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Dosimetric Evaluation of 3D-CRT and IMRT Treatment Techniques in Medulloblastoma

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Abstract

A primitive neuroectodermal tumor (PNET) of the cerebellum, called medulloblastoma, is an aggressive, fast-growing brain tumor. This study aims to compare the dosimetric distribution of two radiotherapy techniques—three-dimensional conformal radiation therapy (3D-CRT) and intensity-mod ulated radiation therapy (IMRT)—in patients with medulloblastoma by evaluating planning target volume (PTV) and exposure of organs at risk (OARs).

In a 15-year retrospective analysis, considerable number of patients (aged 3–30 years) initially treated with 3D-CRT and subsequently with IMRT (volumetric modulated arc therapy is now used but not included in this comparison) were evaluated. Treatment plans were created in the planning system using the Monte Carlo Convolution/Superposition algorithm. Dose distributions were assessed via dose–volume histograms, and the maximum doses received by the hippocampus, brainstem, and spinal cord were compared between the two techniques.

Both 3D-CRT and IMRT achieved complete coverage of the PTV. IMRT demonstrated a significant reduction in dose to critical structures, thereby lowering the risk of neurocognitive and endocrine side effects, whereas 3D-CRT delivered higher radiation levels to surrounding normal tissues. Average treatment times for IMRT were approximately 20–30% longer than for 3D-CRT. IMRT provides a more conformal dose distribution, with enhanced protection of OAR, potentially permitting higher tumor doses and improved long-term outcomes in pediatric patients. However, the choice between 3D-CRT and IMRT should be made on a case-by-case basis, taking into account the contour delineation, technical availability, and the patient's tolerance for treatment duration. (**International Journal of Biomedicine. 2025;15(4):685-689.**)

Keywords: medulloblastoma • 3D-CRT • IMRT

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Abbreviations

3D-CRT, three-dimensional conformal radiation therapy; **CSI**, craniospinal irradiation; **CT**, computer tomography; **CTV**, clinical target volume; **GTV**, gross tumor volume; **IMRT**, intensity-modulated radiation therapy; **MRI**, magnetic resonance imaging; **OAR**, organ at risk; **PTV**, planning target volume; **VMAT**, volumetric modulated arc therapy.

Introduction

Medulloblastoma is the most common malignant brain tumor in children, accounting for approximately 20% of all pediatric brain tumors. Any patient presenting with neurological symptoms should undergo a complete evaluation, including a neurological examination. If a brain tumor is suspected, the patient is typically referred for brain imaging.

Neuroimaging plays a key role in the diagnosis and assessment of medulloblastoma dissemination. Magnetic resonance imaging (MRI) and computed tomography (CT)

provide detailed images of the brain and spinal cord, enabling the detection of tumors and their anatomical relationships to surrounding structures.[1,2]

In pediatric patients, contrast administration improves lesion visualization, and sedation may be required to obtain high-quality images. In rare cases, a medulloblastoma or another primitive neuroectodermal tumor (PNET) can be detected by prenatal ultrasound.[3]

Some early studies suggested that the diagnosis could be established solely based on imaging without the need for a biopsy.[1,2,3] However, according to the WHO Classification of CNS Tumours 2021 and SIOP-Europe 2023 guidelines, final diagnosis requires histopathological verification and molecular characterization, which are essential for accurate risk stratification and optimal treatment planning.

The modern classification system divides medulloblastomas into four main molecular groups: WNT-activated – very favorable prognosis; often eligible for reduced CSI dose, HH-activated, TP53-wildtype – intermediate prognosis, SHH-activated, TP53-mutant – poor prognosis; often treatment-resistant, Non-WNT/Non-SHH – includes Group 3 and Group 4, with diverse molecular profiles and prognoses.[4,5]

This molecular classification, combined with histological and clinical features, has enabled a more personalized approach to treatment.

Radiotherapy, combined with surgery and chemotherapy, is a cornerstone in the management of medulloblastoma. For standard-risk patients, this multimodal approach achieves 5-year survival rates of 75–85%.[1] Age is a key factor in risk stratification: patients under 3 years of age are treated with specific protocols to avoid or reduce craniospinal irradiation due to the high risk of long-term side effects.

