these small <2cc targets showed that only ray tracing overestimates the minimum dose. For these tumors using D98 there is still a large difference in minimum dose between the RT and MC plans and this difference gradually decreases as the tumor size increases. The dose difference may be a function of the collimator size, since the collimator selection is related to the target size [13] and the RT algorithm being an EPL correction-based algorithm, is not sufficiently accurate to model lateral scatter in these very small fields particularly in a heterogeneous treatment site such as Pituitary Adenoma. In comparison, the monte carlo algorithm can be seen as the gold standard for these types of calculations [14]

3.6.2. Targets >2cc “D98”

ICRU 91 defines the minimum dose for tumors greater than 2cc as D98.The relationship between target size above 2cc and minimum dose can clearly be seen with the MC based plans. While MC plans showed a significant increase in minimum dose with target size (Pearson 0.36), RT plans showed no significant correlation between the target minimum dose and target size (Pearson .063). This can be seen in figure 10 below.

Fig. 10 Min Dose "D98” in tumors > 2cc volume - Ray tracing vs Monte Carlo

The MC plans tended to show a lower minimum dose for the smaller targets gradually matching the RT only for the larger volume targets. This demonstrates that RT overestimates the dose to the smaller tumors in a similar way to the <2cc tumors discussed above. Due to these findings, it is clear that there is a particular need for using the advanced MC algorithm for the specific case of small tumors in heterogeneous regions. In our studies the minimum target dose between RT and MC calculated plans only showed good agreement above 6cc (Fig. 13). Van der Voort has shown Tumors smaller than 2.5cm to 3 cm were more susceptible to 20% or higher differences in mean and minimum target dose however this was for the extreme case of lung [2].

3.7 Cone Size

3.7.1. Cone Size and D50

The target D50 showed very similar results for both the MC and RT calculated plans with a moderately significant decrease in the median dose with increasing cone size. This can be seen in the Pearson correlation of -0.33 for RT and -0.39 for MC with increasing cone size. The larger cone sizes for bigger tumors have a more homogenous dose distribution and thus a greater proportion of the volume of these larger tumors is at a lower dose than the tumor dmax. The smaller tumors tend to be more like a point and thus have a higher median dose closer to dmax. This is typical of a Cyberknife distribution where the 100% or dmax is normally at the center of the target and the 80% isodose line covers the tumors perimeter. This decrease of D50 with increasing Cone Size can be seen in Figure 11.

