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Dosimetric Comparison of Craniospinal Axis Irradiation (CSI) Treatments Using Helical Tomotherapy, Smartarc™, and 3D Conventional Radiation Therapy*

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ABSTRACT

Purpose: Craniospinal axis irradiation (CSI) is a method of treating various central nervous system malignancies. The large target volume typically includes entire spinal cord and whole brain. Dosimetric comparison was performed between tomotherapy, volumetric modulated arc therapy (VMAT), and 3D conformal radiation therapy (3D-CRT) for CSI. **Methods and Materials:** Five (n = 5) CSI patients were planned using 3D-CRT, VMAT, and tomotherapy (normalized such that 95% of PTV received at least 23.4 Gy in 13 fractions). Plans were compared using PTV conformity number (CN) and homogeneity index (HI), normal tissue (NT) dose statistics, integral dose, and treatment time. **Results:** On average, tomotherapy plans showed higher CN (0.932 vs. 0.860 and 0.672 for SmartArc and 3D-CRT). In terms of HI, VMAT plans consistently showed better dose homogeneity (1.07 vs. 1.15 and 1.13 for tomotherapy and 3D-CRT). SmartArc delivered lower maximum dose for majority of NT, but higher mean dose. 3D-CRT plans delivered higher maximum dose but lower mean dose to NT. **Conclusions:** SmartArc treatments achieved better PTV homogeneity and reduced maximum dose to NT. Tomotherapy showed better target conformity, but 3D-CRT was shown to reduce mean dose to NT. Integral doses were similar between treatment modalities, but tomotherapy treatment times were much longer.

Keywords: CSI; TomoTherapy; SmartArc; Medulloblastoma

1. Introduction

Pediatric cases of central nervous system (CNS) tumors account for 20% - 25% of all cancer malignancies that occur in this age group of 0 - 19 years. Of these pediatric CNS tumors, medulloblastoma accounts for 15% - 20% of occurrences [1]. For infants, medulloblastoma makes up 20% - 40% of all CNS tumors. Craniospinal irradiation (CSI) is a necessary method of treatment for many CNS malignancies. The target for CSI consists of the whole brain, spinal cord, and overlying meninges and is typically prescribed a dose of 23.4 Gy for disease of average-risk. Along with a boost to the posterior fossa and chemotherapy, this CSI treatment allows for a five-year survival of 80% or better [2,3]. Radiation therapy, while beneficial, has long-term side effects with regards to the patient's hearing, endocrine function, and cognitive abilities [2]. In order to minimize these future complications and better the long-term outcome for medulloblastoma patients, it is imperative that the most conformal treatment modality be used in order to spare the surrounding critical structures.

With traditional three-dimensional conformal radiation therapy (3D-CRT), two lateral fields are used to treat the brain and a posterior spinal field [4]. The posterior spinal field may consist of two fields in order to encompass the entire spinal axis. Careful planning must be done in order to properly match the fields between the brain and spinal cord. In order to avoid over dosage or under dosage of the cervical spine, a "moving junction" is often employed between the fields of the brain and spinal cord. Angling the brain fields, using a half beam block for the two lateral brain fields, and rotating the couch are other methods that are used to solve the homogeneity problem as well [1].

Because helical tomotherapy is able to treat longer, continuous fields by allowing the couch to move through the bore as it rotates, field matching is not a problem as it is with 3D-CRT. Tomotherapy has a wide range of beam angles that can be employed in order to obtain a more

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conformal dose to the target area, which is ideal for pediatric cases in which the patient's future is highly concerning. Sharma *et al*. reported that tomotherapy was superior to using intensity modulated radiation therapy (IMRT) as well as 3D-CRT in terms of greater homogeneity to the spine area, conformality of dose in the brain, as well as achieving reduced maximum, mean, and integral doses to many organs at risk [5]. Helical tomotherapy has been shown to produce better dosimetric results when compared with conformal arc therapy for vestibular schwannomas, but this may not be necessarily true for other treatment sites and must be tested [6].

Similar to tomotherapy, volume modulated arc therapy (VMAT) can deliver radiation in an arc motion. VMAT uses a cone beam that rotates around the patient in order to create a conformal dose in the target area and spare the surrounding critical structures. VMAT techniques also have the ability to reduce field junction difficulties that are encountered in conventional treatments by accounting for the overlapping area between arcs during the process of optimization. The VMAT technique has been shown to improve dosimetry as well as reduce treatment time when compared to conventional IMRT [7]. When treating CSI pediatric patients, these benefits are extremely useful considering any reduction in treatment time can decrease patient movement errors and increase patient comfort and is therefore important to consider.

