RESEARCH ARTICLE

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Optimal Combination of Pitch, Modulation Factor and Dosimetric Considerations in Treatment Planning for Total Body Irradiation Using Helical Tomotherapy

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Abstract

Objective: The aim of this study is to makethe standard total body irradiation (TBI) protocol for Helical tomotherapy© (HT) and to analyze the optimal pitch and modulation factor (MF) with respect to dose homogeneity index (HI), target dose coverage, target overdose, beam on time (BOT) and mean lung dose. **Materials and Methods:** Ten patients who underwent high-dose TBI were taken for this study. For each patient, 35 dose plans were created by different combination of pitch and MF. The optimal pitch and MF were deduced using scatter plot and regression methodology based on target coverage, HI, target volume receiving 103%($V_{103\%}$), 105%($V_{105\%}$) and 107% ($V_{107\%}$) of the prescription dose and BOT. Using these optimal pitch and MF, the final dose plan was made and the planning aim and achieved dose was compared using two tailed student's t-test. Radiochromic films and ionization chambers were used to measure the delivered dose using anthropomorphic phantom on various points for the head and pelvis regions to verify the skin flash margin and its effect on skin dose. **Results:** The optimal pitch and MF value were 0.287 and 2.4 respectively. Based on optimal pitch and MF, the mean BOT was 1692 seconds with optimal inhomogeneity (7.4%). For target, D95 and D98 were 97.09% (range:94.7-99.6%, p=0.002) and 93.9% (range:91.5-94.4%,p=0.007) respectively, and mean D2 was within 107% with SD of ±1.22% (p=0.04). The mean of PTV receiving V_{103}, V105 and V107 was 24.48% (range=7.7-36.6%, p=0.03), 5.76% (range=1.4-12.1%, SD=±3.3%), 1.93% (range=0.1-4.6%, p=0.008) respectively. Our measurements show that the flash margin did not increase the skin dose. **Conclusion:** In our study, the optimal combination of pitch value of 0.287 and MF value of 2.4 provided acceptable plans for all patients planned for TBI in HT. The flash margin can provide adequate coverage during patient position uncertainty without increasing the skin dose.

Keywords: Helical tomotherapy- total body irradiation- pitch- modulation factor- skin dose

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Introduction

Total body irradiation (TBI) is an important part of the conditioning regimen for stem cell transplant for multiple myeloma, leukemias, lymphomas and some solid tumors (Gruen et al., 2013; Poonsombudlert et al., 2019). The purpose of TBI is to bring about bone marrow depletion, to destroy any cancer cells left behind after cytotoxic chemotherapy and to prevent rejection of donor cells using immunosuppression, all of which together result in a successful stem cell engraftment (Halperin et al., 2013). In TBI, a uniform radiation dose with megavoltage photon beams is delivered to the entire body, including the central nervous system (CNS) and testis, where traditional chemotherapy is not effective (Seung et al., 2013). Generally, the TBI schedules include twice daily 2-Gy fractions given over 3 days (total dose 12 Gy), 1.5-Gy fractions (twice-daily) over 4-4.5 days (total dose 12-13.5 Gy), or 1.2-Gy fractions (thrice-daily) over 4 days (total dose 12-13.2 Gy (Wong et al., 2018). Uniform dose distribution to the whole body during TBI is mandatory as recommended by American Association of Physicist in Medicine Task group-29 (AAPM TG-29) and the dose variation throughout the body should be within ±10% of the prescription dose (Van Dyk et al., 1986). Cleuziou et al., (2021) discussed the methodology to set up the protocol, dosimetric evaluation and pretreatment QA and in-vivo dosimetry of TBI using Helical TomoTherapy® (HT). TBI in HT provides good dose homogeneity and conformity with an acceptable organ at risk (OAR) tolerance which leads to reduced severity and less late complications (Sarradin et al., 2018, Zarghani et al.,

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2021, Peñagarícano et al., 2011). As a result, excellent conditioning is attained with minimal side-effects for lung and other body organs (Gruen et al., 2013).

Each gantry rotation in the HT field is divided into 51 projections with 7.06° of gantry rotation per projection and this single projection is divided into 64 beamlets. These 64 MLC binary leaves open time with inverse planning provides a target dose from its projection (Boyd et al., 2019). Pitch, modulation factor (MF), and the treatment slice width can play important roles in beam-on time (BOT) and acceptable plan quality, and the selection of a lesser pitch value does not increase BOT because the gantry rotational speed is variable (15–60 seconds per rotation) (Langen et al., 2010). Inverse-planning optimization in tomotherapy needs to select MF, which is defined as MF= (Max leaf open time)/(average non-zero leaves open time). The pitch is the ratio between the couch travel per gantry rotation and the treatment slice width. Kissick et al., (2005), proposed a magic number for determining the pitch value ie., = 0.86/n, n; integer; for reducing the thread effect, and it is indicated by ripples in the longitudinal dose profile. During the treatment plan in Tomotherapy, the final MF value was less than the optimization value for reducing the treatment time using the increased average leaf opening time which provides a less OAR dose, and the optimal range of MF for head and neck was between 3.0 and 1.8. But the MF could be increased (up to 2.4) for sparing the critical organ where the target was very close to it (Ryczkowski et al., 2013). The MF directly contributes to the treatment time and the BOT is defined using the following formula, Beam on time (BOT)= gantry period x active gantry rotations. Complex targets and OARs close to the target require a high MF to modulate the dose distribution to the target (Fenwick et al., 2004, Binny et al., 2015). The suggested optimal pitch and MF were 0.215 and 0.25 respectively for prostate cancer patients which provides a balance between BOT and dose distribution (Skórska et al., 2013). Meyer (2015) studied the optimal treatment planning parameters (pitch and MF) for extremity soft tissue sarcomas and stated that the 0.43 pitch value is not optimal, and that for a pitch value of 0.215, optimum MF is more than 2. This same study (Meyer et al., 2015) suggests using pitch 0.287 which could provide an acceptable plan quality and reduced treatment time. Salz (2015) discussed intensity modulated TBI with TomoDirect® method using various MF and pitch and stated that IMRT with TomoDirect®allows a superior homogeneity compared to conventional methods with lung sparing.

