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Improving Treatment Time Delivery By Multileaf Collimator Optimization In Intensity Modulated Radiotherapy

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Abstract:
Background*: Radiation therapy can be administered using Intensity Modulated Radiation Therapy (IMRT), a technique that allows the beam's intensity to be adjusted within the treatment field. To achieve this, a large beam was splitted into numerous smaller beamlets. The specific weights of these numerous beamlets are determined by performing computerized inverse optimization after dose limitations are applied to both the target and sensitive structures. So this study aims to optimize and improve the treatment time delivery for IMRT cases and evaluate its influence on the plan quality.*
Materials and Methods*: The study included cases of head and neck cancer. This study was performed on real CT imaging of cases. The delineated contours for treatment purposes of head and neck retrospective cases. IMRT Plans that used to calculate these cases with a definite number of beamlets, definite fluence map, and definite MLC shape. Calculated plans, and cases already finished treatment, this was done by changing some beamlets, changing the flounce map, and changing the MLC shape. Optimizing plans till reaching the same endpoint to the treatment planning evaluation parameters such as organ at risk (OAR) constraints, maximum, minimum, and hotspot doses, conformity index, and heterogeneity index was used to evaluate the coverage of the treatment target.*
Results*: Compared to the original plan, the optimal time for the modified plan was much shorter. The modified plan reduced the average estimated delivery time. The expected delivery time was much shorter with the modified plan compared to the original plan.*
Conclusion: *The modified plan showed a significant increase over the original plan for the smallest measurements of beams 1, 2, 3, 4, 5, 6, 7, and the mean beam.*
Key Word*: Multileaf Collimator, Intensity-modulated radiotherapy (IMRT), Head & neck cancer; Optimization time delivery.*

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I. Introduction

IMRT has been increasingly popular as a method for treating cancer, particularly in cases where the tumors are in hard-to-reach areas or have complicated anatomical characteristics. The emergence of more sophisticated delivery methods and advancements in imaging technologies like Positron Emission Tomography (PET), magnetic resonance imaging (MRI), Computed Tomography (CT), and Ultrasound (US) have made it a more dependable treatment approach for cancer patients. The dosage escalation, improved Planning Target Volume (PTV) coverage, and improved organs at risk (OARs) sparing capabilities of IMRT make it a highly regarded radiation therapy modality.

An improved kind of external beam radiation, intensity-modulated radiotherapy (IMRT) uses beamlets to divide each beam and adjust its power output. Computerized inverse planning procedures, made possible by MLC motions, allow for the individual adjustment of beamlet intensity. Improved dosage conformation, including concave dose distribution, is achieved by modulating intensity and varying the number of fields inside each voxel. Unlike traditional radiation, which is used to give patients beams of uniform intensity, IMRT deliberately generates non-uniform intensities. By adjusting the radiation dose in relation to the patient's preferred position, IMRT can be used.

IMRT is based on the inverse planning process of the treatment planning system (TPS), which determines the maximum and minimum dosage limits for each delineated part and beam angles following structural delineation. Following this, the computer will determine the beam intensities using a variety of algorithms and repeated calculations to achieve the target dosage distribution. The conformal dose distribution produced by

IMRT has thinner margins, which increases the risk of missing the tumor's microscopic splits during therapy and subsequent tumor recurrence. The necessity for image guided radiation (IGRT) is highlighted by the fact that imaging remains crucial during radiotherapy operations, even when the target is moving or changing its shape, location, or volume. Radiation therapy can be administered IMRT, a technique that allows the beam's intensity to be adjusted within the treatment field. To achieve this, a large beam is split into numerous smaller beamlets. The specific weights of these numerous beamlets are determined by performing computerized inverse optimization after dose limitations are applied to both the target and sensitive structures. As needed, the computer modifies the beamlets' intensities to meet the planning dose goals. , The sequencing process involves breaking down the optimal intensity patterns into a sequence of forms that may be used in multi-leaf collimators (MLCs). Thirdly, the intricacy of an IMRT plan grows one of its primary drawbacks—the enormous spike in the number of Monitor Units (MU) needed to provide a fractionated treatment—becomes increasingly more obvious. A bigger total body dosage and an increased risk of secondary malignancies in patients are consequences of this rise in MU, which is linked to longer treatment durations and more radiation leakage from the MLCs. So, it's important to identify solutions to lower MU without compromising plan quality. , , Inverse planning techniques, which automatically generate the necessary intensity map by dividing the beam into smaller beams, add complexity to IMRT treatment planning. There are many drawbacks to having a complicated plan, including things like dosimeter uncertainty and delivery problems. A lot of processing power is needed since a big search space is needed. , the ideal intensity map is designed without considering the restrictions of the delivery method. As a result, a further step called the sequencing step is necessary to transform the ideal intensity map into a deliverable one. , ,

