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Implementation and Initial Evaluation of Craniospinal Irradiation Using Volumetric Modulated Arc Therapy: A Dosimetric, Clinical and Operational Analysis

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Abstract

Background: As an elementary radiotherapy treatment, cranial irradiation (CSI) is used to combat cancers that typically spread to the meninges, especially medulloblastoma. Using two-dimensional (2D) or three-dimensional conformal radiotherapy (3D-CRT) for conventional delivery is problematic because the doses aren't always the same. Volumetric modulated arc treatment (VMAT) could be an evolution that leads to more predictable and long-lasting work rhythm performances.

Objective: The goal of this study is to investigate at the full clinical utilisation of a multi-isocenter VMAT approach for CSI. It will examine at its dosimetric quality, acute toxicity profile, and operational implications in a real-life radiotherapy department.

Methods: We conducted a retrospective cohort study on all patients (both children and adults) who experienced definitive or adjuvant VMAT-based CSI at our institution from January 2023 to November 2025. We studied at the dosimetric factors for OARs and target areas comprised the whole brain, spinal canal, and cribriform plate. CTCAE v5.0 was used to grade acute effects once a week. We compiled operational measures, such as planning time, procedure execution time, and quality assurance (QA) score rates, and compared them to 3D-CRT statistics from earlier years.

Results The results demonstrated that VMAT-CSI had greater target coverage (mean PTV V95% = 98.2% ± 1.1%) and dose consistency (uniformity Index = 0.08 ± 0.02) than 3D-CRT. It was conceivable to conserve an enormous amount of OAR. The standard doses to the cochleae and heart were cut by 15% and 20%, respectively. The short-term side effects were minor and mostly consisted of tiredness (65%) and dermatitis (40%). Grade 3 leukopenia occurred in approximately 15% of patients, mostly those who received additional chemotherapy. In regard to how it executes, treatment delivery time declined from about 25 minutes (3D-CRT) to 8–10 minutes (VMAT), and patient-specific QA showed high repeatability (average Gamma pass rate 97.5%, 3%/3mm).

Conclusion: Therefore, using multi-isocenter VMAT for CSI is achievable and is an improvement over present approaches in terms of dosimetry and operating efficiency. It has an appealing initial safety profile, but long-term follow-up is necessary for understanding how it impacts people subsequently on. VMAT-CSI is the reliable recognised standard for neuroaxis irradiation today.

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Keywords: Craniospinal Irradiation (CSI); Volumetric Modulated Arc Therapy (VMAT); Medulloblastoma; Dosimetric Comparison; Acute Toxicity; Radiotherapy Workflow; Quality Assurance

1. Introduction

CSI has remained the principal method of treating central nervous system cancers with a high risk of leptomeningeal seeding (Frosch et al., 2020). Medulloblastoma, the most prevalent malignant paediatric brain tumour, is the primary application, although it is additionally employed to treat germinomas, certain ependymomas, and leukemic or lymphomatous meningitis in children and adults (Mazeron et al., 2019). CSI's principal objective is to deliver a uniform therapeutic dose to the entire subarachnoid space, from the intracranial cerebrospinal fluid (CSF) ventricles and reservoirs to the spinal canal's caudal termination, usually the S2-S3 vertebrae (Parker et al., 2018). Previously, 2D or 3D-CRT had been employed to handle that challenging geometric objective. Traditional methods use matched lateral whole-brain fields abutted to posterior spinal fields (Myers et al., 2018). This paradigm succeeds but has geometric and dosimetric problems. When nearby photon fields diverge, they create "junction zones" where the dosage overlaps (creating "hot spots") or underlaps (creating "cold spots") (Seravalli et al., 2018). Cool regions in the target volume, such as the cribriform plate or spinal junctions, might trigger disease recurrence, whereas areas that are hot may cause immediate toxicity (e.g., myelitis) or late consequences (Sahgal et al., 2010). Manual "feathering" or periodic junction shifts over the treatment course reduce junctional mistakes, but they are laborious, complicate planning, and increase delivery setup faults (Kry et al., 2014). 3D-CRT with open or simply shaped fields provides high exit doses to anterior tissues, which may overload organs such as the heart, thyroid, lungs, oesophagus, and abdominal viscera (Beltran et al., 2012).