In this study we aimed to determine the most effective method of delivering CSI treatments based on target coverage and homogeneity, beam-on time, as well as surrounding organ dose statistics. Although there have been papers published on the subject of craniospinal irradiation using different delivery methods, the three methods studied here have not been thoroughly compared and analyzed using the same patients and similar optimization criteria [5,8,9]. By comparing three different treatment techniques, we can ensure that patients are being treated with the most effective plans while minimizing normal tissue complications. Due to the complexity of conventional treatment techniques based on field junctions, developing new ways of treatment delivery using more modern IMRT techniques is essential. Using more advanced forms of treatment may also lead to better patient outcomes as well as better patient comfort throughout treatment which is a critical aspect of any course of treatment.

2. Materials and Methods

Five random patients ($n = 5$) were chosen for this project that were previously treated with a TomoTherapy Hi-Art (TomoTherapy Inc., Madison, WI) unit. A single radiation oncologist contoured the target volumes and organs at risk in the Pinnacle^3 Treatment Planning System (TPS) (Philips Medical, Fitchburg, WI). These contours were then exported to the tomotherapy TPS. The contoured organs included the brain, spinal canal, liver, heart, colon, orbits, lungs, kidneys, thyroid, and breasts for the female patients. Plans for the same patients were also created for SmartArc and 3D conformal deliveries using the Pinnacle^3 TPS. For all patients, the planning target volume (PTV) was obtained as the union of the spinal canal after isotropic expansion by 0.7 cm and the brain with no expansion. The prescription was such that 95% of the PTV would receive at least 23.4 Gy in 13 fractions. Objectives for tomotherapy and SmartArc plans were placed on the: PTV, liver, heart, colon, orbits, lungs, kidneys, thyroid, and breasts for the female patients.

2.1. Tomotherapy

The tomotherapy plans were optimized using field width of 5.02 cm, pitch of 0.287 to minimize the thread effect [10] and a modulation factor of 2.0 were used during optimization. A "NORMAL" dose grid, which in our case corresponds to $0.375 \times 0.375 \times 0.25$ cm^3 voxels, was used during dose calculation. An example of objectives used during optimization is shown in **Table 1**. These objectives varied depending on the patient and throughout the optimization in order to achieve an optimal plan.

2.2. SmartArc

The SmartArc plans, were optimized using two arcs, a superior and inferior arc as shown in **Figure 1**. A Varian 21EX linear accelerator (Varian Medical Systems, Palo Alto, CA) equipped with 120 millennium leaf multileaf collimator (MLC) was chosen for the optimization. The placement of the two isocenters was determined by the superior-inferior length of the PTV.

Both arcs were optimized with a gantry rotation span from 1 to 359 degrees, and a final gantry angle spacing of 4 degrees. Both arcs used a 6MV photon beam, and

Table 1. An example of optimization parameters for tomotherapy plans.

Structure	Maximum Dose	DVH Constraint
PTV	23.4 Gy	95% volume ≥ 23.4 Gy
Liver	10.0 Gy	10% volume < 6.0 Gy
Heart	9.0 Gy	10% volume < 6.0 Gy
Colon	7.0 Gy	10% volume < 6.0 Gy
Left & Right Orbits	16.0 Gy	10% volume < 15.0 Gy
Left & Right Lungs	15.0 Gy	10% volume < 12.0 Gy
Left & Right Kidneys	12.0 Gy	10% volume < 9.0 Gy
Thyroid	12.0 Gy	10% volume < 9.0 Gy
Left & Right Breasts	3.0 Gy	10% volume < 2.0 Gy

Table 2 shows the field sizes and collimator rotations for each of the five patient plans in this study. Similar objectives to those used in the tomotherapy (**Table 1**) planning for the surrounding critical organs were used to optimize the SmartArc plans. A dose grid that covered the entire patient was selected for each plan using a 0.3 × 0.3 × 0.3 cm^3 voxel size. After optimization was completed, the plans were normalized such that 95% of the PTV received the prescription of 23.4 Gy in 13 fractions.