One of the most common and detrimental late effects of treatment is neurocognitive decline, which is directly related to the radiation dose delivered to the brain.[6,7] The hippocampus and temporal lobes are critical structures for memory formation and cognitive function. Studies in both animal models and patients have demonstrated that radiation-induced disruption of hippocampal neurogenesis leads to significant cognitive deficits.

For this reason, modern radiotherapy techniques such as intensity-modulated radiation therapy (IMRT), volumetric modulated arc therapy (VMAT), and proton therapy are increasingly used to limit the dose to critical structures while maintaining tumor control. Hippocampal-sparing craniospinal irradiation (CSI) is an emerging strategy designed to reduce the risk of long-term cognitive impairment.

In standard treatment, craniospinal irradiation (CSI) is delivered at a dose of 23.4–36 Gy, followed by a boost to the posterior fossa up to 54–55.[8] Gy.1,7 Typical margins for the gross tumor volume (GTV) and clinical target volume (CTV) range from 0.5cm to 1.5 cm, with an additional 0.5 cm added to generate the planning target volume (PTV). In WNT-activated and standard-risk patients, protocols with reduced CSI doses are being investigated to minimize toxicity without compromising survival.

Methodology

Over 15 years at our center, a considerable number of patients diagnosed with primitive neuroectodermal tumors (PNET), including medulloblastoma, were treated. The patients' ages ranged from 3 to 30 years, encompassing both pediatric and young adult populations. Initially, treatments were delivered using the three-dimensional conformal radiation therapy (3D-CRT) technique, followed by the introduction of IMRT, and more recently, VMAT.[8] Since the majority of treatments (about 90%) were performed using either 3D-CRT or IMRT, the present study focuses on a comparative evaluation of these two techniques using representative clinical cases. Both 3D-CRT and IMRT are established modalities in the treatment of medulloblastoma; however, they differ in terms of dose distribution, organ-at-risk sparing, acute and late toxicity profiles, and potential long-term outcomes (Table 1).[9-13]

Table 1.

Comparative features of IMRT and 3D-CRT in the treatment of medulloblastoma.

Feature	IMRT	3D-CRT	Notes / Evidence
Precision	Higher precision with inverse planning; better dose sculpting around the PTV and improved conformity	Less precise; often results in higher dose to surrounding healthy tissue	Difference most pronounced in boost fields; less marked in large-field CSI
Dose to normal tissue	Potentially reduces mean dose to brain, cochlea, and spinal cord when OAR constraints are applied	Higher dose to adjacent normal tissues; limited sparing capacity	IMRT may increase low-dose bath (V5–V10) to larger body volumes
Toxicity	Lower potential risk of neurocognitive decline, ototoxicity, and endocrine dysfunction when OAR sparing is implemented	Higher incidence of late effects, especially neurocognitive and endocrine toxicity	Benefits depend on plan quality; CSI without hippocampal/cochlear sparing may show minimal difference
Effectiveness	Similar tumor control compared to 3D-CRT; better quality-of-life outcomes when sparing OARs	Effective tumor control but with a higher risk of late toxicities	No survival advantage demonstrated for IMRT
Use in CSI	May allow better sparing of critical organs (thyroid, esophagus, cochlea); requires more complex planning and QA	Standard CSI technique historically; exposes more normal tissue to moderate–high doses	IMRT/VMAT CSI more sensitive to setup errors; requires daily IGRT

For pediatric patients, IMRT is often preferred due to its ability to reduce radiation dose to developing brain structures, the cochlea (lowering the risk of hearing loss), and endocrine glands, thereby reducing the risk of long-term neurocognitive, auditory, and hormonal dysfunction.[9,11] IMRT achieves highly conformal dose distributions, precisely targeting the PTV while minimizing exposure to organs at risk (OARs).

