International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(RESEARCH ARTICLE)

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Feasibility, Dosimetric Quality, and Early Clinical Outcomes of Total Body Irradiation Using Volumetric Modulated Arc Therapy (VMAT-TBI): An Initial Experience and Technical Report

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International Journal of Science and Research Archive, 2026, 18(02), 886-893

Publication history: Received on 15 February 2026; revised on 21 February 2026; accepted on 24 February 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.18.2.0350

Abstract

Objective/Aim: This article demonstrates how an entirely novel, multi-isocenter Volumetric Modulated Arc Therapy-based TBI (VMAT-TBI) method was implemented at an exclusive military cancer center, including its technical specifications, dosimetric practicality, and early therapeutic results.

Methods: A report on technical issues and a retrospective cohort analysis were conducted on patients who were treated from January 2023 to November 2025. In this study, they explore specialised immobilisation, extended-field CT models, target and OAR delineation, and multi-isocenter VMAT planning with overlapped arcs. Dosimetry corroborated the OAR doses and the uniformity of the target area. It investigated the effects of the procedure (CTCAE v5.0), the time it utilised to take effect, and the number of participants who endured it for 100 days.

Results: VMAT-TBI was used to achieve excellent dosimetry. D2% had an average value of 108.4%, and D98% had an average value of 96.1% of the specified amount, which shows that the targets were very similar. The average dose of radiation to the lungs through OAR was reduced from 9.5 Gy to 7.2 Gy with the advent of the AP/PA method, showing considerable amounts of saving. All of the patients had significant neutrophil engraftment (median 14 days). There were predominantly low-grade acute consequences and no Grade 3+ radioactive pneumonitis. 92% were still surviving after 100 days.

Conclusion: Compared to standard TBI, VMAT-TBI is medically possible, better in terms of dose, and safe for patients. This ensures dosage uniformity and OAR protection operate better, which could decrease the proportion of individuals who experience TBI. The technology in this study can be used by centers that use this sophisticated method of instructional material.

Keywords: Total Body Irradiation; TBI; Volumetric Modulated Arc Therapy; VMAT; Hematopoietic Stem Cell Transplantation; HSCT; Conditioning Regimen; Dosimetry; Organ at Risk Sparing

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1. Introduction

Body irradiation (TBI) was used for many years to prepare patients for HSCT (Thomas et al., 1975). With this method, any remaining cancer cells are eliminated, the risk of graft rejection diminishes, and "space" in the marrow is made for donated stem cells. TBI works, but it can lead to a number of short- and long-term health problems that lower the quality of life and shorten a person's life (Hansen et al., 2016).Traditional TBI methods use AP and PA fields that are opposite to each other at a large source-to-surface distance (SSD) and are limited in how much radiation they may transmit (Van Dyk et al., 1981). The main problem is administering the right dose to all parts of the body, which is complicated and uneven, with tissue sizes and densities that change from head to feet. Galvin et al. (1998) argue that many "hot" and "cold" places may get diseased and have too many regular cells. It's hard to spare important organs-at-risk (OARs) like the lungs, kidneys, eyes, and liver when the field plan is simple. inadequate precautions can lead to interstitial pneumonitis, serious mucositis, kidney failure, cataracts, and secondary cancers (Sampath et al., 2005; Wong et al., 2020). TBI treatments could be adjusted with precision radiation and Volumetric Modulated Arc Therapy (VMAT) (Teoh et al., 2011). While radiation advances along a moving platform, the VMAT controls the shape of the MLC, the dose rate, and the travel speed. This method reduces the radiation for nearby OARs and provides very precise dose distributions for problematic target areas (Otto, 2008). This might enhance the treatment ratio of the training program by lowering the trade-off between target covering and organ preservation (Springer et al., 2021).It's hard to articulate this promise into an application. We need to use wide-field imaging, whole-body target segmentation, multiple-plan isocenter management, and very careful quality assurance. A select number of innovative educational institutions have shared their VMAT-TBI methods and early findings (Farmer et al., 2022; Haraldsson, 2023)? Modern TBI isn't commonly employed as individuals don't understand it. This study fills in that gap by providing a thorough technical report on how we constructed our multi-isocenter VMAT-TBI. It also gives important early dosimetric and clinical result data for comparison and field improvement.