2.3. 3D Conformal Radiation Therapy

The 3D conformal treatment plans were also created with the Pinnacle^3 TPS. Two lateral, opposing brain fields and one posterior spinal field were used in each plan using 6MV photon beams as shown in **Figure 2**. As mentioned in the Introduction, two spinal fields are sometimes necessary based on the length of the PTV. For this study, none of the five patients required this extra spine field to cover the PTV. Using techniques such as extended source to surface distance (SSD) adequate PTV coverage was obtained with a single spinal field on all patients evaluated in this study. Blocks were drawn to shield the face of the patient for each of the brain fields and were implemented using the 120-leaf MLC. The collimator rotation for the lateral brain fields was adjusted in order to match the divergence of the posterior spinal field. The gantry angle was also rotated in order to avoid divergence of the brain fields into the orbits of the patient. The "gap match" technique, or locating the 50% isodose line at a point on the anterior of the spinal cord, was used at the junction of the brain and spinal fields as described by Khan [11].

Two prescriptions were set to deliver 23.4 Gy to two calculation points, one each in the brain and spinal cord, and the plan was normalized so that 95% of the PTV received at least the prescription dose in 13 fractions for comparison with the two other delivery methods.

2.4. Comparison

The Tomotherapy, SmartArc, and 3D-CRT plans were compared based on PTV conformity number (CN), PTV dose homogeneity index (HI), normal tissue dose statistics, integral dose and overall treatment time. The CN was used to quantify the ability of the treatment method to cover the PTV with the prescribed dose as well as how well the normal tissue surrounding the target was spared. The equation used for CN is shown below in Equation (1):

$$CN = \frac{V_{PTV,pres}^2}{V_{PTV} \times V_{pres}} \quad (1)$$

where $V_{PTV,pres}$ is the defined as the volume of the PTV that is receiving at least the prescribed dose, V_{PTV} is the volume of the PTV or target, and V_{pres} is the total volume receiving at least the prescribed dose [12]. The ideal CN is a value of 1.0 indicating optimal coverage and sparing.

The HI was used to quantify the uniformity of the dose over the PTV volume. Areas of over- or under-dosage

Table 2. SmartArc plan parameters for each of the five patients.

Patient Number	Superior Arc		Inferior Arc	
	Collimator Rotation	Field Size (cm) X/Y	Collimator Rotation	Field Size (cm) X/Y
1	180	23.1/35.0	180	8.5/32.0
2	185	21.8/36.0	185	14.0/32.0
3	175	26.7/40.0	185	17.3/39.0
4	180	20.9/28.5	180	18.1/37.0
5	175	20.8/29.0	185	18.0/40.0

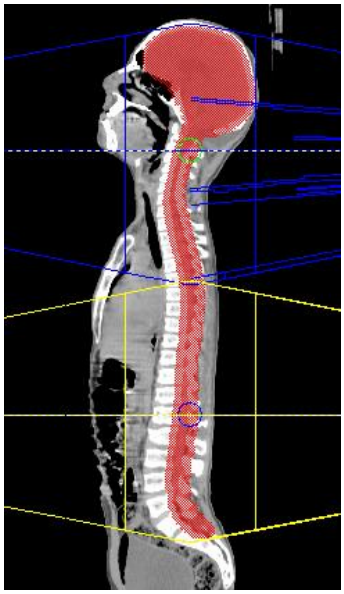

Figure 1. Beam setup for a sample SmartArc CSI treatment plan.

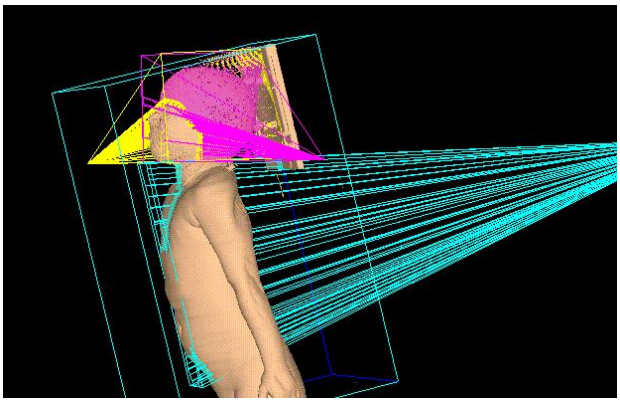

Figure 2. Beam arrangement for a sample 3D-CRT CSI treatment plan.

must be avoided in order most advantageously treat the patient's disease. The HI was calculated for each plan as shown below in Equation (2):

$$HI=\frac{D_{max}}{D_{pres}} \quad (2)$$

where D_{max} is the maximum dose deposited to 1% of the PTV and D_{pres} is the prescribed dose [13]. The ideal HI value is 1.0 which would indicate a perfectly homogeneous plan in the PTV region.