The present study aimed to find out how optimizing and improving treatment time delivery for IMRT cases affects the quality of the plan. It is proposed that for many clinical cases, using a smaller number of MLC segments, with large MU and area per segment can result in more efficient treatment delivery with less total treatment time, with little effect on treatment plan quality.

II. Material And Methods

The delineated contours for treatment purposes of head and neck retrospective cases. IMRT Plans that used to calculate these cases with a definite number of beamlets, a definite flounce map and a definite MLC shape. Calculated plans and cases already finished treatment, changing a number of beamlets, changing the flounce map, and changing the MLC shape, did this. Optimizing plans until reaching the same endpoint to the treatment planning evaluation parameters such as organ at risk (OAR) constraints, maximum, minimum, and hotspot doses, conformity index, and heterogeneity index were used to evaluate the coverage of the treatment target. The materials used are:

1- Monaco Treatment Planning System [(Elekta AB, Stockholm, Sweden, version 5.11.02).

2- Computed Tomography Simulator [CT-SIM (Siemens), VA48A, Siemens Medical Solutions USA. This study was a retrospective analysis of comparative dosimetric data on 35 patients of head & neck cancer referred to Menoufia University Clinical Oncology Department. All cases were based on patients who had already undergone CT imaging. Contours were drawn for previous treatment cases involving these cancers, and IMRT plans were calculated with predetermined beamlets, fluence maps, and multi-leaf collimator (MLC) shapes.

The expected outcomes include setting intensity limits, putting penalties on the cost function and using smoothing filters Direct Aperture optimization (DAO) incorporates the limitations of the delivery technology at the initial design of the intensity map thereby eliminating the sequencing step. It also gives control over the number of segments and hence control over the complexity of the plan although the design of the segments is independent of the person preparing the plan.

Our study was designed to explore how optimizing and improving treatment time delivery for IMRT cases can significantly influence the overall quality of treatment plans. The primary motivation behind this research stems from the need to enhance patient outcomes by decreasing both therapy duration and the number of patient visits. Reducing treatment time can lead to less physical and emotional strain on patients, particularly those undergoing prolonged radiation sessions. Furthermore, streamlining the treatment process can contribute to minimizing the cumulative radiation exposure to healthy tissues, which is vital for reducing the risk of long-term side effects.

Echner et al; 2019; research looked specifically at the Monaco treatment planning system and its features, which include the ability to precisely plan and administer radiation. It proved that optimizing MLCs is crucial for enhancing treatment efficiency and decreasing delivery time. Wu et al; 2011 research incorporated MLC optimization as part of a comprehensive optimization strategy for IMRT planning. While making sure dose-volume limitations were satisfied, the researchers showed that their method improved treatment time delivery.

According to Jalil et al; 2018; as a cutting-edge kind of external beam radiotherapy, IMRT tailors a high radiation dose to the target while minimizing exposure to organs at risk (OARs), making it an asset to any modern facility. There was a lack of evidence supporting IMRT's clinical superiority over other radiation methods in the previous papers. Modern therapy and imaging methods have rendered its quick practical application indisputable, dispelling concerns about its complexity and cost. Modern IMRT has advanced beyond its humble beginnings as a treatment that relied solely on metal compensators to produce uneven beam intensities. Instead, it employs robotic arm linear accelerators, multileaf collimators (MLCs), and beam delivery systems that rotate fans and cones to combat deadly cancers. IMRT has several drawbacks despite its many improvements, such as a high price tag, more staff effort, more time spent planning, and the possibility of minor misses.