The optimal pitch and MF have been evaluated for various sites by several authors (Skórska et al., 2013; Meyer et al., 2015), but to our knowledge, the optimal pitch and MF for TBI using HT mode, has not been analyzed. The aim of this study to make the standard TBI protocol for HT and to analyze the optimal pitch and MF with respect to dose homogeneity index (HI), target dose coverage, target overdose, BOT and lung sparing for TBI in HT. Further, this study aims to validate the flash margin and its effect with skin dose using radiochromic External Beam Therapy 3 (EBT3) and ionization chamber in anthropomorphic phantom.

Materials and Methods

Patient selection, Immobilization and CT simulation

Ten patients who underwent high-dose TBI in our center from 2019 to 2021 were taken for this study (Table 1). Patients were positioned in the supine position in a vacuum cushion with a headrest. A thermoplastic cast was used to immobilize the head and both the arms were positioned by the side. Leg separation between the two legs was fixed within 40 cm so that TomoDirect® (AP/PA) could be used for below thigh treatment. For patient setup, the laser alignment markings were fixed at head, thorax, pelvis and knee region. Fiducials were placed in the thorax and knee region for the reference position. 5mm slice thickness was acquired in computed tomography (Siemens Biograph 64, Siemens Healthinners, Erlangen, Germany) scanner. If the height of the patient was more than 120 cm, then two scans, one each in the head-first supine (HFS) and feet-first supine (FFS) positions, were acquired. Radio-opaque catheters were placed at the thigh (5cm from knee) level in both HFS and FFS scans for summation of dose plans. The acquired image was exported to the treatment planning system (Precision Version 3.2.0, Accuray incorporated Sunnyvale USA).

Target and Normal structure delineation

The planning target volume (PTV) of total body, created by using the body structure at 3 mm inside the body was contoured as a PTV and this PTV was split into PTV_HFS (up to radio-opaque (RO) marker at thigh level) for HFS scan and PTV_FFS for FFS scan. The step wedge technique was used to create the uniform distribution at junction. Total 7 structures (step wedge) with 1cm thickness were drawn at the level of junction for both HFS and FFS scan (Figure 1). The normal structures including lungs, eyes, kidney and others were contoured as per standard institutional protocol. The PTV was taken inside the lung for 1cm to avoid the under dosage for rib regions. The avoidance volume was drawn by subtracting PTV from lung as an OAR. The body structure was created using auto segmentation of skin creation tool which provides the outer edge of the patient body. The manual correction of body structure was done for removing the immobilization devices which were overlapping with body contour. For taking care of setup uncertainties, 2cm margin from PTV was created and named as PTV_Flash.

The right and left hand were separately contoured for removing high / low dose during optimization. The planning process started with choosing the density model for the calculation which provided mass density value using the Hounsfield units. Subsequently machine parameters like treatment machine, delivery mode, plan mode and jaw mode were selected. In our center, for single fraction TBI, the direct delivery mode with 3DCRT is preferred if the width of the patient is less than 40cm. For high dose TBI/multiple fractions, Helical mode with IMRT planning technique is used for sparing the lung. For keeping the account of patient setup uncertainties, fixed jaw mode is kept for direct as well as helical mode. The couch replacement was performed as per vendor recommendation for modeling the couch in Treatment

Planning System (TPS). The patient position in TPS, as guided by green lasers, was kept at the center of the patient volume, which comes at chest level in HFS scans in anterior-posterior (AP), superior-inferior (SI), and left-right (LR) directions. The red laser was aligned with the fiducial markers kept at the chest-level of the patient. Before moving to the optimization process, the machine geometry was carefully verified from head to thigh, for any missing or out-of-field geometry parameters.

Treatment Planning

In this study, the helical mode with IMRT was used for HFS position in all plans. The optimization process was performed by choosing four target structures, PTV_HFS, PTV_Flash (2cm margin to PTV_HFS), Rt hand, and Lt hand. The target and OAR objectives were provided in such a way that the 95% PTV_HFS volume should get at least 95% of the prescription dose. The dummy structures at the junction area were assigned a dose constraint in such a way that it could reduce a dose by 1Gy on each strip. The initial optimization started with these parameters and if the high or low dose region were in the hand region, then separate target objectives were assigned for those regions. For sparing the lung, lung - PTV (Right & Left) was assigned a critical structure constraint with a high penalty. Once an optimal solution was achieved, the process was repeated for various pitch and modulation factors. Starting the pitch value from 0.2 to 0.5 with an increment of 0.05 with a combination of modulation factors of 2 to 4 (increment with 0.5). By using the above combination each patient had 35 plans and all the other planning parameters were kept constant (unchanged). The initial iterations of the plan were approximately 80,000 with medium optimization resolution. The dose distribution for each beamlet was calculated and the number of beamlets depended on slice width, pitch, target volume, and shape. The least-square optimization method was used to optimize the objective function (Mackie et al., 2003) and the final dose calculation was performed at a high resolution with a grid size of 3.91x5x3.91 mm using a convolution superposition algorithm. For FFS plan, if the target had more than 40 cm separation in LR direction then HT was used otherwise Tomo-Direct (TD) was preferred. For FFS, a similar planning process was used as explained in HFS plan.