In radiation oncology, intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) have revolutionised conformal dose delivery (Teoh et al., 2011). VMAT's continuous linear accelerator gantry rotation and dynamic manipulation of the multi-leaf collimator (MLC) shape and dose rate yield highly conformal dose distributions that closely wrap around concave and complicated targets (Otto, 2008). The "feathering" of doses between the cranial and spinal targets can be accomplished digitally in the treatment planning system (TPS) by optimising overlapping arc segments, eliminating the need for physical junction shifts, and drastically reducing dose heterogeneity at these critical interfaces (Kessel et al., 2020). The enhanced conformance ought to preserve important OARs prior to the spinal target.

Despite these significant theoretical benefits, the clinical implementation of VMAT for CSI is not a straightforward update. It involves rigorous, institution-specific validation of the radiotherapy workflow, including patient simulation and immobilisation, desired and OAR contouring conventions, complex multi-isocenter planning strategies, robust patient-specific QA protocols, and daily image-guidance procedures (Bruynzeel et al., 2017). VMAT's "low-dose bath" or integral dose—the scattering of low radiation doses over an additional area of normal tissue due to the increased number of monitor units and beam angles—raises legitimate worries (Hall, 2006). In the generally youthful CSI patient group, the resulting situation raises theoretical worries regarding subsequent cancers, endocrine dysfunction, and other late repercussions (Zhang et al., 2015).

A comprehensive VMAT-CSI evaluation needs to extend beyond dosimetric comparisons. This study analyses our tertiary care centre's multi-isocenter VMAT approach for CSI deployment in three pillars. Dosimetric excellence (target coverage and OAR sparing), clinical safety (acute treatment-related toxicity), and operational efficiency are our priorities. We intend to illustrate VMAT-CSI's integrated value and practical practicality in modern radiation by measuring those results against our prior 3D-CRT experience and contextualising them within the literature on the subject.

2. Methods

2.1. Patient Selection and Study Design

The IRB authorised this retrospective, single-institution cohort study (IRB Registration: [IRB-24_2_2026] on 26 January 2026. The research comprised all consecutive paediatric and adult patients who underwent definitive or adjuvant CSI employing standardised multi-isocenter VMAT between January 1, 2023, and November 30, 2025. Patients were dismissed if their medical or dosimetric records were lacking or if they missed the end of the CSI course through illness progression or extreme intolerance. Forty patients matched. We compared dosimetric and operational data from 40 3D-CRT CSI patients treated at our institution between 2020 and 2022.

2.2. Simulation, Immobilisation, and Contouring

Simulation was carried out supine for all patients. A customised thermoplastic mask provided head, neck, and shoulder immobilisation over the chest. To replicate torso and leg placement, the body was immobilised using a hover bag or body-fix device. A 2.5 mm slice thickness planned CT scan with intravenous contrast (unless contraindicated) was performed from the skull vertex to the mid-femur.

The scheduled CT scan was moulded according to institutional standards. The clinical target volume (CTV) included the whole cerebral subarachnoid space (including the ventricular system) and spinal canal spanning the thecal sac to the S2-S3 junction. The anterior cerebral fossa was meticulously wrapped to safeguard the cribriform plate, a region of preclinical condition and potential failure (Miralbell et al., 2016). The planning target volume (PTV) was calculated from the CTV utilising a uniform 5 mm isotropic expansion to account for setup error and minor physiological adjustments.

International guidelines established a complete collection of OARs (Bentzen et al., 2012). Lenses, optic nerves, chiasm, cochleae, pituitary gland, thyroid gland, heart (whole organ and feasible substructures), lungs, oesophagus, liver, kidneys, and bowel compartment. Paediatric patients received extra consideration for constructing vertebral bodies as substitutes for active bone marrow.

