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ORIGINAL ARTICLE

Technical Feasibility and Planning Challenges of Delivering Total Body Irradiation Using Halcyon Elite O Ring Gantry

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ABSTRACT

Purpose: Total Body Irradiation (TBI) is a critical component of conditioning regimens prior to hematopoietic stem cell transplantation (HSCT). This report presents the first clinical implementation of VMAT-based TBI for a 19-year-old male patient using a Halcyon™ Elite linear accelerator, with treatment planning performed in Eclipse™ Treatment Planning System (TPS) version 17.0. The prescribed dose was 12 Gy delivered in 10 fractions, consistent with a reduced-intensity conditioning protocol.

Methods: The patient was simulated in head-first supine (HFS) positions using vaclock immobilization and full-body support. A planning target volume (PTV) was defined by cropping 3 mm from the external contour to avoid build-up issues.

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VMAT plans were created using 12 isocenters with 6 MV flattening-filter-free (FFF) beams. The treatment was planned using Eclipse v17.0, with emphasis on achieving uniform PTV coverage while minimizing dose to critical organs-at-risk (OARs) including lungs, kidneys, lenses, and testes. Pre-treatment quality assurance (QA) was performed with portal dosimetry.

Results: The treatment plan achieved adequate PTV coverage, with $D_{95\%}$ of 10.76 Gy, ensuring acceptable dose homogeneity (HI = 0.26). The mean doses to the left and right lungs were 11.45 Gy and 11.48 Gy, respectively. The mean kidney doses were 11.09 Gy for the left kidney and 10.98 Gy for the right kidney. The doses to the lenses (5.38 Gy) and testes (14.27 Gy) remained within institutional tolerance limits. The total monitor units (MU) delivered were 2704.9.The total beam-on time per fraction was approximately 15 minutes, with overall treatment time including setup and imaging averaging 1 hour 30 minutes. Gamma analysis using 3%/3 mm criteria demonstrated 100% passing rates ($\gamma < 1.0$) for both head-first supine (HFS) and feet-first supine (FFS) setups, exceeding the 97% institutional tolerance.

Conclusion: Halcyon VMAT-based planning provided satisfactory target coverage and organ sparing within an efficient and reproducible workflow. Halcyon may be considered a suitable platform for TBI delivery in adolescent and young adult (AYA) patients undergoing transplantation.

KEYWORDS

• Patient • Treatment • Planning • Conditioning

INTRODUCTION

Total Body Irradiation (TBI) remains a fundamental component of conditioning regimens for hematopoietic stem cell transplantation, particularly in patients with hematological malignancies such as leukemia and lymphoma. Traditional TBI delivery methods pose several challenges, including complex patient setup, suboptimal dose homogeneity, and limited patient comfort, often requiring large treatment rooms and extended delivery times.

Advancements in radiotherapy have led to the integration of image-guided, intensity-modulated techniques using modern linear accelerators. The Halcyon™ ELITE system (Varian Medical Systems) represents a new-generation ring-gantry accelerator, offering enhanced automation, rapid delivery, and improved dosimetric precision.[1] When paired with Volumetric Modulated Arc Therapy (VMAT), this platform allows for more conformal dose distributions, reduced organ-at-risk exposure, and improved workflow efficiency in TBI treatments.

This study aims to evaluate the clinical implementation of a standardized TBI protocol using the Halcyon ELITE system with ARC-based VMAT delivery. Key aspects such as fractionation schema, patient immobilization techniques, the role of bolus material, and preliminary toxicity outcomes are explored to assess the feasibility and safety of this novel approach.

MATERIALS AND METHODS

Patient Selection:

A 19-year-old male diagnosed with Acute Lymphoblastic Leukemia (ALL) was initially treated with the BFM 2002 protocol. He experienced a CNS relapse and received intrathecal chemotherapy, radiotherapy, and systemic reinduction with agents including ARAC, VCR, Cyclophosphamide, and HD-MTX. Following a negative MRD, he was referred for Total Body Irradiation (TBI) as part of the conditioning regimen for hematopoietic stem cell transplantation. Written informed consent was obtained.