Plan evaluation

Initially, the HFS plan and FFS plan was summed up using the Medical Image Merge software (MIM use with Precise RTX version 6.8) and the under- or over-dosage at the junction was assessed (Figure 2). The HFS plan selection criteria were based on the target dose homogeneity, target volume getting 103% ($V_{103\%}$),105% ($V_{105\%}$) and 107% ($V_{107\%}$) of the PD, beam-on time, and fractional monitor units. The target dose homogeneity was calculated as per the international commission on Radiation Unit and measurements (ICRU) report 83,using the following equation:

$$\mathbf{HI} = \frac{\mathbf{D2\% - D98\%}}{\mathbf{D50\%}} \mathbf{X\ 100} \quad (1)$$

Where $D_{2\%}$, $D_{98\%}$ and $D_{50\%}$ were dose received by 2%, 98% and 50% of PTV_HFS volume respectively. If the HI value is lesser, then the plan provides a more homogeneous distribution to PTV_HFS. $V_{103\%}$ and $V_{105\%}$ of the target were evaluated using a Dose-Volume histogram (DVH). Beam-on time was noted for each of the HFS plan with gantry period and arc rotation. The minimum beam-on time provides a lesser monitor unit with lesser patient setup uncertainty. The goal of this plan selection process is the minimum beam-on time with acceptable target inhomogeneity, $V_{103\%}$, and $V_{105\%}$ Using the x-y scatter plot. The pitch and modulation factor was kept in the x-axis and the t homogeneity was kept in Y-axis. The quadratic equation is created by choosing the feasible pitch and modulation factor using the plan number and minimum HI. The same process was used for beam-on time, $V_{103\%}$ and $V_{105\%}$. In this evaluation process, the spare lung volume mean dose was kept at less than 6.5Gy for all the plans). From above method, the suitable pitch and MF were calculated for each one of the scatter plots. Finally, the suitable pitch and MF were selected as per minimum BOT at appropriate clinical needs. By using this pitch and MF, the final plan was optimized for treatment delivery verification with the same other planning parameters. Once the deliverable plan was verified, the quality assurance of the above plan was processed to verify the delivery uncertainty.

Delivery verification and Quality Assurance

The Quality Assurance (QA) of the final deliverable plan was split into two parts. 1. Point dose verification with cylindrical Tomotherapy Phantom (Cheese Phantom, Med-Cal Inc, Verona, WI, USA) for all the patients. 2. Surface dose measurements on anthropomorphic phantom using radiochromic film. Each of the deliverable final plans for all the patients were transferred to cheese phantom® with the same planning parameters. Three different points were chosen (head, thorax, and pelvis) to verify the TPS calculated dose on cheese phantom using 0.053 cm3 ionization chamber (A1SL, Exradin®, Standard Imaging, Middleton, WI, USA). By using the final pitch and MF, the dose plan was created in anthropomorphic phantom. In TBI, as the total body is the target, patient positioning in one area may not provide the cumulative patient setup and if the target (patient body) deviates from its position, even by a millimeter, there may be a dosimetric deviation from the planned dose. For avoiding the above uncertainty, the skin flash should be used in TBI treatment plans. In our study, we a created 2 cm flash margin from the PTV and assigned as a target volume with dose constraints. This was verified with films and chamber. Radiochromic films and ionization chambers were used to measure the delivered dose on anthropomorphic phantom with various points for the head-neck (Vertex, Forehead, Right Buccal mucosa, Left Buccal Mucosa, Sternum) and Pelvis regions (Superior, inferior, left, right and Pubis). Radiochromic films are placed in the surface of the anthropomorphic phantom to verify the skin doses. Apart from these measurements, the flash margin validation and its importance were verified with anthropomorphic phantom using radiochromic films and cylindrical

ionization chamber (Figure 3a-c). The anthropomorphic phantom (both Head&Neck and Pelvis) was scanned in CT scanner with the slice thickness of 3mm and the PTV was generated to mimic the TBI. Two type of dose plans were created with and without flash margin (2cm from PTV). The customized bolus which has the dimension of 8 cm (length) x 9cm (width) x 2cm (height) has been attached in the head&neck and pelvis phantom during the dosimetric measurements (for both the plans) to verify the effect of flash margin. The pre-measurement image was acquired using Mega-Voltage on-board CT (TrueCT®) images and it was co-registered with reference planned CT to verify the setup uncertainty. Both the plans were executed to anthropomorphic phantom with attached customized bolus.

Statistical Analysis

Plan selection process was made using the scatter plot and regression methodology (using the quadratic equation) as mentioned earlier. The comparison between dosimetric objectives and achieved dose was done using two tailed Student's T-test using IBM SPSS Statistics for Windows, version 24 (IBM Corp., Armonk, N. Y., USA). The significance level was set at 0.05.

Results

For analyzing the HI with respect to MF and pitch, the homogeneity decreased (HI increased) on increasing pitch and MF (Figure 4a). A minimal increase in HI was observed when the pitch value was increased from 0.2 to 0.3 but increasing the pitch value beyond 0.3 resulted in more inhomogeneous plans with respect to MF. For a constant pitch value, the BOT increased with increasing MF. A sharp decrease of BOT was observed when increasing the pitch and its corresponding MF (Figure 4b). The $V_{103\%}$ of PTV increased with pitch and constant MF (Figure 4c) but for the constant pitch value, the increasing MF provided a lesser $V_{103\%}$. The above pattern was observed for $V_{105\%}$ and $V_{107\%}$ also (Figure 4d, 4e). From the above analysis, the optimal pitch and MF was evaluated, and the quadratic equation was plotted to find the optimal pitch and MF for $V_{103\%}$, $V_{105\%}$, and $V_{107\%}$ without increasing the BOT and HI. The optimal pitch and

Table 1. Patient Demographics, PTV Volumes, Prescription Dose and Lung Volume

Patient No #	Age (Years)	Sex	Diagnosis	Height (cm)		Max Width (cm)	PTV (HFS) Volume (cm^3)	PTV Total Volume (cm^3)	PTV+2cm (HFS) Volume (cm^3)	Prescribed DosePD for Total Body (Gy)	Total fractions
				HFS	FFS						
1	13	M	ALL	100	62	36	25,506	30,835	41,736	12	6
2	18	M	ALL	111	66	44	42,415	52,895	66,545	8	8
3	40	F	ALL	105	62	44.5	43,187	49,836	63,153	13.2	6
4	22	M	ALL	116	72	59	70,524	110,688	92,445	8	8
5	21	M	ALL	109	73	45	40,515	46,663	62,199	8	8
6	39	M	ALL	109	69	53	68,843	80,191	95,517	8	8
7	24	F	ALL	107	64	42	32,929	39,679	53,778	12	6
8	24	M	CML	109	67	50	50,945	68,605	81,264	8	8
9	19	M	ALL	121	40	44.1	39,273	47,071	62,576	8	8
10	32	F	MS	102	52	39.4	33,021	41,904	50,534	8	8

