RESEARCH PAPER

A Planning Study on the Feasibility of Total Body Irradiation in Halcyon Linear Accelerator with MV-CBCT Image Guidance Facility

Kannan Muniyappan[1], Karunanidhi Gunaseelan[1,*], Neelakandan Vijayaprabhu[1]

[1]Department of Radiation Oncology, Regional Cancer Centre, JIPMER, Puducherry-India
muniyappan85@gmail.com gunapgi@gmail.com vijayaprabhu.n@gmail.com

*** Corresponding author;** Karunanidhi Gunaseelan
gunapgi@gmail.com

Introduction Total Body Irradiation is a conditioning regimen before bone marrow transplantation (BMT) for leukaemia. Earlier, the TBI was delivered using conventional techniques with extended SSDs. Evolution in optimization and delivery techniques like VMAT improved dose homogeneity in target volume with lesser doses to OARs. This study analyses the feasibility of TBI planning in the Halcyon-D™ linac equipped solely with the MV-CBCT capability.
Methods and Materials: The whole-body PET-CT of 32 patients were used as no planning CT was acquired. The TBI treatment plans were created in Eclipse TPS with a prescription of 12 Gy in 6 fractions for the Halcyon-D unit using a 6-MV FFF photon beam and equipped only with the MV-based IGRT. TBI VMAT plans were generated using an average of 10 isocentres and 33 arcs. The optimization objectives include achieving a homogeneous dose to target while keeping the mean lung and kidney doses at 10 Gy and the Lens maximum doses at less than 10 Gy.
Result and Discussion: The samples were categorized as males, females, and paediatric patients, and the dose matrices were compared. TBI plans resulted in a mean PTV dose of 1126±17 cGy, 1114±28 cGy, and 1151±17 cGy for males, females and paediatric patients, respectively, without normalization. The mean HI were 0.4, 0.5 and 0.3 for males, females and paediatric patients, respectively. The CIs were 0.8, 0.7, and 0.8 for males, females, and paediatric patients, respectively. The mean MU were 3579±422, 3508±329 and 2297±276 for males, females and paediatric patients, respectively. The lung mean doses were 955,967 and 943 cGy for males, females and paediatric patients, respectively. The kidney mean doses were 937,924 and 924 cGy for males, females and paediatric patients, respectively. The lens maximum doses were 951±55, 937±55, and 942±11 cGy for males, females and paediatric patients, respectively. All the QA plans were delivered and analysed using 3mm/3% DTA and DD with area gamma <1, 95% criteria and found the average area gamma <1, 95% is 99.72.
Conclusion: The TBI planning is feasible in Halcyon-D with MV-CBCT capability and with acceptable doses to PTV and OARs.

Keywords: Total Body Irradiation, O-ring Gantry Halcyon, VMAT, Homogeneity, Conformity
How to cite this article: Muniyappan K, Gunaseelan K, Vijayaprabhu N. A Planning Study on the Feasibility of Total Body Irradiation in Halcyon Linear Accelerator with Mv-Cbct Image Guidance Facility. Int J Drug Deliv Technol. 2026;16(30s):989-998. DOI: 10.25258/ijddt.16.30s.102

Introduction

Haematological malignancies are generally treated using bone marrow transplantation (BMT). Prior to the BMT procedure, high-dose Chemotherapy is used as a conditioning regimen, but its effectiveness depends on the drugs' biodistribution. Moreover, Chemotherapy drugs do not reach specific vascular structures called sanctuary structures, such as the brain and testis; thus, these structures remain unaffected. These sanctuary structures are effectively treated only when total body irradiation (TBI) is included as an adjuvant treatment to the BMT(1–3). During TBI, the entire body is irradiated to minimize the risk of failure or relapse of the disease, and so it is independent of biodistribution, unlike Chemotherapy. However, there is an increased risk of normal tissue complications, especially in the lungs, after TBI treatments(4). In old methods, TBI treatments were given to patients using a few larger fields, with the patient positioned at extended treatment distances and treatment units like Telecobalt or conventional C-Arm linear accelerator. During such treatments, the patient is kept in a standing or sitting position at two to three meters from the isocenter along the beam central axis of the treatment unit. However, such techniques fail to conform the prescribed dose to the target, spare the critical structures and lack an imaging facility for setup verifications. In addition, these treatment methods require a long setup and treatment times(5).
Technological advancements, both in software and hardware, of treatment planning computing systems, their algorithms and C-arm linear accelerator units made it possible to position the patient on the treatment couch of the linear accelerators with setup verification facilities and treatments delivered with advanced delivery techniques such as Intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) (6–9). Moreover, these advancements have made it possible to increase dose conformity to the target and reduce doses to the organs at risk (OARs). TBI is also performed in O-ring gantry-based linear accelerators, viz., TomoTherapy® unit (M/s Accuray Incorporated); its feasibility and clinical experience have

*Author for Correspondence: gunapgi@gmail.com

been reported elsewhere (10–15). In contrast, the feasibility and an extensive dosimetry study of TBI treatment in the recently introduced O-ring-based linear accelerator system, viz., Halcyon® version D (M/s Varian Medical System, Palo Alto, CA), have not been done yet. Halcyon® linear accelerator uses a single 6-MV Flattening Filter-Free (FFF) beam and has cone beam computed tomography (CBCT) (MV-CBCT and kV-CBCT -depending on the version) for setup verification facility. This study is thus designed to check the planning feasibility of TBI in the Halcyon® Linear Accelerator, which is fitted only with an MV-CBCT facility, using dosimetry analysis.

