

Streamlining VMAT-TBI: A Single CT Scan Workflow for Enhanced Clinical Efficiency and Dosimetric Precision

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Abstract

Objectives: To report the implementation and dosimetric evaluation of a single-CT, size-adapted VMAT-TBI workflow designed to simplify planning and treatment delivery across a heterogeneous cohort of pediatric and adult patients undergoing total body irradiation for transplant conditioning, providing a practical and reproducible clinical solution using standard linear accelerator infrastructure.

Methods: Sixty-seven patients treated with 1200 cGy in 5 fractions between December 2020 and July 2024 were retrospectively analyzed. Patients were assigned to three workflow groups according to body size: Group A (height ≤135 cm), Group B (height >135 cm), and Group C (body width >40 cm). All patients underwent a single head-first supine CT simulation. Treatment plans were generated in Monaco using multi-isocenter VMAT; taller patients received supplementary anterior and posterior AP/PA open fields for the lower extremities, and broader patients were planned using dual partial-arc arrangements. Dosimetric endpoints, organ-at-risk doses, workflow timing, and patient-specific quality assurance results were evaluated descriptively.

Results: The workflow was successfully implemented across all patient groups. Mean PTV D95 was 94.6%, 94.0%, and 94.0% for Groups A, B, and C, respectively, with limited high-dose volumes (V110%: 0.35%, 1.5%, and 1.3%). Mean lung doses remained below 920 cGy across groups, and kidney, heart, thyroid, liver, and lens doses were maintained within institutional planning objectives. Average planning time was approximately 12 hours. Mean beam-on treatment time for the VMAT component was 16.6 ± 3.1 minutes for shorter patients, 18.2 ± 1.8 minutes for taller patients, and 25.4 ± 2.5 minutes for broader patients. Quality assurance demonstrated acceptable agreement between planned and measured dose delivery.

Conclusion: This study demonstrates the feasibility of a single-CT, size-adapted VMAT-TBI workflow that provides reproducible target coverage, organ sparing, and manageable planning and treatment times in a relatively large mixed-age cohort. The principal contribution lies in the practical standardization of VMAT-TBI implementation rather than the introduction of a novel irradiation technique, and clinical outcomes were not analyzed and should be addressed in future work.

Keywords: Total body irradiation, radiotherapy, intensity-modulated, radiotherapy planning, computer-assisted, bone marrow transplantation, quality assurance, health care

Introduction

Total body irradiation (TBI) remains a core component of conditioning regimens before allogeneic hematopoietic stem cell transplantation. Historically, conventional TBI techniques have relied on extended-distance AP/PA or lateral fields, simplified point-based dose prescription, patient repositioning between supine and prone setups, and manual lung shielding. Although widely used, these approaches may be associated with dose inhomogeneity, limited organ sparing, substantial setup burden, and reduced patient comfort.^{1–4}

Over the last decade, volumetric modulated arc therapy for total body irradiation (VMAT-TBI) has emerged as an attractive alternative because it improves target dose conformity, enables more individualized organ-at-risk (OAR) sparing, and allows image-guided delivery in a stable supine position.^{3,5–8} Nevertheless, implementation remains heterogeneous across institutions. Published workflows differ in simulation strategy, patient rotation or repositioning requirements, number of scans, infrastructure needs, junction management, and automation resources.^{5,8–10}

Recent technical recommendations have emphasized the need for reproducible and standardized workflows for conformal multi-isocenter TBI.⁸ In this context, the present study does not propose VMAT-TBI as a new modality; rather,

it describes a practical implementation model based on a single CT simulation, size-adapted planning templates, and one reproducible supine immobilization strategy that can be applied across pediatric and adult body sizes, including broader patients.

Accordingly, the principal contribution of this work is the demonstration that a single-CT VMAT-TBI workflow can be implemented in routine practice with reproducible dosimetry, acceptable quality-assurance performance, and clinically manageable planning and treatment times in a relatively large mixed-age cohort.