Oliver et al; 2009 ; study aims to analyze tomotherapy, single and dual arc RapidArc, 5- and 9-field sliding window IMRT, treatment planning time, and the quality of the plans for these procedures. Plans for single- and dual-arc RapidArc and tomotherapy were developed for four phantoms, as well as for 5- and 9-field IMRT. Factors such as the capacity to fulfill dose-volume restrictions, radiation conformance index, planning time, projected delivery time, integral dose, and volume receiving more than 2 and 5 Gy were used to assess the plans. During planning, tomotherapy was able to meet the most optimal criteria for all phantoms: 50% for P1, 67% for P2, 0% for P3, and 50% for P4. While IMRT never failed to satisfy any of the constraints, RapidArc only managed to do so for 25% of the optimization criteria for P1, 17% for P2, and 0% for P4. In addition, the uniform dosage was generated via tomotherapy designs. Time spent planning, time spent estimating treatment, conformance index, and integral dose were all negatively impacted by tomotherapy programs. In the axial plane, tomotherapy plans outperform IMRT and RapidArc in terms of plan quality and dose distribution conformance, but they show an increase in dose both above and below the target volume. On the other hand, for the test cases that were considered in this study, RapidArc was able to provide superior plans than IMRT.

Alber et al; 2002; conducted that IMRT is increasingly being administered using multi-leaf collimators (MLCs). However, the distribution of exposure periods in MLCs is subject to various limitations, including piecewise linear functions in dynamic mode and piecewise constant functions in static mode. To optimize dosage, it is crucial to consider MLC-related restrictions to reduce total leaf movement. An update to a generic gradient-based IMRT dosage optimization methodology addresses numerical issues caused by non-convexity of MLC constraints. The method uses bistable penalty functions to choose desirable leaf configurations from the MLC configuration space, with an 'annealing' escape mechanism from local minima. The algorithm can discover the optimal solution to an IMRT problem as leaf sequences with minimal leaf travel, making it an effective tool. By using a small number of field segments, static IMRT can achieve efficiency levels comparable to unmodulated fields, making it a more practical option for clinical application.

All designs conducted by Kantz et al; 2015; meet the hard limitations since constrained optimization is utilized. The nine plans that are created for every patient do not deviate from critical structural doses by more than 1Gy. Due to enhanced scatter, not avoiding structures while employing the full range of gantry rotation, and improved leaf sequencing with advanced segment shape optimization for VMAT plans, the only areas that differ up to 1.5Gy (Dmean or Dmax) or 7% (volume-constraint) are the larynx, parotids, and eyes. The Agility-MLC enhances EUD, Dmean, homogeneity, and conformity. On the other hand, technique has a greater impact on PTV coverage. dMLC and VMAT both lead to an increase in MU, whereas Agility-MLC decreases MU. When used in conjunction with VMAT, Agility-MLC always results in the quickest treatments.

III. Result

There were 35 patients with head & neck cancer, 68.6% of them were males and 31.4% were females with male to female ratio was 2.18:1, The mean optimization time was 12.63± 9.02 min. in the original plan while the mean time was 8.58± 4.03 min. in modified plan. The modified plan showed significantly lower optimization time compared to the original plan (p=0.019), as demonstrated in Table 1.

The number of segments showed significant decrease in modified plan when compared to original plan (p<0.001) as demonstrated in Table 2 and figure 1. In addition, the number of MU showed significant decrease in modified plan when compared to original plan (p=0.002) as shown in table 2 and figure 2. The estimated MU Efficiency was 100% in both types of plans.

The mean estimated delivery time was 6.08± 1.04 min. in the original plan while the mean time was 4.89± 0.72 min, in modified plan. Modified plans showed significant lower estimated delivery time compared to original plan (p<0.001) as demonstrated in Table 3.

Table 1: Optimization time according to plan in head & neck cancer patients

		Original plan (N = 35)	**Modified plan (N = 35)**	**Test value**	**P-value**
Optimization time (min.)	Mean± SD	12.63± 9.02	8.58± 4.03	T= 2.430	0.019 (S)
	Range	0.38- 35.34	1.78- 15.09		

P value< 0.05 is significant, P value< 0.01 is highly significant, SD: Standard deviation, T: Student T test

Table 2: Number Of segment & MU according to plan in head & neck cancer patients

		Original plan (N = 35)	Modified plan (N = 35)	Test value	P-value
Number of segments	Median (IQR)	316.0 (271.0- 391.0)	132.0 (126.0- 149.0)	ZMWU= 7.160	<0.001 (HS)
	Range	176.0- 587.0	74.0- 200.0		
Number Of MU	Mean± SD	821.16± 160.56	692.48± 616.86	T= 3.225	0.002 (HS)
	Range	573.51- 1312.72	428.96- 964.74		
Estimated MU Efficiency	100%	35 (100%)	35 (100%)	-	-

P value< 0.05 is significant, P value< 0.01 is highly significant, SD: Standard deviation, IQR: Interquartile range, ZMWU = Mann- Whitney U test, T: Student T test.