ALL, Acute Lymphoblastic Leukemia; MS, Myeloid sarcomaTable 1 Patient demographics; PTV volumes, prescription dose and lung volume; ALL, Acute Lymphoblastic Leukemia; MS, Myeloid sarcoma; CML, Chronic Myeloid Leukemia

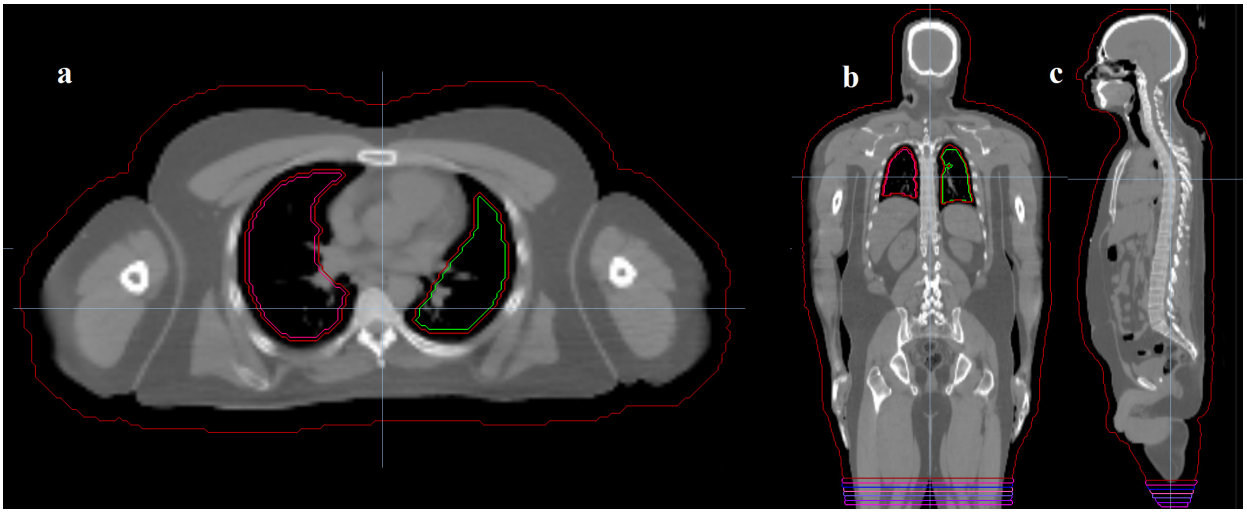

Figure 1. Target and OAR Delineation for TBI_HFS scan. Figure 1 a. axial section shows the sparing Lung volume and margin taken for covering the rib without underdose. Figure 2 b and 2 c shows the 2cm flash margin throughout body to take care the setup uncertainty and 7 dummy strips with 1cm thickness in the inferior direction used for creating step wedge for an uniform dose at the junction

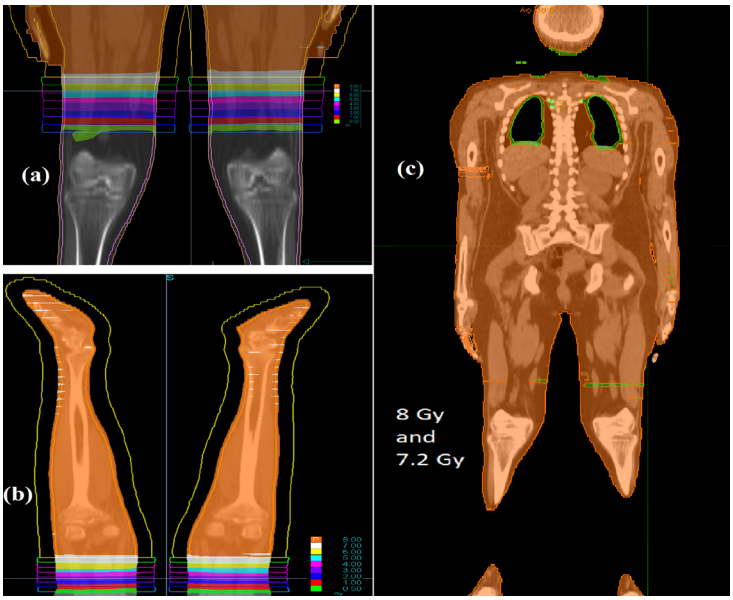

Figure 2. Dose Planning of HFS and FFS and Its Summation was Shown. 2a. PTV_HFS plan was shown with step wedge dose distribution in inferior part 2b. PTV_FFS plan shows step wedge dose distribution in superior part 2c. Summation of HFS and FFS plan with uniform dose distribution at junction

MF value were 0.287 and 2.4 respectively. Based on this pitch and MF, the treatment plans were generated for all patients. The dosimetric outcomes were compared with other pitch and MF values. The minimum BOT was found when the pitch was 0.45 and MF was 2.0 (Table 3). But the dose inhomogeneity was increasing at the level of 20% and this inhomogeneity was not acceptable for treatment. Based on optimal pitch and MF, the mean BOT was 1692 seconds with optimal inhomogeneity (7.4% %).

The planning aim and achieved doses were compared in HT. For PTV_HFS, D95% and $D_{98\%}$ were 97.09% (range: 94.7-99.6%, SD=±1.77% and p=0.002) and 93.9% (range:91.5-94.4%, SD=±1.7%, p=0.007) respectively, and mean $D_{2\%}$ was within 107% with SD of ±1.22% (p=0.04). The mean of PTV receiving $V_{103\%}$, $V_{105\%}$, and $V_{107\%}$ was 24.48% (range=7.7-36.6%, SD=±10.44, p=0.03), 5.76% (range=1.4-12.1%, SD=±3.3%, p=0.005), 1.93% (range=0.1-4.6%, SD=±1.19%, p=0.008) respectively and all the values were within the planning constraints. The mean dose to the combined lung was 8.62 Gy (range=8.4-8.7 Gy, p=0.01) for 12 Gy prescription and 5.74Gy (range=5.2-6.2Gy, p=0.04) for an 8 Gy prescription (Table 2). Dose to eyes and lenses were within the planning aim. The plan specific QA for all the dosimetric plans were within 2% from TPS calculated dose. The measured dose using the ionization chambers with flash margin plans shown closer to 2 Gy but no-flash plans were provided the less than 2 Gy in all points. The mean deviation between these flash and no-flash margin was 26.18% and 26.66% for head-neck and pelvis respectively. In skin dose measurements using the EBT3 films, the average difference between flash and no-flash plans were 0.9 % and 0.43% for head-neck and pelvis plans respectively in anthropomorphic phantom (Table 4).

