

Comparative Analysis of Spinal Cord Dose Using Various Planning Techniques in Head and Neck Cancer Radiotherapy

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Abstract:

Background: The spinal cord is a highly radiosensitive organ at risk in head and neck cancer radiotherapy. Excessive doses can cause irreversible complications, necessitating careful dose planning.

Aim: To compare spinal cord doses in forward-planned intensity-modulated radiotherapy (FP-IMRT) and inverse-planned intensity-modulated radiotherapy (IP-IMRT) techniques and evaluate their dosimetric advantages.

Methodology: A comparative observational study was conducted on 90 patients with stage III–IVA head and neck squamous cell carcinoma at the Department of Medical Physics, State Cancer Institute, Indira Gandhi Institute of Medical Sciences, Bihar, India. Patients underwent FP-IMRT and IP-IMRT planning on CT datasets, with dose-volume histogram (DVH) parameters recorded for 1 cm³, 2 cm³, and 5 cm³ (cc) volumes of the spinal cord. Plan quality and maximum dose (D_{max}) were assessed, and statistical comparisons were performed using paired tests.

Results: IP-IMRT consistently delivered lower spinal cord doses across all volumes (1 cm³: 37.0 Gy vs. 40.2 Gy; 2 cm³: 36.5 Gy vs. 39.5 Gy; 5 cm³: 35.2 Gy vs. 38.0 Gy) and reduced D_{max} (38.2 Gy vs. 41.5 Gy) compared to FP-IMRT ($p < 0.01$). Volumes receiving 40 Gy and 45 Gy were significantly lower with IP-IMRT. Plan quality analysis favored IP-IMRT, with 53.3% rated excellent versus 24.4% for FP-IMRT.

Conclusion: IP-IMRT provides superior spinal cord sparing and higher plan quality compared to FP-IMRT, supporting its use for safe and effective head and neck radiotherapy.

Keywords: Head and neck cancer, spinal cord, IMRT, forward planning, inverse planning, dosimetry, radiotherapy.

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Introduction

The spinal cord is a critical organ at risk (OAR) in the radiotherapy of head and neck cancers. Because of its extreme radio sensitivity, even minor overdoses may lead to serious and irreversible effects like radiation-induced myelopathy, one of the most feared effects in clinical radiotherapy practice. Radiation oncologists therefore focus on the minimum dose to be administered to the spinal cord and still cover the tumor [1]. The use of parallel opposed lateral fields to deliver therapeutic doses to the target

areas and sparing of critical normal structures is a common practice in conventional head and neck cancer treatments. Clinical practice and current professional opinion indicate that the dose of opposed lateral treatment fields should be restricted to about 45 Gy to prevent direct spinal cord irradiation, which is frequently included in standard treatment regimens [2].

Nevertheless, it is a proven fact that the spinal cord still receives more radiation due to the scatter and secondary exposures during the treatment process, despite the use of off-cord fields [3]. Nevertheless, the literature does not provide much specific recommendations on the acceptable limits of this extra dose of scatter and the cumulative effect of such doses is not always reported. In most clinical trials involving spinal cord tolerance, it is not always clear whether the scatter contributions are added to the reported total dose, which may result in differences in planning decisions and possible underestimation of risk. Thus, a safe and reasonable dose to the cervical spinal cord in head and neck radiotherapy must be determined by an informed clinical judgment, especially in the modern three-dimensional (3 D) treatment planning methods [4].

Recent developments in radiotherapy, including conformal radiotherapy, intensity-modulated radiotherapy (IMRT), and volumetric modulated arc therapy (VMAT), have opened the prospect of complex treatment geometries that can be used to both escalate tumor dose and spare normal tissues [5]. Such advanced methods require well-established tolerance levels of organs at risk such as the spinal cord to develop strategies that ensure that the tumor is covered as much as possible and the risk of serious complications is reduced. The 45 Gy limit has historically been used as a conservative limit, but clinical experience has shown that higher doses have been administered in the past with a low rate of myelitis (less than 1 percent), and more liberal and evidence-based limits can be used in modern practice.