Materials and Methods

Patient Population and Treatment Regimen

This retrospective implementation study included 67 patients treated with TBI as part of bone marrow transplant conditioning between December 2020 and July 2024. The cohort comprised 30 patients with height ≤135 cm, 30 patients with height >135 cm, and 7 patients with body width >40 cm. Ages ranged from 2 to 42 years, with a median age of 13.4 years. The study was approved by the Scientific and Medical Advisory Committee and the Institutional Review Board, and written informed consent was obtained from patients or guardians.

CT Simulation and Patient Immobilization

Simulation and Immobilization

All patients underwent CT simulation in the head-first supine position using a single scan acquired during free breathing. A vacuum mattress was used for immobilization, with arm positioning adjusted to minimize body width and improve reproducibility. For taller patients, the upper body was immobilized in the vacuum mattress while the legs remained available for supplementary lower-extremity treatment. Longitudinal reference lines and radiopaque markers were used to facilitate setup reproducibility. We used a Siemens Somatom scanner (Somatom Definition AS) at a maximum scan length of 1970 mm, 120 kVp, and the maximum available field of view (50 cm).

Target and OAR Definition

The planning target volume (PTV) included the entire body minus a 5 mm skin margin. Organs at risk were excluded using institutionally defined margins, while major bony structures were deliberately retained within the target to preserve marrow coverage. All contours and margins were reviewed clinically to balance OAR sparing with adequate target irradiation.

Single-CT Workflow Concept

A central feature of the workflow was the generation of dual-orientation treatment plans from a single CT dataset using the Monaco 5.51.10 treatment planning system. Rather than acquiring separate head-first and feet-first scans, the same CT geometry was used to support all planning configurations. This approach was intended to reduce simulation burden, avoid inter-scan fusion uncertainty, and simplify coordinate handling during treatment planning.

Size-Adapted Planning Strategies

Group-Based Planning Approach

Three size-adapted planning strategies were used. Group A (height ≤ 135 cm) received a head-first VMAT-only plan with three to four full arcs (Figure 1). Group B (height >135 cm) received upper-body VMAT plus supplementary feet-first AP/PA open fields for the lower extremities (Figure 2). Group C (body width >40 cm) received a modified arrangement using multiple sets of dual partial arcs with lateral isocenter offsets to achieve adequate transverse coverage (Figure 3 and 4).

Planning Parameters

All VMAT plans were generated in Monaco 5.51.10 using the Monte Carlo algorithm on an Elekta Versa HD linear accelerator with 6 MV photons and an Agility multileaf collimator. A multi-isocenter approach with approximately 10–15 cm longitudinal overlap was employed. Optimization was first performed at reduced statistical precision of 5% uncertainty (5 mm voxels) for efficiency and then recalculated at higher precision of 1% uncertainty (3 mm voxels) for final dose evaluation.

Quality Assurance, End-To-End Testing, and Image Guidance

Patient-specific quality assurance consisted of:

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- Point-dose verification using an ionization chamber in a solid phantom, guided by the TRS-398 dosimetry protocol.¹¹ Agreement within $\pm 3\%$ was considered acceptable, consistent with international standards for reference-point dosimetry.^{11,12}