Discussion

Hui et al., (2005) reported the dose homogeneity was worsened by 2% with every 10% change in the pitch from 0.46 to 0.556, and the higher pitch values impacted the average dose to the critical structures. The above effect was obtained in our study also and increasing the pitch

Table 2. Planning Aim and Achieved Dose for the Target and Organ at Risks

Structures	Planning Aim		Achieved (mean, range, SD)	p
PTV	$D_{95\%}$	>95%	97.09, 94.7-99.6, 1.77	0.002
	$D_{98\%}$	>90%	93.9, 91.5-94.4, 1.70	0.007
	D_{2}	<107%	106.82, 104.8-109.2, 1.22	0.04
	V_{103}	<30%	24.48, 7.7-36.6, 10.44	0.03
	V_{105}	<10%	5.76, 1.4-12.1, 3.30	0.005
	V_{107}	< 2%	1.93, 0.1-4.6, 1.19	0.008
Combined Lung	D_{mean}	<8.5 Gy (for 12 Gy PD)	8.62, 8.4-8.7, 0.2	0.01
		<6.5Gy (for 8Gy PD)	5.74, 5.2-6.2, 0.34	0.04
Eyes	D_{mean}	≤100%	100.46, 89-103, 4.17	0.04
Eye Lens	D_{mean}	≤100%	98.08, 70-102.5, 10.06	0.047

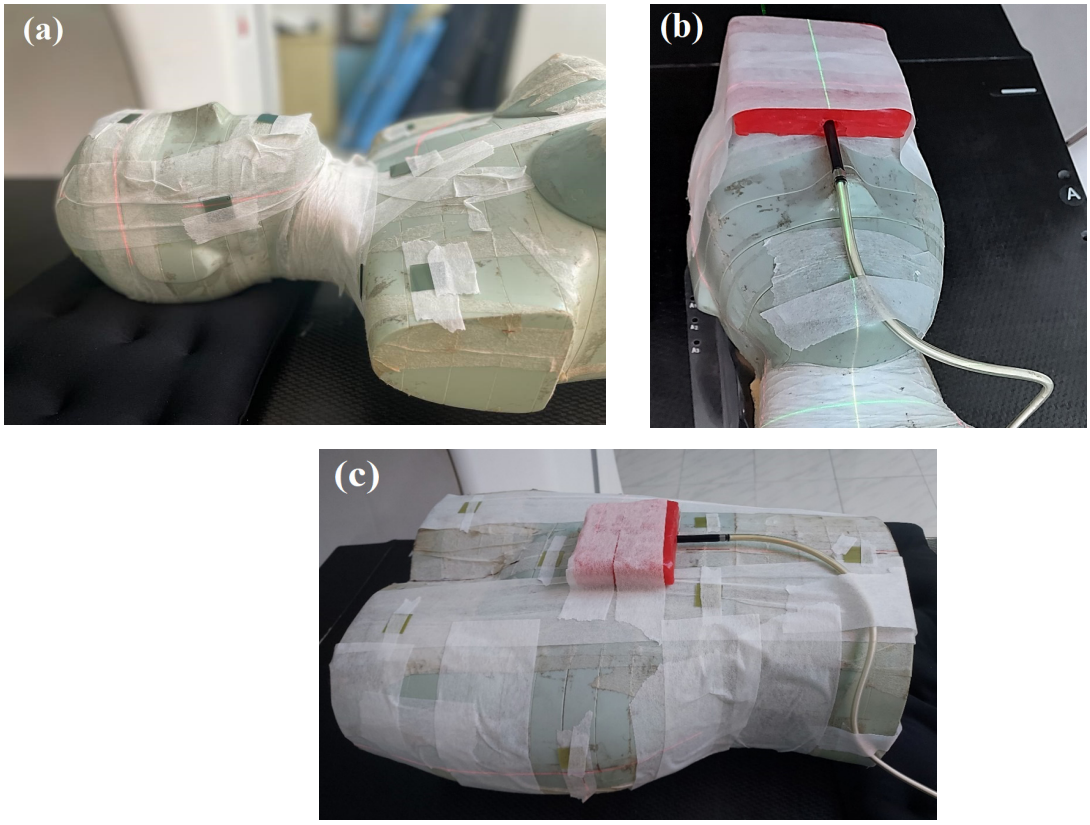

Figure 3. a, Anthropomorphic head-neck phantom with and gaffchromic film at 5 position (Vertex, Rt Buccal mucosa, Lt Buccal mucosa, sternum); b, Anthropomorphic head-neck phantom with chamber insertion in wax bolus; c, Anthropomorphic pelvis phantom with chamber insertion gaffchromic film at 8 positions (Superior, Superior-Left, Superior-Right, left, right, left thigh and right thigh)

value increased the HI approximately by 10% (more inhomogeneity) on increasing the pitch from 0.3 to 0.5, independently of MF. The V_{103} gradually increased from 35% to 65% when the pitch is increased from 0.35 to 0.5, again independent of MF. The same study (Hui et al., 2005), also showed that with increase in MF from 2 to 2.5, the homogeneity was slightly greater (DHI decreased 2%). In our results, the HI was increased (more inhomogeneous) mainly with pitch value. The MF value has lesser impact when comparing the pitch values in view of dose homogeneity but the particular pitch value with increasing MF could reduce the inhomogeneous at the edges of the body.

Standard TBI protocols recommend the median lung dose to be less than 10Gy, and lung toxicity is minimal if the lung doses are kept less than 8Gy (Buchstab et al.,

Table 3. Pitch, MF and Beam on Time (Mean) for the PTV_HFS Plan. The Beam on time for optimal pitch and MF was also shown.