Methods and Materials

In this dosimetric study, the whole-body PET-CT images of 32 anonymized patients with 5-mm CT slice thickness were obtained from the nuclear medicine department, where the patients had undergone whole-body Positron Emission Tomography- Computed Tomography (PET-CT) imaging earlier for diagnostic purposes. PET-CT images were taken in Model Discovery MI Digital Ready (M/s General Electric Healthcare, USA). Anonymized PET-CT image datasets were transferred to the Eclipse Treatment Planning System (TPS) version 16.10 (M/s Varian Medical Systems, Palo Alto, USA, CA). The dose-volume optimizations for the TBI planning with the Halcyon® unit were done after incorporating dose due to MV-CBCT imaging for each isocentre using the Photon Optimizer (PO) algorithm and the analytical anisotropic (AAA) calculation algorithm.

The Halcyon (D 3.0) linear accelerator system is equipped with a 6-MV FFF beam, capable of delivering a maximum dose rate of 800 MU/min at depth of maximum (Dmax), with a dual-stacked and staggered 57 pairs of Multileaf collimators (MLCs) leaves, with an effective leaf width resolution of 5 mm at isocentre. The maximum field size possible with this system is 28 cm x 28 cm at the isocenter. The MLC leaf speed is up to 5 cm per second; the gantry rotation speed is up to 4 revolutions per minute during beam off and up to two revolutions per minute during VMAT treatments. The daily image guidance for the setup verification of patients is achieved in the Halcyon D with MV-radiograph pairs (MV-MV orthogonally-paired radiographs) or MV-CBCT using 6-MV FFF beam. The kV-based imaging system, like kV-CBCT, is unavailable in this Halcyon variant. Hence, during each image verification using MV CBCT, up to 6 cGy is delivered to the patient, which is incorporated in the dose optimization.

The planning target volume (PTV) for TBI was created by cropping 3 mm from the body structure. The OARs, such as kidneys, lungs, and eye lenses, were delineated manually. The plans were computed with the prescription of 12 Gy in 6 fractions with two fractions per day. The accepted dose heterogeneity for the PTV is 90% to 110% of the prescription dose. As for the OARs, the accepted tolerance doses for lungs and kidneys were kept at ≤ 10 Gy mean dose; for the eye lens, 10 Gy maximum dose.

The metrics for the analysis of dose coverage to the PTV were the homogeneity index (HI) and the conformity index (CI), which were used to quantify the homogeneity of the prescribed dose distribution and its conformity to the PTV. The formulas for computing these indices are as follows:

- Homogeneity index, HI = $\frac{D_{2\%} - D_{98\%}}{D_{50\%}}$,

$D_{2\%}$, $D_{98\%}$, and $D_{50\%}$ are the PTV near maximum, near minimum and model doses – as defined in the ICRU 83 (2010).

- The conformity index, CI=V_{RI}\TV, i.e., CI is the ratio of reference isodose volume (V_{RI}) to the target volume (TV) – as defined by the RTOG guidelines (16,17)

The convenience sampling method was used with a discordant rate of 5% and a tolerance probability of 80%. This study required a sample size of 32 PET-CT image datasets and was approved by the Institute Ethics Committee. As an observational study, all the dosimetric data are reported as mean and standard deviation.

TBI Planning

In Halcyon, a maximum of 2 isocentres can be generated in one plan with an interspacing of 10.5 cm between these two isocentres by the Eclipse TPS (v.16.1). Treatment plans were generated using the CT image data of the PET-CT image datasets, with 5 to13 isocentres (Figure-1), depending on the PTV length, and with14 – 44 arcs fields – the upper body used four full arcs and the lower body used two full arcs. The fixed collimator angles of 0 and 90 degrees for counter-clockwise (CCW) arcs and clockwise (CW) arcs, respectively, were used in all plans. The patients' heights or treated lengths varied from 100 to 174 cm (Table 1**)**, and isocentre interspacing of 12 to 25 cm was used. Since setup verification using MV-CBCT images cannot be automatically created for each of these isocentres, a workaround was done, whereby separate plans were created, each with MV-CBCT setup verification fields alone for the given isocentre, and the dose was calculated due to this verification imaging. A plan sum, which was made for the MV-CBCT imaging field plans alone, was used as the base plan before starting dose optimization. Hence, to make a plan deliverable after achieving an acceptable plan, each isocentre needs to be created as a separate plan along with an imaging field and calculated without performing optimization again. Completing optimized plans took around 22-35 hours. The graphical processing unit (GPU) available in the TPS does not work for multiple isocentre plans; hence, it was not used for this TBI planning study. Initial TBI plans often resulted in cold spots, the under-coverage of PTV regions, and hotspots in some areas. These cold and hot spots were converted as dose structures, and reiterations were done till an acceptable plan was generated.