Simulation and Immobilization

For treatment planning, patient immobilization was achieved in the **supine position** using two Vac-Lok cushions. A full-body Vac-Lok integrated with an All-In-One (AIO) board was used for head-to-foot stabilization, while an additional half-body Vac-Lok was employed specifically to support the lower extremities.

To ensure dose build-up and reproducibility, a 1 cm thick wet cotton bolus was uniformly placed above and below the entire body surface.

Simulation imaging was performed using a PET-CT scanner (United Imaging) covering the entire cranio-caudal extent in a single acquisition. The CT images were obtained with a slice thickness of 5 mm. To facilitate accurate patient positioning and delta couch shift adjustments on the treatment unit, four radiopaque CT lead markers were placed at specific anatomical landmarks: (1) clavicular region, (2) upper umbilical level, (3) mid-thigh, and (4) the region of the superficial fibular area.

The acquired images were then transferred to the Varian Eclipse Treatment Planning System (Version 17.0) for contouring and planning. Target volumes (PTVs) and organs-at-risk (OARs) were delineated by an experienced radiation oncologist in accordance with institutional protocols and international contouring guidelines. Dose prescriptions and OAR constraints were applied as per our hospital's standard radiotherapy protocols.

Treatment Planning:

Treatment planning was performed using the Eclipse™ Treatment Planning System (Version 17.0, Varian Medical Systems, USA). The total length of the patient was approximately 196 cm, necessitating a dual-volume planning strategy. The entire body Planning Target Volume (PTV) was divided into two sub-volumes: Upper PTV and Lower PTV, to facilitate planning feasibility and maintain dose conformity. All plans were generated for delivery using 6 MV flattening filter-free (FFF) photon beams at a dose rate of 800 MU/min, optimized to achieve efficient treatment delivery while maintaining dosimetric accuracy.

For the Upper PTV-Head Fist Supine, six isocenters were utilized with an inter-isocenter spacing of 14 cm. A total of 16 full arcs were employed, with collimator angles alternated between 0° and 90° to enhance dose modulation. A 1 cm thick uniform bolus was used in conjunction with the plan to ensure adequate surface dose.

For the Lower PTV - Feet Fist Supine, an additional six isocenters were planned, also spaced 14 cm apart. Twelve full arcs were used with the same collimator angle strategy (0° and 90°) and bolus application as in the upper segment. Dose calculation was performed using the Anisotropic Analytical Algorithm (AAA) and optimized using the Photon Optimizer with VMAT settings. Heterogeneity corrections were applied, and appropriate expansion margins were considered during optimization to ensure accurate dose delivery and coverage.

Figure 1 illustrates the isocenter arrangement, arc configuration, and dose distribution strategy used for both the upper and lower PTV segments, highlighting the comprehensive planning approach employed in this protocol.