Normal tissue dose statistics were also used to compare the two treatment methods in order to assess the treatment technique's ability to limit dose to the surrounding critical structures. These statistics included the mean dose and maximum dose to the following structures: total lungs, total kidneys, thyroid, heart, liver, colon, and total breasts for female patients.

Integral dose (ID) was also chosen as part of the plan evaluation parameters. ID was computed based on the averaged organ density, averaged organ dose and volume as defined in Equation (3) as follows [14]:

$$ID = \bar{D} \times \bar{\rho} \times V \quad (3)$$

where $\bar{D}$ is the averaged organ dose, $\bar{\rho}$ is the averaged organ density, and V is the organ volume.

Beam-on time of each respective tomotherapy, 3D-CRT, and SmartArc plan was obtained and compared against one another. The beam-on times were obtained from the plan reports for tomotherapy and SmartArc plans from their respective TPS. Assuming a dose rate of 600 monitor units per minute for the 3D-CRT plans, the beam-on time was then estimated for comparison with tomotherapy and SmartArc using the monitor units for each plan obtained from the TPS. Total in-room patient time was also calculated taking into consideration time to get the patient in and out of the room, setup time, time due to isocenter shifting, and imaging time.

3. Results

Figures 3 and **4** show an example comparison of dose distributions for the same patient from: 1) a tomotherapy plan; 2) a SmartArc plan; 3) a 3D-CRT plan. The PTV, shown colorwashed in the above figure, is 95% covered by the 23.4 Gy isodose line for each technique. Isodose lines of 110%, 105%, 100%, 95%, 70%, and 50% of the prescribed dose are also displayed in the figure.

Figures 5 and **6** show a chart summary of the CN and HI values for each of the five patient plans based on the technique used as well as the average for each technique. **Figure 7** shows an example dose volume histogram (DVH) for the PTV for one patient. On average, SmartArc had HI values closer to 1.0 (1.075 vs. 1.149 and 1.130), which indicates better uniformity throughout the

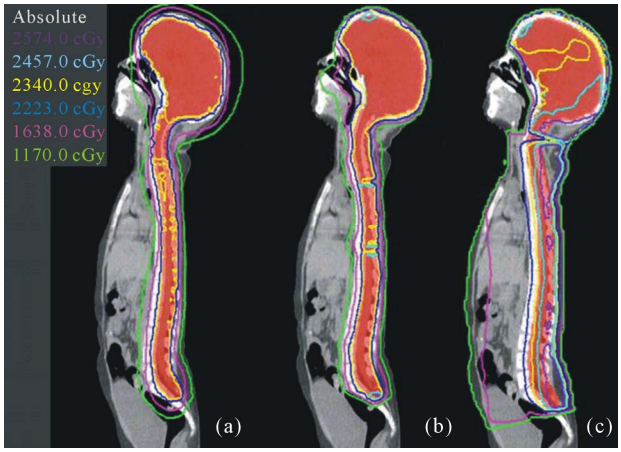

Figure 3. Example sagittal dose distribution for the same patient on: (a) tomotherapy; (b) SmartArc; (c) 3D-CRT.

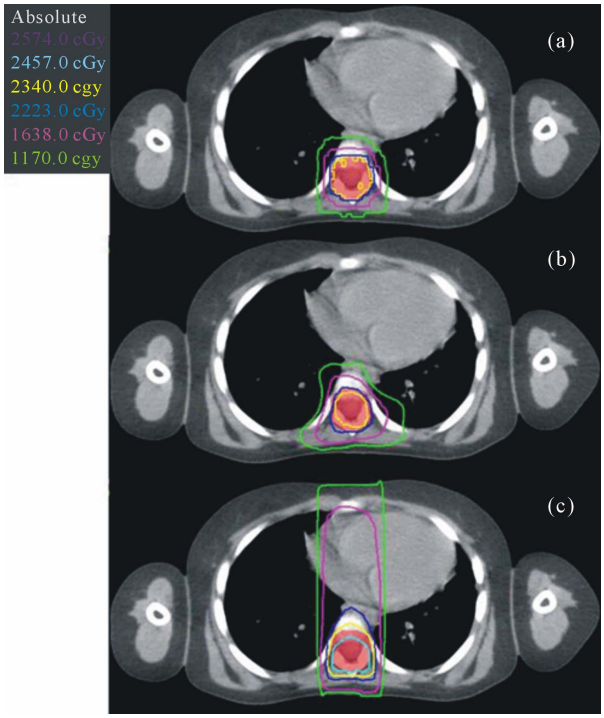

Figure 4. Example axial dose distribution for the same patient on: (a) Tomotherapy; (b) SmartArc; (c) 3D-CRT.