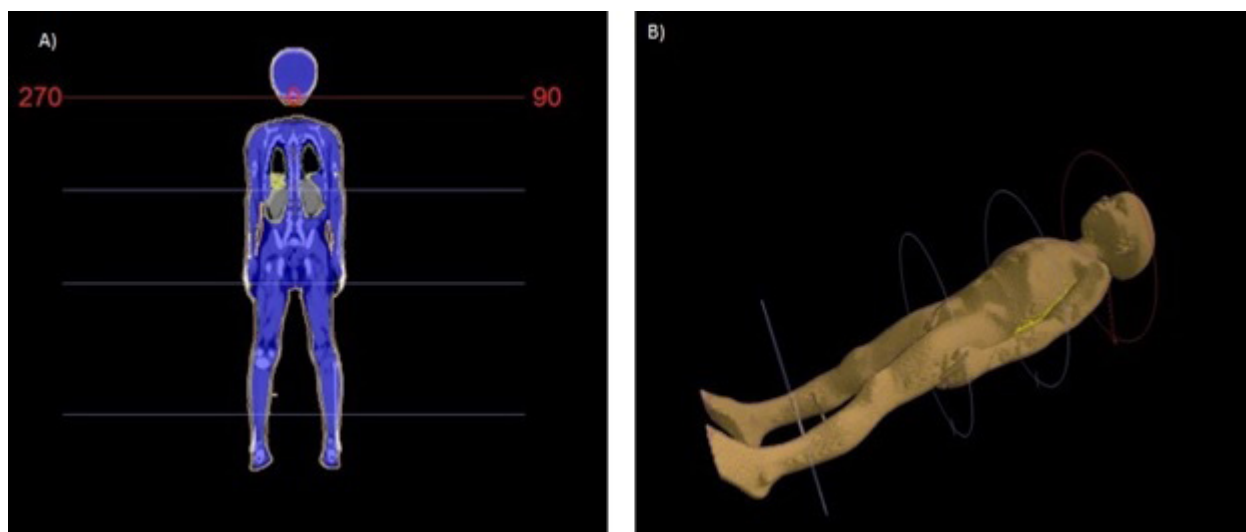


Fig. 1 Group A strategy (111.6 cm height). Mean lung doses: 8.8 Gy (right) and 8.9 Gy (left). A) Dose distribution (blue: 95% isodose line); 95% of target received 95.35% of prescription. B) Treatment plan arc arrangement.

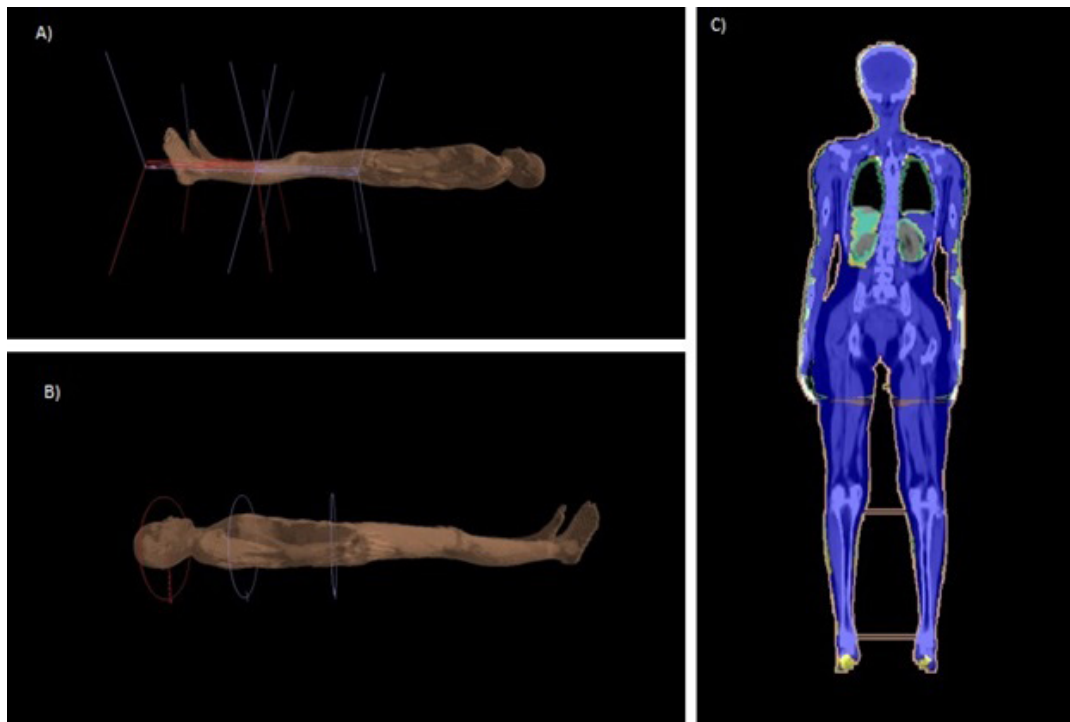


Fig. 2 **Group B plan strategy (172 cm height) with mean lung doses of 8.3 Gy. A) Open beam arrangement for lower extremities. B) VMAT arc arrangement. C) Dose distribution (blue: 95% isodose line) showing 96% of the target received 95% of the prescription.**

