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A Qualitative Dosimetric Comparison of Helical Tomotherapy, Coplanar Volumetric Modulated Arc Therapy, and Non-coplanar Volumetric Modulated Arc Therapy for Radiotherapy of Centrally Located Brain Tumors

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August 4, 2021

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Graduate Medical Dosimetry Program

Abstract

Introduction

The purpose of the work is to see if there is a dosimetric benefit to using one treatment modality over another when treating centrally located brain tumors. These modalities include helical tomotherapy, non-coplanar VMAT, and coplanar VMAT.

Methods

Thirty plans were created from ten previously treated patient's datasets. All patients were planned using a simultaneously integrated boost with a PTV54 and PTV 60. The conformity index and homogeneity index were compared for targets. Dose maximums and means were compared for critical structures between the plans and modalities.

Results

A significant difference was found for the conformity index for 5400 cGy where helical tomotherapy was the furthest from 1 by more than 10%. For 95% of the higher prescription dose of 6000cGy (5700cGy), the mean conformity index was significantly closer to 1 for helical tomotherapy by more than 20% compared to the other two modalities. Helical Tomotherapy had a significantly higher dose to both lenses and both optic nerves as well as a higher mean dose for the brain stem and normal brain subtracting the PTVs. Helical tomotherapy met all dose constraints for all plans where coplanar VMAT and non-coplanar VMAT did not for two patients where the brainstem was within 3mm of the PTV60.

Conclusion

For centrally located brain tumors, helical tomotherapy was able to meet all constraints and had a higher CI for 95% of higher target volume. Non-coplanar and coplanar VMAT's dose to normal structures were comparable and lower than helical tomotherapy but were unable to

meet brain stem dose constraints for 2 patients. While all modalities have proven acceptable and useful in treating centrally located brain tumors, the author recommends using HT.

Introduction

According to Ostrom, there should have been an estimated 83,830 cases of central nervous system cancer diagnosed in the year 2020. Roughly thirty percent of those cases were expected to be malignant.[1] Malignant gliomas are tumors that arise from glial cells and are the most common central nervous system tumor. They account for an estimated 20,000 cases per year.[2] For malignant brain tumors, the median survival length of patients after diagnosis can range from 8 months for patients diagnosed with glioblastoma, to 139 months for patient diagnosed with malignant pituitary cancers.[1] The five year relative survival rate for patients diagnosed with primary malignant brain and other central nervous system (CNS) tumors is 23.5%. The five year relative survival rate for patients diagnosed with non-malignant brain and CNS tumors is 82.4%.[1]

CNS tumors are typically treated with medical therapy, surgery, radiation therapy or a combination of those depending on type of tumor and symptoms. Medical therapy includes the use of steroids like dexamethasone and some chemotherapy agents such as temozolomide and bevacizumab.[3] For emergent symptoms, surgical resection or a placement of a shunt (a passage or tube made to allow fluid to move and drain) is often necessary. Steroids are also utilized, such as dexamethasone.[4]

Treatment options vary for gliomas depending on the grade of the tumor. For grade I tumors, surgery alone is the standard. Current practices for grade II include a safe gross total resection including close follow up with radiologic scans. The goal for treatment of grade III and grade IV tumors include a safe gross total resection, concomitant chemoradiation, and follow

up with radiologic scans.[2] For high grade gliomas, according to Khan, the standard radiation fractionation is "45 to 50 Gy to a clinical target including all surrounding postoperative flair signal plus a 2-cm margin" followed by a boost up to 60 Gy.[4] Other sources say for grade III and IV gliomas, the standard Stupp protocol is radiotherapy and concomitant chemoradiation using a total of 60 Gray with 2 Gray per fraction with temozolomide.[2]

Considerations should be taken into account when delivering doses of radiation this high next to critical structures and organs at risk (OAR). There are some serial structures in the brain that need to be evaluated as a max point dose in addition to volumetric dose.[5] Intensity modulated radiation therapy (IMRT) is more beneficial when the proximity of the targets are close to radiosensitive OARs such as the optic chiasm, optic nerves, and brainstem.[6] The OAR immediately around centrally located brain tumors are the brain stem, cochleas, hippocampus, lenses of the eyes, optic chiasm, optic nerves, and spinal cord.[5]