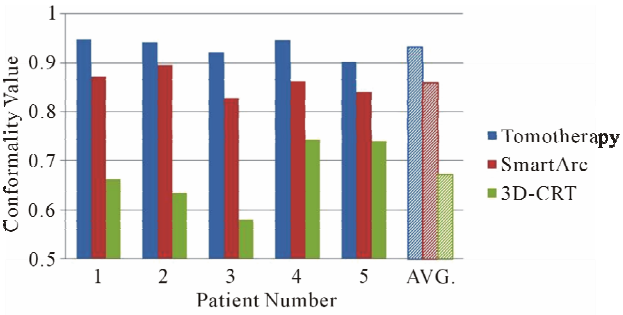

Figure 5. Chart of the CN values for each of the 5 patients and an average for each method.

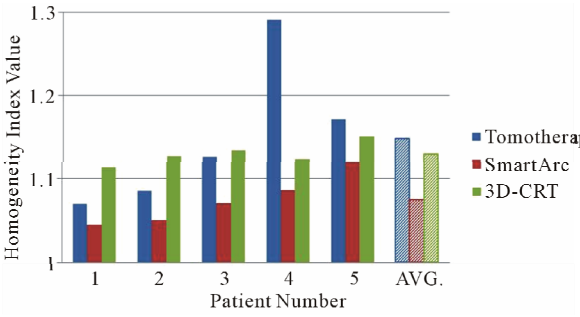

Figure 6. Chart of the HI values for each of the 5 patients and an average for each method.

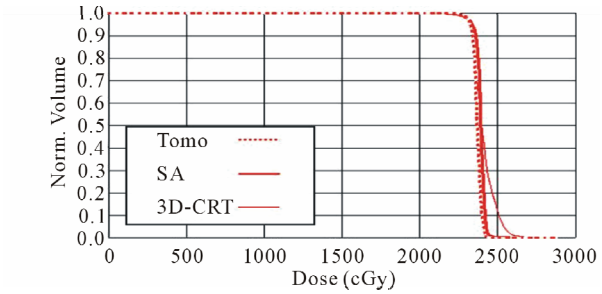

Figure 7. Example PTV DVH for one patient.

PTV for SmartArc plans. Tomotherapy, however, on average had better CN values (0.932 vs. 0.860 and 0.672) indicating better coverage of the target and sparing of the surrounding critical structures. The 3D-CRT plans overall had the poorest performing conformity and homogeneity values. **Figure 7** shows an example dose volume histogram (DVH) for the PTV for one patient.

Table 3 shows a summary of the mean and maximum doses to the surrounding critical structures as well as their averages. On average, SmartArc delivers lower absolute maximum dose values to each of the surrounding critical structures while 3D-CRT delivers the highest maximum dose on average. 3D-CRT, however, has lower mean dose values to the critical structures on average, and SmartArc has the highest average mean doses overall. **Figure 8** shows this in an example DVH of the total lung dose for one patient.

Table 4 shows a summary of the integral doses calculated for each of the five patients for each treatment method. On average, the three treatment methods have similar integral dose values. 3D-CRT provided the lowest average integral dose values while SmartArc plans showed the highest overall values.

Table 5 shows a summary of the beam-on times for each of the three methods for each patient and an average. The tomotherapy and SmartArc beam-on times were taken from the plan reports generated from the tomotherapy and Pinnacle TPS. The beam-on times for the 3D-CRT plans were estimated by taking the total monitor units for each plans and using a dose rate of 600 monitor

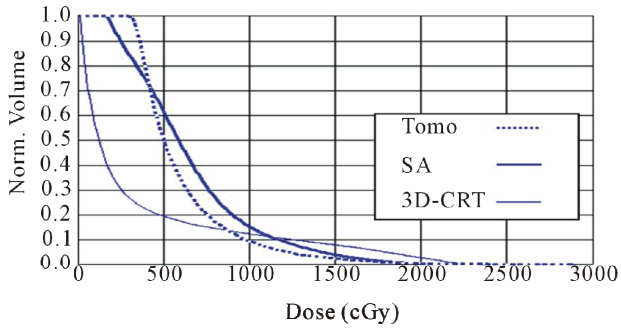

Figure 8. Example total lung DVH for one patient.