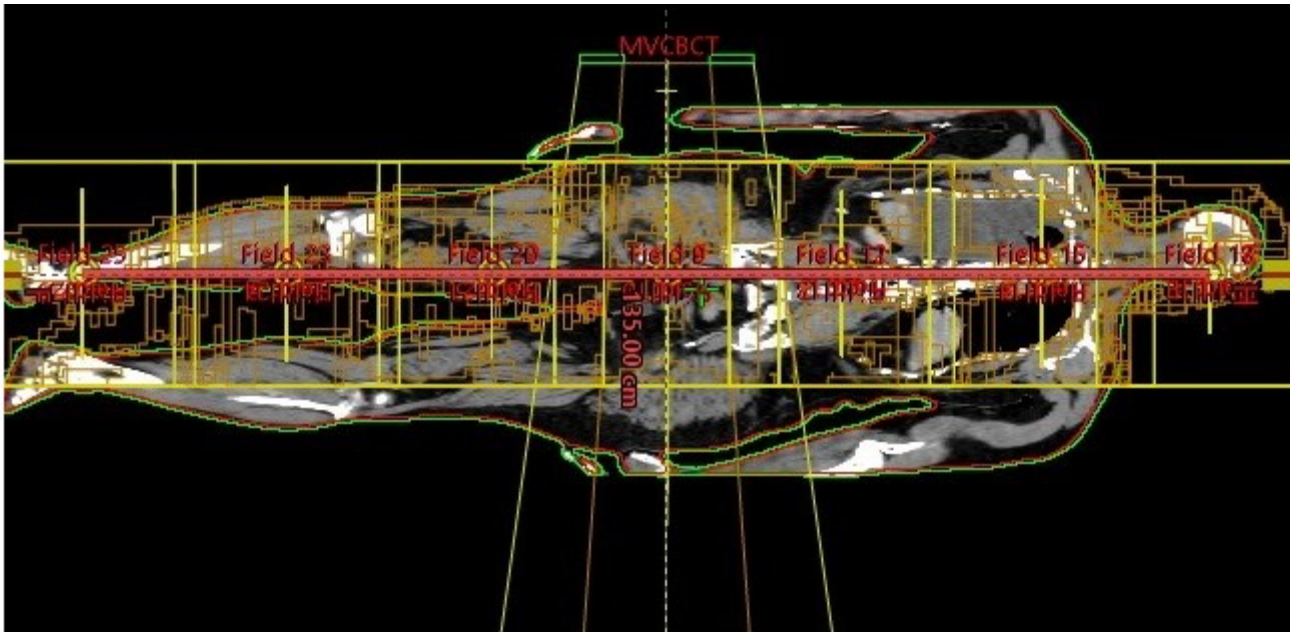


Figure-1 shows the typical placement of isocentres for a typical TBI plan for better coverage and sparing of OAR with seven isocentres in the Halcyon Linear accelerator.

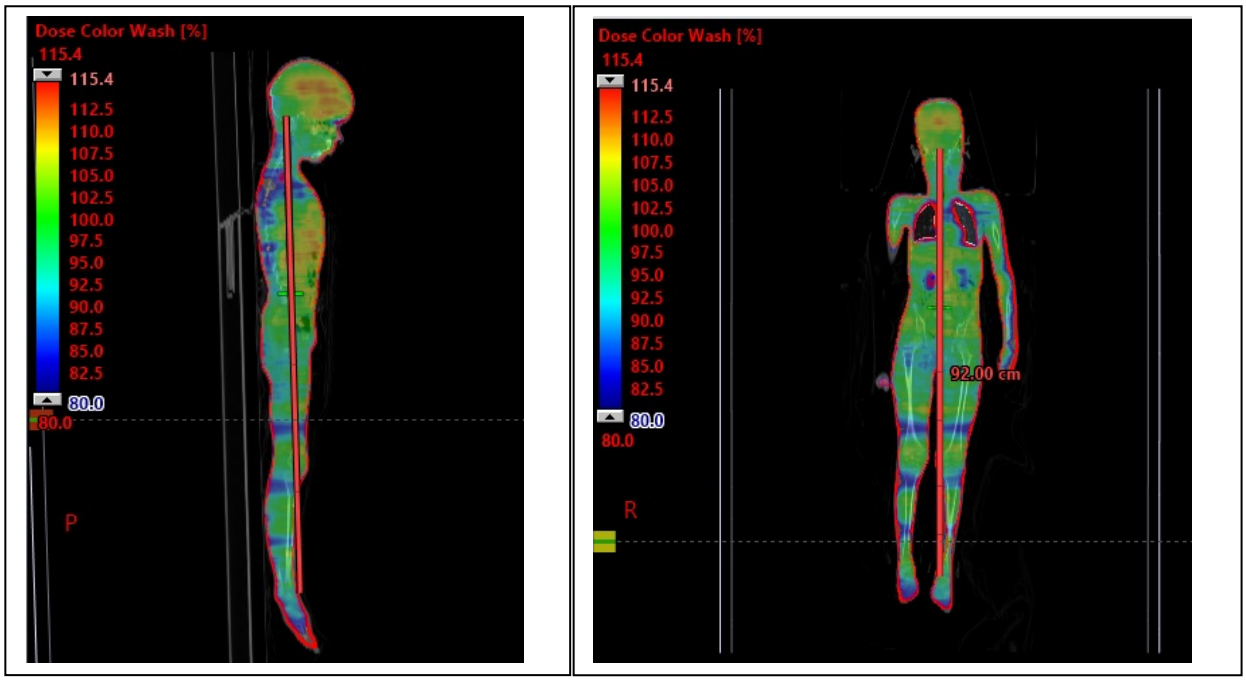


Figure 2 shows the typical dose distribution for a patient in the frontal and sagittal planes in the Halcyon Linear accelerator.

Results

Table 1: Patient metrics

Female				
S .No	Patient	Length in cm	Maximum Thickness	Target Volume (cc)
1	F1	144.5	41	45668.3
2	F2	155.0	44	63539
3	F3	155.0	45	51269
4	F4	155.0	45	50949

5	F5	153.0	45	48385
6	F6	167.0	43	45932.4
7	F7	152.5	45	51086
8	F8	155.0	45	62680
9	F9	153.0	60	93834
10	F10	144.5	45	65215
11	F11	155.0	43	42139
12	F12	155.0	43	42174
13	F13	145.0	44	52855
14	F14	144.0	45	53894
15	F15	151.0	40	37428
16	F16	145.0	40	35324.7
17	F17	156.0	45	53753
18	F18	152.0	40	38848.1
19	Mean	152	45	51018
20	SD	5.6	4.2	13184.3
Male				
S .No	Patient	Length in cm	Maximum Thickness	Target Volume In cc
1	M1	160.0	42	39504.5
2	M2	174.0	40	33298.1
3	M3	155.0	44	49423
4	M4	156.0	45	55399
5	M5	165.0	44	42528
6	M6	156.0	41	42004
7	M7	155.3	45	57721
8	M8	145.5	43	43384
9	M9	154.5	41	36745
10	M10	155.0	43	43526
11	M11	158.0	42	42356
12	M12	165.0	45	56256.5
	Mean	158	43	45179
	SD	6.8	1.7	7516.6
Paediatric				
S .No	Patient	Length in cm	Maximum Thickness	Target Volume In cc
1	C1	135.0	28	13593.8
2	C2	100.0	27	12100.6
	Mean	118	28	12847
	SD	17.5	0.5	746.6