3D-CRT remains in routine use, especially for craniospinal irradiation (CSI), due to its simplicity, robustness, and effectiveness in covering the entire neuroaxis. This technique delivers a uniform dose across large target volumes but provides less sparing of OARs compared to IMRT or proton therapy, resulting in higher radiation exposure to normal tissues.[15,16,17]

For this study, treatment plans were created using both techniques for comparative purposes. Dose–volume histograms (DVHs) were generated, and dose metrics for the PTV and all relevant OARs were analyzed to identify potential advantages and disadvantages of each approach.

All patients undergo immobilization using pediatric thermoplastic masks and vacuum cushions. Simulation CT scans encompass the entire craniospinal axis with slice thicknesses of 1–2 mm. Target volumes are contoured according to international pediatric radiotherapy guidelines (SIOP-Europe, 2023).

Stage 1 – CSI: Standard-risk patients typically receive 23.4–36 Gy to the craniospinal axis, while high-risk patients may receive up to 36 Gy, depending on age and risk profile.

Stage 2 – Boost An additional 15–20 Gy is delivered to the posterior fossa or tumor bed, bringing the total dose to \~54–55.8 Gy for standard-risk cases.

For low-risk WNT-activated patients, dose de-escalation to 18–23.4 Gy CSI is considered, as per current protocols.

"Step-by-step" or "moving junction" techniques are applied for 3D-CRT CSI to avoid overdose/underdose at field junctions. IMRT/VMAT CSI eliminates the need for manual junction shifts.

All patients are managed within a multidisciplinary pediatric oncology team comprising radiation oncologists, neurosurgeons, pediatric oncologists, anesthesiologists, medical physicists, and radiation therapists.

Surgery: Maximal safe resection is performed before radiotherapy to obtain histopathological and molecular diagnosis and to debulk the tumor.

Chemotherapy: Administered pre- or post-radiotherapy in high-risk patients, those under 3 years of age, or in relapsed disease. Standard regimens include vincristine, etoposide, carboplatin, and cyclophosphamide.

Patients are classified according to a combination of clinical, radiological, and molecular features:

Low-risk: Residual tumor <1.5 cm², negative CSF cytology, no metastases, favorable molecular subgroup (e.g., WNT-activated). Expected 5-year survival >75%.

High-risk: Age <4 years, disseminated disease, incomplete resection, unfavorable histology, or molecular subgroup (e.g., Group 3). Expected 5-year survival 35–50%.[5,17]

Method 1: In this study, the first treatment approach involved the use of 3D-CRT for a patient diagnosed with medulloblastoma. The craniospinal irradiation (CSI) dose was 36 Gy, delivered in three different sequential treatment plans within the same session each day. This approach was chosen to optimize target coverage and minimize the occurrence of hot spots. To ensure optimal and reproducible patient positioning, Civco blue vacuum cushions were used for immobilization. Treatment was delivered on an Elekta Synergy linear accelerator. For the secondary beams, a motorized wedge was employed to achieve the desired dose distribution and improve homogeneity across the target volume Figure 1.

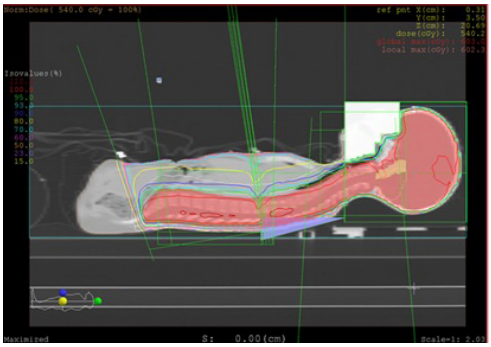

Fig. 1. *Medulloblastoma 3D-CRT treatment plans.*

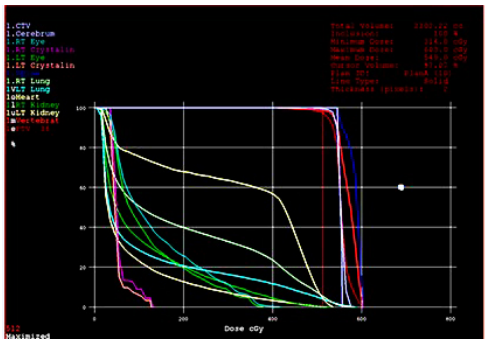

Fig. 2. *DVH for 3D-CRT medulloblastoma treatment.*

During treatment with this method, more precise results are expressed in the dose-volume histogram (Figure 2).