units per minute. Beam-on times for 3D-CRT were significantly shorter than those for tomotherapy and SmartArc plans (41.0 seconds vs. 1902.1 and 340.2 seconds). It should be mentioned that in the case of the 3D-CRT, one should consider the time necessary for the beam setup for each of the fields as well as the time for setup of the second isocenter. Tomotherapy treatment times are significantly longer which must be taken into account for the patient's comfort as well as patient movement during the treatment. Faster treatment times ensure more efficiency in the clinic as well as greater patient comfort and less risk for patient movement that will negatively affect the patient's treatment accuracy.

Table 6 shows a summary of the additional in-room patient times that were added to the beam-on times and the better estimate of the total treatment time for the patient. The times reported are average times based on our clinic for each treatment method and are added to the average beam on time from **Table 5** in order to report the overall, average treatment time for the patient. Patient in/out time consists of the time required to bring the patient to the treatment room, time for the patient to change into and back out of a gown, and the time to exit the treatment room. Initial setup time is the amount of time, on average, that the therapist at our clinic uses to setup the patient according to the patient marks and the localization lasers in the treatment room. Imaging/registration time is the time needed by the therapist to image the patient and correct the patient's setup location based on the image acquired. This time varies between the three modalities due to the differences in types of imaging performed. Tomotherapy utilizes a helical, MVCT image, SmartArc would use a kV cone beam computed tomography (kV-CBCT) image, and 3D-CRT uses two, one lateral brain and one posterior spinal field, electronic portal imaging device (EPID) images for patient registration. Isocenter shift time is required for SmartArc and 3D-CRT treatments due to the multiple isocenters used, whereas tomotherapy is able to treat the patient without needing to shift during the treatment. On average, SmartArc and 3D-CRT have comparable total treatment times. Tomotherapy, due to the large number of monitor

Table 3. Normal structure maximum and mean doses in Gy for the 5 patients planned with helical tomotherapy (HT), SmartArc (SA), and 3D-CRT (3D) techniques, as well as averages (AVG.) for each method.

Patient #/ Method		Total Lungs		Total Kidneys		Total Breasts		Colon		Thyroid		Heart		Liver	
		D_{max}	D_{mean}	D_{max}	D_{mean}	D_{max}	D_{mean}	D_{max}	D_{mean}	D_{max}	D_{mean}	D_{max}	D_{mean}	D_{max}	D_{mean}
	HT	18.30	6.19	14.40	6.09	3.72	2.75	7.20	4.61	12.30	6.58	10.18	5.28	10.27	4.68
1	**SA**	18.34	6.52	13.35	6.40	2.56	1.80	8.46	5.09	11.90	7.98	10.31	4.99	11.60	4.88
	3D	21.76	3.44	19.67	2.75	4.40	0.73	16.21	2.74	22.15	20.87	21.36	10.85	19.71	4.28
	HT	15.54	6.38	12.01	6.65	3.40	2.14	6.06	4.11	10.85	6.93	6.39	3.30	9.39	4.17
2	**SA**	16.98	7.23	11.88	6.09	2.35	1.65	7.17	4.82	10.86	7.37	9.06	4.45	11.36	4.86
	3D	20.35	2.21	17.93	1.62	2.64	0.48	15.69	3.82	20.56	16.08	20.23	11.05	18.97	3.69
	HT	16.92	4.93	10.20	4.05	N/A	N/A	8.57	5.19	12.09	8.71	8.19	4.53	9.11	4.51
3	**SA**	19.22	6.67	9.99	4.61	N/A	N/A	10.47	5.54	10.54	7.21	10.16	5.13	10.09	4.71
	3D	21.48	3.31	18.68	2.06	N/A	N/A	19.23	6.55	21.10	19.51	20.79	10.92	19.31	4.06
	HT	20.63	6.52	20.26	5.84	4.24	3.37	10.33	6.93	17.70	9.45	13.99	6.81	12.55	5.26
4	**SA**	19.19	7.91	14.98	6.37	2.34	1.75	8.54	6.18	11.47	7.08	9.63	5.35	11.84	5.40
	3D	21.56	3.10	21.29	2.67	1.17	0.68	17.04	6.35	21.41	20.39	21.19	11.39	19.54	4.36
	HT	20.41	7.49	15.63	6.46	N/A	N/A	20.41	8.63	15.54	10.35	10.87	6.12	12.18	5.75
5	**SA**	19.71	8.76	14.01	6.34	N/A	N/A	16.27	7.87	14.04	8.00	9.56	5.40	12.93	6.20
	3D	23.48	6.16	22.82	5.53	N/A	N/A	25.55	10.05	20.99	19.89	20.92	15.33	20.58	5.79
	HT	18.36	6.30	14.50	5.82	3.79	2.75	10.51	5.89	13.70	8.40	9.92	5.21	10.70	4.87
AVG.	**SA**	18.69	7.42	12.84	5.96	2.42	1.74	10.18	5.90	11.76	7.53	9.74	5.06	11.56	5.21
	3D	21.73	3.65	20.08	2.93	2.74	0.63	18.74	5.90	21.24	19.35	20.90	11.91	19.62	4.44