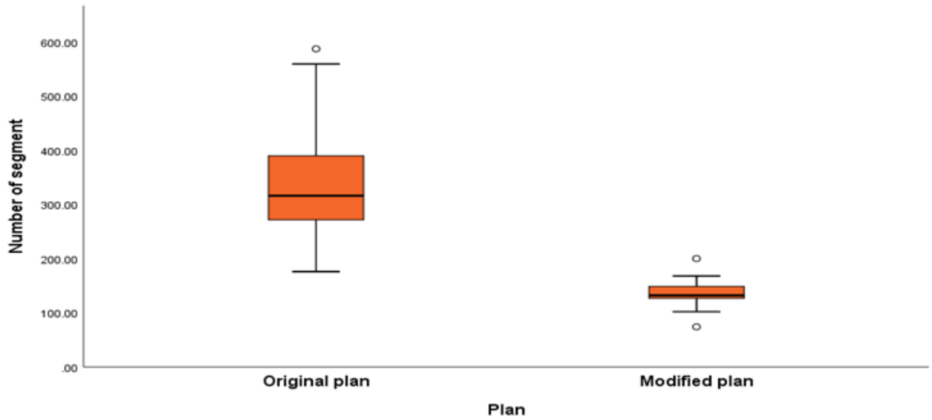


Figure (1): Comparison between the studied groups regarding number of segment

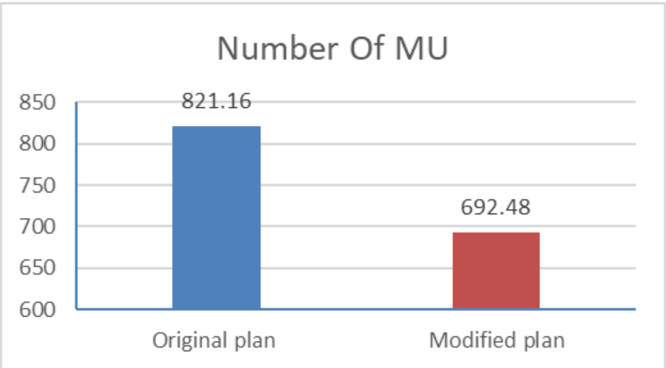


Figure (2): Comparison between the studied groups regarding number of MU

Table 3: Estimated Delivery time according to plan in head & neck cancer patients

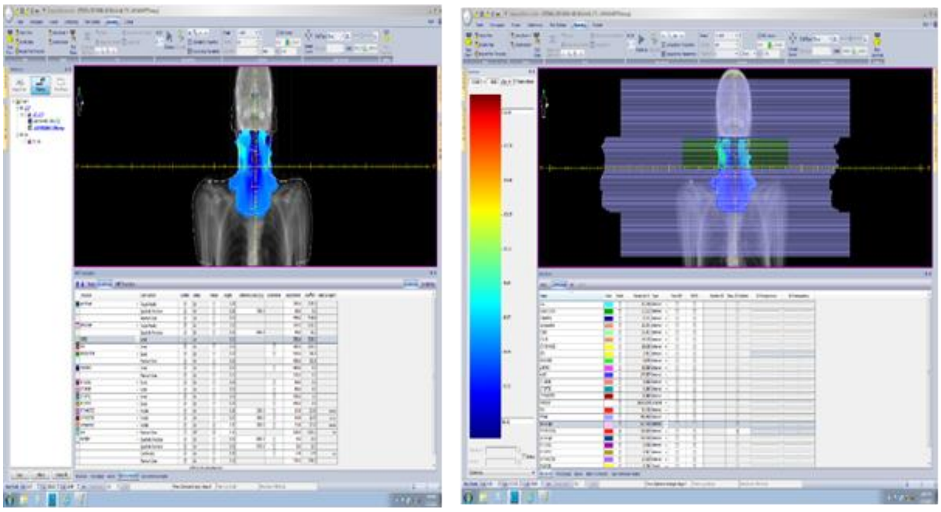
		Original plan (N = 35)	Modified plan (N = 35)	Test value	P-value
Estimated Delivery time (min.)	Mean± SD	6.08± 1.04	4.89± 0.72	T= 5.560	<0.001 (HS)
	Range	4.47- 8.80	3.45- 6.94		

P value< 0.05 is significant, P value< 0.01 is highly significant, SD: Standard deviation, T: Student T test.

