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Scalp dosimetry as a predictor of radiation-induced alopecia in primary brain tumours: a retrospective study from a tertiary cancer centre in south India

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Abstract

Introduction: Radiotherapy is essential in treating primary brain tumours, but radiation-induced alopecia (RIA) remains a common side effect that significantly affects patients' quality of life (QOL). With its psychosocial impact on self-image, emotional well-being, and social interactions, alopecia warrants focused attention. This study aims to evaluate the scalp as an organ at risk by defining dose constraints that minimize RIA while maintaining optimal target coverage.

Materials and methods: A retrospective analysis was conducted on 70 patients with primary brain tumours who received focal cranial radiotherapy between January 2022 and December 2024. Scalp dose-volume histograms (DVHs) were generated from treatment planning systems, and the mean scalp dose (D mean), maximum scalp dose (D max), median volume of scalp, volume of scalp receiving ≥ 30 Gy (V30Gy), dose received by 20cc (D20cc), and 30cc (D30cc) scalp volume were recorded. RIA was graded according to the Common Terminology Criteria for Adverse Events (CTCAE) version 5.0. ROC statistical analysis was performed to evaluate the predictive value of scalp dosimetric parameters for RIA severity.

Results: The median age of the cohort was 57 years, with a male-to-female ratio of 1.08:1. The median D max, D mean, V 30 Gy, D20cc were 60.4 Gy, 17.5 Gy, 19.2%, and 46.4 Gy, respectively. Grade 2 and higher RIA was observed in 63% of patients. V30Gy, either independently or in combination with Scalp D mean, was identified as a significant predictor of Grade 2 or higher RIA.

Conclusion: Optimising scalp dose parametric during radiotherapy planning may help mitigate RIA and improve QOL.

Keywords: Scalp dosimetry, Radiotherapy-induced alopecia, Primary brain tumours, VMAT, QOL

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Introduction

Despite major advances in radiation technology and treatment planning of primary brain tumours, damage to healthy tissues is inevitable, especially in the skin and hair follicles. These structures are particularly vulnerable because they contain rapidly dividing keratinocytes and a high concentration of epithelial and melanocyte stem cells. As a result, radiation exposure can disrupt skin regeneration, leading to side effects such as redness, hair loss, and, over time, scarring or changes in pigmentation (1). Cicatricial or scarring alopecia occurs due to the permanent destruction of the hair follicle, resulting in the effacement of follicular orifices in a patchy or diffuse distribution. The occurrence of acute radiotherapy-induced alopecia (RIA) is reported to be as high as 85–90% in patients who receive cranial RT, with up to 60% of patients experiencing incomplete hair regrowth even after six months of completing radiation therapy (2).

Hair is an integral part of physical appearance and self-image, often influencing self-esteem. As a result, radiation-induced alopecia (RIA) can lead to significant psychological distress, including feelings of shame, depression, and social isolation due to the stigma associated with hair loss. RIA may be temporary; it tends to become persistent with increasing radiation dose (3) and can continue to progress long after the cessation of radiotherapy.

Management strategies focus on both prevention and treatment. Prophylactic measures emphasise patient education on proper scalp hygiene, while topical corticosteroids are used to manage scalp dermatitis, and topical antibiotics are prescribed to treat infections. In cases where skin reactions become severe, brief treatment interruptions may be necessary to allow the skin to heal.

A promising approach to reduce these side effects involves limiting radiation exposure to the scalp by delineating it as an organ at risk (OAR) and incorporating dose constraints during radiotherapy planning. However, reduced scalp toxicity should not be at the expense of compromised target coverage or exposure of critical brain structures, including the brainstem, optic nerves, and optic chiasm beyond their respective tolerances (4)

This study aims to highlight and address a significant lacuna in the existing literature concerning the prediction of radiation-induced alopecia based on scalp dosimetry and its potential for prevention. We aim to evaluate the feasibility and clinical relevance of integrating scalp-sparing techniques into routine radiotherapy planning without compromising target coverage or treatment delivery.

Materials and methods

We retrospectively identified patients with primary brain tumours who underwent surgical resection followed by adjuvant radiotherapy with curative intent at our institution between 2022 and 2024. The study included adult patients diagnosed with primary intracranial neoplasms, specifically gliomas, meningiomas, and medulloblastomas. All patients received conventional volumetric modulated arc therapy (VMAT) without scalp-sparing optimization, to a total dose of 54–60 Gy in 30 fractions over 6 weeks (5 days per week), with concurrent chemotherapy administered when clinically indicated. Patients with brain metastases and pediatric brain tumours were excluded from the study.