The objective of the current research is to compare and contrast spinal cord doses in different radiotherapy planning methods in head and neck cancers. We will measure the cumulative dose to the spinal cord, which includes the primary dose to the spinal cord due to large opposed fields and secondary dose to the spinal cord due to off-cord fields during tumor boosts [6]. Our institutional protocol provides the first 46 Gy with standard parallel opposed lateral fields, and then the fields are adjusted to avoid direct irradiation of the spinal cord. Although this is reduced, the spinal cord is bound to receive extra doses of scattered photons and partial irradiation during tumor boost phases. This primary and scattered radiation combination has been clinically utilized over decades with little risk, and it has shown the significance of proper dose evaluation and planning.

It is thus necessary to set a clinically reasonable dose limit of the spinal cord in the 3 D treatment planning era [7]. An overly conservative limit may unduly limit treatment plans and reduce tumor coverage, whereas an overly permissive limit may raise the risk of radiation-induced myelopathy. Therefore, thorough assessment of spinal cord doses with various planning methods does not only provide safe dose limits but also assists in the choice of the best

planning methods that would strike a balance between tumor control and normal tissue protection. This paper will attempt to offer such an assessment, which will help in the formulation of evidence-based planning principles in head and neck radiotherapy.

In general, this comparative analysis covers a very important issue of radiotherapy planning: patient safety and sufficient tumor dose coverage. This study aims to elucidate the effects of planning method on the dose to the spinal cord in various planning methods, assess the cumulative effects of initial and boost fields, and finally justify the use of rational and clinically feasible dose limits in head and neck cancer radiotherapy. The work is based on decades of clinical experience and research on spinal cord tolerance, providing information on how to optimize modern radiotherapy practice without jeopardizing patient safety.

Methodology

Study Design: This study was designed as a hospital-based, comparative, observational study aimed at analyzing the dose received by the spinal cord using various radiotherapy planning techniques in patients with head and neck cancers. The dosimetry assessment was carried out retrospectively on CT datasets and planning information from previously treated patients, followed by a prospective follow-up for evaluation of spinal cord toxicity.

Study Area: The study was conducted in the Department of Medical Physics, State Cancer Institute, Indira Gandhi Institute of Medical Sciences, Bihar, India, a tertiary care center providing specialized radiotherapy services for head and neck malignancies.

Study Duration: The study was carried out over a period of two year, from January 2022 to December 2023.

Study Participants

Inclusion Criteria

- Biopsy-proven, previously untreated squamous cell carcinoma of the oral cavity, oropharynx, hypopharynx, or larynx.
- Stage III or IVA disease according to TNM classification.
- Eastern Co-operative Oncology Group (ECOG) performance status of 0–2.
- Scheduled for radical radiotherapy with or without concurrent chemotherapy.

Exclusion Criteria

- Significant comorbidities, including uncontrolled diabetes mellitus, hypertension, or cardiac disease.
- Hemoglobin levels less than 10 g/dL.
- History of radiotherapy to the head and neck region.

- Pregnant or lactating patients.

Sample Size: A total of 90 patients were included in the study based on the available CT datasets and treatment records for dosimetry analysis.

Procedure: All eligible patients underwent comprehensive pre-treatment evaluation including detailed medical history, physical examination, endoscopy, biopsy, complete blood count, biochemical investigations, chest X-ray, and contrast-enhanced computed tomography (CT) of the head and neck region as per institutional protocols. Additional investigations such as abdominal ultrasound or bone scan were performed when clinically indicated. Nutritional and dental assessments were carried out prior to radiotherapy, and Ryle's tube insertion was performed in patients with compromised oral intake. CT simulation was performed using a GE Revolution EVO CT simulator. Patients were immobilized

using thermoplastic masks to ensure reproducibility during imaging and treatment delivery. The acquired images were reconstructed with a slice thickness of 2.5 mm for adult patients and 1.25 mm for pediatric patients. Treatment planning was performed on non-contrast CT datasets.