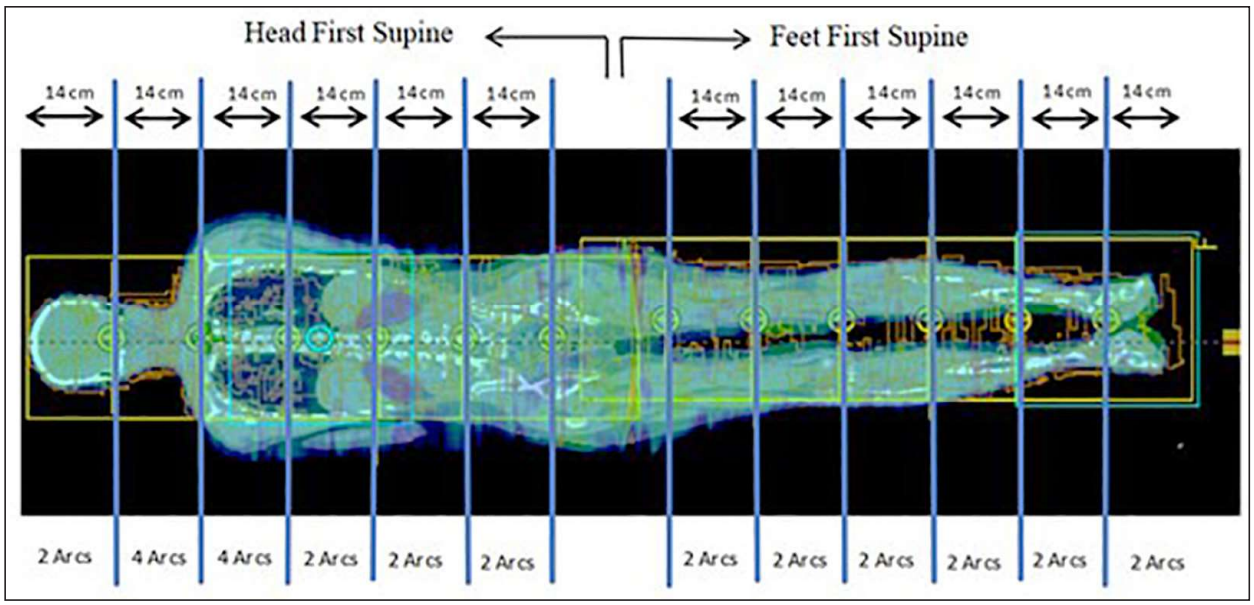


Figure 1: Isocenter and Arc Configuration for VMAT-Based TBI Planning

Treatment Protocol

Machine: Halcyon™ ELITE Linear Accelerator (Varian Medical Systems)

Technique: ARC-based Total Body Irradiation (VMAT-TBI)

Dose Prescription: 12 Gy in 10 fractions (1.2 Gy per fraction), delivered twice daily over 5 consecutive days with a minimum inter-fraction interval of 6 hours.

Bolus: A uniform 1 cm wet cotton bolus was applied over the entire body surface during both CT simulation and treatment sessions to ensure adequate build-up and skin dose coverage.

Imaging and Contouring: Whole-body CT simulation scans were acquired with the bolus in place using 5 mm slice thickness. Target volumes (PTVs) and Organs at Risk (OARs) were delineated in collaboration with an experienced radiation oncologist, following institutional contouring guidelines.

Immobilization: Patients were immobilized in a supine position using a custom whole-body cradle with Vac-Lok™ cushions to ensure reproducibility and comfort.

Image Guidance: Megavoltage (MV) 2D imaging was performed before the delivery at each isocenter to ensure accurate patient positioning and alignment with reference markers, thereby minimizing setup uncertainties across the extended treatment length.

Dosimetric Objectives: Treatment plans were optimized to achieve a homogeneous dose distribution with at least 95% of the PTV receiving ≥95% of the prescribed dose (D95 > 95%). OAR dose constraints adhered to institutional and published guidelines.

Data Collection:

Patient demographics, treatment data, acute toxicities (per CTCAE v5.0), dosimetric parameters, and treatment duration were recorded.

Patient-Specific Quality Assurance (QA)

To ensure the safe and accurate delivery of total body irradiation (TBI), patient-specific quality assurance (QA) procedures were conducted. Dose distribution accuracy was assessed by comparing calculated and measured values using the gamma index analysis. All the HFS 6 segments were combined by applying appropriate Y-Off sets, in the similar way all the segments of FFS are also combined and analyzed before treatment. A gamma passing rate was determined based on criteria of 3% dose difference and 3 mm distance to agreement (DTA), with an acceptance threshold set at ≥90%. Figure 2 represents the 95% dose colour wash for the two divisions of the plan with their respective gamma analysis. All measurements were performed using the Halcyon™ ELITE V3 linear accelerator, equipped with a fixed source-to-detector distance of 154 cm and the AS-1200 electronic portal imaging device (EPID).