Beam arrangement for head and neck cancer

The total prescribed dose for each patient was 7000 cGy, administered in 35 fractions, with a fractional dose of 200 cGy. Treatment planning was performed using a multifield IMRT approach tailored to each patient's individual anatomy and tumor location. A 7-field approach was used, with gantry angles carefully selected to optimize dose distribution while sparing critical structures. The Gantry angles used were 0°, 51,102, 153, 207, 258, and 309. The collimator angle was set to 0 for all.

The beam was delivered using a Dynamic Multi-Leaf Collimator (DMLC). The treatment planning process included a two-stage optimization to ensure optimal dose distribution and compliance. The first step, “Optimize One,” focused on creating the fluence map to ensure that the radiation dose was precisely matched to the target volume. The second phase, “Optimize Two,” included precise positioning of the MLCs and finalization of the treatment plan, adjusting meet the defined dose constraints for both the target and the OARs. As shown in figure 3.



[A] [B]

Figure (3): [A] shows first optimization stage creating fluence map,
[B] shows second optimization stage creating MLC.

Strict dose limitations were applied to the planning target volume (PTV) to ensure comprehensive coverage while preventing excessive radiation exposure. The target penalty required a prescription dose of 7000 cGy to cover at least 95% of the volume. A quadratic overdose restriction was established with a maximum allowable dose of 7500 cGy and an RMS dose exceedance of 50 cGy.

The absolute maximum dose allowed for PTV was set at 7600 cGy. Given the anatomical complexity of the head and neck region, OAR limitations were carefully defined. The spinal cord, treated as a serial organ, had an Equivalent Uniform Dose (EUD) limitation of 4500 cGy with a power law exponent of 10. The brainstem, another critical serial organ, was treated with an EUD of 5400 cGy and a power law restricted exponent of 12. For the parotid glands, which are treated as parallel organs, a median dose limit of 2600 cGy was established to maintain salivary function.

Table 4: Organ dose constraints & evaluation form

Organ dose constraints & evaluation form site: head & neck		
Structure	Constraint (allowed variation) [complication rate]	
PTVs¥		
PTV70 Gy	V7000 c Gy ≥ 95%	
	D max < 112%	
PTV60 Gy	V6000 cGy ≥ 95%	
	D max < 112%	
OARs		
Brain stem€	Dmax < 5400 c Gy	
Lens – RTΦ	Dmax < 500 c Gy	
	Dmax < 1200 c Gy	
Lens – LTΦ	Dmax < 500 c Gy	
	Dmax < 1200 c Gy	
Optic Chiasm€	Dmax < 5500 c Gy	
Optic nerve–RT€	Dmax < 5500 c Gy	
Optic nerve–LT€	Dmax < 5500 c Gy	
Parotid – RT¥	Dmean < 2600 c Gy	Combined
	Dmean < 2000 c Gy	Single
Parotid – LT¥	Dmean < 2600 c Gy	Combined
	Dmean < 2000 c Gy	Single
Spinal Cord€	Dmax < 5000 c Gy	
Cornea _LT	D max<5000 c GY	
Cornea _RT	D max <5000 c GY	
RTOG 05 €: QUANTEC Φ: Emami 1991		

The original treatment plan, the so-called original plan, was calculated with a grid spacing of 0.4 cm. The sequencing parameters allowed a maximum of 250 control points per beam with a minimum segment width of 1 cm. To evaluate the impact of control point restrictions on treatment efficiency and plan quality, a modified plan was developed in which the maximum number of control points per beam was reduced to 25. This modified plan was recalculated using the same two-stage optimization process as the original plan to ensure consistent assessment of treatment quality and effectiveness as shown in figure 4.