To minimize OAR side effects, the normal brain should be kept to below a maximum dose of 72 Gy for a less than 5% chance of side effects. The entire brain stem should have a maximum dose of below 54Gy. Between 1-10cc can go up as high as 59 Gy in the brain stem. Cochleas should be kept to a mean dose of less than or equal to 45 Gy. The optic nerve and chiasm should have a maximum dose of less than 54 Gy. The spinal cord should also be kept below 50 Gy.[7] Due to the high mortality rate for glioma's, compromising coverage for hippocampus protection is not recommended.[8] Each lens should be kept below 10 Gy, ideally less than 6Gy.[9]

The location of the tumor and these organs needs to be mapped out in a radiation simulation.[4] A simulation should include the use of computed tomography (CT) treatment planning.[4] The patient should be lying supine with immobilization of the head. This will include

an aquaplast mask with a custom head holder to help prevent the head from moving while delivering treatment. The mask and head holder also help aid in reproducibility.[4,5]

Magnetic resonance imaging (MRI) has proven to be extremely useful in defining some of the OARs, as well as delineating the tumors and surrounding enhanced abnormalities for the clinical target volume (CTV). The CTV includes the entire tumor and the invisible microscopic disease. It can be estimated only clinically and that is why it is named CTV.[4] MRI is the gold standard for imaging both benign and malignant CNS tumors. T1 and T2 weighted images are registered and fused with the CT scan done for simulation. Physicians use MRIs to create the gross tumor volume and the clinical target volume.[4,5]

There are a number of different types of radiation treatment modalities that have been used to treat brain tumors: fixed field step and shoot intensity modulated radiation therapy (IMRT), conventional (2D), 3D conformal radiotherapy, coplanar volumetric modulated arc therapy (cVMAT), non-coplanar volumetric modulated art therapy (nVMAT), helical tomotherapy (HT), stereotactic radiotherapy (SRT), stereotactic radiosurgery (SRS), as well as radioactive implants. Many of these techniques can achieve acceptable plans and have been researched in other literature.[4,9–11]

Previous studies compare cVMAT, nVMAT, and fixed field static field IMRT.[12–14] One study suggests that nVMATs help reduce dose to certain OARs when compared to cVMAT, such as the hippocampus. The study found the mean dose was 6.8 Gy for nVMAT when compared to 10.8 Gy for cVMAT. The dose threshold this study used for the hippocampus was 7.3 Gy.[14] Another study showed that cVMAT and nVMAT didn't affect organs at risk greatly in glioblastoma radiotherapy when compared to each other. However, it showed that either type of

VMAT had statistically significant reduction in the mean dose to the optic chiasm and a reduction in the amount of MUs used when compared to step and shoot IMRT.[12]

Additional studies compare cVMATs, HT, and fixed field static field IMRT.[9,15] One study states that HT had improved conformity and lower dose to OARs when compared to cVMAT and static field IMRT in treatment of high grade gliomas. The study showed similar planned treatment volume (PTV) coverage between cVMAT, HT, and IMRT. The author said that HT has a better homogeneity index (HI) when compared to IMRT and cVMAT but that it was not statistically significant. The conformity index (CI) of HT was statistically significant and better than cVMAT and IMRT. As for the sparing of OARs, HT had a statistically significant advantage in the D_{mean} and D_{max} of the planning organ at risk volume of the brain stem, as it was lower. The same applied to the lenses of the eyes. It was shown that there was a statistically significant difference for which HT had reduced dose to the lenses when compared to cVMAT and IMRT. There was a not a statistically significant difference between cVMAT and IMRT. For the optic nerves, there was not a statistically significant difference between the three planning modalities. Coplanar VMAT had the greatest reduction of the optic chiasm when compared to HT and IMRT.[9]

When looking at hippocampus sparing during whole brain radiotherapy, one study concludes that HT has a better homogeneity index for treatment in the brain when compared to cVMAT and step and shoot IMRT. However, the time taken to deliver was significantly shorter for VMAT when compared to HT (2.5 minutes compared to 18 minutes). The same study also found that the dose to the eyes and lenses were statistically significantly different when comparing HT to VMAT and IMRT. HT has lower doses for the lenses and globes of the eye. The study discusses this may be due to the planning constraints use for VMAT and IMRT.[15]