Pitch	MF	Beam on time (Sec)	p	Pitch	MF	Beam on time (Sec)	p	Pitch	MF	Beam on time (Sec)	p
0.2	2	2,354		0.25	2	1,883	0	0.3	2	1,569	
	2.5	2,354	0		2.5	1,883			2.5	1,583	0
	3	2,354			3	1,935			3	1,715	
	3.5	2,382			3.5	2,045			3.5	1,845	
	4	2,484			4	2,176			4	1,982	
0.35	2	1,376	0.148	0.4	2	1,214		0.45	2	1,138	
	2.5	1,453			2.5	1,335	0.149		2.5	1,268	
	3	1,589			3	1,465			3	1,414	0
	3.5	1,722			3.5	1,610			3.5	1,606	
	4	1,879			4	1,801			4	1,722	
0.5	2	1,087									
	2.5	1,222		0.287	2.4	1,692					
	3	1,395	0								
	3.5	1,648									
	4	1,834									

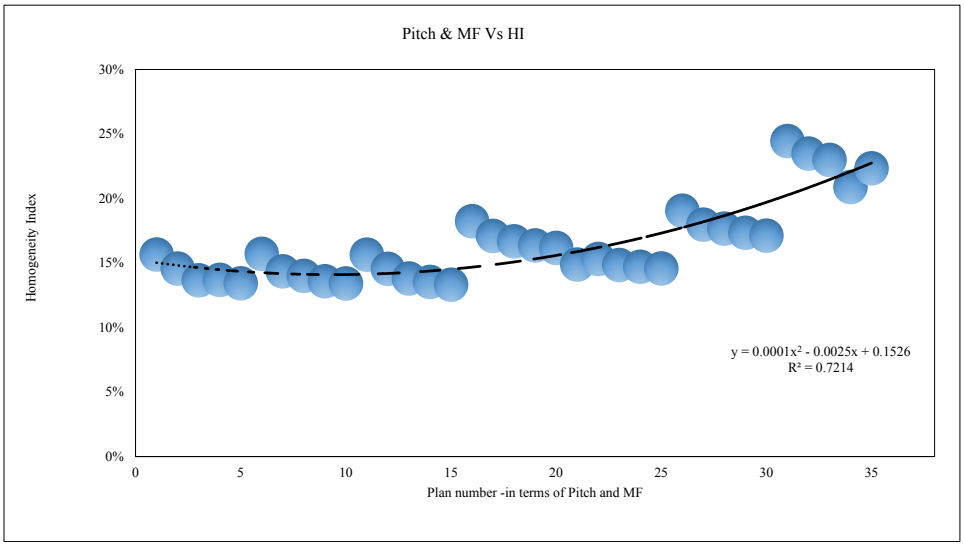

Figure 4a. Pitch and MF Versus Homogeneity Index; Increasing the Pitch (0.2 to 0.5) with MF (2 to 4) could Increase the Inhomogeneity

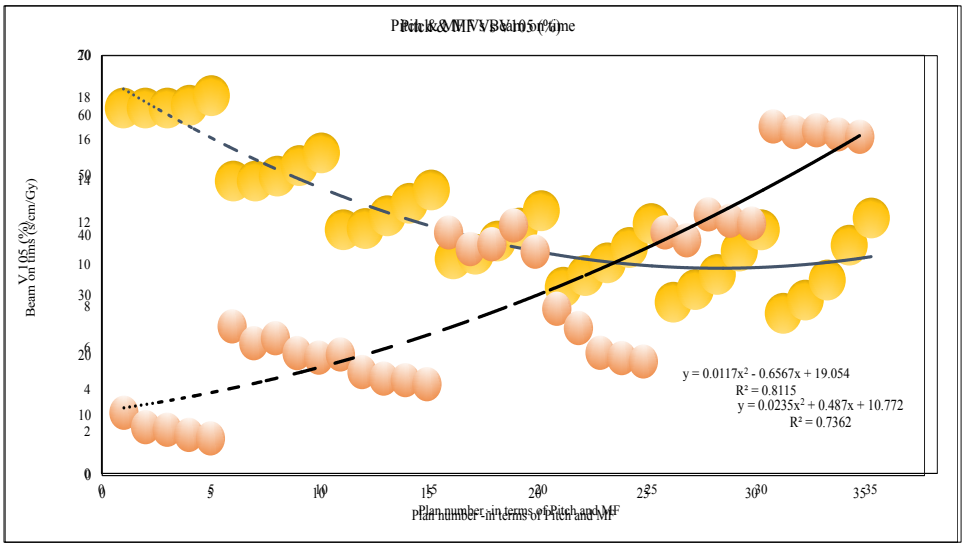

Figure 4b. Pitch and MF Versus Beam on Time; Increasing the Pitch (0.2 to 0.5) with MF (2 to 4) could Decrease the Beam on Time.

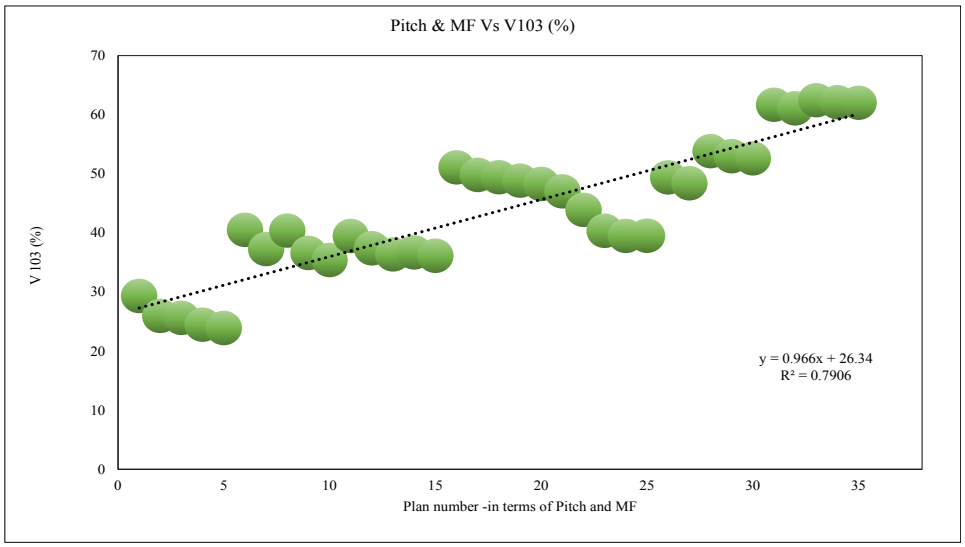

Figure 4c. Pitch and MF Versus $V_{103\%}$ Received by PTV_HFS; increasing the pitch (0.2 to 0.5) with MF (2 to 4) could increase the $V_{103\%}$ of PTV_HFS