During 3D-CRT treatment for medulloblastoma, the minimum, maximum, and mean doses received by OARs were analyzed to assess their protection and exposure during therapy (Table 2).

Table 2.

The minimum, average, and maximum doses for OAR during 3D-CRT treatment.

Dose /OAR	Min Dose (cGy)	Max Dose (cGy)	Mean Dose (cGy)
Crystalline left	314	605	320
Crystalline right	314	605	320
Left Eye	310	605	335
Right Eye	310	605	330
Heart	320	605	550
Left Lung	314	610	350
Right Lung	315	610	350
Left Kidney	310	610	340
Right Kidney	310	610	340

The data show that the left and right crystalline lenses received a minimum dose of 314 cGy and a maximum dose of 605 cGy, with a mean dose of 320 cGy. The left and right eyes were exposed to minimum doses of 310 cGy and maximum doses of 605 cGy, with mean doses of 335 cGy and 330 cGy, respectively.

Regarding other vital organs, the heart received a relatively high mean dose of 550 cGy, ranging from 320 cGy to 605 cGy. The left and right lungs had minimum doses of \~314–315 cGy and maximum doses of 610 cGy, with equal mean doses of 350 cGy each. The left and right kidneys received minimum doses of 310 cGy and maximum doses of 610 cGy, with a mean dose of 340 cGy.

These results indicate that, although the dose distribution to the OARs was maintained within acceptable limits according to international protocols, there is considerable variability among the organs, with thoracic structures, such as the heart and lungs, being exposed to higher levels compared to ocular and renal structures. This dose profile is characteristic of 3D-CRT techniques, which provide uniform coverage of the target volume but have limitations in optimally sparing certain OARs compared to more advanced techniques such as IMRT or proton therapy.

Method 2: In this case, the IMRT technique was employed to maximize protection for OARs and surrounding healthy tissues. IMRT utilizes modulated beam intensities, enabling a non-uniform dose distribution, unlike the uniform distribution characteristic of 3D-CRT. This allows for the delivery of higher doses to the tumor target while minimizing exposure to OARs.[18,19]

IMRT is widely applied in the treatment of head and neck tumors. In the case of medulloblastoma, this technique enables precise dose escalation to the target volume, allowing delivery of up to 5600 cGy to the posterior fossa, while ensuring that doses to critical structures remain within recommended tolerance limits Figure 3.

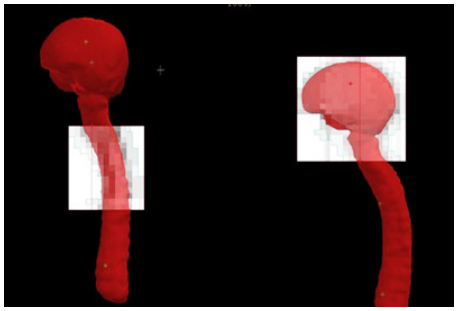

Fig. 3. *Delivery of radiation by IMRT beams.*

The IMRT treatment plan is delivered at multiple angles and divided into many small isodoses Figure 4.

During treatment with this method, more precise results are expressed in the dose-volume histogram (Figure 5).

Table 3 presents the minimum, maximum, and mean doses (in cGy) delivered to various OARs during IMRT for medulloblastoma. The crystalline lenses of both eyes received a maximum dose of 605–605 cGy, with a mean dose of 300 cGy, reflecting adequate sparing of these radiosensitive structures. The left and right eyes received similar maximum doses (605 cGy and 600 cGy, respectively) with mean doses limited to 300 cGy. The heart received a minimum dose of 220 cGy, a maximum dose of 605 cGy, and the highest mean dose among all OARs (≈350 cGy), indicating partial exposure due to its proximity to the inferior treatment fields. The left and right lungs showed maximum doses of 610 cGy and mean doses of 310–311 cGy, respectively. Renal exposure was kept minimal, with both kidneys receiving maximum doses of 600 cGy and mean doses limited to 300 cGy. Overall, the IMRT technique demonstrated effective dose modulation, ensuring OAR doses remained within clinically acceptable limits while optimizing target coverage.