Previous studies show that nVMAT and HT seem to be the preferred option in many of these cases.[9,12–14] However, to the authors current knowledge, no studies compare nVMAT to HT for centrally located brain tumors. Both nVMAT and HT have been proven to reduce doses to OARs when compared with IMRT and cVMAT.[9,12–14] HT also has been shown to increase the CI and HI of the plans when compared to IMRT and VMAT.[9,15]

The purpose of the current study is to perform a dosimetric radiation treatment plan evaluation in order to determine which radiation treatment modality (cVMAT, nVMAT, or HT) has the highest conformity index and homogeneity index as well as the lowest mean dose and lowest maximum dose for critical structures for centrally located brain tumors. This will allow more appropriate modality decisions when deciding which modality to treat patients with centrally located brain tumors. The researcher hypothesizes that HT will achieve better HI and CI while at the same time having a lower dose to the OAR.

Null hypothesis (H_0): There will not be a difference between homogeneity index, conformity index, and dose to organs at risk when comparing helical tomotherapy, non-coplanar VMAT, and coplanar VMAT.

Alternative hypothesis (H_a): There will be a difference between homogeneity index, conformity index, and dose to organs at risk when comparing helical tomotherapy, non-coplanar VMAT, and coplanar VMAT.

Materials and Methods

Subjects

This retrospective study was conducted using medical chart data from 10 patients who had received radiation therapy to the brain. The study was completed in collaboration with a medical center located in the midwestern United States. To be included in the study, all of the

subject's diagnosis needed to include a parent grouping ICD 10 code of C71, which corresponds to malignant neoplasms of the brain. The patient also had to have a centrally located brain tumor where the CTV was within 5cm of the sella turcica.

A report was run in MOSAIQ (version 2.64) radiation oncology management system to see which datasets were available and had the proper ICD 10 diagnosis code. Selection started with the most recent patient who had completed radiotherapy and went backwards chronologically to limit the number of charts reviewed for inclusion and exclusion criteria. In order to make sure each patient had a centrally located brain tumor, during patient selection, each set of contours for the subject was reviewed to make sure the clinical target volume was within 5 centimeters from the sella turcica. Demographics were reviewed to exclude subjects who were pregnant women, prisoners, and 25 years old and younger at the time of their planning simulation. Scans for re-irradiation and recurrent brain tumors were also excluded. Subjects who, at the time of consent for radiation treatment, indicated that they did not want to participate in research studies were excluded as well.

Ethical Considerations

All study protocol was reviewed and approved by the Midwest hospital's institutional review board. In addition, the study protocol was reviewed and approved by the first author's academic institutional review board. Patient names were genericized (Patient 1, Patient 2, etc) prior to use within this study. Paper copies of medical chart documents were kept in a locked file cabinet or locked office. After the paper documents were used, they were shredded using the Midwest hospital system's shredding bins. The integrity of digital data was kept secure in a password secure OneDrive account associated with the Midwest hospital. A code for linking the

data to the patient was kept in a password protected file in the Midwest hospital's OneDrive per institution policy.

Treatment planning

Previously completed datasets of each the subjects had the patient scanned in the supine position, had used an aquaplast mask, and was scanned on the Philips Big Bore CT scanner with 2 mm for slice thickness. Scans started above the head and continued down below the fifth cervical vertebrae. The contours for targets and normal structures were imported into the Pinnacle treatment planning system (version 16.2.1) from the previously approved plans.

All of the plans were given the prescription of 54 Gy to PTV54 and 60Gy to PTV60 in 30 fractions using a simultaneous integrated boost. Both the cVMAT and nVMAT were planned on the Pinnacle treatment planning system (version 16.2.1) using the autoplan feature. The HT plan was done on the Accuray Precision (version 3.1.0.0) planning system. All plans were done by the same planner.

For the cVMAT, two 6MV beams were planned for use on the Varian Truebeam at the Midwest Hospital. Both beams use 354 degree arcs from 178 to 182 degrees and from 182 to 178 degrees with couch at 0 degrees. Collimator rotation was 30 degrees and 330 degrees respectively. Equal weighting to the beams was applied before autoplanning was initiated. Motion constraint was at .46 cm. The planning goal for the PTV was 1% higher than the prescription dose due to Midwest Hospitals standard workflow. Final dose was calculated using the CC convolution algorithm. See Table 1 for dose constraints to OARs used in all planning modalities.