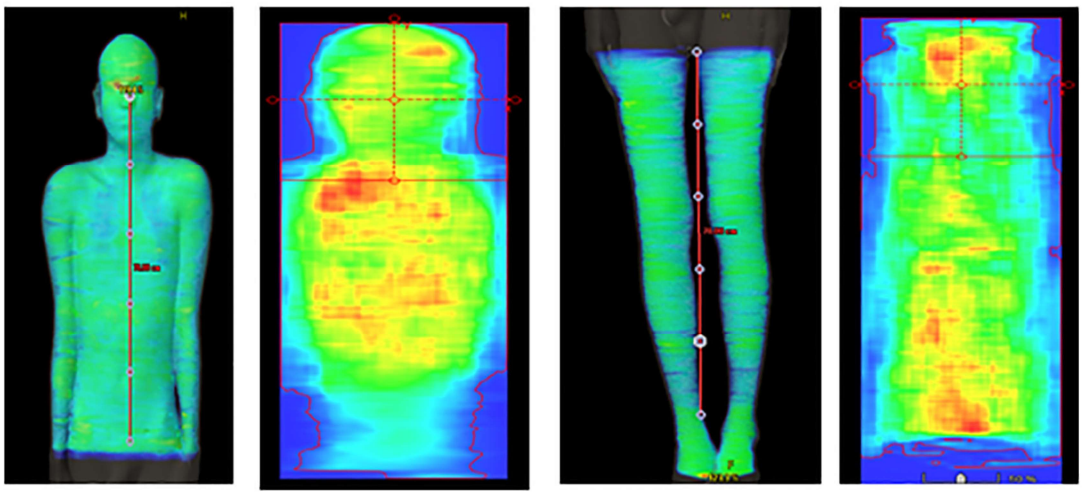


Figure 2: Representation of **(a)** Dose colour wash of 95% for the first half of the patient treated in Head First Supine Position (HFS); **(b)** Combined Portal analysis for the first half plan of the patient; **(c)** Dose colour wash of 95% for the second half of the patient treated in Feet First Supine Position (FFS); **(d)** Combined Portal analysis for the second half plan of the patient.

RESULTS

Dosimetric Outcomes:

The treatment plan achieved adequate Planning Target Volume (PTV) coverage, with $D_{95\%}$ reaching 10.76 Gy and $D_{98\%}$ at 9.98 Gy. The dose homogeneity within the PTV was acceptable, with $D_{50\%}$ and $D_{2\%}$ recorded at 12.11 Gy and 13.10 Gy, respectively. Based on the formula ($D_{2\%}$ - $D_{98\%}$) / $D_{50\%}$, the calculated Homogeneity Index (HI) was 0.26, indicating a moderate level of dose uniformity (ideal HI = 0).The total number of monitor units (MU) required for the plan was 4800.2 MU. The PTV dosimetric parameters have been discussed in the tabulation 1.

Table 1: PTV Dosimetric Parameters

PTV Parameters	Value
$D_{98\%}$	9.98 Gy
$D_{95\%}$	10.7 Gy
$D_{50\%}$	12.11 Gy
$D_{2\%}$	13.10 Gy
HI	0.26
Volume	51500.9 CC
Monitor Units	4800.2 MU

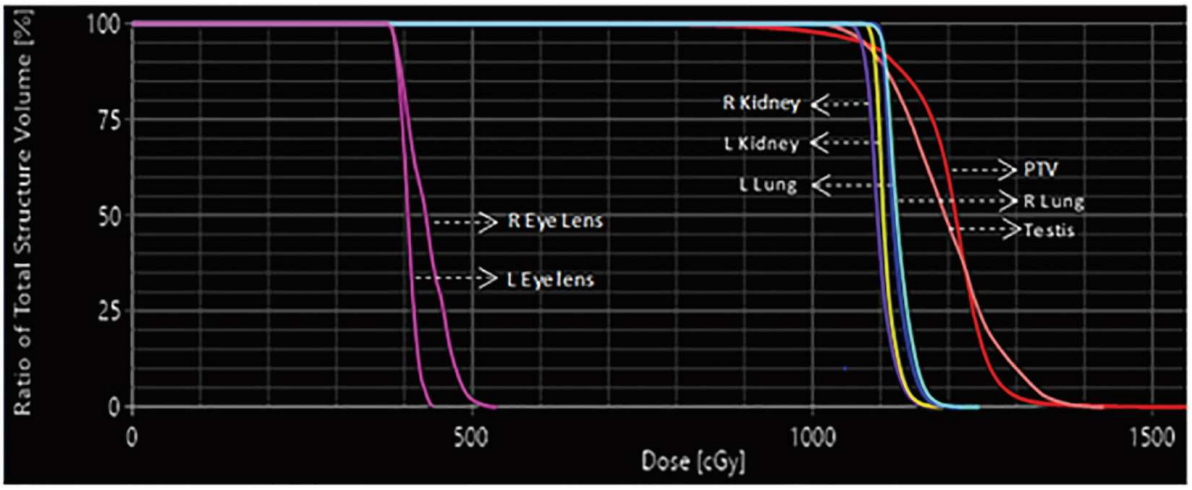
Abbreviation: PTV - Planning Treatment Volume; $D_{2\%}$, $D_{50\%}$, $D_{50\%}$, $D_{95\%}$, and D98% - Dose received by $2_{\%}$, 50%, 95%, and 98% volume of PTV; CI - Conformity Index; and HI - Homogeneity Index.