Contouring of target volumes, scalp and other OARs

CT simulation scans were obtained from the vertex to the C7 vertebrae, with a slice thickness of 3 mm. The European Organization for Research and Treatment (EORTC) guidelines were used to generate the CTV, GTV, and PTV contours. According to EORTC guidelines, the gross tumour volume (GTV) is defined as the enhancing lesion observed on T1 post-contrast MRI, along with the postoperative surgical cavity. The GTV is expanded by 1.5 to 2 cm to create the clinical target volume (CTV). which is then edited from the natural barriers hindering tumour growth, such as the bones, tentorium, and falx. The planning target volume (PTV) is then generated by geometrically expanding the CTV by 3 mm. PTV was prescribed doses ranging from 54 Gy to 60 Gy in 30 fractions at 1.8-2 Gy per fraction (5). The scalp, a layered structure directly

beneath the cranial skin surface, was delineated. This scalp contour was extended caudally to the level of the foramen magnum (6) as depicted in Figure 1 given below.

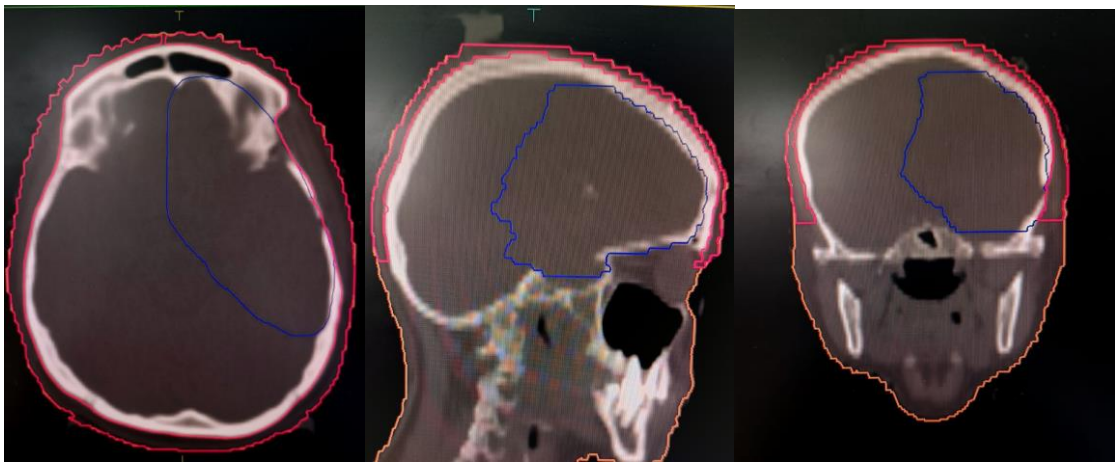


Figure 1. shows scalp contours in axial, coronal, and sagittal planes.

Intracranial OARs, namely the brainstem, optic chiasm, optic tract, optic nerves, lens, and eye, were also delineated.

Radiation planning and dosimetry

Patients were simulated in a supine position, with thermoplastic masks used to immobilise the head and neck areas in a neck-neutral position. The Volumetric Modulated Arc Therapy (VMAT) technique was utilised for treatment planning. All plans were generated using either the Eclipse version 13.7 (VARIAN) or the Monaco version 6.1.4 (ELEKTA) treatment planning systems with 6 MV photons. Each plan incorporated 1–2 non-coplanar arcs. Plans were optimised to ensure that 95% of the PTV received 100% of the prescribed dose.

The prescribed dose constraints for organs at risk were:

Optic nerves D max < 54 Gy, Optic Chiasm D max < 54 Gy, Brainstem D max < 54 Gy, Lens D max < 10 Gy, and Cochlea D max < 45 Gy (7). Scalp-specific dose parameters followed were: Scalp D mean < 20 Gy, Scalp D20cc < 50 Gy, Scalp D30cc < 40 Gy (8). Adequate PTV coverage was prioritised over scalp dose constraints.