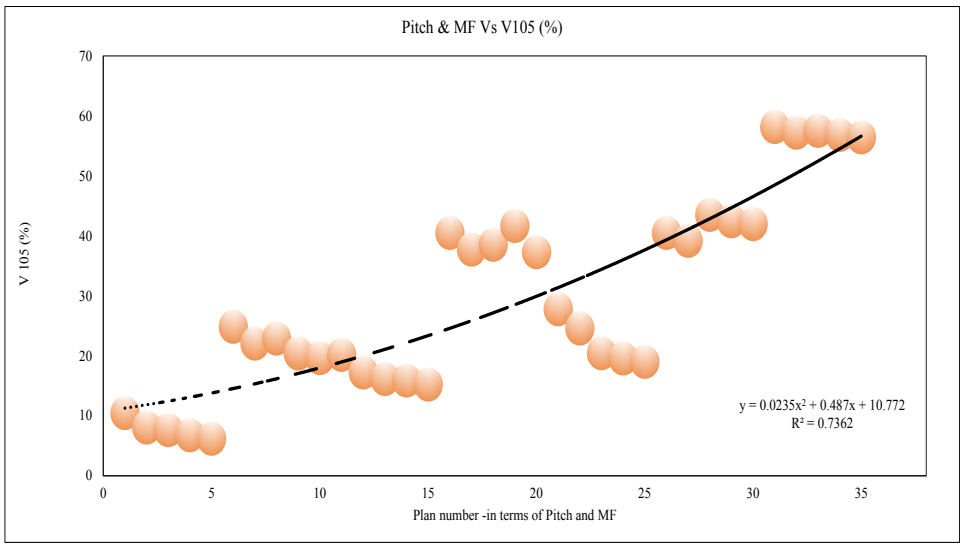

Figure 4d. Pitch and MF Versus $V_{105\%}$ Received by PTV_HFS; increasing the pitch (0.2 to 0.5) with MF (2 to 4) could increase the $V_{105\%}$ of PTV_HFS

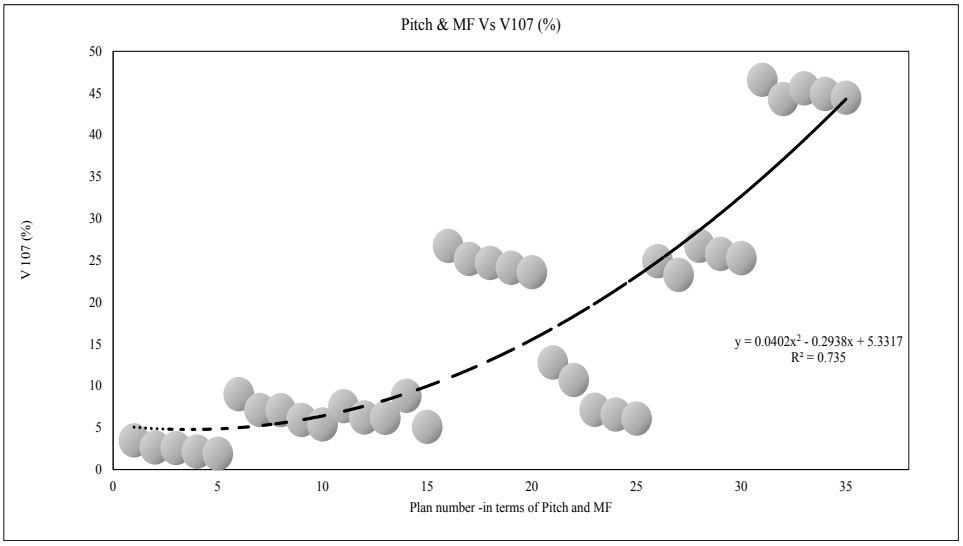

Figure 4e. Pitch and MF Versus $V_{107\%}$ Received by PTV_HFS; increasing the pitch (0.2 to 0.5) with MF (2 to 4) could increase the V107% of PTV_HFS

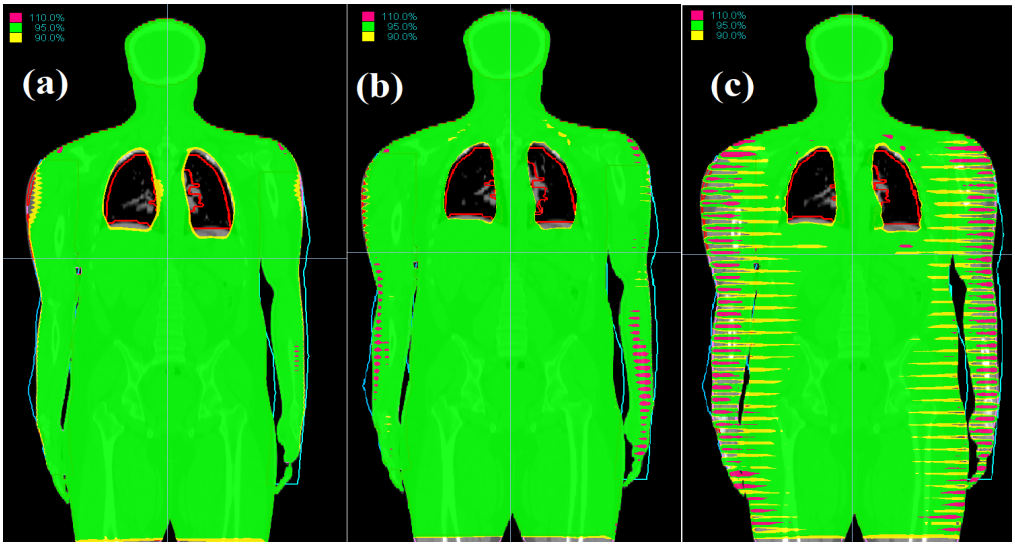

Figure 5. PTV Received by 90%, 95% and 120% Isodoses were Shown for the PTV HFS Plan. 5a. Dose distribution for the Pitch value of 0.2 and with MF 2.0 ; 5b. Dose distribution for the Pitch value of 0.287 and with MF 2.4 ; 5c. Dose distribution for the Pitch value of 0.5 and with MF 4.0