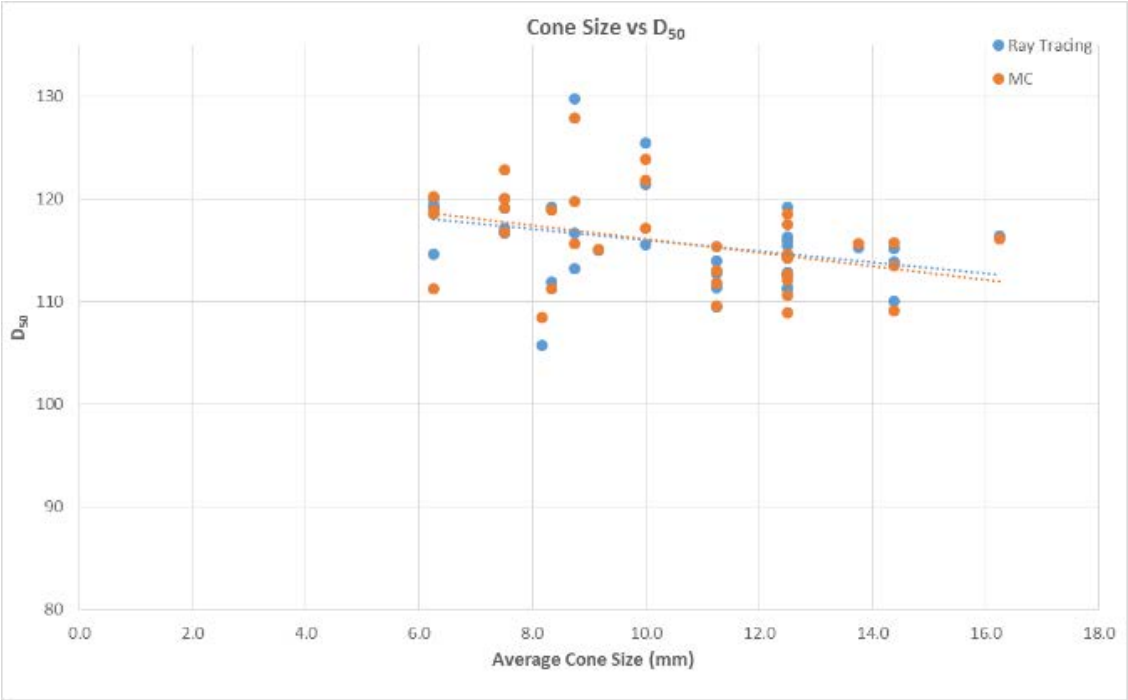

Fig. 11 Cone size effect in relation to the Target D50

3.7.2 Cone Size and Min Dose

In the smaller field sizes used for tumors <2cc the minimum target dose showed a statistically significant correlation with cone size when calculated with Ray Tracing (pearson -0.34), however calculating with the MC algorithm showed no statistically significant correlation with cone size (pearson -0.17). This can be seen in Figure 12.