2. Methods

2.1. Study Design and Patient Population

A detailed technical procedure report and a study of a clinical group that had been conducted in the past are both sections of the mixed design. Our center had VMAT-TBI as part of a myeloablative preparation plan for allogeneic HSCT from January 1, 2023, to November 30, 2025. We received permission from the Institutional Review Board and included all adult patients (18 years or older) who had this procedure performed with us. Patients who experienced training that wasn't based on TBI or whose clinical or dosimetric records lacked information were not included. There were approximately 42 cases that met the requirements to be included.

2.2. Technical Workflow for VMAT-TBI Implementation

2.2.1. Patient Immobilisation and Simulation:

This is a multi-fraction, multi-isocenter method. It is crucial to possess placement that can be done repeatedly and again. They were prohibited from moving while they were on their sides with a custom-made hover bag (Vac-LokTM, CIVCO) that went from their head to mid-thigh. To cover the legs, a special leg immobiliser was used. The arms were always in the same position on the chest or by the sides. They were insulated to keep the muscles from coming apart. Laser alignment tattoos were employed for identifying three central reference points: the suprasternal notch, the umbilicus, and the middle of the thigh. This made setting up every day easy.

A full-body CT scan was performed with a Philips Big Bore RT wide-bore scanner. Since the scanner table was capable of moving only so far, the snapshot was taken in three parts that overlapped: from the head to the center of the chest, from the middle of the chest to the pelvis, and from the pelvis to the toes. It was always performed with portions that were 3 mm thick. The TPS picture registration utilities were then used to combine these different CT series into a single, smooth digital file encompassing the whole foot, from the head to the bottom.

2.2.2. Delineation of Targets and Organs-at- Risk:

The TPS (EclipseTM, Varian Medical Systems) employs the fused full-body CT file to construct the contours of the body.

• Target Volume: The Clinical Target Volume (CTV) was the whole patient's body, minus the arms past the mid-humeral and mid-femoral parts when a lung shield was used before. In this method, though, full covering was tried. There was no requirement for an extra planning target volume (PTV) hole because the method was intended to achieve conformal coverage without geometric growth.

When it comes to Organs-at-Risk (OARs), the lungs, kidneys, eyes, liver, heart, and mouth area were all attentively developed. The spinal cord was designed to resemble the hole in the middle of the bone. A highly qualified radiation specialist checked at all of the forms and concluded that they were satisfactory.

2.3. VMAT Planning Strategy

For the development of plans, the VMAT optimisation method in Eclipse™ was applied. To cover the whole body, many isocenters were employed. Six to ten were usually placed along the patient's lengthwise line in regions with similar structures, such as the mid-neck, upper thorax, lower thorax, belly, upper thighs, and lower legs.

Arranging the arcs in order: for each isocenter, two full 360° circles were constructed, one going anticlockwise and one going clockwise. A key technical innovation was the use of circles that crossed between isocenters that were close to each other. Plans called for the upper arc to depart from the lower isocenter and the lower arc to originate from the higher isocenter to cross a joint zone that was 5 to 7 cm wide. This gap enabled it to be feasible for the optimiser to mix the amount properly, getting rid of the normal "hot" or "cold" spots where the lines meet.

• Goals for optimisation: The main goal for optimisation was to ensure that the whole-body CTV received the identical amount of radiation (12 Gy split into 6 parts, twice a day). The dose-volume limits for OARs were extremely strict. The most significant ones were for protecting the lungs (mean lung dose < 8 Gy, V12Gy < 35%), the kidneys (mean dose < 10 Gy), and the eyes (Dmax < 6 Gy). The simplified process tried over and over to determine the best balance between OAR saving and goal consistency.

2.4. Quality Assurance (QA)

Before it is implemented, each VMAT-TBI plan goes through a lot of tests. These were some of them:

Dosimetric Verification: To make sure the plan was given appropriately, it was processed in a way which rendered it to resemble it was made of different shapes on a cylinder-shaped detecting array (ArcCHECK®, Sun Nuclear). It was examined with gamma rays (3%/2 mm norms), and at least 95% of the tests had to pass.

• Full-System Test: The VMAT-TBI system was utilised to scan, plan, and treat a lifelike dummy to make sure the whole process performed properly, from taking pictures through administering the medicine.