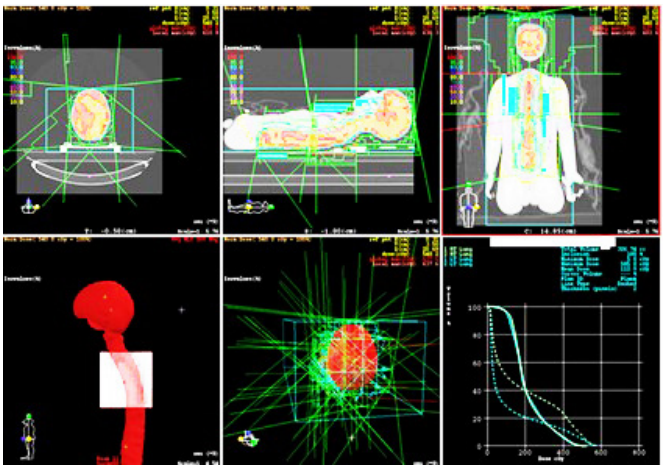

Fig. 4. *Medulloblastoma IMRT treatment plans.*

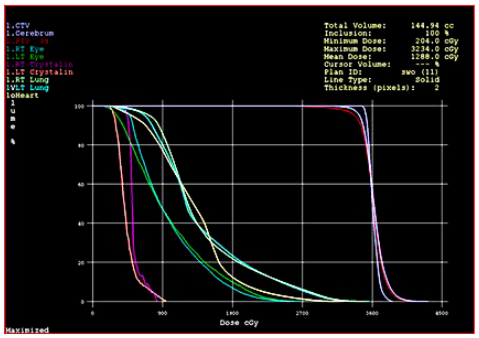

Fig. 5. *DVH for IMRT medulloblastoma treatment.*

Table 3.

The minimum, average, and maximum doses for OAR during IMRT treatment.

Dose /OAR	Min Dose (cGy)	Max Dose (cGy)	Mean Dose (cGy)
Crystalline left	300	600	300
Crystalline right	300	605	300
Left Eye	310	605	300
Right Eye	300	600	300
Heart	320	605	550
Left Lung	314	610	310
Right Lung	315	610	311
Left Kidney	310	600	300
Right Kidney	310	600	300

Conclusions

For a patient diagnosed with medulloblastoma, treatment plans were generated using both three-dimensional conformal radiotherapy (3D-CRT) and intensity-modulated radiation therapy (IMRT) techniques. In both approaches, the prescribed dose adequately covered the PTV. The plans were compared using dose–volume histograms (DVHs) and by evaluating the doses received by organs at risk (OARs).

This comparison aimed to evaluate the advantages and disadvantages of the two three-dimensional radiotherapy planning methods and to determine the optimal approach based on patient-specific characteristics, total prescribed dose to the PTV, and contour delineation defined by the radiation oncologist.

1. OAR sparing: IMRT provided superior protection for critical organs compared to 3D-CRT, resulting in lower expected side effects.

2. Dose escalation potential: Greater OAR sparing with IMRT may allow safe escalation of the tumor dose, potentially improving tumor control and clinical outcomes.

3. Treatment time: IMRT generally requires a more extended treatment delivery time compared to 3D-CRT.

The DVH comparison shows that for the same prescribed tumor dose, the OARs received lower radiation exposure with IMRT compared to 3D-CRT.

IMRT offers an optimized dose distribution for medulloblastoma by reducing radiation exposure to critical organs while maintaining effective tumor coverage. However, for craniospinal irradiation (CSI), proton therapy remains the most effective modality in reducing long-term toxicity.

3D-CRT, while capable of delivering a uniform dose to the craniospinal axis, exposes more normal tissue to radiation. It remains an effective and widely accessible technique, but when available, IMRT or proton therapy is preferred to reduce the risk of late side effects.

Conflicts of Interest

The authors declare that they have no competing interests.

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