For organs at risk (OARs), the mean doses were as follows: left lung 11.45 Gy, right lung 11.48 Gy, left kidney 11.09 Gy, right kidney 10.98 Gy, testis 14.27 Gy, and lens 5.38 Gy. All mean doses were within acceptable institutional tolerance levels and are tabulated in table 2.

Table 2: Doses to Organ at Risks

Organs	D_{mean} (GY)
Left lung	11.45
Right lung	11.48
Left Kidney	11.09
Right Kidney	10.98
Testis	14.27
Lens	5.38

Figure 3 displays the Dose Volume Histogram (DVH) for the total treatment plan, illustrating the dose distribution across the PTV and critical organs at risk. These dosimetric values demonstrate that the VMAT-based TBI plan was able to achieve clinically acceptable PTV coverage and organ-at-risk sparing using the Halcyon ELITE platform



R - Right, L - Left, PTV - Planning Target Volume

Figure 3: Dose Volume Histogram of the plan sum of upper and lower plans

The average treatment time was approximately 1 hour and 30 minutes per session, with no unplanned breaks, and all treatments were successfully completed within 5 calendar days. During the first 10 days, no significant acute toxicities were observed. There were no reported cases of nausea (Grade I/II), mucositis, or erythema. Additionally, no Grade ≥3 toxicities or any signs of organ dysfunction were observed throughout the initial treatment period. Prior to initiation of radiotherapy, the patient's leukocyte (white blood cell, WBC) count was 6,460 cells/μL, within normal physiological limits. Post-radiotherapy, the

WBC count decreased substantially to 50 cells/μL, indicating a near-complete ablation of circulating leukocytes. This profound leukopenia is consistent with the expected hematologic response to radiotherapy-based myeloablative conditioning and supports the efficacy of the regimen in suppressing the host immune system prior to donor cell engraftment.

Gamma index analysis was performed using the commonly accepted gamma criteria of 3%/3 mm (dose difference/distance to agreement). For the head-first supine (HFS) treatment setup, gamma analysis within the portal dose evaluation area yielded a gamma passing rate of 100% for points with a gamma value <1.0. This result exceeds the institutional tolerance threshold of 97%, indicating excellent agreement between the measured and calculated portal doses. Similarly, for the feet-first supine (FFS) setup, the gamma analysis within the portal dose area also demonstrated a 100% passing rate for gamma values <1.0, likewise meeting and surpassing the 97% tolerance level. These results confirm the high accuracy and consistency of dose delivery for both patient orientations within the evaluated regions.

The treatment planning and quality assurance measurements took longer than typical work flow. Contouring took 2 to 3 hours; dose calculation and optimization took 6-8 hours; delivery of portal dose took 30 minutes; the beam on time lasted for 15 minutes excluding patient set up and image verification.