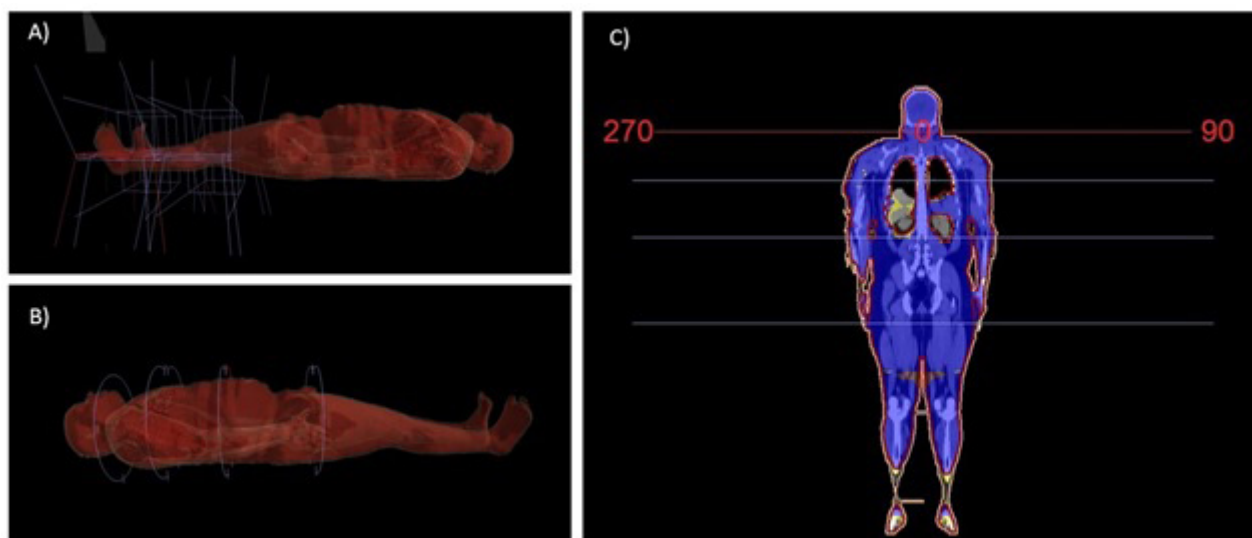


Fig. 3 **Treatment strategy for a Group C patient (175.2 cm, 120.3 kg, 61 cm width). Mean lung doses were 8.4 Gy (right) and 8.81 Gy (left). A) Open beam arrangement for lower extremities. B) VMAT arc arrangement. C) Dose distribution (blue: 95% isodose line); 96.9% of the target received 95% of the prescription.**

- Dose-distribution verification was performed using the IBA MatriXX Resolution system. A gamma criterion of 3% dose difference and 3 mm distance-to-agreement (3%/3 mm) was applied, with a pass rate threshold of 95%. These results confirmed a high degree of agreement between planned and delivered dose distributions.^{13,14}
- In addition, an end-to-end test was performed with thermoluminescent dosimeters in a pediatric anthropomorphic phantom. A Theratron Cobalt-60 machine with a dose rate of 60 rad/min at 1 m was used to determine the sensitivity and dose response for the TLD samples. The dose rate was measured using a PTW dosimetry system, calibrated at the National Institute of Standards and Technology (NIST) for traceability to SI units. A set of 3 TLDs was inserted at various locations in the pediatric phantom, including the lungs, bone, and skin surface (Figure 5).
- Daily image guidance was used during clinical treatment to verify setup at each isocenter.