For nVMAT, three 6MV beams were planned for use on the Varian Truebeam at the Midwest Hospital. The first beam was with the couch at 350 degrees and the arc from 178 to

302 degrees. The second beam's arc was from 182-62 degrees with the couch at 10 degrees. The third beam's arc was from 0 to 36 degrees with the couch at 270 degrees. Collimator angles were 30, 330, and 0 degrees respectively. Weighting was applied in proportion to arc length. The autoplanning dose for the PTV was 1% higher than the prescription dose due to the standard workflow of the Midwest Hospital. Motion constraint was at .46cm before initiating autoplanning. Final dose was calculated using CC convolution algorithm.

The HT plans were planned with Accuray Precision version 3.1.0.0 planning software. Field width was set at 2.5cm, pitch at .275, and the modulation factor was set at 2.2. Target dose was set at 54 Gy to PTV 54 at 50% of the volume and 60Gy to the PTV60 at 50% of volume. Both percentages moved up until 98% of PTV reached 95% of the prescription dose or higher in accordance with the Midwest Hospital's planning workflow for HT.

Plan coverage quality was evaluated by using Paddick's Conformity Index (CI) and homogeneity index (HI). Paddick's CI was calculated by using the formula $PCI=(TV_{PIV})^2/(TV*PIV)$ where TV_{PIV} is the target volume covered by the prescription isodose volume, TV is the Target Volume, and PIV is the prescription isodose volume.[16] The closer the number to 1, the more conformal and better the plan is considered to be.[17] Homogeneity index is calculated by using the formula HI= D95/D5, where D95 is the dose at 95% volume of the PTV and D5 is the dose at 5% of the volume of the PTV.[18] Plan quality was also compared using the D_{max} and D_{mean} values of the OARs.

Data Analysis

Variables were analyzed using one way repeated measure analysis of variance (ANOVA) followed by Bonferroni post hoc test using SPSS statistical software (version 26.0.0.0) . CIs and HIs were compared as well as D_{max} and D_{mean} values of the OARs. Statistical

significance was determined by p values less than 0.05. Mauchly's test of sphericity was conducted, and when applicable, Greenhouse-Geisser results were reported.

Results

The goal of this study was to compare and evaluate the differences between the planning modalities of cVMAT, nVMAT, and HT for centrally located brain tumors. CI and HI were evaluated for target coverage and dose maximums and means were evaluated for critical structures. Descriptive statistics for the statistically significant values of CI and HI can be found in Table 2 while the descriptive statistics for OARs with statistically significant maximum dose differences can be found in Table 3. Table 4 shows the descriptive statistics for OARs with a statistically significant mean dose difference. A summary of ANOVA results for can be found in Table 5.

Target Volumes

For the CI for the 95% of the prescription dose to PTV 54 (5130 cGy), ANOVA was found to be significant, $F(2, 18) = 3.641$, $p = 0.047$. No statistically significant reaction was found between planning modalities during post hoc analysis.

In regards to CI of the prescription dose (5400 cGy) to PTV 54, ANOVA was found to be significant, $F(1.28, 11.523) = 5.949$, $p = 0.026$. A significant reaction was found between nVMAT and HT, $p = 0.036$. The mean difference was 11.1 % closer to 1 for nVMAT when comparing HT to nVMAT.

Concerning the CI of 95% the prescription dose to PTV 60 (5700 cGy), ANOVA was found to be significant, $F(1.138, 10.24) = 20.11$, $p = 0.001$. A significant reaction was found between cVMAT and HT, $p = 0.003$, and nVMAT and HT, $p = 0.005$. The mean difference was

21.5% closer to 1 for HT when comparing HT to cVMAT and 22.1 % closer to 1 for HT when comparing nVMAT to HT.

For the HI of PTV 60, ANOVA was found to be significant, F (1.114, 10.026) = 5.703, p = 0.035. No statistically significant reaction was found between planning modalities during post hoc analysis. See Figure 2 for comparison of HI for PTV 54 and PTV 60.

Critical Structures and Organs at Risk

For the brain stem mean dose, ANOVA was significant, F (1.093, 9.836) = 7.69, p = 0.018. A significant reaction was found between cVMAT and HT, p = 0.047. The mean difference was 334.16 cGy higher with HT.

In regards to the left lens maximum dose, ANOVA was found to be significant, F (1.188, 10.691) = 15.76, p = 0.002. A significant reaction was found between cVMAT and HT, p = 0.007, and nVMAT and HT, p = 0.009. The mean difference was 278.57 cGy higher for HT when comparing HT to cVMAT and 309.48 cGy higher for HT when comparing nVMAT to HT.