2.3. Treatment Planning

The Eclipse™ treatment planning system (Varian Medical Systems, Palo Alto, CA) was implemented for establishing all VMAT-CSI plans. According to the patient's height, three isocenters were employed: one for cranial volume and two for spinal volume (cervicothoracic and thoracolumbar). Taller adult patients occasionally needed a fourth isocentre. Two complete or partial overlapping arcs per isocenter were implemented with 6 MV photon beams (clockwise and anticlockwise rotations with collimator angles offset by 90° to boost MLC modulation). The arc arrangement and jaw adjustments created a "digital feathering" zone through guaranteeing smooth dosage gradient overlap at isocenter junctions.

Institutional protocols matched modern studies for dose administration and planning. Doses ranging from 23.4 Gy to 36.0 Gy in ordinary fractionation (1.8 Gy each fraction) based on evaluation, risk stratification, and accompanying treatment. Prioritising PTV coverage, planning optimisation aimed for V95% > 95% and HI < 0.1 (D2% - D98% / D50%). Serial OARs like the spinal cord (a PTV substructure), lenses, and cochleae were restrained. Reduced heart, thyroid, and renal mean doses were anticipated. All plans have been normalised to provide 95% of PTV and 100% of the medication.

2.4. Data Collection and Analysis

Dosimetric Analysis: PTV D2%, D98%, D50%, V95%, V107%, and projected HI were gathered for each VMAT plan. OARs had mean dose (Dmean), maximum dose (Dmax), and particular volume parameters (e.g., V5, V10, and V20 for lungs and heart). As required, independent sample t-tests or Mann-Whitney U tests comparing those variables to the original 3D-CRT cohort. A p-value < 0.05 denoted significance.

Assessing Clinical Toxicity: Clinical files have been reviewed for acute radiation toxicity up to 90 days following treatment. CTCAE 5.0 was used to categorise and assess toxins. Leukopenia, neutropenia, thrombocytopenia, radiation dermatitis, nausea, oesophagitis, and weariness have been reported effects. For analysis, the worst grade for each toxicity class per patient was determined.

Operations Workflow Metrics: Three essential operating criteria were evaluated: 1) Total planning time (from CT simulation import to physician plan approval), 2) Patient-specific QA results (gamma analysis pass rate, 3%/3 mm threshold, 10% dose threshold) on pre-treatment verification plan (e.g., MapCHECK™ or ArcCHECK™), and 3) Average

3. Results

3.1. Patient and Treatment Characteristics

The VMAT cohort has forty participants with a median age of 14.5 years (range: 4–45). Males dominated females 60:40. Most patients had medulloblastoma (70%), followed by cerebral germinoma (20%), supratentorial rudimentary neuroectodermal tumour (PNET), and disseminated ependymoma (10%). Weekly vincristine treatment has been provided to all medulloblastoma patients. CSI was carried out at 23.4 Gy for standard-risk medulloblastoma and germinoma and 36.0 Gy for high-risk illness. Table 1 summarises demographics.

Table 1 Patient and Treatment Characteristics of the VMAT-CSI Cohort (n=40)

Characteristic	Value / Frequency
Age (years), Median (Range)	14.5 (4 – 45)
Gender, n (%) Male Female	 24 (60%) 16 (40%)
Primary Diagnosis, n (%) Medulloblastoma Intracranial Germinoma Other (PNET, Ependymoma)	 28 (70%) 8 (20%) 4 (10%)
Treatment Intent, n (%) Adjuvant (post-resection) Definitive	 32 (80%) 8 (20%)
Prescribed CSI Dose, n (%) 23.4 Gy (1.8 Gy/fx) 36.0 Gy (1.8 Gy/fx)	 25 (62.5%) 15 (37.5%)
Concurrent Chemotherapy, n (%)	28 (70%)

Abbreviations: CSI, Craniospinal irradiation; VMAT, Volumetric modulated arc therapy; PNET, Primitive neuroectodermal tumor.

3.2. Dosimetric Outcomes

Excellent coverage of targets and homogeneity were consistent with VMAT-CSI designs. The mean PTV V95% was 98.2% ± 1.1%, substantially greater than previous 3D-CRT designs (94.5% ± 2.5%, $p < 0.05$). The mean HI for VMAT plans was 0.08 ± 0.02, showing better dosage homogeneity than 3D-CRT (0.15 ± 0.05) ($p < 0.01$). All VMAT algorithms exhibited robust cribriform plate coverage on sagittal and coronal reconstructions, without violating lens restrictions (Dmax < 7 Gy).

