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ORIGINAL ARTICLE

# An evaluation of Pencil Beam vs Monte Carlo calculations for intracranial stereotactic radiosurgery

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## Summary

***Purpose:*** *To compare the accuracy of two separate models when calculating dose distributions in patients undergoing stereotactic radiosurgery (SRS) treatment for brain cancer.*

***Methods:*** *For this comparison, two dose calculation algorithms were evaluated on two different treatment planning systems (TPS): Elekta's Monaco Version 5.11.00 Monte Carlo Gold Standard XVMC algorithm and Brainlab's iPlan Pencil Beam algorithm. The DICOM files of 11 patients with a total of 19 targets were exported from iPlan and then imported into Monaco to be recalculated. Using the dose distributions of the original (pencil beam/PB) and recalculated (Monte Carlo/MC) plans, four indices for plan quality were evaluated: coverage (Q), conformity index ($CI_{RTOG}$), homogeneity index (HI), and gradient index (GI).*

***Results:*** *There was a significant difference in the $CI_{RTOG}$ and HI between the two TPS calculations. However, the magnitude of these differences is often not substantial enough to cause the plan to fall outside of RTOG protocol deviation limits. Only 3 of the 19 targets had $CI_{RTOG}$ values which moved to a new level of deviation, and these targets were unique in terms of size (<0.1 $cm^3$).*

***Conclusion:*** *It was found that the difference between systems is often not enough to cause the plan to fall outside of RTOG protocol deviation limits. This is an indication that a PB-based treatment planning system is sufficient for the mostly homogeneous conditions of intracranial SRS planning when the target is larger than 0.1 $cm^3$. If below 0.1 $cm^3$, the prescribing physician may need to evaluate TPS differences.*

***Key words:*** *SRS, Monte Carlo, Pencilbeam, dose calculation, treatment planning*

## Introduction

A significant number of cancer patients that underwent treatment will ultimately develop metastases. One study estimated that 8.5% of cancer patients present with brain metastases at the time of their initial diagnosis [1]. Stereotactic radiosurgery (SRS) is a focal irradiation technique, characterized by the ability to precisely deliver a large dose in a single fraction to a small localized lesion. Prescribed doses are usually between 1000-4000 cGy and are often delivered with localization precision of ± 1 mm [2]. Multiple beams are used and are all directed at the isocenter to produce the desired steep dose gradient at the edge of the target. Due to the small size of the target (ranging up to 5 cm in maximum diameter), the targeting of GTV with minimal margins (if any), and the high doses of radiation, it is very important that the treatment is delivered as accurately as possible to spare healthy tissue surrounding the target and minimize adverse effects. Because of this, SRS treatments are most commonly used to treat brain metastases [3].

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The Radiation Therapy Oncology Group (RTOG) published quality assurance guidelines for SRS that should be considered when evaluating the quality of a treatment plan. The guidelines offer several methods for evaluating the quality of a plan [3]. The report defines metrics used to quantify the coverage of the target with the prescription dose, the dose homogeneity within the target, and the conformation of the prescription dose to the target. Quality assurance guidelines are provided for each of these metrics to determine the level of deviation from the treatment protocol. The levels include compliance per protocol, minor deviation, and major deviation.

There are several treatment planning systems that offer a module for SRS planning. Often, a significant difference between TPS platforms is the dose calculation algorithm being implemented. For this study, a pencil beam (PB) algorithm and a Monte Carlo (MC) algorithm from two separate treatment planning systems were compared in the context of SRS treatment planning. PB algorithms have often been implemented for SRS treatment planning because the calculations are fast and work sufficiently well in mostly homogeneous mediums such as the brain. MC algorithms are used historically less frequently for brain because of the homogeneity of the brain tissue but also because they are more demanding in computational resources and usually less time efficient. However, MC is considered the benchmark for analytic calculations and provides the highest accuracy achievable when the statistical uncertainly is kept low [4]. Various MC algorithms have been developed to reduce the amount of time required for dose computation. An improved version of the Voxel Monte Carlo (VMC) electron algorithm was developed by Fippel to perform fast MC calculations for photon beams and is known as XVMC [5]. The purpose of this study is to determine whether an XVMC algorithm produces significant differences in dose calculations as compared to the PB algorithm, and whether it should be considered as the standard for SRS treatment planning.

Several studies have focused on the differences between MC and PB algorithms for highly heterogeneous regions such as the lung [6-9]. However, there have been less focusing on more homogeneous regions, such as the brain. Studies by Kang et al [10] and Wilcox et al [11] have both explored the use of MC and PB for intracranial lesions. Both determined that there was no need for performing MC calculations in regions with less heterogeneity, as there were no gross differences between the two methods. However, these two studies focused on delivering via CyberKnife with circular collimators. There is potential for different results when delivering with an MLC collimator, which this study explores.