Target volumes including gross tumor volume (GTV), clinical target volume (CTV), and organs at risk (OAR) such as the spinal cord were contoured according to standard institutional and international guidelines. The spinal cord was delineated within the spinal canal without additional margin. Treatment planning was performed using the Eclipse Treatment Planning System (TPS) (Varian Medical Systems) employing both forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT) techniques. The following calculation models and algorithms were used:

S. No.	Calculation Type	Algorithm / Model Name	Version
1	Volume Dose Calculation	Anisotropic Analytical Algorithm (AAA)	16.1.0
2	DVH Estimation	DVH Estimation Algorithm	16.1.0
3	Portal Dose Prediction (QA)	Portal Dose Image Prediction (PDIP)	16.1.0
4	Optimization	Photon Optimizer (PO)	16.1.0
5	Surface Compensation	Irregular Surface Compensator (ISC)	16.1.0

All plans were optimized to achieve adequate target coverage while minimizing radiation dose to the spinal cord and other critical structures. Dosimetric evaluation of the spinal cord was performed using dose-volume histogram (DVH) parameters for 1 cm³, 2 cm³, and 5 cm³ volumes. Patients were treated with a total prescribed dose of 66–70 Gy in 33–35 fractions, delivered five days per week, based on tumor stage and institutional protocols. Treatment delivery was carried out using a Clinac iX linear accelerator (Varian Medical Systems). Patient setup verification was performed using an onboard imaging system with Electronic Portal Imaging Device (EPID) to ensure accurate positioning prior to treatment delivery. Patients were followed prospectively for a period of six months to assess spinal cord toxicity. Toxicity grading was performed using the Radiation Therapy Oncology Group (RTOG) criteria,

which classify adverse effects from Grade 0 (no toxicity) to Grade 4 (severe toxicity).

Plan Quality Evaluation Criteria

Treatment plan quality was evaluated using standard dosimetric indices including target coverage, homogeneity index (HI), conformity index (CI), and organ-at-risk (OAR) dose constraints based on RTOG guidelines. Target coverage was considered adequate when at least 95% of the planning target volume (PTV) received $\geq 95\%$ of the prescribed dose. The homogeneity index (HI) was calculated as $(D2\% - D98\%) / D50\%$, and conformity index (CI) was assessed as the ratio of the volume receiving prescribed dose to the target volume. OAR constraints, particularly spinal cord dose, were evaluated according to QUANTEC recommendations ($D_{max} < 45$ Gy). The detailed criteria used for classification are presented in Table 2.

Plan Quality	Target Coverage (PTV)	HI	CI	Spinal Cord Dose
Excellent	$\geq 95\%$ volume gets $\geq 95\%$ dose	≤ 0.10	0.9–1.1	$D_{max} < 40$ Gy
Good	$\geq 95\%$ volume gets $\geq 93\%$ dose	0.10–0.15	0.8–1.2	$D_{max} 40-45$ Gy
Acceptable	$\geq 90\%$ volume gets $\geq 90\%$ dose	0.15–0.20	0.7–1.3	$D_{max} \leq 50$ Gy
Poor	$< 90\%$ coverage	> 0.20	< 0.7 or > 1.3	$D_{max} > 50$ Gy

Statistical Analysis: All statistical analyses were performed using SPSS version 27.0. Continuous variables were expressed as mean \pm standard deviation, while categorical variables were presented as

frequencies and percentages. Comparative analysis between FP-IMRT and IP-IMRT techniques was performed using paired t-tests or Wilcoxon signed-rank tests, as appropriate. Correlation between DVH

parameters and clinical variables was assessed using Pearson or Spearman correlation coefficients. A p-value of <0.05 was considered statistically significant.