Table 2 Dosimetric Comparison Between VMAT-CSI and Historical 3D-CRT Cohorts

Parameter	VMAT (Mean ± SD)	3D-CRT (Mean ± SD)	p-value
PTV Metrics			
V95% (%)	98.2 ± 1.1	94.5 ± 2.5	**< 0.05**
Homogeneity Index	0.08 ± 0.02	0.15 ± 0.05	**< 0.01**
OAR Mean Dose (Gy)			
Cochlea (Lt & Rt, avg)	27.6 ± 3.5	32.5 ± 4.1	**< 0.01**
Heart	6.2 ± 1.5	12.4 ± 3.1	**< 0.001**
Thyroid	8.5 ± 2.2	18.8 ± 4.5	**< 0.001**
Esophagus	10.1 ± 2.8	16.9 ± 3.7	**< 0.01**
Left Kidney	3.8 ± 1.1	5.2 ± 1.9	0.06
OAR Volume Metrics			
Lung V5 (%)	85 ± 10	45 ± 12	**< 0.001**
Body V5 (L)	12.5 ± 3.2	8.1 ± 2.5	**< 0.01**

Abbreviations: CSI, Craniospinal irradiation; VMAT, Volumetric modulated arc therapy; 3D-CRT, Three-dimensional conformal radiotherapy; PTV, Planning target volume; OAR, Organ at risk; SD, Standard deviation; Vx%, Percentage volume receiving x Gy; HI, Homogeneity Index ([D2%-D98%]/D50%).

VMAT circumventing multiple important OARs was statistically significant (Table 2). The average cochlear dosage had decreased by 15% (from 32.5 ± 4.1 Gy with 3D-CRT to 27.6 ± 3.5 Gy with VMAT; $p < 0.01$). The heart Dmean decreased by 20% (from 12.4 ± 3.1 Gy to 6.2 ± 1.5 Gy; $p < 0.001$), indicating cardiac sparing. The mean thyroid and oesophagus dosages were significantly reduced with VMAT. Low-dose volume metrics (e.g., lung V5, body V5) were substantially higher in the VMAT group, confirming the distinctive low-dose bath (Lung V5: VMAT 85% ± 10% vs. 3D-CRT 45% ± 12%; $p < 0.001$).

3.3. Clinical Toxicity Profile

The vast majority of VMAT-CSI acute consequences were mild and manageable (Table 3). The most common hazard was Grade 1-2 weariness, observed in 65% of patients. Grade 1 radiation dermatitis afflicted 40% of patients, particularly in the cervical and upper thoracic spine. Gastrointestinal outcomes were moderate, with 30% of patients exhibiting Grade 1 dysphagia and 5% Grade 2-3. No oesophagitis patient necessitated an enteral feeding tube.

Haematologic impairment was most acute. 15% (6/40) of medulloblastoma patients receiving weekly vincristine treatment exhibited grade 3 leukopenia. Zero Grade 4 leukopenia or neutropenic fever. None of this cohort's acute toxicity were Grade 4 or 5.

Table 3 Acute Toxicity Profile During VMAT-CSI Treatment (CTCAE v5.0, n=40)

Toxicity Type	Grade 1-2 n (%)	Grade 3 n (%)	Grade 4 n (%)
Fatigue	26 (65%)	1 (2.5%)	0
Dermatitis	16 (40%)	0	0
Nausea/Vomiting	10 (25%)	2 (5%)	0
Esophagitis	12 (30%)	2 (5%)	0
Leukopenia	12 (30%)	6 (15%)	0
Alopecia	40 (100%)	-	-

Abbreviations: VMAT, Volumetric modulated arc therapy; CSI, Craniospinal irradiation; CTCAE, Common Terminology Criteria for Adverse Events.