Table 2: Dose-volume metrics of the female patients for TBI planning in Halcyon Linear Accelerator

Female												
S.No	ID	Mean dose in cGy						Maximum dose in cGy			D80% in cGy	D90% in cGy
		PTV	L Lung	R Lung	L Kidney	R Kidney	Liver	L Lens	R Lens	PTV		
1	F1	1123	919	903	869	884	1209	900	913	1447	1037	942
2	F2	1083	1113	1056	1042	1065	1172	951	960	1460	917.6	797
3	F3	1145	1014	1033	999	970	1212	965	974	1405	1071.4	998
4	F4	1147	1045	1040	1000	1013	1181	964	970	1399	1069	989
5	F5	1145	989	1002	988	1023	1176	1007	1033	1398	1072.5	1000
6	F6	1172	1056	1051	1007	1025	1212	1038	1028	1419	1101.9	1024
7	F7	1144	952	973	929	961	1200	1020	987	1379	1074.8	987
8	F8	1122	932	906	1025	1015	1195	956	1007	1420	987.7	873
9	F9	1047	933	998	913	967	1243	970	941	1421	850	726
10	F10	1100	896	910	901	917	1199	939	940	1453	939.2	847
11	F11	1088	877	920	864	871	1166	894	919	1375	947	859
12	F12	1103	892	940	891	895	1164	848	905	1379	979.3	888
13	F13	1127	893	909	884	892	1164	870	871	1392	1017.1	926
14	F14	1125	950	944	877	881	1228	877	905	1388	1020.7	926
15	F15	1116	895	930	876	909	1179	799	903	1408	1029.5	934
16	F16	1122	875	886	911	903	1194	912	917	1418	1030.5	922
17	F17	1122	921	978	882	901	1221	912	958	1378	1025.1	916
18	F18	1112	892	941	863	911	1193	873	902	1400	1010	916
	Mean	1119	947	962	929	945	1195	927	946	1408	1010	915
	SD	28	67	54	61	59	22	61	45	25	62	74

Table 3: Dose-volume metrics for male patients for TBI planning in Halcyon Linear Accelerator

Male												
S.No	ID	Mean dose in cGy						Maximum dose in cGy			D80% in cGy	D90% in cGy
		PTV	L Lung	R Lung	L Kidney	R Kidney	Liver	L Lens	R Lens	PTV		
1	M1	1135	1020	989	923	933	989	1031	1023	1470	1029	947
2	M2	1152	1018	968	974	979	1153	983	983	1427	1076.4	996
3	M3	1137	928	976	876	907	1236	872	917	1424	1044.6	933
4	M4	1099	1048	1051	1064	1051	1179	955	975	1458	934.1	836
5	M5	1127	939	936	874	898	1201	941	939	1425	1035.6	946
6	M6	1138	1014	1038	935	954	1174	907	1061	1467	1050.7	990
7	M7	1121	974	956	901	899	1153	1019	972	1391	1018.1	928
9	M8	1113	955	981	890	899	1223	946	985	1391	1002	917
10	M9	1109	883	904	875	901	1198	922	885	1396	1005.5	895
11	M10	1154	922	943	887	901	1248	950	906	1487	1081	1004
13	M11	1121	945	932	907	943	1201	967	932	1345	1066	985
14	M12	1111	933	966	906	896	1208	800	945	1415	990	899
	Mean	1126	965	970	918	930	1180	941	960	1425	1028	940

	SD	17	48	40	52	45	64	60	48	39	40	48

Table 4: Dose-volume metrics of Paediatric patients for TBI planning in Halcyon Linear Accelerator

Paediatric												
S.No	ID	Mean dose in cGy						Maximum dose in cGy			D80% in cGy	D90% in cGy
		PTV	L Lung	R Lung	L Kidney	R Kidney	Liver	L Lens	R Lens	PTV		
1	C1	1167	981	991	961	951	1194	947	958	1360	1115	1056
2	C2	1135	894	908	891	895	1203	931	933	1385	1079	1030
	Mean	1151	937	950	926	923	1199	939	945	1373	1097	1043
	SD	17	44	42	35	28	4	8	12	12	18	13

Tables 2, 3, and 4 summarise target and OAR dose data for 18 females, 12 males and two paediatric patients, viz., the total MUs, the mean distance between isocenters, HI, CI, patient length and the total number of fields used in the plans. Figure-2 shows the typical dose distribution of 80%-115% of the prescribed dose for one of the samples in frontal and sagittal planes. The PTV received a mean maximum dose of 1425±39 cGy, 1408±25 cGy, and 1373±12 cGy for males, females and paediatric patients. The mean volumes were 45179±7517cc, 51018±13184 cc and 12847±747 cc for males, females and paediatric patients. Most female sample cases were obese with a mean maximum thickness of 45±4 cm, resulting in reduced dose in thoracic and pelvis regions. The mean maximum thickness of males and paediatric patients was 43 ±2 cm and 28±1 cm, respectively. The mean height of the males, females and paediatric patients was 158±7cm, 152±6cm and 118±18 cm, respectively. The OAR doses were within the limits for all the samples to control the normal tissue complication. Figure 3 shows the Dose Volume Histogram (DVH) of PTV, Kidneys, Lungs and lenses for one of the sample cases. In this study, mean HI were 0.4, 0.5 and 0.3 for males, females and paediatric patients, respectively. The CIs were 0.8, 0.7, and 0.8 for males, females, and paediatric patients.