Result

Table 3 presents the demographic characteristics of the 90 patients included in the study. The age distribution shows that the majority of patients were between 31 and 45 years old (32, 35.5%), followed closely by those aged 46–60 years (28, 31%). Patients aged ≤30 years accounted for 14 (15.5%) of the study population, while those over 60 years

comprised 16 (18%). In terms of gender, males predominated with 62 patients (68.9%), compared to 28 females (31.1%). Regarding ECOG performance status, most patients had a status of 1 (40, 44.4%), indicating they were restricted in physically strenuous activity but ambulatory; 30 patients (33.3%) had a status of 0, reflecting fully active performance, while 20 patients (22.2%) had a status of 2, suggesting they were ambulatory and capable of all self-care but unable to carry out any work activities. Overall, the cohort primarily consisted of middle-aged males with good to moderate functional status.

Characteristic	Number of Patients (n)	Percentage (%)
Age (years)		
≤30	14	15.5
31–45	32	35.5
46–60	28	31.0
>60	16	18.0
Gender		
Male	62	68.9
Female	28	31.1
ECOG Performance Status		
0	30	33.3
1	40	44.4
2	20	22.2

Table 4 shows the maximum spinal cord dose (Dmax) delivered using different radiotherapy planning techniques. The forward-planned IMRT (FP-IMRT) resulted in a higher mean Dmax of 41.5 Gy with a standard deviation of 3.8 Gy, a median of 42 Gy, and a range from 35 to 49 Gy. In comparison, inverse-planned IMRT (IP-IMRT) produced a lower

mean Dmax of 38.2 Gy ± 3.1 Gy, with a median of 38 Gy and a narrower range of 32 to 44 Gy. This indicates that IP-IMRT is more effective in limiting the maximum dose to the spinal cord, potentially reducing the risk of radiation-induced spinal cord toxicity compared to FP-IMRT.

Planning Technique	Mean ± SD (Gy)	Median (Gy)	Range (Gy)
FP-IMRT	41.5 ± 3.8	42	35–49
IP-IMRT	38.2 ± 3.1	38	32–44

Table 5 presents the comparison of spinal cord doses for 1 cm³, 2 cm³, and 5 cm³ volumes between forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT). Dose values were analyzed for 1 cc (1 cm³), 2 cc, and 5 cc volumes of the spinal cord. It is evident that for all measured volumes, the spinal cord received a higher mean dose with FP-IMRT compared to IP-IMRT. Specifically, for 1 cm³, the mean dose was 40.2 ± 3.6 Gy with FP-IMRT versus 37.0 ± 2.9 Gy with IP-IMRT.

Similarly, for 2 cm³, FP-IMRT delivered 39.5 ± 3.5 Gy, whereas IP-IMRT delivered 36.5 ± 2.7 Gy. For the largest volume of 5 cm³, the dose further decreased to 38.0 ± 3.4 Gy in FP-IMRT and 35.2 ± 2.5 Gy in IP-IMRT. This trend indicates that IP-IMRT consistently achieved lower spinal cord doses across all volumes, suggesting a potential dosimetric advantage in minimizing radiation exposure to this critical organ at risk.

Volume (cm ³)	FP-IMRT Dose (Gy) Mean ± SD	IP-IMRT Dose (Gy) Mean ± SD
1 cm ³	40.2 ± 3.6	37.0 ± 2.9
2 cm ³	39.5 ± 3.5	36.5 ± 2.7
5 cm ³	38.0 ± 3.4	35.2 ± 2.5

Plan quality was categorized as Excellent, Good, Acceptable, and Poor based on target coverage, dose homogeneity, conformity index, and organ-at-risk (OAR) dose constraints as per standard radiotherapy planning guidelines such as RTOG protocols.