The pattern of appearance of RIA was clinically observed at weekly intervals during radiotherapy in review outpatient clinics; while grading and documentation were done at the 3rd and 6th month follow-up visits post-radiotherapy, using the Common Terminology Criteria for Adverse Events (CTCAE) version 5.0. Alopecia severity was graded as follows:

- Grade 1: Hair loss of <50% of normal for that individual that is not obvious from a distance but only on close inspection
- Grade 2: Hair loss of ≥50% normal for that individual that is readily apparent to others
- Grade 3: Complete hair loss

Results

Patients receiving focal brain radiotherapy at the Department of Radiation Oncology at Kidwai Memorial Institute of Oncology between 2022 and 2024 were selected for our study.

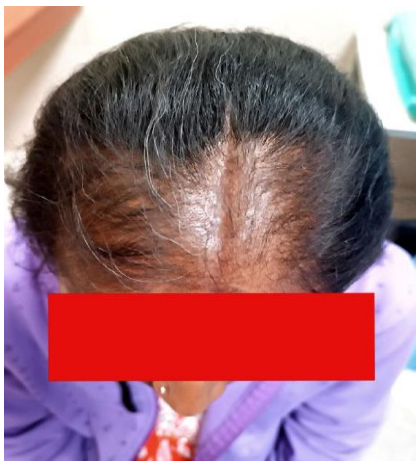
The median age of the cohort was 57 years (range: 32 to 77 years), with 52 per cent male and 48 per cent female patients. Among the analysed patient cohort, 84 percent had a diagnosis of glioma, of which 13 per cent had low-grade glioma, while 71 per cent had high-grade glioma. Additionally, 10 per cent of the cohort had medulloblastoma, whereas the remaining 6 per cent had meningioma. Concerning radiotherapy, 70 percent received 60 Gy in 30 fractions, while 30 percent

received 54 Gy in 30 fractions. **Table 1** given below summarises these baseline patient characteristics.

Table 1. shows the baseline patient characteristics.

Baseline characteristics	Median Value
Age	57 years
Gender	**Percentage**
Male	52%
Female	48%
Radiotherapy Dose	**Percentage**
54 Gy	30%
60 Gy	70%
Diagnosis	**Percentage**
Glioma	84%
Low grade	13%
High grade	71%
Medulloblastoma	10%
Meningioma	6%

These patients were routinely followed up in the clinic weekly during radiotherapy and subsequently at regular intervals, where RIA was assessed. Grade 2 and higher RIA was observed in 63% of patients, while Grade 1 RIA was observed in 37% of patients, respectively, as per CTCAE v5.0 grading which is represented in **Figure 2**.



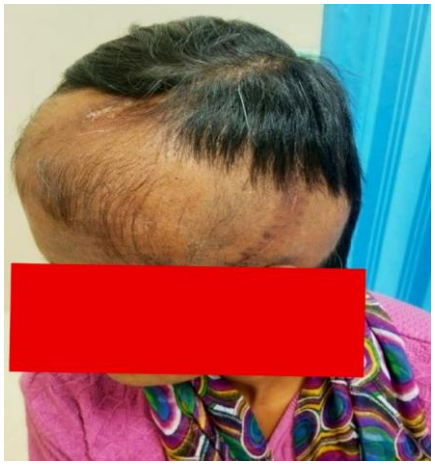


Figure 2. visually depicts the RIA severity, showing Grade 1 and Grade 2 and higher, respectively, in representative patients.

These values reflect aggregate assessments recorded at the third- and sixth-month follow-ups; however, the subjective perception of alopecia was reported by patients at a median of two weeks after the initiation of radiotherapy. Retrospectively, patients were analysed for scalp dosimetric parameters. **Table 2** given below summarises the various scalp dosimetric parameters.

Table 2. shows Scalp dosimetric parameters.

	Median Value	
Volume	382.7cc	
Dmax	60.4 Gy	
Dmean	17.5 Gy	
	Median Value	
	cc	%
V30cc	70.1	19.2
V40cc	35.2	8.5
	Median Value	
D20cc	46.4 Gy	
D30cc	42.2 Gy	

The median scalp volume measured was 382.7 cc (ranging from 166.518 to 573.498 cc). The median scalp D max was 60.4 Gy, while the median scalp D

mean was 17.5 Gy. Median scalp D20cc and D30cc were 46.4 Gy and 42.2 Gy, respectively. Additionally, the median volumes of the scalp receiving 30 Gy and 40 Gy were 70.1 cc (19.2%) and 35.2 cc (8.5%), respectively. The various planning parameters have been depicted in Figures 3 and 4 as follows.