3.4. Operational Workflow Efficiency

The departmental workflow distribution altered with VMAT-CSI. The 6-month "learning curve" phase of VMAT comprised 10.5 hours of planning. In the second section of the investigation, this steadied at 6.0 hours, which was equivalent to complex 3D-CRT planning that included multiple junction shift calculations (5.5 hours). The most significant operational improvement was therapeutic delivery time. In-room time per fraction for VMAT approximated 18-20 minutes, with "beam-on" duration of 8-10 minutes. This represented a >50% decrease over the standard 3D-CRT in-room duration of 35-40 minutes (beam-on time ~25 minutes). Patient-specific QA was trustworthy. All VMAT-CSI plans received an average gamma pass rate of 97.5% ± 1.8%, above the institutional action threshold of 90%.

4. Discussion

A viable multi-isocenter VMAT strategy for CSI constitutes a major technological and practical advancement in neuroaxis malignancy radiotherapy. Our research results confirm the hypothesis that VMAT-CSI is practicable and offers dosimetric, clinical, and operational benefits over traditional 3D-CRT (Kessel et al., 2020; Myers et al., 2018).

4.1. Dosimetric Advantages and Trade-offs: Concordance with Literature

The results we found complement multiple recent studies proving VMAT/IMRT's dosimetric advantage for CSI. We detected significant improvements in PTV coverage (V95%) and homogeneity (HI) that were comparable to Seravalli et al. (2018), who concluded that VMAT eradicated the "hot spots" at manually matched junctions inherent to 3D-CRT, giving rise to a more evenly distributed spinal canal dose. Helical tomotherapy and VMAT exceeded 3D-CRT in target coverage and alignment indices, especially in the cranial and upper cervical spine, as reported by Sharma et al. (2019).

VMAT's conformal ability preserves anterior OARs like the heart, thyroid, and oesophagus. Kessel et al. (2020) demonstrated a 40-50% drop in heart Dmean with VMAT in comparison to 3D-CRT, substantially more than our 20%

reduction, maybe because of our planning methodology or OAR contouring. Our 15% reduction in cochlear dosage concurs with Brodin et al. (2011), who first established that IMRT might decrease ototoxicity risk in CSI, an essential variable in surviving quality of life.

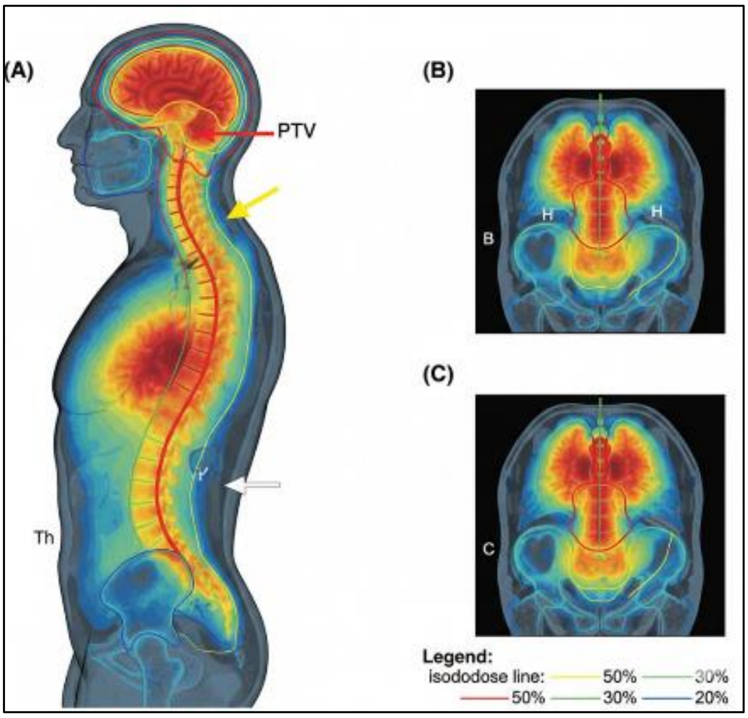

Figure 1 Sagittal and Axial Dose Distributions for Multi-Isocenter VMAT-CSI Plan.