A study by Menon et al [12] also explores the differences between MC and PB calculations for MLC delivered intracranial lesions. Their findings

**Table 1.** Prescription and volume for each target used in this study

| *Patient* | *Target* | *Prescription [cGy]* | *Volume [cc]* |
|---|---|---|---|
| 1 | 1 | 2400 | 10.247 |
| 2 | 2 | 2400 | 0.38 |
| 3 | 3 | 1400 | 0.371 |
| 4 | 4 | 2400 | 1.603 |
| 5 | 5 | 2000 | 5.642 |
| 6 | 6 | 1400 | 0.307 |
| 7 | 7 | 1400 | 1.728 |
| 7 | 8 | 1400 | 1.642 |
| 8 | 9 | 2400 | 0.592 |
| 8 | 10 | 2400 | 0.259 |
| 8 | 11 | 2400 | 0.273 |
| 9 | 12 | 2400 | 3.207 |
| 10 | 13 | 2400 | 1.194 |
| 10 | 14 | 2400 | 0.555 |
| 10 | 15 | 2400 | 0.509 |
| 11 | 16 | 2400 | 0.043 |
| 11 | 17 | 2400 | 0.95 |
| 11 | 18 | 2400 | 0.099 |
| 11 | 19 | 2400 | 0.099 |

were that a MC calculation may be beneficial when delivering with small fields where lateral charged particle equilibrium may be lost. However, this study was performed using iPlan's MC dose calculation algorithm and focused on a very specific subset of AVM patients with high-density Onyx embolization. Furthermore, their justification for suggesting MC use may be necessary was based solely on the existence of a significant difference between the two approaches. This study further aims to explore the clinical impact of the two calculation methods using the protocol deviation guidelines recommended by the RTOG [3].

## Methods

In this comparison study of SRS treatment planning systems, two algorithms were evaluated: Monaco Version 5.11.00 Monte Carlo Gold Standard XVMC algorithm (Elekta AB, Stockholm, Sweden) and Brainlab iPlan Pencil Beam algorithm (Brainlab AG, Munich, Germany). While iPlan offers their own implementation of VMC, our clinic does not have the rights to this tool for comparison. This is a retrospective analysis in that all the Brainlab iPlan patient treatment plans were delivered to patients and then recalculated in Monaco using the same contours, beam arrangements, and monitor units from the iPlan. A total of 11 SRS patient treatment plans were retrieved from the institution's archived patients in iPlan to be used in this evaluation. There was a total of 19 targets for those 11 patients, indicating that some patients had more than one tumor that was treated. The volumes and prescriptions for each target are listed in Table 1. All treatment plans utilized the Novalis Tx (Varian Medical Systems, Inc., Palo Alto, CA, USA) 120HD multileaf collimator (MLC) rather than stereotactic cones.

Treatment plans were selected and exported from iPlan in DICOM format. Each export consisted of the CT image, dose, plan, and structure files. For patients with multiple targets, a file group for each target was exported individually. Once the DICOM files had been exported from iPlan, they were imported into Monaco for recalculation and evaluation. The plans were recalculated in Monaco with a grid resolution of 0.1 cm for the entire volume. The Monaco dose distributions were then compared to the original dose distributions from iPlan which were also performed with a grid resolution of 0.1 cm for the entire volume. Both plans were analyzed in Monaco to eliminate any potential bias that may arise from evaluating in different systems.

Using the prescribed dose for each target, the dose volume histogram (DVH) statistics tool within Monaco was utilized to retrieve relevant data from both plans for comparison. From the DVH statistics of the gross target volume (GTV), the following values were obtained: target volume (TV), volume of target receiving the prescribed dose (TVPI), minimum dose deposited in the target (MIN, defined as the dose deposited in 98% of the target volume), maximum dose deposited in the target (MD, defined as the dose deposited in 2% of the target volume), and mean dose deposited in the target. The total patient volume receiving the prescribed dose (PI) and the total volume receiving at least 50% of the prescribed dose (PI50%) were also recorded. Using these values, the coverage (Q), conformity index ($CI_{RTOG}$), gradient index (GI), and homogeneity index (HI) were calculated as a measure of plan quality.

Coverage, Q, is used to describe the minimum isodose line that fully encapsulates the target and is displayed as a percentage. The value of Q was determined by dividing the MIN by the prescription dose (PD) as in Equation 1 [3]. Full coverage (Q= 100%) is desired to ensure proper delivery of the prescription dose.

Equation 1: $Q = \left(\frac{MIN}{PD}\right) x 100$

$CI_{RTOG}$ is a conformity index defined by the RTOG radiosurgery quality guidelines [3]. This index is a ratio of the total volume receiving the prescription dose (PI) to the volume of the target (TV) and is provided in Equation 2. Ideally, the value should be equal to unity. If the value is less than unity, then the target will not be fully covered at the prescription dose. If the value is greater than unity, then healthy tissue will be irradiated.