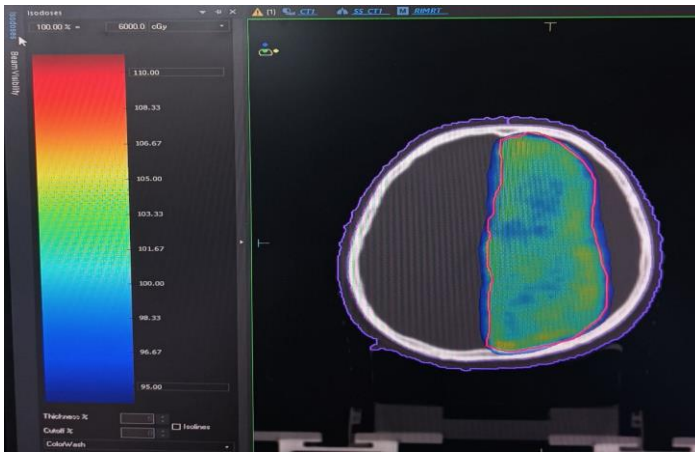


Figure 3. is a visual depiction of scalp dose in a representative patient via a VMAT plan. The scalp is represented by the purple colour contour, and PTV is demarcated by the red contour. Dose wash encompasses an area covered by the 95% iso-dose line.

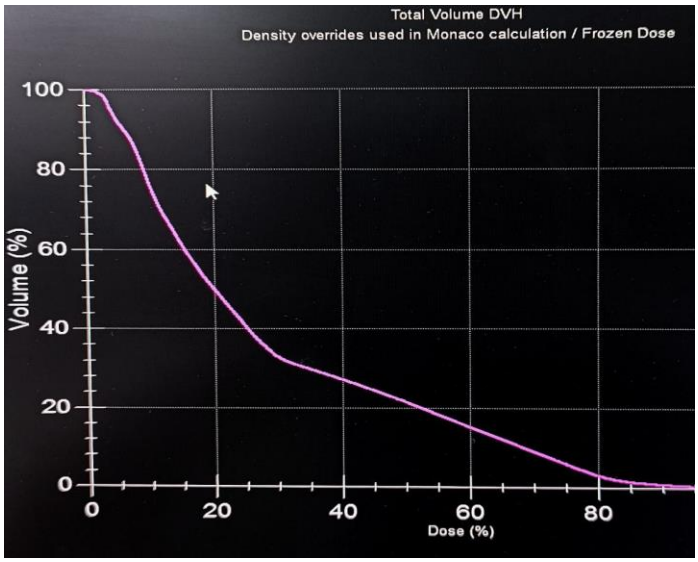


Figure 4. shows a scalp dose volume histogram (DVH).

Descriptive statistics were used to summarise patient characteristics. The predictive value of scalp dosimetric parameters for RIA severity was assessed using Receiver Operating Characteristic (ROC) analysis, specifically the Area Under the Curve (AUC). ROC curve analysis was conducted to assess the predictive performance of various scalp dosimetric parameters (e.g., Dmean, Dmax, V10, V20) with alopecia outcomes. The analysis was performed using IBM SPSS Statistics version 30.0.0, which offers advanced ROC analysis tools. The AUC was calculated along with 95% confidence intervals (CIs) to quantify the discriminative ability of each parameter. Optimal threshold values were determined using the Youden index (J = Sensitivity + Specificity − 1), which identifies the point that maximizes the balance between sensitivity and specificity. A p-value < 0.05 was considered statistically significant.

Direct statistical comparison between individual ROC curves (e.g., Dmean vs. V20) was not performed, as each dosimetric parameter represents a distinct physical quantity with different biological implications. Therefore, the ROC curves were interpreted independently to respect the variable-specific nature of the dosimetric data.