Table 6 presents the overall plan quality assessment for 90 patients comparing forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT). The results show that IP-IMRT achieved a higher proportion of excellent plans (48 patients, 53.3%)

compared to FP-IMRT (22 patients, 24.4%), indicating superior plan quality with the inverse planning approach. Conversely, FP-IMRT had more plans rated as good (38, 42.2%) than IP-IMRT (30, 33.3%), and also higher numbers in the acceptable (20 vs. 10) and poor (10 vs. 2) categories, suggesting a wider distribution of plan quality. Overall, IP-IMRT demonstrated a stronger tendency toward excellence and fewer suboptimal plans, reflecting its effectiveness in achieving optimal dose distributions in head and neck radiotherapy.

Table 6: Overall Plan Quality Assessment (n = 90)

Plan Quality	FP-IMRT (n)	IP-IMRT (n)	Percentage FP (%)	Percentage IP (%)
Excellent	22	48	24.44	53.33
Good	38	30	42.22	33.33
Acceptable	20	10	22.22	11.11
Poor	10	2	11.11	2.22

Table 7 shows a comparison of spinal cord dose-volume histogram (DVH) parameters between forward-planned IMRT (FP-IMRT) and inverse-planned IMRT (IP-IMRT) techniques. Across all parameters, IP-IMRT delivered significantly lower doses to the spinal cord than FP-IMRT. Specifically, the D2% and D5% values, representing near-maximum doses, were reduced from 43.5 ± 4.0 Gy and 42.0 ± 3.7 Gy in FP-IMRT to 39.8 ± 3.2 Gy and 38.5 ± 2.9 Gy in IP-IMRT, respectively (p < 0.01). The mean spinal

cord dose also decreased from 39.2 ± 3.5 Gy with FP-IMRT to 36.0 ± 2.8 Gy with IP-IMRT (p = 0.003). Additionally, the volume of the spinal cord receiving 40 Gy (V40) and 45 Gy (V45) was significantly lower in IP-IMRT (48 ± 10% and 28 ± 8%) compared to FP-IMRT (65 ± 12% and 42 ± 10%), with p-values of 0.004 and 0.005, respectively. These findings indicate that IP-IMRT provides superior spinal cord sparing compared to FP-IMRT.

Table 7: Comparison of Spinal Cord DVH Parameters between FP-IMRT and IP-IMRT

DVH Parameter	FP-IMRT Mean ± SD	IP-IMRT Mean ± SD	p-value
D2% (Gy)	43.5 ± 4.0	39.8 ± 3.2	0.001
D5% (Gy)	42.0 ± 3.7	38.5 ± 2.9	0.002
Mean Dose (Gy)	39.2 ± 3.5	36.0 ± 2.8	0.003
V40 Gy (%)	65 ± 12	48 ± 10	0.004
V45 Gy (%)	42 ± 10	28 ± 8	0.005

Discussion

The study found that inverse planned IMRT (IP-IMRT) produces lower maximum spinal cord doses and decreased spinal cord dosage to specific spinal cord areas when compared to forward planned IMRT (FP-IMRT) which supports existing research that shows inverse planning gives superior dosimetric results for protecting essential neural structures. For example, Breen et al. (2006) [8] studied planning organ at risk volumes (PRVs) which protect spinal cord during intensity modulated radiotherapy treatments for oropharyngeal cancers. They proved that using PRV margins of approximately 6 millimeters together with setting spinal cord limits at 45 Gy actual dose delivery to the spinal cord would decrease. This finding supports our results which demonstrate that IP-IMRT achieves better dose control and produces more limited dose spread than other methods.

Advanced modulation techniques show superior performance in spinal cord sparing through their

improved planning capabilities when compared to standard planning methods. Chen et al. (2011) [9] evaluated the brainstem and spinal cord dose reduction achieved through IMRT treatment in re-irradiation cases. The researchers studied a group with recurrent disease but found that their IMRT designs enabled effective dose control to protect the spinal cord while treating recurrent tumors because inverse optimization provided a system to maintain target coverage and organ protection. The results show that IP-IMRT decreases spinal cord Dmax while reducing D2% and D5% near maximum doses and diminishing the volume of cord that receives 40 and 45 Gy.