DISCUSSION

In the present study, a VMAT plan with Halcyon™ V 3.0 Linac for TBI was evaluated. This study revealed that this method can be clinically used for TBI. Van *et al*. and Yao *et al*. reported that conventional TBI techniques required large treatment fields with lung blocks to irradiate the patient's entire body, while the patient is in a standing or lying-on-the-side position at an extended SSD (for instance, 5 m), which required costly, large, linear accelerator vaults.[2,3] The use of the Halcyon™ ELITE platform for Total Body Irradiation (TBI) in our setting has shown promising results in terms of dosimetric accuracy, workflow efficiency, and patient safety. Its design, optimized for high-throughput radiotherapy, offers several distinct advantages over conventional TBI delivery systems. The integration of ARC-based Volumetric Modulated Arc Therapy (VMAT) allows for a more homogeneous dose distribution across the extended cranio-caudal length of the patient, overcoming one of the primary limitations associated with traditional linear accelerators, which often struggle with field matching and dose uniformity across large treatment volumes. Tamura *et al*. described that the dose delivery of the Halcyon™ Linac was accurate because of the minimal leakage dose and penumbra size of the dual-layer MLC.[4]

A key aspect of our protocol was the consistent application of a 1 cm wet cotton bolus across the entire body surface during both simulation and treatment. This step is critical for ensuring adequate dose buildup at the skin level, thereby reducing the risk of leukemic cell persistence in sanctuary sites such as the dermis and subcutaneous regions. This approach also improved the reliability of dose delivery, especially in areas where under dosing is commonly reported due to the skin-sparing effect of megavoltage photon beams. The Halcyon ELITE system offered several practical and clinical advantages: **1. Rapid Setup and Delivery**: The streamlined workflow, with reduced treatment room time, minimizes patient discomfort and motion, which is particularly beneficial in pediatric or debilitated patients. **2. Integrated Imaging**: Onboard megavoltage (MV) 2D imaging was utilized for patient setup verification prior to the delivery at each isocenter. This approach allowed precise alignment with reference markers across the entire treatment length, enhancing reproducibility and reducing setup errors despite the absence of volumetric image guidance. 4. **Improved Immobilization**: The bore-based design of Halcyon facilitated consistent and simplified patient positioning using full-body Vac-Lok cushions and AIO boards, enhancing both comfort and reproducibility. 5. **Efficient Beam Modulation**: The ARC (VMAT) approach enabled superior dose conformity with minimized hotspots, while effectively sparing critical structures such as the lungs, kidneys, and lenses. While our initial outcomes are encouraging, it is important to note the limitations. The present study had one TBI case planning study. However, Chakraborty S *et al*. described that TBI with VMAT was feasible in one case planning study, the same as in our study.[5]

Furthermore, the auto feathering algorithm was not applied for junctions because of the extension of the optimization time (over five hours for each segment). Maddalo *et al*. described the auto feathering algorithm for the cranio-spinal radiation treatment with the VMAT technique.[6] Therefore, the use of the auto feathering algorithm should be considered for TBI with VMAT. Alternatively, we utilized the "base dose plan" function, which could be achieving optimal plan sum by making up for inadequacies (hot and cold spots).[7]

Springer *et al*. demonstrated that contouring, dose calculation, optimization, and QA took 5–6hr, 25–30hr, and 6–8 h, respectively.[8] However, the dose calculation and optimization times in our study were still long because of repeated re-optimization. The relatively short follow-up period restricts our ability to draw conclusions on long-term toxicity, relapse rates, and overall survival. However, acute tolerance was favorable, and no immediate Grade ≥3 toxicities were observed during the early post-treatment period. MV-2D imaging was done for each isocenter and matching was done as necessary before the treatment. The total time taken for delivery of a single fraction is 1 h 15 min.[9] Similarly in our study treatment delivery time 1 hour 30 minutes.

CONCLUSION

Total Body Irradiation (TBI) delivered using the Halcyon™ ELITE V.[3] platform with ARC-based VMAT and a twice-daily fractionation schedule of 12 Gy in 10 fractions has proven to be clinically feasible, dosimetrically robust, and well-tolerated in our initial experience. The consistent use of a uniform bolus during both simulation and treatment played a critical role in achieving adequate skin dose, an essential component of effective TBI. These early results support the integration of Halcyon ELITE into modern TBI protocols, offering advantages in workflow efficiency, dose uniformity, and patient comfort compared to conventional methods of performing TBI. Continued follow-up is underway to assess long-term outcomes, including late toxicity, engraftment success, and overall survival, to fully validate the role of this platform in routine clinical practice.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

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Conflicts of interest: There are no conflicts of interest.

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