The mean MU were 3574±422, 3508±329 and 2297±276 for males, females and paediatric patients, respectively. The mean number of isocentres used for generating TBI plans were 10 ± 2, 10±2 and 7±2, with the mean number of fields being 35, 34 and 22 for males, females and paediatric patients, respectively. The mean interspacing distance between isocentres was 18± 5 cm, 17±4 cm and 19±5 cm for males, females and paediatric patients. Contouring both target and OAR took 5 to 7 hours, and the time for planning ranged between 22-35 hours. The planning time was increased as the number of isocentres increased.

Figure 3 - Dose Volume Histogram of PTV, Kidneys, Lungs and Lenses for one of the samples

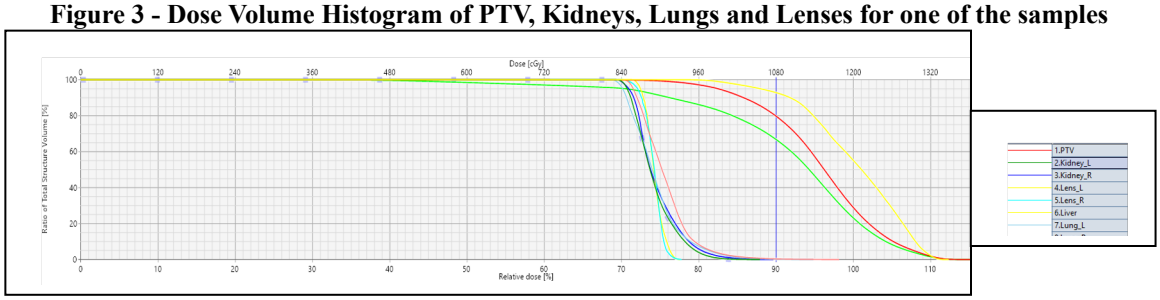
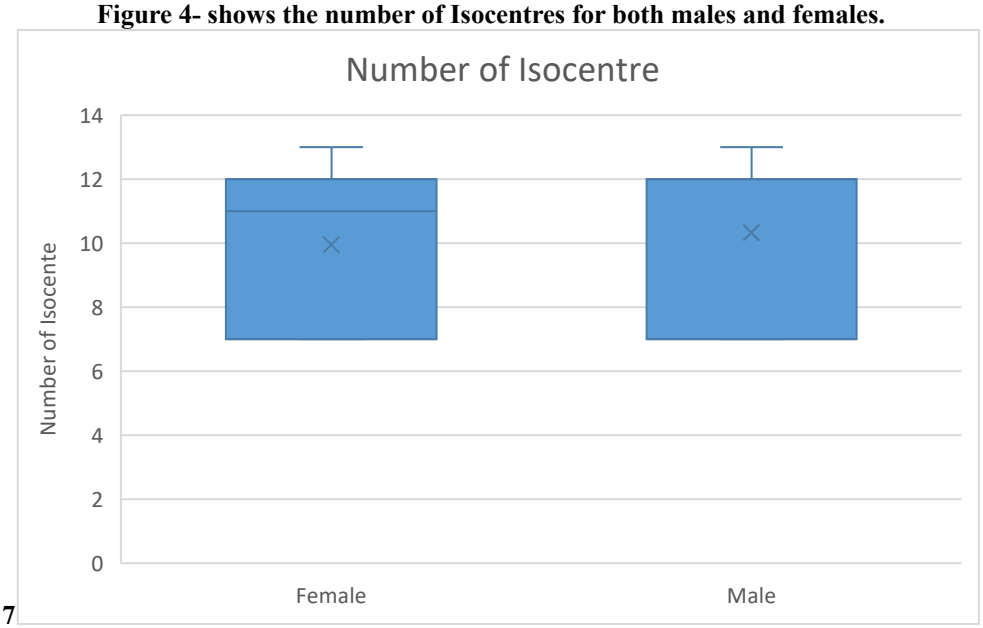


Figure 4- shows the number of Isocentres for both males and females.



7

Figure 5- shows the number of fields for males and females.

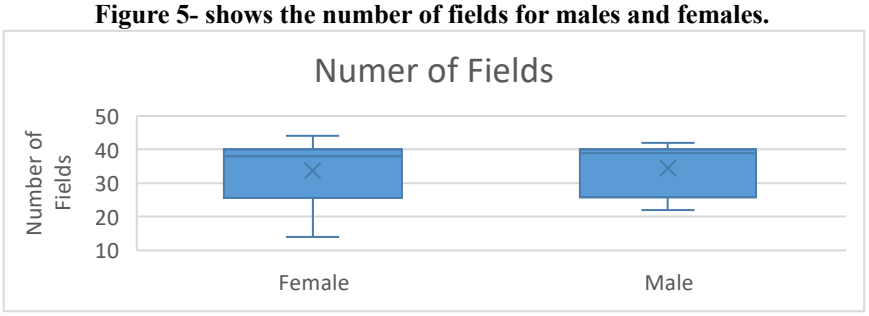


Figure 6- shows the isocentre interspacing distance for males and females.