It was observed that V30Gy demonstrated the highest predictive value for Grade 2 or higher radiation-induced alopecia (RIA), with an AUC of **0.604** (95% CI: 0.431–0.777, p = 0.258). Using a cut-off value of **28.140%**, V30Gy had a sensitivity of 37.0% and a specificity of 93.8%, indicating a strong ability to correctly identify patients who are unlikely to develop Grade 2 or severe RIA. Similarly, Scalp D mean (Gy) exhibited a moderate predictive ability, with an AUC of **0.557** (95% CI: 0.388–0.726, p = 0.530). At a cut-off value of **20.210 Gy**, Scalp D mean had a sensitivity of 48.3% and a specificity of 81.3%, suggesting a more balanced ability to identify patients at risk of developing Grade 2 or higher RIA. Although neither parameter reached statistical significance (p > 0.05), their AUC values and high specificity indicate that scalp dosimetry could play a potential role in predicting Grade 2 or higher RIA severity

Discussion

Although the mechanisms behind radiotherapy-induced alopecia (RIA) are not fully understood, significant damage from radiotherapy can affect both the epithelial stem cells in the bulge region and the rapidly dividing matrix cells in the hair follicle bulb. This damage to these critical cells preferentially induces anagen effluvium, a type of hair loss where hair

in the growth phase (anagen) is shed prematurely. This hair loss is consistent with nonspecific scarring alopecia (9). Typically, this process begins within 2–3 weeks after the initiation of radiotherapy. Hair follicle radiosensitivity is also dependent on the hair cycle stage: anagen matrix cells are more radiosensitive than telogen matrix cells due to relative differences in proliferation rates. A dose of 3 Gy produces complete, reversible anagen alopecia, whereas permanent alopecia begins to occur at 5 Gy (10). Complete hair regrowth generally occurs 2−4 months after irradiation in the reversible type of radiation-induced alopecia (11). In certain patients, RIA may continue to progress well beyond the completion of radiotherapy (12). This observation suggests the initiation of a chronic pathogenic cascade that extends far beyond the early phase of radiation-induced skin and hair follicle damage. Also considering that anagen hair follicles lie about 4–5 mm deep embedded within human scalp skin, dose fraction sizes and total cumulative doses have a direct effect on RIA (13). Due to the lack of reliable data on scalp dosimetry, clinicians often have difficulty accurately predicting and explaining the likelihood of alopecia to patients, even after carefully reviewing treatment plan metrics.

The results of our study suggest that while these dosimetric factors may have individual relevance, they may not independently serve as strong predictors of severe RIA. However, combining multiple parameters could enhance predictive accuracy, supporting the integration of scalp dose optimisation into radiotherapy planning to reduce the risk of radiation-induced alopecia.

This study has several limitations that warrant consideration. First, the retrospective design inherently introduces the potential for selection bias and limits control over confounding variables such as baseline scalp condition, prior treatments, and comorbidities that may influence the risk of alopecia. Second, the sample size was relatively small, which may reduce the statistical power of the findings and limit their generalizability. While the study identified dosimetric thresholds predictive of alopecia, these results should be interpreted with caution and validated in larger, prospective cohorts. Additionally, the assessment of alopecia was based on available clinical documentation and grading scales, which may be subject to interobserver variability. Finally, although ROC curve analysis provided insight into the predictive performance of individual dosimetric parameters, multivariate analysis was not performed to adjust for potential confounding factors such as age, chemotherapy exposure, or concurrent treatments, all of which may independently contribute to hair loss.

Although our study is retrospective, scalp dosimetric parameters did not compromise planning target volume (PTV) coverage or pose a risk to adjacent critical organs. This highlights the potential for Scalp Sparing Volumetric-Modulated Arc Therapy (SSV) as a feasible strategy in radiotherapy. Further studies with larger sample sizes and multivariate analysis may refine predictive models, establish clinically actionable scalp dose constraints, and support routine implementation in clinical practice.

Conclusion

Scalp-sparing Volumetric Modulated Arc Therapy (VMAT) is a promising technique that can effectively reduce radiation exposure to the scalp whilst ensuring optimal target coverage. This approach holds the potential to markedly reduce both acute and late radiation-induced toxicity to the scalp, ultimately enhancing patient outcomes by alleviating the psychological burden of hair loss, promoting faster recovery, and improving overall quality of life.

Author contribution

GHB and **IKh** conceptualization and validation, **LNS** and **GHB** methodology and Software, **LNS** formal analysis and writing original draft, **LNS**, **VBR**, **AKT**, **PT** and **SR** investigation, **VBR**, **AKT**, **PT** and **SR** resources acquisition and data curation, **LNS**, **GHB** and **IKh** reviewing and editing and project administration, **LNS** and **VBR** visualisation, **GHB** supervision.

Conflict of interest

The author declares no conflict of interest.

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