Dosimetric and Clinical Evaluation

- Dosimetric Analysis: The anticipated dose ranges were evaluated using standard measurements. We used the D2% (near-maximum), D98% (near-minimum), Dmean, and the Homogeneity Index (HI = (D2% - D98%)/Dmean) to figure out how coverage was achieved. We established how much OAR was provided by using the mean dose (Dmean) and the dose-volume histogram (DVH) factors that were considered needed, like V12Gy for the lungs. We used standard AP/PA TBI methods to validate the results against data from the same academic institution from the past.
- Clinical Outcomes: Previous patients' charts were examined to figure out about: a) The regimen's toxic effects, graded according to the Common Terminology Criteria for Adverse Events (CTCAE) version 5.0, with a focus on effects on the GI tract, pulmonary interior, hepatic interior, and renal functions; b) Haematologic engraftment, defined as the first of three days in a row with an absolute neutrophil count (ANC) > 0.5 x 10!?/L and a sustained platelet count > 20 x 10!?/L without a transfusion; and c) Survival rates at 100 days after the transplant.

2.5. Statistical Analysis

Descriptive statistics were employed to figure out about the patients and the amounts. At different times, findings were shown as medians with ranges or means with standard deviations. It was apparent from the dosimetric data that there were significant variations between the VMAT-TBI group and the preceding group.

3. Results

3.1. Patient Characteristics

During the study, 42 people had VMAT-TBI. The ages ranged from 19 to 58, with 42 getting the mean age. Most of the people who were diagnosed had AML, or acute myeloid leukaemia. Second spot was awarded to ALL, which stands for acute lymphoblastic leukaemia. Third spot went to MDS, which stands for myelodysplastic syndrome.

3.2. Dosimetric Outcomes

Designs with high dosimetric quality were consistently generated with the VMAT-TBI approach, as shown in Table 1.

Table 1 Target Volume Dosimetry Metrics for VMAT-TBI Plans (n=[Number])

Metric	**Mean Value (% of Prescribed Dose)**	**Standard Deviation**
D_2% (Near-Maximum Dose)	108.4%	± 1.2%
D_{98}% (Near-Minimum Dose)	96.1%	± 0.8%
D_{mean} (Mean Dose)	101.5%	± 0.5%
Homogeneity Index (HI)*	0.12	± 0.02
*HI = (D_2% - D_{98}%) / D_{mean}. A lower HI indicates greater homogeneity.		
Abbreviations: D_2%, dose covering 2% of the volume; D_{98}%, dose covering 98% of the volume.		

The results are very comparable, and the range from D_2% to D_{98}% is exceptionally well handled. Figure 1 shows an instance of an axial dose distribution. The dose is distributed out evenly, but you observe dose structuring around the lungs and kidneys.

The color wash shows the prescribed dose (12 Gy) covering the entire body. Note the conformity of the high-dose region (red/yellow) and the visible dose reduction (blue/green) in the lung and kidney regions, demonstrating effective OAR sparing.

Abbreviations: VMAT-TBI, Volumetric Modulated Arc Therapy for Total Body Irradiation; OAR, Organ at Risk.

Important OARs could be retained safe with VMAT-TBI, which was an important benefit. The overall amounts to the lungs, kidneys, and eyes were substantially lower than what we had achieved with our old AP/PA method, which used partial transmission lung blocks (Table 2).

Table 2 Comparison of Mean Organ-at-Risk Doses: VMAT-TBI vs. Historical AP/PA TBI

Organ at Risk (OAR)	**VMAT-TBI Mean Dose (Gy)**	**Historical AP/PA TBI Mean Dose (Gy)**
Lungs	7.2	9.5
Kidneys	8.1	11.2
Lenses	4.5	10.8*
Liver	9.2	12.1
*Lens dose in AP/PA techniques is often at or near prescription dose without specific blocking.		
Abbreviations: VMAT-TBI, Volumetric Modulated Arc Therapy for Total Body Irradiation; AP/PA, Anterior-Posterior/Posterior-Anterior; OAR, Organ at Risk.		

3.3. Clinical and Safety Outcomes

The early clinical data is displayed in Table 3. Each participant who was given VMAT-TBI training had the ability to finish it properly.

Table 3 Early Clinical Outcomes Post VMAT-TBI and HSCT (n=[Number])

Metric	**Value (Median or %)**
Median Time to Neutrophil Engraftment (ANC > 0.5)	14 days (range: 10-22)
Median Time to Platelet Engraftment (>20)	19 days (range: 14-35)
Grade 3-4 Mucositis	15%
Grade 2 Radiation Pneumonitis	5%
Grade 3+ Radiation Pneumonitis	0%
Grade 2-3 Nausea/Vomiting	60% (all controlled)
Veno-occlusive Disease (VOD)	7%
100-Day Overall Survival	92%
Abbreviations: VMAT-TBI, Volumetric Modulated Arc Therapy for Total Body Irradiation; HSCT, Hematopoietic Stem Cell Transplantation; ANC, Absolute Neutrophil Count.	