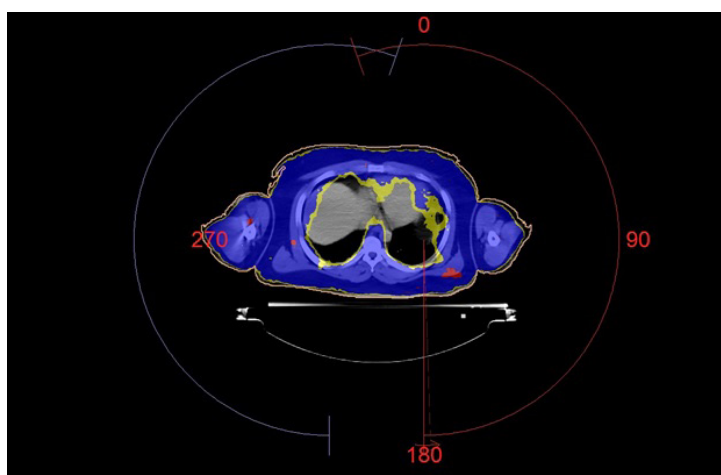


Fig. 4 VMAT-TBI CT slice illustrating a personalized strategy using two 16 cm-spaced partial arcs. Both arcs initiate at 180° and rotate 200° (clockwise and counterclockwise) to provide full-body coverage between the arcs.

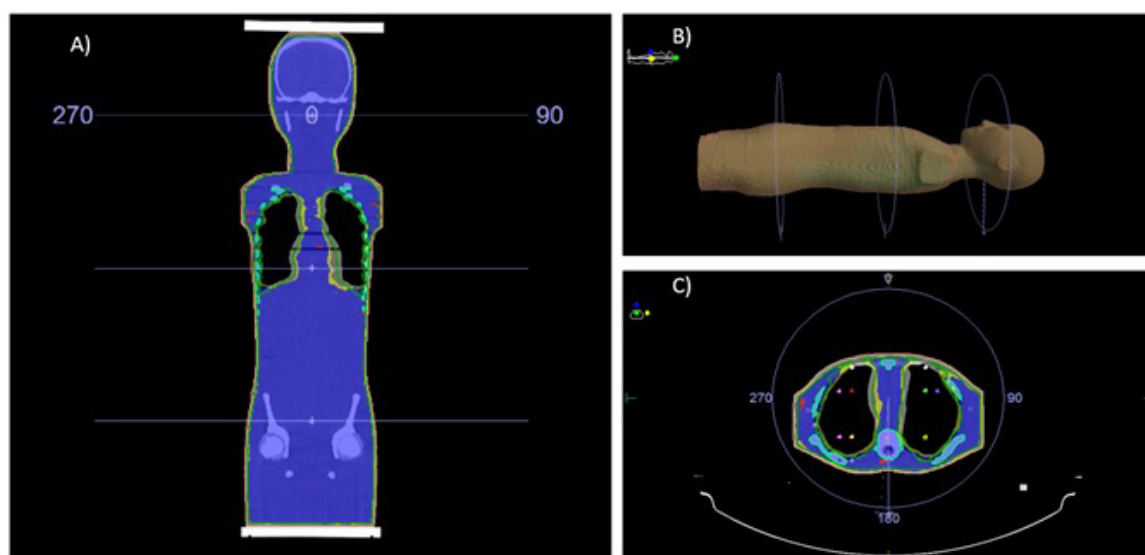


Fig. 5 End-to-end test using a child phantom (<135 cm) to assess workflow and dosimetry. A) Dose distribution showing the 95% isodose line (blue); 95% of the target received 97% of the prescription. B) Treatment plan arc arrangement. C) Transverse lung section with TLDs positioned for dose measurement.

Statistical Methods

Because the three groups were defined pragmatically according to body size and planning approach rather than as biologically or clinically comparable treatment cohorts, the statistical analysis was primarily descriptive. Continuous variables are reported as mean $\pm$ standard deviation or median and range, as appropriate. Categorical variables are summarized as counts and percentages. Formal hypothesis testing was limited because the primary objective of the study was technical feasibility and workflow characterization rather than comparative efficacy between groups. Exploratory between-group comparisons, where reported, should be interpreted cautiously, particularly for Group C because of the small sample size.