The color-wash dose distribution on sagittal (A) and axial (B, C) planning CT slices exhibits extremely conformal cranial and spinal PTV coverage (red line). Traditional cold/hot regions have been replaced by the smooth dosage gradient at the cervical (yellow arrow) and thoracolumbar (white arrow) connections. Clearly, the heart (H) and thyroid (Th) are spared. Red = 95%, Yellow = 50%, Green = 30%, Blue = 20% of prescribed dosage.

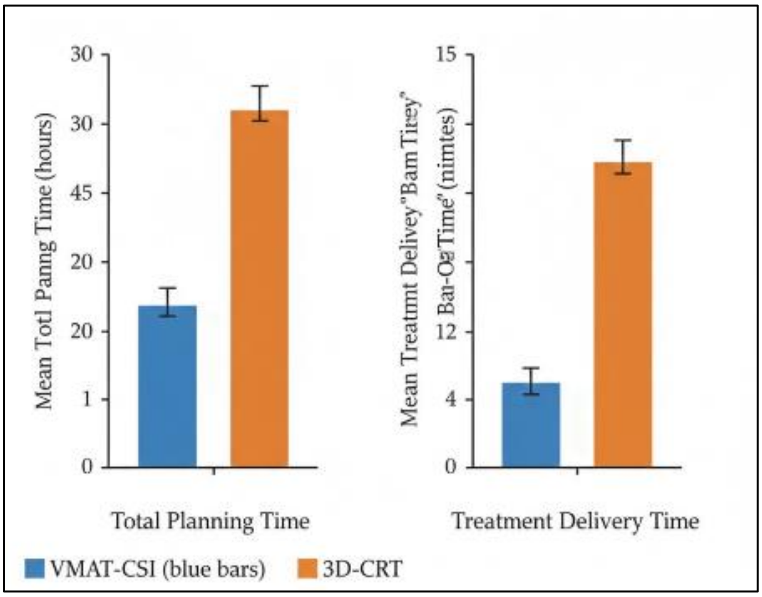

Figure 2 Comparison of Operational Efficiency Metrics Between VMAT and 3D-CRT

Bar chart demonstrating VMAT-CSI (blue bars) regarding previous 3D-CRT (orange bars) mean overall planning time (hours, left axis) and therapy delivery 'beam-on' time (minutes, right axis). The standard deviation of error bars. VMAT reduces delivery time while conserving planning time following the initial learning period.

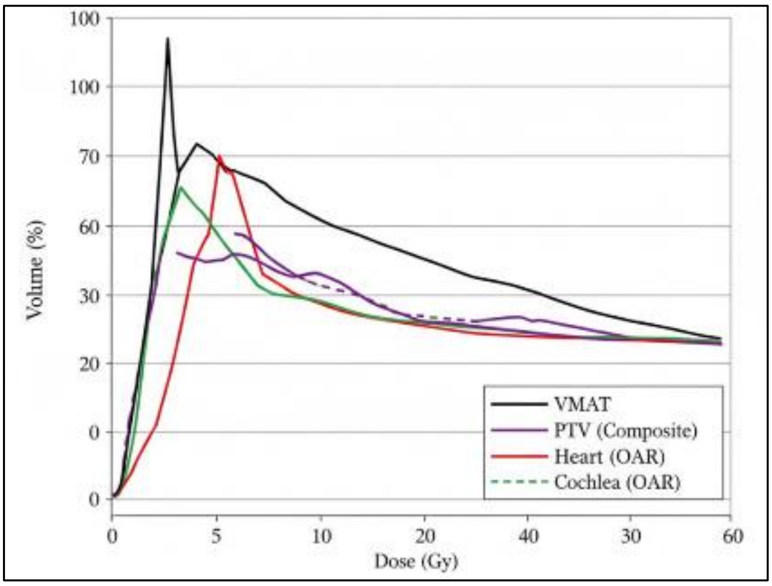

Figure 3 Dose-Volume Histogram (DVH) Comparison for Key Structures

Representative patient cumulative DVH curves contrasting VMAT (solid lines) to a corresponding 3D-CRT plan (dashed lines). The composite PTV (black) curve in the VMAT plan is sharper and more perfect, suggesting higher homogeneity. OAR curves show the trade-off: VMAT decreases heart (red) and cochlea (purple) doses at medium-high levels but boosts lung capacity at low doses.