Concerning the left optic nerve maximum dose, ANOVA was significant, F (1.245, 11.207) = 14.94, p = 0.002. A significant reaction was found between cVMAT and HT, p = 0.01, and nVMAT and HT, p = 0.008. The mean difference was 1212.8 cGy higher for HT when comparing HT to cVMAT and 1317.56 cGy higher for HT when comparing nVMAT to HT.

For the mean dose for the volume of the normal brain minus the volume of the PTV, ANOVA was found to be significant, F (2, 18) = 14.77, p < 0.001. A significant reaction was found between cVMAT and HT, p = 0.009, and nVMAT and HT, p = 0.008. The mean difference was 475.49 cGy higher for HT when comparing HT to cVMAT and 400.7 cGy higher for HT when comparing nVMAT to HT.

In regards to the right cochlea mean dose, ANOVA was found to be significant, F (1.057, 9.515) = 5.645, p = 0.039. No statistically significant reaction was found between planning modalities.

Concerning the right lens max dose, ANOVA was found to be significant, F (1.117, 10.049) = 8.396, p = 0.014. A significant reaction was found between cVMAT and HT, p = 0.028. The mean difference was 257.39 cGy higher for HT when comparing HT to cVMAT.

For the right optic nerve max dose, ANOVA was found to be significant, F (1.065, 9.584) = 15.66, p = 0.003. A significant reaction was found between cVMAT and HT, p = 0.011, and nVMAT and HT, p = 0.008. The mean difference was 1392.92 cGy higher for HT when comparing HT to cVMAT and 1477.79 cGy higher for HT when comparing nVMAT to HT.

Discussion

In this study, maximum and mean dose values were compared for organs at risk while Paddick's conformity index as well as homogeneity index was compared for targets. Two different planning systems were used to create the plans. For the nVMAT and cVMAT plans, Pinnacle version 16.2.1 was used and for the HT, Precision version 3.1.0.0 was used. The planning methods are different between the planning systems. There was a statistically significant difference between a number of OARs, the CIs, and the HIs. This rejected the null hypothesis because the data favored the alternative hypothesis. Some of the results of the study were similar to previous literature and some was different.

One similarity to Hou's research was that cVMAT and nVMAT did not affect OAR doses between the two of those modalities.[12] This study is also similar to Liu's research in that HT had better HI when compared to cVMAT but in this study, it was statistically significant for PTV 60.[9] HT showed some improvement for CI compared to cVMAT for 5700cGy and 6000

cGy, which was similar to Liu and Rong.[9,15] HT did not provide lower dose to OARs in this study like it did in Liu's and Rong's study.[9,15]

The differences between the HT and the VMAT plans for OARs may be attributed to the difference in the planning systems as well as the end planning constraints for the plans. For the HT plans, all the planning constraints were first set at the tolerance dose. After more than 100 iterations, constraints were lowered to bring the dose maximum's down. If the doses were significantly below tolerance, the constraint was not lowered again because the plan could have potentially lost coverage. This is a large difference in between how Pinnacle autoplan operates. For Pinnacle, it will bring the dose maximums and means below what is requested if the iterative process can find a lower global minimum for the planning. This may account for many of the differences where HT was statistically significantly higher when compared to nVMAT and cVMAT, but neither of the VMAT plans were significant compared to each other.

Another large difference is the way the planning system deals with prescribed dose. For Pinnacle, the way the Midwest Hospital plans is by prescribing 1% higher for the prescription dose while for Precision, the prescription dose is started out getting prescribed to 50% of the volume and slowly gets increased until 98% of the volume gets 95% of the prescription dose. This may cause significant difference for the conformity index as well as the homogeneity index.

Limitations

Something that was not reflected in the results was the fact that some of the tumors abutted certain critical structures such as the brainstem and optic chiasm. Most of the values that did not meet constraints were close to tolerance, such as 5420 cGy whereas the tolerance was 5400 cGy. All dose constraints were able to be met on HT whereas on two patients (Patient 4 and Patient 8) the brain stem constraints were violated on the cVMAT and nVMAT plans, averaging

around 5700 cGy. This would not be acceptable for treatment. This was not able to be met because of the proximity of the PTV60 to the brainstem in both cases. The brainstem was 3mm away from PTV 60.