Table 4. A summary of the integral doses calculated for each patient and technique in units of Gy·kg.

Patient #	Tomotherapy	SmartArc	3D-CRT
1	138.70	138.32	123.44
2	115.41	120.72	99.40
3	198.61	223.28	196.27
4	85.12	96.11	75.77
5	99.49	107.21	95.83
Average	127.47	137.13	118.14

Table 5. A summary of the beam-on times for each technique.

Patient Number	Beam-on Time (seconds)		
	Tomotherapy	**SmartArc**	**3D-CRT**
1	1780.3	285.0	36.4
2	1745.6	283.0	40
3	2400.5	352.0	52.8
4	1842.1	361.0	38.4
5	1741.6	420.0	37.6
Average	**1902.1**	**340.2**	**41.0**

units used to deliver plans, has the longest total treatment time for the patient.

4. Discussion

In this study we compare three different methods for CSI treatments. Although studies for CSI planning and delivery have been reported for these modalities alone or a comparison of two of them [5,8,9,15], there are no studies to compare all three of them on the same patient data set. Our study aims to cover this gap and serve as reference when CSI implementation is considered.

In order to evaluate the clinical effectiveness of 3D-CRT, VMAT, and HT delivery, the dose distribution uniformity in the target volume and the dose level costraints are usually defined as the evaluation and classification parameters of the different radiation modalities. In **Figures 3** and **4**, it is seen that the 3D-CRT, VMAT, and

Table 6. A summary of the treatment times for each technique.

Time Factor	Tomotherapy (seconds)	SmartArc (seconds)	3D-CRT (seconds)
Patient in/out	480 ± 60	480 ± 60	480 ± 60
Initial Setup	300 ± 30	300 ± 30	300 ± 30
Imaging/Registration	720 ± 60	480 ± 120	360 ± 30
Isocenter Shift	0	90 ± 10	90 ± 10
Average Beam-on	1902 ± 281	340 ± 58	41 ± 7
Average Treatment	3402.1 ± 295	1690.2 ± 150	1271.0 ± 138

HT plans, were forced to cover the PTV with the prescribed dose as mentioned in the Materials and Methods section. However, the involved OARs are better spared with the VMAT and the HT compared to the 3D-CRT in most cases. An exception is the total breast D_{max} and D_{mean} where 3D-CRT shows lower breast doses on average. These results are in agreement with the results reported by others [5,9].

As seen in **Figure 5** the conformity was highest for all the HT plans. The SmartArc plans had the second best conformality. The conformity index for HT, SmartArc and 3D CRT plans was 0.93 ± 0.02, 0.86 ± 0.03, and 0.67 ± 0.07. The 3D-CRT plans are inferior because the volume receiving the prescription dose is much larger than the PTV. In fact, as the data suggests, the volume of healthy tissue receiving the prescribed dose is approximately 25% more that in the case of 3D-CRT when compared to HT and 20% when compared to SmartArc. As shown in **Figures 3** and **4**, in order to cover the anterior of the spinal canal, PTV hot spots on the order of 130% can exist in the normal tissue. These results are in agreement with published results [16-18] for comparisons between HT and 3D-CRT and VMAT and 3DCRT.