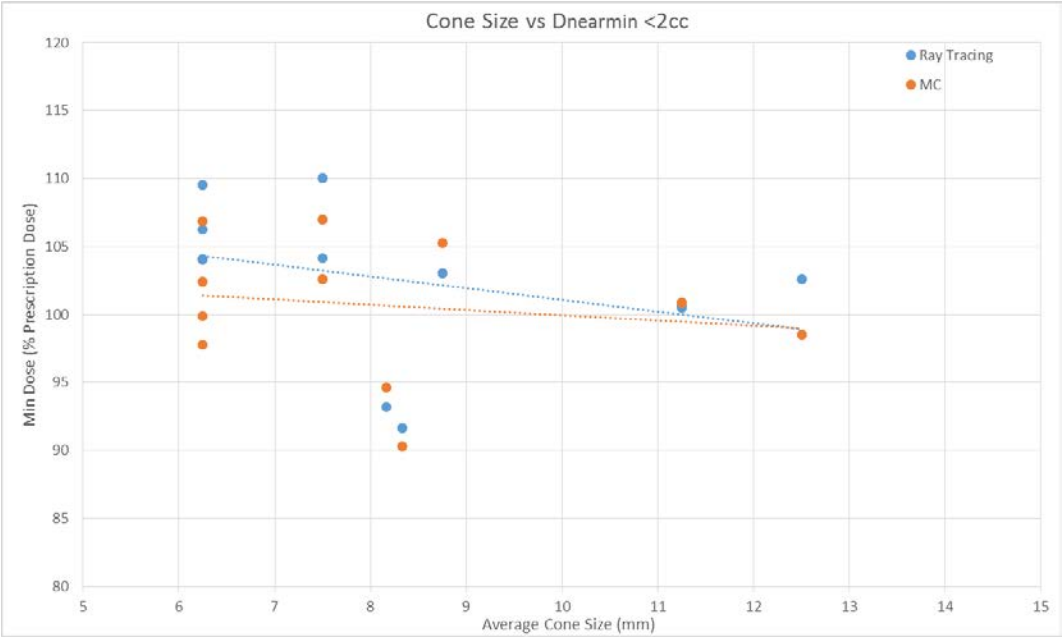

Fig. 12 Cone size vs Min Dose ICRU91 <2cc

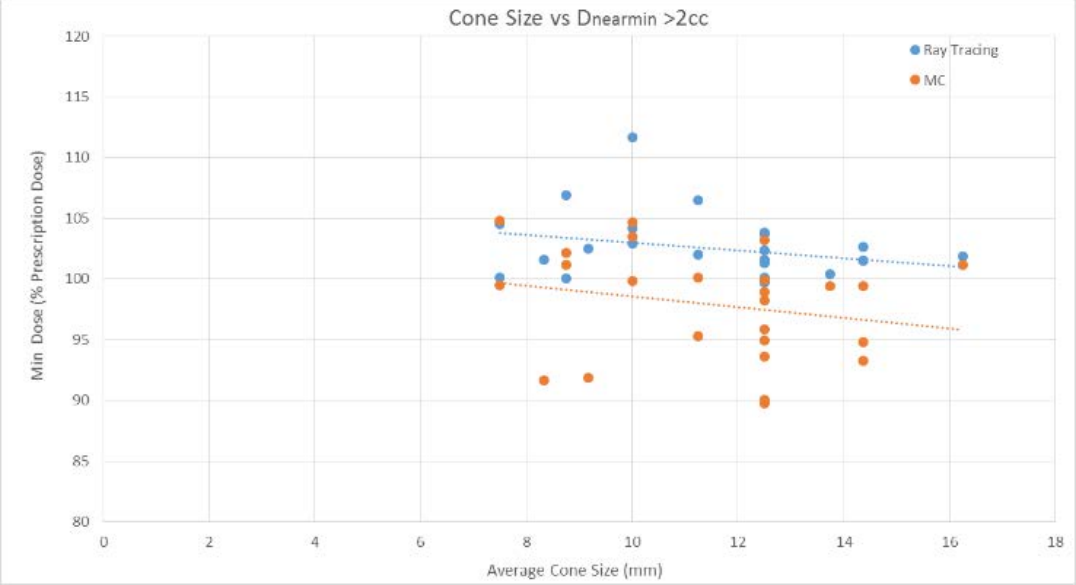

Fig. 13 Cone size vs Min Dose ICRU91 >2cc

This can again be attributed to the RT algorithm being unable to account for lateral scatter with the effect greater for fields smaller in width than the range of secondary charged particles. This leads to the RT algorithm overestimating the target minimum dose. For the larger average cone sizes used for tumors> 2cc, the D98 Min dose was analysed. There was no significant correlation between cone size and min dose for either the RT or MC algorithm (Pearson -0.08, -0.12). However overall the RT algorithm consistently overestimated the minimum dose when compared to MC across all Cone Sizes (Figure 13).

3.8 CI and HI

The Raytracing plans showed a higher conformity index (CI) than the MC plans with a mean increase per target of 6.58% ±4.2%. This can be attributed to Ray Tracing overestimating the coverage and calculating a greater dose splash outside of the PTV. Conversely MC calculated plans with lower coverage showed a lower CI. In terms of the Target Homogeneity Index, there was no difference between MC and RT plans with the ratio of Dmax to Prescribed dose staying the same. This was expected as the target maximum dose did not differ significantly between the RT and MC calculated plans.

3.9 OAR Doses

The OAR doses for the Brainstem, Optic Nerves and Optic Chiasm were recorded for both the MC and RT calculated plans. A summary of these results can be seen in tables 3 and 4. The OAR doses increased with the MC calculation with the point dose increasing by between 2% and 3.7% depending on the OAR. The volume dose increased by between 2.7% and 7.17%. The MC doses were slightly higher than the RT ones however for the pituitary treatment site the effect was minimal with a maximum increase of 0.9Gy on the optical apparatus when recalculating with MC.

The average difference of 3.2% on the Optic Chiasm between the RT and MC calculated plans would be less than half a Gray on the average 15Gy prescription. These differences are reflective of dose to water vs dose to medium but MC plans must report dose to medium for consistency with previous radiotherapy experience [15].