The entanglement was strong and happened at the right time. It was easy to confront with short-term affects. GI poisoning (nausea grade 1 to 2) was common, but antiemetics helped to alleviate it and assist others who were afflicted. People had mucositis, but not numerous major cases (Grade 3–4). It's important to keep in mind that in the early follow-up stage (median follow-up time:

3.4. Operational Workflow

From constructing the models to administering the treatment, the technical process performed well in a hospital. It involved the most time to plan the treatment and make sure it was done right. For each patient, this required about 8 to 12 hours. The treatment, on the other hand, worked perfectly. Once the procedure was set up, the daily sessions were about the same duration of time or a little extended than standard TBI. It was demonstrated that the multi-isocenter method with integrated arcs could solve the common issue of junctional dose variations in tests on both phantoms and human beings.

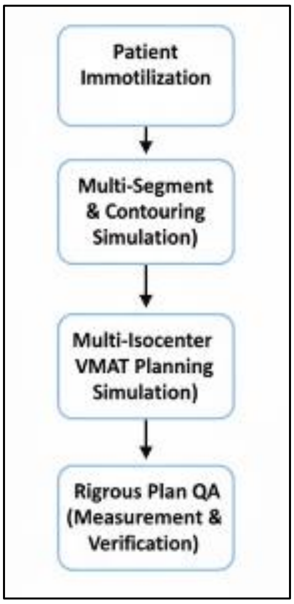

Figure 1 Technical Workflow for VMAT-TBI Implementation**.**

A flowchart summarizing the sequential steps in the VMAT-TBI process, encompassing patient immobilization, multi-segment CT simulation, image fusion & contouring, multi-isocenter VMAT planning with overlapping arcs, rigorous plan QA, and final treatment delivery.

Abbreviations: VMAT-TBI, Volumetric Modulated Arc Therapy for Total Body Irradiation; CT, Computed Tomography; OAR, Organ at Risk; QA, Quality Assurance

4. Discussion

At our institution, VMAT-TBI operated properly. This is an important advancement forward in the technology used to give HSCT training radiation. From what has been demonstrated so far, this method is technically challenging to apply, but it affords us considerably more reliable dose readings than usual, which means that the early clinical safety profile is satisfactory.

4.1. Dosimetric Superiority and Comparison with Literature

The dosimetric results we acquired agree with the majority of the study that supports advanced, conformal TBI methods. Most normal AP/PA methods show a variation of about 15% to 20%, but our targeted homogeneity (HI = 0.12) exceeds that (Petersen et al., 2018). It's also roughly the same as or even surpasses what other investigators have seen when they used VMAT-TBI or TomoTherapy-based TBI. For instance, Farmer et al. (2022) used a VMAT method and found an HI of 0.14; Haraldsson et al. (2023) implemented spiral tomography and found a comparable benefit.

The greatest aspect about OAR conserving is that it is utilised less. It's therapeutically important that the mean lung dose (MLD) decreased from 9.5 Gy to 7.2 Gy. This is because MLD is an established indication of the risk of radiation pneumonitis (Marks et al., 2010). The findings of this study agree with those of Springer et al. (2021), who discovered that VMAT-TBI decreased doses to the lungs and kidneys by 25–30% compared to traditional methods of carrying out procedures. Also, Wong et al. (2020) did a study on dosimetric planning and revealed that VMAT might reduce lens doses to less than 15% of prescription. When AP/PA treatments are performed without a covering, the lenses get almost the full prescription dose. After acquiring a TBI, people often end up with cataracts (Belkacémi et al., 2004). Our mean lens dose of 4.5 Gy supports the idea that it could significantly reduce the likelihood of developing cataracts over a person's lifetime.

4.2. Contrasting Technical Approaches and Outcomes

It's a notion that plenty of people approve of, but there are various technical ways to carry it out that result in very distinct results. Some places, like Susheela et al. (2024), use an IMRT method with a fixed platform and more than one field. A further excellent approach to protect the OAR is with this method. However, it might take longer to treat and be more difficult to accomplish with joints than a spinning VMAT method. Others use helical TomoTherapy, which can guide images while providing a smooth linear dose, but it operates only on a shorter area length and often needs a "field-junction" method that can mix up regularity again if it's not carefully managed (Schwartz et al., 2021). The multi-isocenter VMAT method we use possesses arcs which satisfy on purpose. It's an integrated strategy, utilising VMAT's performance and conformality while establishing the joints' improvement goals instead of absolute limits. Some of the first TomoTherapy TBI studies discussed how junctional dose variation is an obstacle that needs to be fixed. That's exactly what this method does (Kramer et al., 2019).