This limitation likely increased the conformity and homogeneity for the targets on the nVMAT and cVMAT. While a physician may have approved the treatment plan for the doses that were close to the 54 Gy, if the limit was increased to that maximum for the HT plans, coverage may have been better on the HT plans. See Figure 1 to look at mean CI for all dose planning levels. There are some organs where the physician would not have accepted above tolerance dose. In this way, the plans for HT were better because they met all tolerance doses. The conformity index and homogeneity index may have been better for the VMAT plans because the dose to these structures were higher. This makes it very difficult to compare and figure out which type of treatment modality may be better.

Even though all tumors were centrally located and the CTV was less than 5 cm away from the sella turcica, some tumors were located more laterally. For these, HT was significant below the tolerance dose at first run through, so it was not pushed as hard in Precision as it was in autoplan on Pinnacle. For example, for patient 1, the optic chiasm averaged 550cGy for the nVMAT and cVMAT plans whereas, the HT plan it was nearly 3 times that much at 1568cGy. This is very far below tolerance (5400cGy) so it would not have necessarily been attempted to be lowered. This was the case for all of the OARs that had a statistically significant difference between the VMATs and HT but not between the cVMAT and nVMAT.

Another cause that may have led to the difference between OAR max doses could have been the lack of experience of the treatment planner. Before starting to plan the HT plans, only about 10 plans were completed using the Precision software whereas 60+ were completed using

Pinnacle software. Another limitation of the study is that it was a small sample size with only 10 different datasets compared for each modality. A greater number of datasets should be studied in the future for purpose of generalizability.

Conclusion

The purpose of the research was to determine which treatment modality (nVMAT, cVMAT, or HT) had the highest CI and HI and lowest dose to organs as risk to see if there was a clear benefit in treating with one modality over another. There were statistically significant results so there is a link between planning modality and dose to OARs, CI, and HI for centrally located brain tumors. For the conformity index of 5400cGy, nVMAT was better (closer to 1) than HT by 11.1%. The conformity index of 95% of the prescription dose to PTV60 (5700cGy) was significantly better for HT when compared to cVMAT and nVMAT (21.5% and 22.1% closer to 1, respectively). For HI, there was not a significant reaction between the modalities during post hoc testing. Further research could verify if the difference between the CI for the low dose prescription (5400cGy) could be attributed to some of the plans on nVMAT and cVMAT not being able to meet the constraints for the brainstem.

When looking at the max doses of organs at risk, the mean of the HT plans was significantly higher in HT for the left lens, right lens, left optic nerve, and right optic nerve. HT also had a higher mean dose for the brain stem mean dose and normal brain minus PTV mean dose. HT met all dose maximums for all plans whereas nVMAT and cVMAT did not. Future research should be done to see if pushing harder on OARs for HT that are far below tolerance could benefit the patient without losing coverage and make the dose to the OARS not as significant of a difference between treatment modalities. While all modalities have proven acceptable and useful in treating centrally located brain tumors, treatment planners may want to

consider using HT first because it was able to meet all dose constraints while still achieving acceptable PTV coverage.

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Table 1

Dose Constraints Used in Planning

Structure	D_{max} (Gy)	D_{mean} (Gy)
Brainstem	54	
Normal Brain Tissue-PTV	65	
Right Cochlea		45
Left Cochlea		45
Right Lens of Eye	10	
Left Lens of Eye	10	
Optic Chiasm	54	
Right Optic Nerve	54	
Left Optic Nerve	54	
Spinal Cord	50	

Table 2

Descriptive Statistics of Statistically Significant Conformity and Heterogeneity Indexes

Index and Level	Modality	Mean	Std Deviation	N
CI of 5130 cGy	cVMAT	1.048	0.459	10
	nVMAT	1.228	0.608	10
	HT	1.384	0.663	10
CI of 5400 cGy	cVMAT	0.709	0.301	10
	nVMAT	0.654	0.301	10
	HT	0.544	0.267	10
CI of 5700 cGy	cVMAT	0.465	0.133	10
	nVMAT	0.459	0.136	10
	HT	0.68	0.116	10
HI of PTV 60 Gy	cVMAT	0.044	0.012	10
	nVMAT	0.044	0.010	10
	HT	0.06	0.018	10

Table 3

Descriptive Statistics for OARs with Statistically Significant Maximum Dose Differences