Table 3: Brainstem and Optic Chiasm Doses RT Vs MC

Algorithm	Brainstem	Optic Chiasm
Ray Tracing Avg from all plans	35mm^3=7.48Gy 200mm^3=5.38Gy	35mm^3=9.73Gy 200mm^3=6.88Gy
Monte Carlo Avg from all plans	35mm^3=7.62Gy 200mm^3=5.52Gy	35mm^3=10.03Gy 200mm^3=7.11Gy
Avg % Diff per plan (MC Vs RT)	35mm^3=2.11% SD±1.6% 500mm^3=2.72% SD±2.0%	35mm^3=3.21% SD±2.0% 200mm^3=3.52% SD±4.1%
Max Diff per plan (MC Vs RT)	35mm^3=0.36Gy 500mm^3=0.31Gy	35mm^3=0.87Gy 200mm^3=0.84Gy

Table 4: Optic Nerve Dose RT vs MC

Algorithm	Rt Optic Nerve	Lt Optic Nerve
Ray Tracing Avg from all plans	$35mm^3$=7.06Gy $200mm^3$=3.52Gy	$35mm^3$=6.6Gy $200mm^3$=3.09Gy
Monte Carlo Avg from all plans	$35mm^3$=7.26Gy $200mm^3$=3.69Gy	$35mm^3$=6.77 Gy $200mm^3$=3.26Gy
Avg % Diff per plan (MC Vs RT)	$35mm^3$=3.3% SD±2.3% $500mm^3$=5.1% SD±3.2%	$35mm^3$=3.67% SD±2.4% $200mm^3$=7.17% SD±7.4%
Max Diff per plan (MC Vs RT)	$35mm^3$=0.52Gy $500mm^3$=0.51Gy	$35mm^3$=0.65Gy $200mm^3$=0.67Gy

3.10 Prescription -From EPL based to MC Based

With prescriptions primarily based on EPL empirical data, there have been many attempts to rescale prescriptions in heterogeneous regions so that the new MC prescription is equivalent to the old EPL based one [2] While Van der Voort et al proposed another prescription for peripheral lung treatments based on tumor diameter this was in the extreme heterogeneous case of lung. This is necessary in very heterogeneous cases such as lung where the PTV coverage D95 to the PTV can drop by on average 21% for tumors less than 3cm [2]. However, in this study, when recalculating EPL based plans with Monte Carlo, the average absolute drop in minimum dose to the PTV was 4.4 %. The D50 was also largely the same for both the MC and RT plans 1.4% ±1.2%. For this reason, a change in prescription is not required when moving from RT to MC treatment planning in the specific case of Cyberknife Stereotactic Pituitary treatments.

4. Conclusion

When calculating with RT, the Dnearmin Minimum Dose was artificially high particularly for smaller targets <6cc and with increasing air in the target. In these cases, MC should be used so as not to underdose the target. RT consistently overestimates the minimum dose of these smaller targets. The recommended D50 coverage metric from ICRU91 showed no significant difference between the MC and RT calculated plans and should be used with caution as it does not reflect cold spots in the volume. It should be used in conjunction with the Dnearmin when assessing coverage to avoid a loss of local control. There was no significant difference in Dnearmax Maximum Dose between the RT and MC calculated plans.

For very small tumors in particular below 1cc the Dnearmin can be skewed artificially high by a volume effect and should be used with caution. Also, for these small tumors the new ICRU91 maximum dose formula Dnearmax can be skewed artificially low, so caution should be used when using these metrics in the specific case of small volume tumors. OAR's showed a consistent increase in both point and volume dose when calculated using the MC algorithm, Given MC plans in this study had poorer coverage and similar max doses, these differences are most likely caused by dose to

medium being used by the MC algorithm instead of absorbed dose to water in the volume. Larger cones offer a more homogenous dose distribution with a lower median dose.

There is no need to scale down the prescription of MC calculated pituitary plans as the D50 is too similar between MC and RT calculated plans. Therefore, the Biological Effective Dose (BED) would be too close in this case of Pituitary Adenoma to warrant a change in prescription when using the MC algorithm.

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