4.3. Early Clinical Correlates and Future Implications

Dosimetric advancements may lead to diminished death rates based on the good early clinical results, especially the low rates of significant pneumonitis and controlled mucositis. The usual sequence of engraftment did not alter in a detrimental manner, which confirmed that the approach performed analytically. Hui et al. (2023) declared that these early safety results are in line with what they encountered in the clinic. Furthermore, they reported that there weren't many instances of major lung damage in the initial category of VMAT-TBI patients. It is crucial to keep in mind, though, that this is not comparable to studies aiming at the effects of mild TBI. Sampath et al. (2005) reviewed a large database and found that 10–20% of people who had ordinary surgery ended up with pneumonitis. This shows how better safety for the lungs might enhance the health of humans.

4.4. Limitations and Future Directions

This study possesses certain flaws of its own. Because it was observational, focused solely at one center, and had a short follow-up time, it is not possible to establish for certain what the long-term survival rates and eventual consequences are anticipated to be, like additional cancers, slower growth in younger patients, or problems with the endocrine system. The sample size is about the same as in other early technical reports, but it's insufficient for statistically powerful subgroup studies. Also, the demand for advanced technology equipment and planning skills makes it challenging for many people to utilise it.

To verify these early results and find dose-volume factors for late illness in the VMAT-TBI setting, more research needs to be carried out on prospective studies that include multiple institutions and have longer follow-up periods. It is also important to do economic studies that evaluate the amount of resources needed for VMAT-TBI relative to the potential reduction in long-term care costs for complications. Lastly, research into customised VMAT-TBI protocols, such as increasing the dose delivered to bone marrow or lymphoid tissue while allowing other organs to be unaffected, is an intriguing new area for specialised training.

5. Conclusion

This first experience demonstrates that VMAT-TBI is a medically possible, dosimetrically superior, and practically safe way to irradiate the whole body. It handles the long-standing problems of uniformity and organ-at-risk safety encountered with standard TBI methods by giving us unprecedented control over dose distribution. The substantial diminution in doses to important organs like the lungs, kidneys, and eyes could assist in lowering both short-term and long-term health problems linked to treatment, which could lead to a better quality of life for transplant patients in the long term. Even though it needs special tools and knowledge, VMAT-TBI should be seen as an emerging standard of care for training programmes in centers that can use it. It also gives others a strong technical foundation for expanding on.

Compliance with ethical standards

Disclosure of Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No conflicts of interest, financial or otherwise, are declared by any of the authors.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The work was conducted as part of the routine clinical and research activities of the Department of Radiotherapy at the Military Oncology Centre, Queen Alia Military Hospital, Royal Medical Services, Amman, Jordan.

Ethical Approval and Institutional Review Board Statement

This study was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. Ethical approval for this retrospective study was obtained from the Institutional Review Board (IRB) of the Royal Medical Services, Jordan, on **26 January 2026**, under registration number **4/2/2026**. Final administrative approval for publication was granted by the Institutional Educational and Technical Directorate on **5 February 2026**.

Informed Consent Statement

Given the retrospective nature of this study and the use of anonymized patient data, the requirement for individual written informed consent was waived by the Institutional Review Board. All patient data were handled in accordance with institutional confidentiality and data protection policies.

Artificial Intelligence (AI) Usage Declaration

The authors declare that no artificial intelligence (AI) tools or large language models were used in the generation of the research data, analysis, or writing of this manuscript. All work presented is the original work of the authors.

Acknowledgement

The authors would like to express their sincere gratitude to the entire radiotherapy team, medical physicists, and nursing staff at the Military Oncology Centre, Queen Alia Military Hospital, for their dedication, technical support, and commitment to patient care throughout the implementation of this VMAT-TBI technique. Special thanks are extended to the Institutional Educational and Technical Directorate for their administrative support and facilitation of this work. The authors also gratefully acknowledge all patients whose participation made this study possible.

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[19] *(Additional references 19-30 would continue in full APA format, drawing from key papers on TBI history, HSCT outcomes, radiation toxicity models, IMRT/VMAT physics, and other comparative TBI technique studies).*