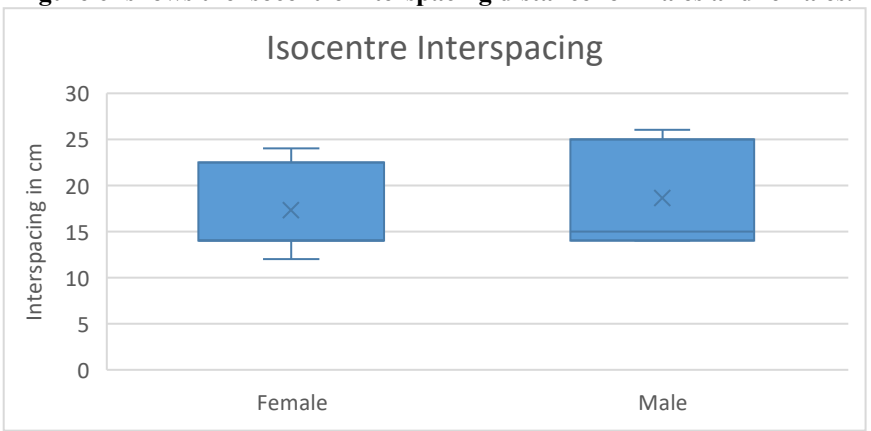
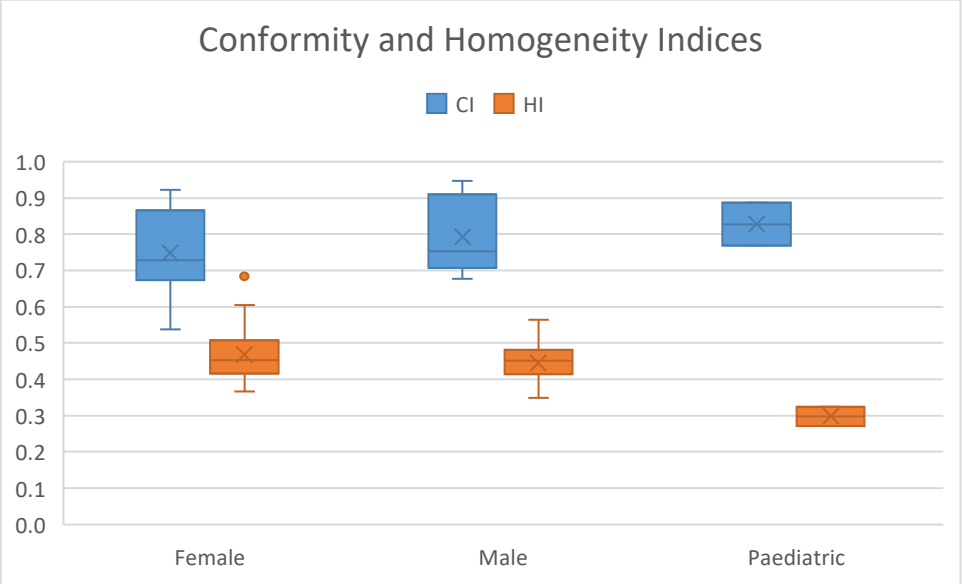


Figure 7- shows the conformity and homogeneity indices for all the cases.



Discussion

Conventional TBI treatment techniques, like 2-dimensional radiotherapy (2DRT) and 3-dimensional conformal radiotherapy (3DCRT), deliver heterogeneous doses to target volumes and higher doses to OARs, especially lungs, which may develop pneumonitis as a sequela(18,19). Moreover, the patients' set-up positions are not usually verified using portal imaging or kV-based setup verification imaging during these conventional TBI treatments, and verifications are limited only to the in-vivo dosimetry checks to ensure that the prescribed doses are delivered within acceptable limits. The treatment dose is prescribed to the midpoint, usually at the umbilicus level (20). Tomotherapy-based TBI improved the target dose homogeneity and OAR sparing, but the treatment delivery was longer, which is more of a concern in a busy treatment unit. Uehara et al. from Kindai University, Osaka, Japan, described the Halcyon-based TBI planning feasibility study with one patient(21). Talapatra et al. from India also described the delivery of TBI treatment to a leukaemia patient(22). Shahid et al. described the total marrow irradiation/total marrow and lymphoid irradiation (TMI/TMLI) using VMAT for five patients in a higher variant of Halcyon-E that has kV-based CBCT set-up verification imaging capability, and the dose due to multiple imaging for set-up verifications is not a concern. They reported a better target coverage with sparing of OARs(23).

This study used Halcyon-D with MV-CBCT capability for patient setups. MV-CBCT is done using the same 6 MV FFF treatment beam, which means some part of the prescribed dose is delivered invariably during the patient setups. This imaging dose needs to be accounted for in every planning. TBI uses multiple plans, each with a pair of isocentres; the dose due to this patient setup is considerable and must be included during dose optimization in TPS.

PET-CT whole-body scanning images of 32 anonymized patients, who were scanned for diagnostic purposes and not for TBI treatments, were included in this dosimetry study to verify the feasibility of TBI treatments in Halcyon-D unit that is equipped only with MV-CBCT imaging capability. Another challenge is that since these patients were not intended for radiotherapy, let alone TBI, their PET-CT scans were not done in the appropriate set-up positions required for the TBI treatments, nor were immobilization devices used. Thus, their CT images contained a lot of air gaps between the body parts and, consequently, resulted in less-than-ideal dose conformity to the target in these plans. The data generated from this study can be considered a typical TBI scenario done to patients without proper CT positioning and immobilization. Nevertheless, these drawbacks were overlooked as the study focused on treatment feasibility from a planning viewpoint in a Halcyon-D linear accelerator with 6 MV FFF-based MV CBCT for compulsory setup image verification. For all the plans generated in this study, pre-treatment QA plans were generated for PTW-Octavius 4D based dose fluence verifications. The measured fluences were compared with the computed ones using 3%/3mm dose criteria. After gamma analysis, all the plans were found to pass the set criteria of 95% of the total evaluated points with gamma value<1, with a mean pass percentage of 99.72% ranging from 99.3 to 100%. Thus, after fluence verifications, it was found that all the plans generated in this study are deliverable ones.

The VMAT TBI plans in Halcyon-D resulted in the PTV mean dose with SD of 1126±17 cGy, 1119±28 cGy and 1151±17 cGy for males, females and paediatric patients,

respectively. One female patient's thickness was 60 cm with 93834 cc volume, resulting in a higher hotspot with reduced coverage. Children's PTV mean dose is higher with reduced hotspots among the three groups. There were no appreciable changes in the target mean dose and hotspot for both males and females. The mean maximum thickness for females and males was 45 cm and 43 cm, which resulted in PTV under coverage for female patients but increased OAR dose.