2020). In our study, patients planned for 12 Gy and 8Gy prescription dose received mean lung doses less than 8.6 Gy and 5.7Gy, respectively. For analyzing the lung dose with change in pitch and MF, the deviation in lung dose was minimal but the dose coverage at the rib region was less (cold spot) when the pitch values was higher. To reduce the lung dose, the central lung region was contoured separately and assigned as complete block (full block), which helped provide a uniform gradient from rib to central lung. We observed that this type of planning could provide a lesser mean lung dose when comparing with normal planning methodology.

Takahashi et al., (2013) described about thread effect and peripheral dose heterogeneity for total marrow irradiation in HT. In this study, they found that pitch value of 0.2 improves the target homogeneity arms for extremely large body width. But in our study, the pitch value was kept as 0.86/n (n=3, pitch=0.287) for all patient plans, but the MF has been deduced from the HI and from analysis of other dosimetric parameters. We found that the homogeneity varies at the left and right arm, not only with pitch value but also with MF. For correlation between homogeneity and plan analysis, we chose 2.4 as the optimal pitch value, and the same could provide a suitable HI and treatment time. Figure 4 shows the dose distribution of three different pitch and MF values (Plan a= pitch 0.2 and MF 2.0 (Figure 5a), Plan b=Pitch 0.287 and MF 2.4 (Figure 5b) and Plan c= pitch 0.5 and MF 4.0 (Figure 5c). The homogeneity and dose coverage for both the arms are superior in plan a, but the treatment time is marginally high (2354 seconds) and in plan c, the treatment time is lesser, but the homogeneity and coverage are sub-optimal. In plan b, the homogeneity and coverage are optimal with suitable treatment time (1692 seconds) (Table 3). In a previous study (Takahashi et al., 2013), the authors found that the thread effect was minimal in the central region if the MF was used higher. In our findings, the higher MF could provide the high homogeneity, but it could increase the treatment time.

The radiochromic EBT films have been used by several authors to measure the superficial skin dose in tomotherapy (Hardcastle et al., 2008, Ramsey et al., 2007). Avanzo et al., (2013) studied the skin dose in HT treatments and found that radiochromic EBT films are suitable for surface dose measurements, but the TPS overestimates the skin dose when comparing with the measured dose. Uncertainty in the dose delivered to the patient ranged from 1% to 25% or overdosage of up to 10% when there was a positioning or volume uncertainty in the target volume (Avanzo et al., 2013). The skin flashes can be used to avoid this uncertainty which increases in the target volume closer to the surface. Our measurements show that the flash margin did not increase the skin dose (Table 4), and at the same time, it could provide adequate coverage to the target if the target deviated from its position.

In conclusion, the overall planning workflow for TBI in HT with its dosimetric verification was analyzed and the optimal combination of pitch and MF was deduced, using homogeneity index, beam-on time and dosimetric parameters. In our study, the optimal combination of pitch value of 0.287 and MF value of 2.4 provided acceptable

Table 4. Chamber and Film Verification of Flash Margin and Skin Dose. The use of flash margin was verified with cyindrical ionization chamber with customized wax slab and the skin dose was verified with Gaffchromic film in anthropomorphic phantom.

Chamber/Film Position	HN-Flash			HN-Flash Skin dose			Film Position	Pelvis-Flash			Pelvis-Flash Skin dose		
	Flash and Without Flash Chamber measurement			Flash and Without Flash Film measurement				Flash and Without Flash Chamber measurement			Flash and Without Flash Film measurement		
	Flash (Gy)	No Flash (Gy)	% Diff	Flash (Gy)	No Flash (Gy)	% Diff		Flash (Gy)	No Flash (Gy)	% Diff	Flash (Gy)	No Flash (Gy)	% Diff
Scalp	1.99	1.45	27.14	2.05	1.98	3.41	Superior-Up	1.74	1.4	19.95	1.94	1.92	0.85
Vertex	2.11	1.55	26.54	2.11	2.05	2.84	Superior left	2.14	1.54	28.22	2.08	2.06	0.87
Chin	2.09	1.39	33.49	1.98	1.99	-0.51	Superior-right	1.73	1.47	14.88	1.95	1.91	2.14
Rt BM	1.94	1.48	23.71	1.88	2.01	-6.91	Inferior- Left	2.18	1.39	36.46	2.03	2.07	-1.9
Lt BM	2.08	1.55	25.48	2.08	2.05	1.44	Inferior- Right	2.27	1.5	33.82	2.09	2.07	1.04
Rt Shoulder	1.96	1.52	22.45	1.98	2.11	-6.57	Pubis	2.11	1.4	33.65	1.96	1.94	1.09
Lt Shoulder	1.94	1.39	21.65	2.05	2.04	-2.93	Rt Thigh	2.08	1.52	26.92	1.71	1.82	-6.17
Sternum	2.07	1.47	28.99	2.01	1.97	1.99	Lt Thigh	2.01	1.62	19.4	1.88	1.91	-1.33

plans for all patients planned for TBI plan in HT. The flash margin can provide adequate coverage during patient position uncertainty without increasing the skin dose.

Author Contribution Statement

All authors reviewed the data, results and approved the manuscript. Study design, data collection, statistical analysis, results verification and manuscript draft.

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General

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Data Availability

The data of this study are available on request.

Ethical Declaration

Ethical approval is not required for this study as this is a dosimetric study not used for patients' treatments.

Conflicts of Interest

The authors declare no conflict of interest.

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