Our results from **Figure 6** show that HT and VMAT may produce dose distributions with homogeneous doses to the PTV while 3D-CRT had the worst homogeneity. From the five patient plans, the SmartArc plans were the most homogeneous while the HT and 3D-CRT homogeneity was comparable between them. Only one of the patients showed higher homogeneity index for the HT plans. Similar results on HT and 3D-CRT comparison are reported in the literature [14,16,18] and by Lee *et al*. [17] on comparison between VMAT and 3D-CRT for CSI plans.

Table 4 displays the results of the integral dose calculations for each patient and each treatment method as well as the overall average for each treatment method. These whole body integral doses were tabulated using a normal tissue volume of the patient, taken to be from the top of the head to approximately 5 cm below the end of the spinal cord, and the average density of this volume. The results indicate that the whole body integral dose is lower for the 3D-CRT treatment technique followed by tomotherapy and SmartArc with the overall highest integral dose. The findings here are similar to those found by Penagaricano, *et al*. [19] for the cases of conventional and helical delivery.

Three of the five patients used for this study were female patients and therefore breasts were contoured in order to be considered for this study. The breasts for young, developing females should be considered during treatment planning as was discussed by one of our physicians. The treatment modalities did not play a significant role in how much dose was delivered to the breasts. Due to the very low doses received by these organs, they did not significantly impact the optimization for any of the treatment modalities and therefore the data presented is used more to monitor dose they may receive and verify that they will not receive any highly significant amount of dose. Therefore, we do not believe the treatment modality decision will need to be altered based on these organs.

The beam-on time and overall treatment time plays a crucial role in patient comfort, patient movement during the treatment, and efficiency for the clinic. Because of its importance to the patient as well as the clinic, treatment time must be taken into account when comparing different treatment modalities. **Table 5** gives the beam-on times for each patient based on each method. On average beam-on time is comparable for 3D-CRT and SmartArc plans, and significantly longer for tomotherapy (41.0 and 340.2 vs. 1902.1 seconds). However, beam-on time is not necessarily representative of the total time the patient will spend in the treatment room. Factors such as shifting patients during treatment to different isocenters, couch shifts, gantry rotations, and patient setup and imaging must be considered for timing purposes (**Table 6**). During the 3D-CRT and SmartArc treatments, a patient is initially setup at one isocenter and imaged and treated, and then the therapist must enter the treatment room to move the patient to the next isocenter. Including the average beam-on times, the total treatment time would be approximately 1271.0 seconds for 3D-CRT and 1690.2 seconds for SmartArc (assuming one spinal field for the 3D-CRT plans as was the case for all of the patients in this study). This assumes one spinal field for the 3D-CRT plans as was the case for all of the patients in this study. It is important to note however that the values for the 3D-CRT plans in **Table 6** for isocenter shift and imaging/registration times would have to be doubled if a second spinal field is required, and therefore this would add approximately 450 seconds to the overall treatment time for conventional plans. Tomotherapy also requires image-guidance for patient setup, but may not require an interruption in the treatment due to its ability to treat long

fields without shifting isocenters. Some institutions, however, split longer tomotherapy treatment deliveries into two deliveries so that the patient can be re-imaged halfway through the treatment to ensure the patient remains accurately positioned on the treatment couch. Without treatment interruption, total treatment time would be approximately 3402.1 seconds. The need for patient sedation is another component that could affect the overall treatment time. Sedation is determined on a patient-by-patient basis and can add a considerable amount of time to the patient in the clinic. This time component however does not directly affect the time the patient is at the treatment unit and the length of time it takes to treat the patient. Sedation would cause the patient to require additional time in pre-treatment clinical aspects. Because this time is common to the three methods discussed in this study, it is not considered to be a factor in the comparison analysis. 3D-CRT and SmartArc treatment methods would be more advantageous than tomotherapy in terms of maximizing patient comfort and clinical efficiency while minimizing intrafraction patient movement.

5. Conclusion

The study served to show that SmartArc treatments achieve slightly better PTV homogeneity, and was noted to have reductions in maximum dose of selected organs at risk when compared to tomotherapy and 3D-CRT plans. Tomotherapy showed better target conformity. 3D-CRT plans were shown to have the poorest PTV conformity and homogeneity as well as the highest maximum doses to the surrounding organs. The mean dose values to the surrounding organs however, were shown to be lowest with the 3D-CRT plans. Beam on times are significantly greater for the tomotherapy plans as compared to the other two methods with the 3D-CRT treatments having the shortest beam-on time.

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