Figure 4 shows the number of isocentres among male and female patients with no variation in the mean of 10, whereas children required a mean of 7 isocentres. Unlike paediatric cases, male and female patients require more isocentres as the PTV length increases. Figure 5 shows the number of fields employed by male and female patients. The mean number of fields was 35, 34, and 22 for males, females, and paediatric patients, which indicated that an increased number of isocentres and higher thickness required more fields. Figure 6 shows the isocentre interspacing among males and females. The increased thickness necessitates lesser interplane distance, which means that escalation of dose coverage requires more isocentres and fields. For paediatric cases, the interplane distance was 19 ±5 cm. Figure 7 shows the HI and CI for males, females and paediatric patients. The mean CIs were 0.8, 0.7, and 0.8 for males, females, and paediatric patients. The mean HI was 0.4, 0.5, and 0.3 for males, females, and paediatric patients. The CI is higher for paediatric patients among the three groups as the lower volume and length resulted in better target coverage. The heterogeneity is also reduced for paediatric patients. Among the two paediatric patients, a higher-length patient resulted in better coverage than the shorter one despite increased isocentre and fields. The dose reduction in the shorter paediatric patient is due to improper positioning. Patient positioning is vital for TBI treatment delivery and better prognosis. Both HI and CI were less in female patients because of increased thickness. This observation shows that a smaller volume with lower patient height resulted in better coverage of the prescribed dose, comparable to the previously reported Halcyon and Tomotherapy-based TBI planning studies ((21,23,24). In this study, the overall mean HI was 0.33±0.07, which is better than the study reported by Uehara et al., which showed 0.42 ((21)). Reduced HI indicates that the dose heterogeneity is lesser for TBI plans in Halcyon-D. The mean CI was 0.78±0.13 for the TBI target. However, the earlier Halcyon-TBI studies with lesser sample sizes have not quoted the CI values. The CI is almost close to 1, meaning the target's coverage is as good as C-Arm Linac-based VMAT techniques. Despite the limitations, such as the lack of proper positioning and immobilization in this study, Halcyon D-based VMAT plans resulted in better dose conformity and reduced heterogeneity with its FFF beam to the whole body. The mean maximum dose for the PTV was 1411.88±33.8 cGy, comparable to or lesser than other studies using higher versions of the Halcyon unit with kV-CBCT facilities.

The left lung mean dose was 965±48 cGy, 947±67 cGy and 937±44 cGy for males, females and paediatric patients. The right lung mean dose was 970±40 cGy, 962±54 cGy and 950±42 cGy for males, females and paediatric patients. The lung doses were less or comparable with both the earlier studies(6,13,25). The left kidney mean dose was 918±52 cGy, 929±61 cGy and 926±35 cGy for males, females and paediatric patients. The right kidney mean dose was 930±45 cGy, 945±59 cGy and 923±28 cGy for males, females and paediatric patients. Kidney dose was comparable with those in both earlier studies(25). The left lens maximum dose was 941±60 cGy, 927±61 cGy, and 939±8 cGy for males, females and paediatric patients. The right lens maximum dose was 960±48 cGy, 946±45 cGy, and 945±12 cGy for males, females and paediatric patients.

$D_{80\%}$ mean dose was 1028±40 cGy, 1010±63 cGy and 1097±18 cGy for males, females and paediatric patients. The mean MU were 3579±422, 3508±329 and 2297±276 for males, females and paediatric patients, nearly half of the values reported in the earlier studies(21–23). The MUs being lesser in this study than the earlier studies could be because of the limited OAR constraints used in this study.

Conclusion

In Halcyon-D, with its MV-based CBCT setup verification, the unavoidable setup imaging dose is incorporated before starting the optimization and, thus, incorporated in the delivered prescribed dose. The higher dose rate of 800 MU/min reduces the treatment time. Dosimetrically, a comparable target coverage, acceptable doses to the OARs as that of the C-arm Linacs, and but with lesser MUs make the TBI treatments feasible in Halcyon-D units with MV-CBCT capability. Moreover, the sturdy design of the Halcyon unit, with faster movements of the gantry, couch and collimator, ensures quicker delivery of TBI treatments. However, the TBI planning in Halcyon requires an average of ten isocentres due to field size limitations to ensure acceptable homogeneous doses to the target and lesser doses to the OARs within its tolerance limits.

References

1. Thomas ED, Buckner CD, Banaji M, Clift RA, Fefer A, Flournoy N, et al. One hundred patients with acute leukemia treated by chemotherapy, total body irradiation, and allogeneic marrow transplantation. Blood. 1977 Apr;49(4):511–33.
2. Cahu X, Labopin M, Giebel S, Aljurf M, Kyrcz-Krzemien S, Socié G, et al. Impact of conditioning with TBI in adult patients with T-cell ALL who receive a myeloablative allogeneic stem cell transplantation: a report from the acute leukemia working party of EBMT. Bone Marrow Transplant. 2016 Mar 30;51(3):351–7.
3. Davies SM, Ramsay NKC, Klein JP, Weisdorf DJ, Bolwell B, Cahn JY, et al. Comparison of Preparative Regimens in Transplants for Children With Acute