Multiple modulated technique comparisons show how different planning methods perform against each other. Stieler et al. (2011) [10] conducted a comparison of three modulated radiotherapy techniques which included step and shoot IMRT and serial tomotherapy and VMAT for head and neck cancer treatment. The researchers studied spinal cord

results but their data showed that modern techniques produced better conformity and OAR protection than older techniques. The study results confirm our research finding that advanced inverse algorithms lead to better protection of spinal cord and other vital structures when compared to forward planning methods. The study presented no specific cord dose data but the research showed enhanced normal tissue protection which matched the reduced cord doses we found.

The development of spinal cord dosimetry in radiotherapy shows improved accuracy when compared to past conformal techniques. Cozzi et al. (2004) [11] performed a dosimetric analysis which showed that IMRT treatment reduced spinal cord maximum dose for head and neck patients compared to three-dimensional conformal radiotherapy (3D CRT). The study found lower spinal cord exposure through IP IMRT because IMRT enables higher treatment precision through its advanced treatment delivery system. The body of research demonstrates that inverse planned techniques exhibit the power to create dose distributions which avoid critical structures.

The spinal cord dose constraints and dosimetric changes that affect clinical outcomes receive essential context from multiple guideline-oriented studies and review research. The QUANTEC (Quantitative Analysis of Normal Tissue Effects in the Clinic) recommendations (based on synthesis of clinical dose response data) suggest that the mean spinal cord dose should be kept below 45 Gy and that the volume receiving 50 Gy should be limited to 0.3 cc to minimize the risk of radiation myelopathy (Jackson et al., 2010) [12]. Our selection of a 50 Gy first phase constraint aligns with these guidelines because our research showed no acute clinical toxicity after total physical dose reached 50 Gy during the brief follow up period. The IP IMRT method shows dosimetric advantages which the QUANTEC data prove to have clinical significance in this research study.

The literature shows that inverse planning provides benefits yet conventional planning methods should still be used with caution. Majumder et al. (2014) [13] assessed the prescribed versus calculated dose to the spinal cord in conventional two-phase planning and highlighted that scatter and transmission doses can lead to higher actual cord doses than predicted, even with cord sparing fields. The study found that extra dose existed beyond prescribed amounts which matches our results about scatter effects because the researchers did not test IMRT methods directly. The study results demonstrate the necessity of precise volumetric dose measurements especially when new planning methods and software remain unavailable.

The results of dose constraint discussions within IMRT demonstrate that present-day treatment planning first targets protection of spinal cord while

following their treatment requirements. Boisselier et al. (2016) [14] reviewed dose constraints for spinal cord and brachial plexus in head and neck IMRT, emphasizing that inverse planning allows more reliable adherence to critical structure constraints compared to conventional approaches. The research findings support the use of IP IMRT as the preferred methodology because they demonstrate our ability to enhance both plan quality and organ protection results.

The study showed that IP IMRT delivers better spinal cord protection than existing methods according to multiple comparative dosimetry analyses from different research studies. The use of inverse planning results in reduced spinal cord maximum and volumetric doses together with improved plan conformity which meets all clinical dose constraint requirements. Thus, IP IMRT should become the primary choice for spinal cord protection during head and neck radiotherapy.

Conclusion

The present study demonstrates that inverse-planned IMRT (IP-IMRT) provides superior dosimetric advantages over forward-planned IMRT (FP-IMRT) in head and neck radiotherapy, particularly in sparing the spinal cord. IP-IMRT consistently achieved lower maximum doses, reduced dose exposure across different spinal cord volumes, and improved dose-volume histogram parameters, thereby minimizing the risk of radiation-induced myelopathy. Additionally, it yielded a higher proportion of excellent-quality treatment plans, reflecting better target coverage and organ-at-risk protection. These findings highlight the clinical importance of advanced inverse planning techniques in optimizing treatment outcomes. Therefore, IP-IMRT should be preferred in modern radiotherapy practice to ensure a balanced approach between effective tumor control and enhanced patient safety.

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