Equation 2: $CI_{RTOG} = \frac{PI}{TV}$

HI provides information about the intensity of a hotspot and the homogeneity of dose within the target. It is a ratio of the MD to the prescription dose and is provided in Equation 3 [3]. Ideally, the MD should be no more than double the PD according to the RTOG guidelines.

Equation 3: $HI = \frac{MD}{PD}$

GI is used to measure the dose falloff outside of the target. It is the ratio of the volumes covered by the 50% and 100% isodose lines [13]. The value for GI will always be greater than or equal to unity, with unity being the optimal value. The closer the values of PI50% and PI are, the amount of normal tissue spared will be greater. The calculation method for GI is defined in Equation 4.

Equation 4: $GI = \frac{PI50\%}{PI}$

The MC and PB calculation algorithms were dosimetrically verified through small field measurements in water. One hundred monitor units were delivered at 100 cm SSD with five separate field sizes ranging from 1x1 $cm^2$ to 5x5 $cm^2$ and measured at both 5 cm and 10 cm depth using a microDiamond synthetic diamond detector (PTW, Freiburg, Germany). The exact set-up for the measurements was then modeled in both iPlan and Monaco and calculated. At all points, both treatment planning systems were within 5% agreement with the measured values.

## Results

After retrieving all the necessary metrics from each TPS calculation, the values for Q, $CI_{RTOG}$, HI, and GI were calculated to evaluate the quality

of the plans. A two-tailed, paired t-test at a 95% confidence level was performed for each index to compare the calculated values from each TPS. The null hypothesis was that no significant difference between the values of the systems exists. The calculated p-values as well as the mean value for the indices from each TPS appear in Table 2. According to the results of the t-tests, there was a significant difference between the two TPSs for $CI_{RTOG}$ and HI. The difference in $CI_{RTOG}$ indicates that healthy tissue surrounding the target is receiving lower doses in the Monaco calculations than estimated using iPlan. The difference in HI indicates that the hotspot within the target is lower in the Monaco calculations than estimated using iPlan. Additionally, the minimum, maximum, and mean GTV doses were compared between the two systems. There was found to be a significant difference between the maximum and minimum GTV doses. These results can be seen in Table 3. An example of the effects on isodose lines can be seen in Figure 1.

In addition to the t-tests, Pearson correlation tests were performed to search for any linear correlation between the four indices (Q, $CI_{RTOG}$, HI, GI) and the target volume. There was no significant linear relationship identified between any of the indices and the target volume.

## Discussion

In the RTOG report on radiosurgery quality assurance guidelines, scores are provided for the conformity index, homogeneity index, and the coverage metric to classify the level of deviation from protocol. These guidelines appear in Table 4 [3]. When comparing the RTOG indices for each TPS, it was observed that there were only 3 instances (15.8% of targets) in which the conformity index moved from one level of deviation to another (Table 5). There were two instances in which the status of the $CI_{RTOG}$ worsened when using the MC algorithm versus the PB algorithm, and one instance in

**Table 2.** Results from t-tests between the two systems for each scoring metric. The average scoring metric values from each system are also provided

| | *p value* | *μ iPlan* | *μ Monaco* |
|---|---|---|---|
| $CI_{RTOG}$ | 0.025 | 1.690 | 1.423 |
| HI | 0.000 | 1.323 | 1.274 |
| GI | 0.167 | 3.706 | 6.147 |
| Q | 0.071 | 104% | 102% |

**Table 3.** Results from t-tests between the two systems for minimum, maximum, and mean GTV dose. The averages from each system are also provided

| | *p value* | *μ iPlan [cGy]* | *μ Monaco [cGy]* |
|---|---|---|---|
| Min Dose | 0.080 | 2256.2 | 2211.6 |
| Max Dose | 0.000 | 2873.4 | 2761.3 |
| Mean Dose | 0.001 | 2635.9 | 2552.7 |