OAR	Modality	Mean (cGy)	Std Deviation	N
Left Lens	cVMAT	344.9	186.230	10
	nVMAT	314	182.359	10
	HT	623.5	277.378	10
Left Optic Nerve	cVMAT	2150.6	1673.707	10
	nVMAT	2045.8	1675.267	10
	HT	3363.4	1613.219	10
Right Lens	cVMAT	330.8	211.095	10
	nVMAT	341.4	239.555	10
	HT	588.2	262.836	10
Right Optic Nerve	cVMAT	2019.9	1892.634	10
	nVMAT	1935	1885.363	10
	HT	3412.8	1681.316	10

Table 4

Descriptive Statistics for OARs with Statistically Significant Mean Dose Differences

OAR	Modality	Mean (cGy)	Std Deviation	N
Brain Stem	cVMAT	2900.14	1856.049	10
	nVMAT	2882.74	1881.144	10
	HT	3234.3	1710.749	10
Normal Brain-PTV	cVMAT	1936.11	464.516	10
	nVMAT	2010.89	415.518	10
	HT	2411.6	635.002	10
Right Cochlea	cVMAT	1342.22	1321.207	10
	nVMAT	1363.49	1242.673	10
	HT	2016.5	1778.497	10

Table 5

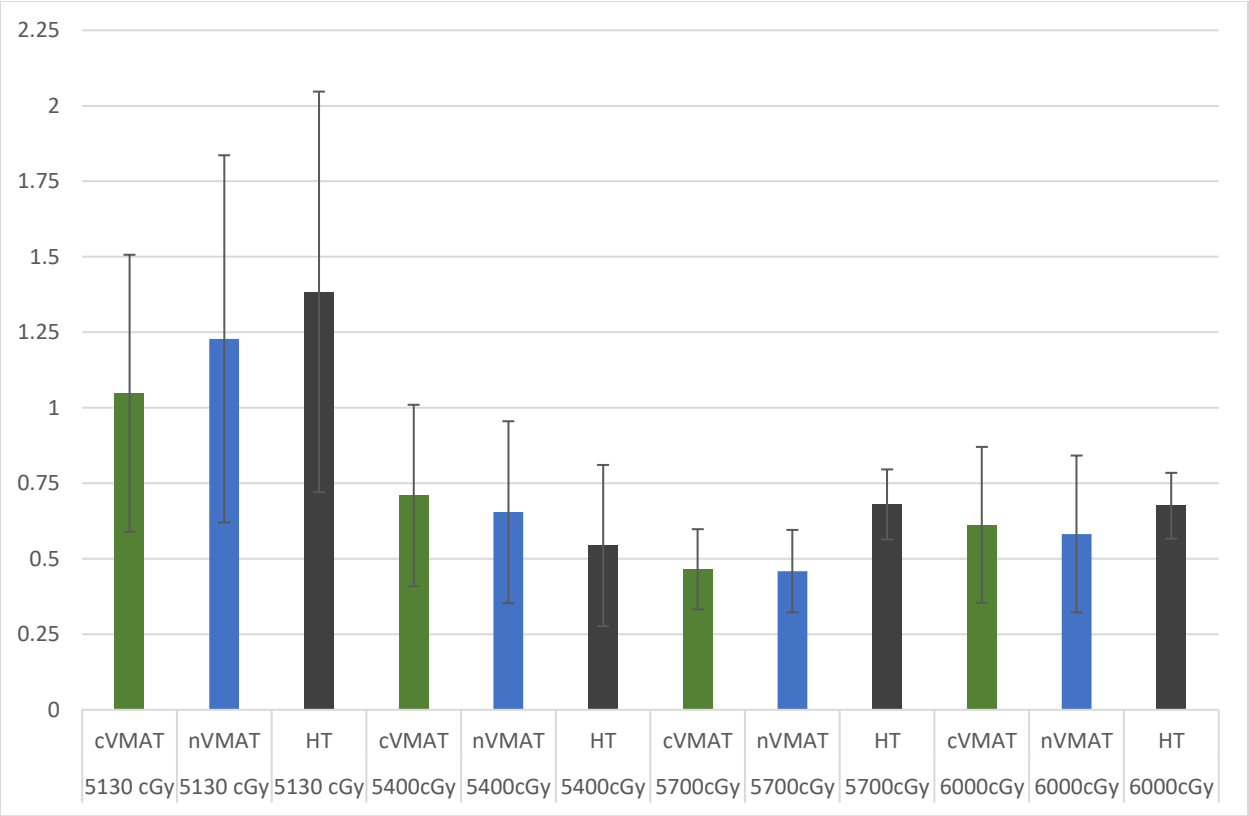
ANOVA Summary Table for OARs, CI, and HI