Results

The single-CT VMAT-TBI workflow was successfully implemented across all three predefined patient-size groups. Target coverage remained consistent despite differences in body size and treatment configuration.

Target Coverage

Mean PTV percentage volume covered by 95% of the prescribed dose (D95) was $94.6 \pm 0.48\%$ in Group A, $94.0 \pm 0.07\%$ in Group B, and $94.0 \pm 0.03\%$ in Group C. Mean target dose was close to prescription in all groups (1224.3 ± 19.4 cGy, 1218 ± 11.6 cGy, and 1220.17 ± 35.4 cGy for groups A, B, and C,

respectively). The volume receiving more than 110% of the prescribed dose remained limited (0.35% for Group A, 1.5% for Group B, and 1.3% for Group C).

Organs at Risk and Quality Assurance

Doses to organs at risk were maintained within institutional planning objectives. Mean bilateral lung doses remained below 920 cGy across all groups. Mean kidney doses were approximately 890–890 cGy, while mean heart, thyroid, liver, and lens doses were also reduced relative to prescription dose, indicating effective modulation and organ sparing. Quality assurance findings demonstrated acceptable agreement between planned and delivered dose, supporting workflow reproducibility across a heterogeneous patient population (Table 1).

Workflow Timing

Workflow timing data support clinical feasibility. Average planning time, covering contouring and optimization only, was approximately 12 hours. Patient specific QA required an additional average of 2 hours. Mean VMAT beam-on treatment time was 16.6 ± 3.1 minutes for Group A, 18.2 ± 1.8 minutes for Group B, and 25.4 ± 2.5 minutes for Group C. These times refer to the VMAT component only and do not include any supplementary AP/PA lower-extremity fields in Group B (Table 2).

Table 1. Average Dose to the OAR (cGy) expressed as the mean

	Group A	Group B	Group C
Rt Lung	893.8 ± 27.0	853.2 ± 31.2	848.0 ± 42.0
Lt Lung	911 ± 28.7	868.3 ± 25.2	853.7 ± 51.5
Heart	853 ± 70.2	899.8 ± 76.7	973.3 ± 69.2
Rt kidney	876.3 ± 38.2	873.0 ± 24.1	894.8 ± 49.0
Lt Kidney	881.2 ± 39.5	875.8 ± 24.9	889.3 ± 52.1
Liver	1045.4 ± 26.1	1000.9 ± 130.8	1039.0 ± 29.0
Rt Lens	852.5 ± 35.1	852.8 ± 31.1	857.7 ± 53.4
Lt Lens	850.5 ± 28.2	848.4 ± 34.5	866.5 ± 44.5
Thyroid	1038.8 ± 51.7	976.4 ± 66.2	1089.1 ± 28.5

Discussion

This study describes the implementation of a practical, size-adapted VMAT-TBI workflow based on a single CT simulation and a reproducible supine immobilization strategy. The principal finding is not that VMAT-TBI itself is novel, but that a streamlined single-CT implementation can be applied across pediatric and adult patients, including broader patients, while maintaining acceptable target coverage, organ sparing, and quality-assurance performance.

The present work should be interpreted in the context of the growing VMAT-TBI literature. Early implementation reports and more recent standardized workflows have shown that conformal multi-isocenter TBI is feasible, but also highlighted substantial heterogeneity in simulation, planning, image guidance, and delivery.^{5,8–10} The practical value of the current study lies in demonstrating a resource-conscious implementation model that avoids multiple CT acquisitions and remains applicable to a relatively large mixed-age cohort.

Workflow Standardization and Efficiency

A notable operational finding is the planning and delivery efficiency achieved in this cohort through a standardized template-based workflow. Although direct comparisons across institutions are often limited by varying time-metric definitions, our reported planning time of approximately 12 hours compares favorably to earlier VMAT-TBI series that required substantially longer contouring and QA workloads.^{5,10} This efficiency is providing a reproducible framework that utilizes initial patient height and weight to apply category-specific CT protocols. Unlike approaches requiring dual CT scans to overcome couch travel limits,^{15,16} our single-scan method enhances accuracy while improving patient comfort. Furthermore, the VMAT beam-on time of 17 to 25 minutes demonstrates that this streamlined approach supports clinically workable throughput without compromising dosimetric goals or the flexibility required for OAR sparing and simultaneous integrated boosts (SIB).