Lymphoblastic Leukemia. Journal of Clinical Oncology. 2000 Jan 1;18(2):340–340.
4. Shank B, Chu FC, Dinsmore R, Kapoor N, Kirkpatrick D, Teitelbaum H, et al. Hyperfractionated total body irradiation for bone marrow transplantation. Results in seventy leukemia patients with allogeneic transplants. Int J Radiat Oncol Biol Phys. 1983 Nov;9(11):1607–11.
5. Wong JYC, Filippi AR, Dabaja BS, Yahalom J, Specht L. Total Body Irradiation: Guidelines from the International Lymphoma Radiation Oncology Group (ILROG). Vol. 101, International Journal of Radiation Oncology Biology Physics. Elsevier Inc.; 2018. p. 521–9.
6. Tas B, Durmus IF, Okumus A, Uzel OE, Gokce M, Goksoy HS, et al. Total-body irradiation using linac-based volumetric modulated arc therapy: Its clinical accuracy, feasibility and reliability. Radiotherapy and Oncology [Internet]. 2018;129(3):527–33. Available from: https://doi.org/10.1016/j.radonc.2018.08.005
7. Losert C, Shpani R, Kießling R, Freislederer P, Li M, Walter F, et al. Novel rotatable tabletop for total-body irradiation using a linac-based VMAT technique. Radiation Oncology. 2019 Dec 30;14(1).
8. Tas B, Durmus IF, Okumus A, Uzel OE. PO-0910: Is Linac-Based Total Body Irradiation (TBI) on the coach by VMAT Feasable? Radiotherapy and Oncology. 2017;123:S504.
9. Jiang B, Dai J, Zhang Y, Zhang K. Feasibility study of a novel rotational and translational method for linac-based intensity modulated total marrow irradiation. Technol Cancer Res Treat. 2012;11(3):237–47.
10. Hui SK, Kapatoes J, Fowler J, Henderson D, Olivera G, Manon RR, et al. Feasibility study of helical tomotherapy for total body or total marrow irradiationa). Med Phys. 2005 Oct 29;32(10):3214–24.
11. Köksal M, Kersting L, Schoroth F, Garbe S, Koch D, Scafa D, et al. Total marrow irradiation versus total body irradiation using intensity-modulated helical tomotherapy. Vol. 149, Journal of Cancer Research and Clinical Oncology. 2023. p. 5965–73.
12. Gruen A, Ebell W, Wlodarczyk W, Neumann O, Kuehl JS, Stromberger C, et al. Total Body Irradiation (TBI) using Helical Tomotherapy in children and young adults undergoing stem cell transplantation. Radiation Oncology. 2013;8(1):2–9.
13. A. G, W. E, W. W, O. N, J.S. K, C. S, et al. Total Body Irradiation (TBI) using Helical Tomotherapy in children and young adults undergoing stem cell transplantation. Radiation Oncology [Internet]. 2013;8(1):2–9. Available from: http://www.ro-journal.com/content/8/1/92%5Cnhttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed11&NEWS=N&AN=2013312740
14. Loginova AA, Kobyzeva DA, Tovmasyan DA, Chernyaev AP, Lisovskaya, Maschan MA, et al. Comparison of total body irradiation using TomoTherapy and volume-modulated rotational radiation therapy Elekta. A single center experience on pediatric patients. Pediatric Hematology/Oncology and Immunopathology. 2019;18(4):49–57.
15. Loginova AA, Tovmasian DA, Lisovskaya AO, Kobyzeva DA, Maschan MA, Chernyaev AP, et al. Optimized Conformal Total Body Irradiation methods with Helical TomoTherapy and Elekta VMAT: Implementation, Imaging, Planning and Dose Delivery for Pediatric Patients. Front Oncol. 2022 Mar 10;12.
16. Feuvret L, Noël G, Mazeron JJ, Bey P. Conformity index: A review. International Journal of Radiation Oncology*Biology*Physics. 2006 Feb;64(2):333–42.
17. Shaw E, Kline R, Gillin M, Souhami L, Hirschfeld A, Dinapoli R, et al. Radiation Therapy Oncology Group: radiosurgery quality assurance guidelines. Int J Radiat Oncol Biol Phys. 1993 Dec 1;27(5):1231–9.
18. Sampath S, Schultheiss TE, Wong J. Dose response and factors related to interstitial pneumonitis after bone marrow transplant. International Journal of Radiation Oncology*Biology*Physics. 2005 Nov;63(3):876–84.
19. Chiang Y, Tsai CH, Kuo SH, Liu CY, Yao M, Li CC, et al. Reduced incidence of interstitial pneumonitis after Allogeneic hematopoietic stem cell transplantation using a modified technique of total body irradiation. Sci Rep. 2016 Nov 10;6.
20. Van Dyk J, Galvin JM, Glasgow GP, Podgorsak EB. AAPM n°17 : The Physical Aspects of Total and Half Body Photon Irradiation. American Institute of Physics. 1986. 54 p.
21. Uehara T, Monzen H, Tamura M, Inada M, Otsuka M, Doi H, et al. Feasibility study of volumetric modulated arc therapy with Halcyon™ linac for total body irradiation. Radiation Oncology [Internet]. 2021;16(1):1–8. Available from: https://doi.org/10.1186/s13014-021-01959-3
22. Talapatra K, Parab AS, Singh A, Barsing S, Gupte A, Padate B. Clinical experience of total body irradiation performed on Halcyon™ for a patient diagnosed with acute myeloid leukemia. International Journal of Molecular and Immuno Oncology. 2022 May 17;7:50–3.
23. Shahid T, Mandal S, Biswal SS, De A, Mukherjee M, Roy Chowdhury S, et al. Preclinical validation and treatment of volumetric modulated arc therapy based total bone marrow irradiation in Halcyon™ ring gantry linear accelerator. Radiation Oncology. 2022 Dec 1;17(1).
24. Gruen A, Ebell W, Wlodarczyk W, Neumann O, Kuehl JS, Stromberger C, et al. Total Body Irradiation (TBI) using Helical Tomotherapy in children and young adults undergoing stem cell transplantation [Internet]. 2013. Available from: http://www.ro-journal.com/content/8/1/92
25. Chakraborty S, Cheruliyil S, Bharathan R, Muttath G. Total Body Irradiation using VMAT (RapidArc): A Planning Study of a novel treatment delivery method. International Journal of Cancer Therapy and Oncology. 2015 Feb 26;3(2):03028.