Source	*df*	MS	F	*p*
Brain Stem Mean Dose	1.093	3005.7	7.69	0.018
Left Lens Max Dose	1.188	427.5	15.764	0.002
Left Optic Nerve Max Dose	1.245	2519.9	14.943	0.002
Normal Brain-PTV Mean Dose	2	2119.5	14.769	<0.001
Right Cochlea Mean Dose	1.057	1574.1	5.645	0.039
Right Lens Max Dose	1.117	420.1	8.396	0.014
Right Optic Nerve Max Dose	1.065	2455.9	15.658	0.003
CI of 5130 cGy	2	1.22	3.641	0.047
CI of 5400 cGy	1.28	0.636	5.949	0.026
CI of 5700 cGy	1.138	0.535	20.109	0.001
HI of PTV 60 Gy	1.114	0.049	5.703	0.035

NOTE: All doses reported in cGy

Figure 1

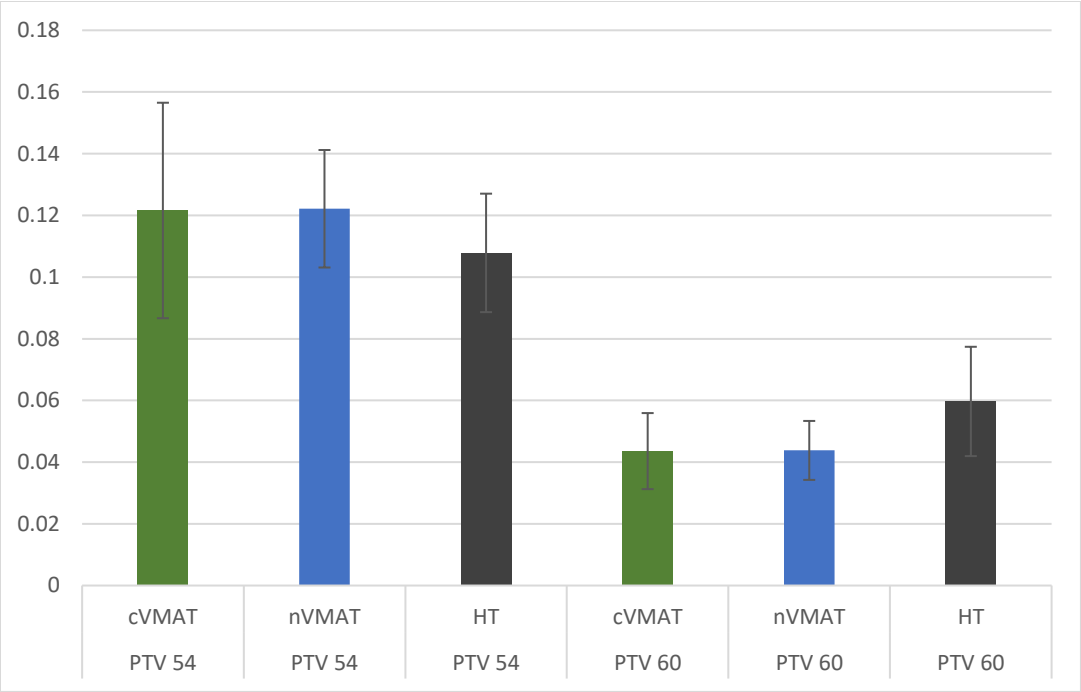
Conformity Index Mean Values



Note. Mean Paddick's Conformity Index values are shown for the different planning modalities (cVMAT, nVMAT, and HT) for different dose levels (5130 cGy, 5400 cGy, 5700 cGy, and 6000 cGy). The error bars show standard deviations. HT had the closest to 1 CI for target volumes 5700 cGy and 6000 cGy. The closest to 1 for 5130 cGy and 5400cGy were cVMAT.

Figure 2

Homogeneity Index Mean Values



Note. Mean homogeneity index values are shown for the different planning modalities (cVMAT, nVMAT, and HT) for the 2 different PTVs (PTV 54 and PTV60). The error bars show standard deviations.