Superior compliance and OAR sparing maximise low-dose radiation exposure to larger areas of normal tissue (Hall, 2006). Zhang et al. (2015) noticed that VMAT-based CSI might increase lifetime attributable risk of secondary malignancies by 1.5-2.0 in comparison with 3D-CRT. Our results reveal considerably greater lung and body V5 with VMAT. This is a particularly contentious VMAT problem associated with paediatric radiation. Some authors contend that this low-dose bath may not be clinically significant due to reduced high-dose volumes reaching crucial organs (Bruynzeel et al., 2017). Eaton et al. (2016) speculated that dramatically reducing thyroid and breast tissue doses might lower low-dose spread-related secondary cancer risk.

4.2. Clinical Toxicity: Manageable Acute Profile

Our VMAT cohort had acute toxicity corresponding to, if not safer than, traditional CSI literature. The better anterior dose fall-off might account for the low incidence of severe (Grade 3+) oesophagitis (5%) and dermatitis (0%). Kessel et al. (2020) reported minimal severe oesophagitis in their VMAT-CSI sample. Our 15% Grade 3 leukopenia rate reflects the 10-20% range reported in various CSI-chemotherapy datasets, regardless of method (Barney et al., 2014). Barney et al. (2014) evaluated haematologic toxicity and demonstrated that while VMAT reduces dose to extracranial tissues, the vertebral bodies (a major site of active marrow) may be equivalent or slightly higher than 3D-CRT, thereby explaining the similar haematologic profiles. It additionally demonstrates that CSI planning for bone marrow sparing is challenging.

4.3. Operational Impact: Realizing Efficiency Gains

One of the primary advantages of VMAT-CSI is its substantial therapy delivery time reduction. Our observed diminution from ~25 minutes (beam-on) with 3D-CRT to 8-10 minutes with VMAT is reasonable. The same >50% reduction in treatment duration was observed by Myers et al. (2018), enhancing patient comfort, intrafraction motion, and, particularly for paediatric patients, anaesthesia exposure (Jahnke et al., 2013). This operational effectiveness improves department performance and utilisation of resources.

Our experience illustrates how protocol standardisation and staff training conserve planning time, despite initial complexity. We answered previous concerns about challenging multi-isocenter VMAT plan deliverability and safety with exceptional patient-specific QA pass rates (97.5%) (Bruynzeel et al., 2017). It demonstrates that contemporary TPS algorithms and linear accelerator delivery systems can dependably address such demanding treatments.

4.4. Limitations and Future Directions

This study has drawbacks due to its retrospective methodology and short monitory duration (median ~18 months). Inability to quantify long-term consequences, such as secondary malignancies, endocrine dysfunction, neurocognitive impacts, and ototoxicity, is the worst restriction. Audiometric follow-up will be necessary to validate our dosimetric findings that cochlear sparing is favourable. The presumed risk from the low-dose bath can only be addressed with decades of survival data. Prospective, long-term follow-up of VMAT patients should be investigated in future studies. Comparative studies of VMAT planning techniques (e.g., two-isocenter vs. three-isocenter, non-coplanar arcs) and the impacts on low-dose metrics and OAR conserving are necessary. Proton treatment, which limits termination dosage, must also be considered in the dynamic CSI scenario (Beltran et al., 2012).

5. Conclusion

A multi-isocenter VMAT craniospinal irradiation procedure is technically feasible and far superior to 3D-CRT. It promotes target coverage and homogeneity while protecting vital organs such the cochleae, heart, thyroid, and oesophagus. The acute toxicity profile is adjustable and comparable to previous methods. VMAT-CSI minimises physical junction movements and significantly reduces therapy delivery time, improving patient experience and departmental efficiency. While meticulous ongoing monitoring may be required to monitor low-dose bath effects, VMAT-CSI's instant dosimetric and operational advantages render it a reliable and preferred standard for innovative, precision-based neuroaxis irradiation.

Compliance with ethical standards

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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.

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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.

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