Dose-Rate Considerations

The discussion of dose rate requires caution. Conventional TBI recommendations historically advocated reduced dose

Table 2. Patient and treatment characteristics

	Group A	Group B	Group C
Patient height (cm)	115.23 ± 12.3	158.57 ± 13.1	174.3 ± 11.6
Patient weight (kg)	25.3 ± 7.4	56 ± 17	105.6 ± 15.3
Body mass index	19.55 ± 6.1	21.8 ± 7.1	34.8 ± 4.4
Number of isocenters	4VMAT	3-4Full ARCs/2-3DCRT	1Full arc/6 Partial arcs/2 DCRT
Number of control points (segments)	787 ± 70	732 ± 111	1021 ± 170
MU efficiency*	$84.2\% \pm 6.9$	$83.47\% \pm 6.3$	$79\% \pm 15.3$
Conformity index	0.874	0.865	0.896
Treatment time (Min)	16.59 ± 1.8	18.22 ± 3.1	25.4 ± 3.2
Monitor unit/Fraction	2442 ± 274.8	3392 ± 678.6	4078.4 ± 588

*The MU efficiency is calculated by comparing the plan's actual MU to the monitor units for the ideal delivery. Therefore, the higher the efficiency, the lower the total MU for the plan (according to Monaco TPS).

rates to limit pulmonary toxicity, but these thresholds were derived from extended-field, non-modulated techniques and cannot be directly extrapolated to highly modulated VMAT delivery.^{1,9} Because the present study did not include a formal clinical analysis of pulmonary toxicity, no conclusion can be drawn from this dataset regarding dose-rate safety beyond technical feasibility.

Flexibility Across Patient Anatomies

The study also demonstrates flexibility across different patient anatomies. The use of supplementary lower-extremity AP/PA fields in taller patients and dual partial-arc arrangements in broader patients allowed the workflow to remain applicable despite field-size and couch-travel limitations. Importantly, overlap regions were managed without clinically meaningful hotspot expansion, as reflected by the low V110% values.

Limitations

The current report has several limitations. First, it is a retrospective single-center experience. Second, the analysis focuses on dosimetry, workflow, and quality assurance without reporting patient-level clinical outcomes such as acute toxicity, engraftment, relapse, or survival. Third, the workflow groups were pragmatic size-based categories rather than comparative treatment cohorts, which further supports a descriptive rather than hypothesis-testing statistical framework.

Clinical Interpretation and Future Work

Accordingly, the findings of this study should be interpreted as evidence of implementation feasibility and technical reproducibility rather than proof of superior clinical efficacy. Future work should integrate prospective follow-up and

transplant-related outcomes to clarify the clinical significance of the observed dosimetric advantages.

Conclusion

In conclusion, this study demonstrates the feasibility of a single-CT, size-adapted VMAT-TBI workflow that provides reproducible target coverage, organ sparing, and manageable planning and treatment times in a relatively large mixed-age cohort. Its principal contribution is the practical standardization of implementation across different patient sizes using standard linear accelerator infrastructure. However, because clinical outcomes were not analyzed, the present findings should be interpreted as technical and workflow evidence rather than evidence of improved clinical efficacy.

Conflict of Interest

All authors declare no conflict of interest.

AI-Assisted Writing Statement

The authors used an AI-assisted language tool exclusively for English language editing, grammar correction, and improvement of readability. All outputs were critically reviewed and revised by the authors, who take full responsibility for the final content of the manuscript.

Protection of Patients' Rights to Privacy

The study received Scientific and Medical Advisory Committee (SMAC) and Institutional Review Board (IRB) approval before patient accrual began. The study was performed in accordance with the Declaration of Helsinki. Informed written consent was obtained from all participating patients or guardians. ■

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