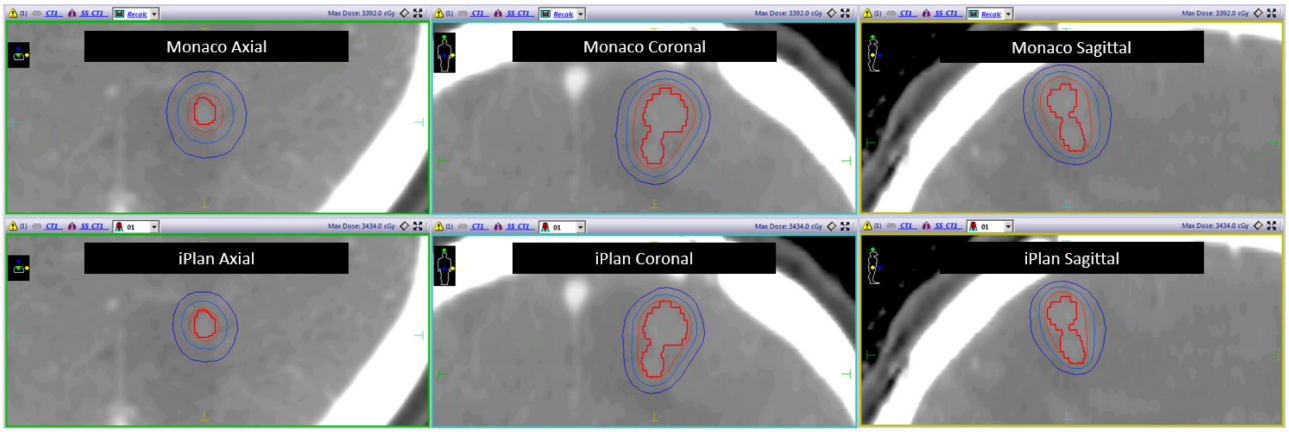


**Figure 1.** Comparison of isodose lines in axial, coronal, and sagittal planes for Monaco and iPlan calculated treatment plans.

**Table 4.** Quality assurance guidelines provided by the RTOG [3]

| *Status* | $CI_{RTOG}$ | *HI* | *Q* |
|---|---|---|---|
| Per Protocol | $1.0 < CI_{RTOG} < 2.0$ | $HI < 2.0$ | $Q > 90\%$ |
| Minor Deviation | $0.9 < CI_{RTOG} < 1.0$ or $2.0 < CI_{RTOG} < 2.5$ | $2 < HI < 2.5$ | $80\% < Q < 90\%$ |
| Major Deviation | $CI_{RTOG} < 0.9$ or $CI_{RTOG} > 2.5$ | $HI > 2.5$ | $Q < 80\%$ |

**Table 5.** Comparison of $CI_{RTOG}$ values calculated by each TPS. The change in status is noted as either a '+' (improved status), '-' (worsened status), or None (no change)

| | *iPlan* | | *Monaco* | | |
|---|---|---|---|---|---|
| *Target* | $CI_{RTOG}$ | *Status* | $CI_{RTOG}$ | *Status* | *Δ Status* |
| 1 | 1.208 | Acceptable | 1.268 | Acceptable | None |
| 2 | 2.337 | Minor Deviation | 2.153 | Minor Deviation | None |
| 3 | 1.857 | Acceptable | 1.694 | Acceptable | None |
| 4 | 1.563 | Acceptable | 1.600 | Acceptable | None |
| 5 | 1.634 | Acceptable | 1.492 | Acceptable | None |
| 6 | 1.531 | Acceptable | 1.308 | Acceptable | None |
| 7 | 1.768 | Acceptable | 1.796 | Acceptable | None |
| 8 | 1.266 | Acceptable | 1.299 | Acceptable | None |
| 9 | 2.108 | Minor Deviation | 2.005 | Minor Deviation | None |
| 10 | 1.795 | Acceptable | 1.441 | Acceptable | None |
| 11 | 1.476 | Acceptable | 1.240 | Acceptable | None |
| 12 | 1.283 | Acceptable | 1.290 | Acceptable | None |
| 13 | 1.518 | Acceptable | 1.522 | Acceptable | None |
| 14 | 1.695 | Acceptable | 1.582 | Acceptable | None |
| 15 | 1.397 | Acceptable | 1.281 | Acceptable | None |
| 16 | 2.140 | Minor Deviation | 0.349 | Major Deviation | - |
| 17 | 1.502 | Acceptable | 1.608 | Acceptable | None |
| 18 | 2.242 | Minor Deviation | 1.189 | Acceptable | + |
| 19 | 1.788 | Acceptable | 0.926 | Minor Deviation | - |

which the RTOG status improved. However, these instances all occurred in targets less than 0.1 cc in volume. This indicates that, while infrequent, it is possible to have a large enough difference in the $CI_{RTOG}$ from each system that may require a re-evaluation of the plan based on RTOG standards, especially for very small targets (<0.1 $cm^3$). From the 19 targets, there was no change in status for the HI or Q between TPS's.

For continuation of this project, results could be improved with the addition of more patients. Additionally, more correlations to plan quality could be explored. One of interest is in the effects of the physical location of each target on the indices. The possibility that there may be significant differences in the capabilities of each TPS that are dependent on the location of the target within the skull could be further investigated.

While this study determined that there are significant differences between the two dose calculation algorithms, there is not enough evidence to support a need for requiring MC algorithms in stereotactic radiosurgery. This study did find, however, with targets below 0.1 $cm^3$ in volume, the RTOG protocol change in deviation status may need to be evaluated by the prescribing physician to determine potential clinical significance.

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## Conflict of interests

The authors declare no conflict of interests.

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