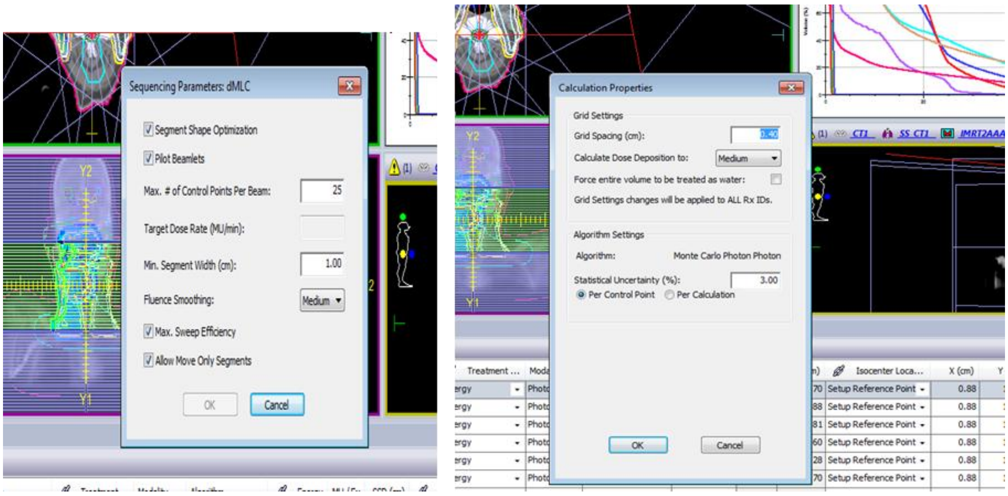


Figure (4): Treatment Plan Calculation and Modification

After completion of both the original and modified plans, a comprehensive comparative analysis was conducted. Key comparison metrics included dose-volume histogram (DVH) statistics, optimization time, number of segments, number of monitor units (MU), estimated MU efficiency, estimated delivery time, and segment area (both smallest and the largest) per beam. These comparisons were designed to evaluate the impact of control point reduction on overall quality of care, efficiency and patient safety. Fig (5)

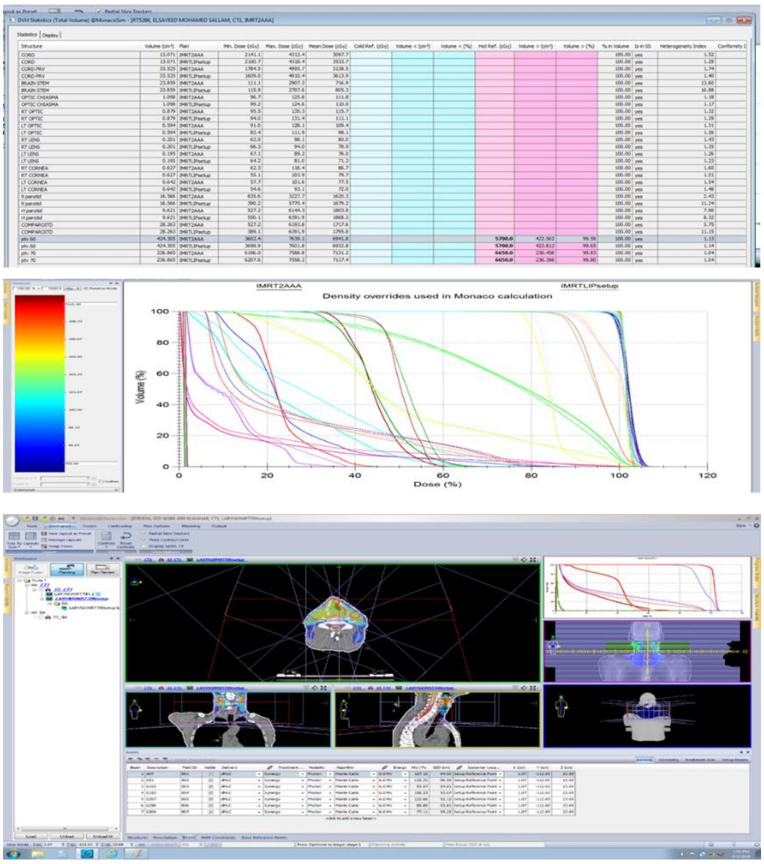


Figure (5): show the dose volume histogram, statistics and color wash of head and neck cancer case

According to the segment area, the smallest reading of beam1, 2, 3, 4, 5, 6, 7 & mean beam showed significant elevation in modified plan compared to original plan. While no significant difference was found between the two plans regarding the largest beam in any of the beams as demonstrated in Figure 6.

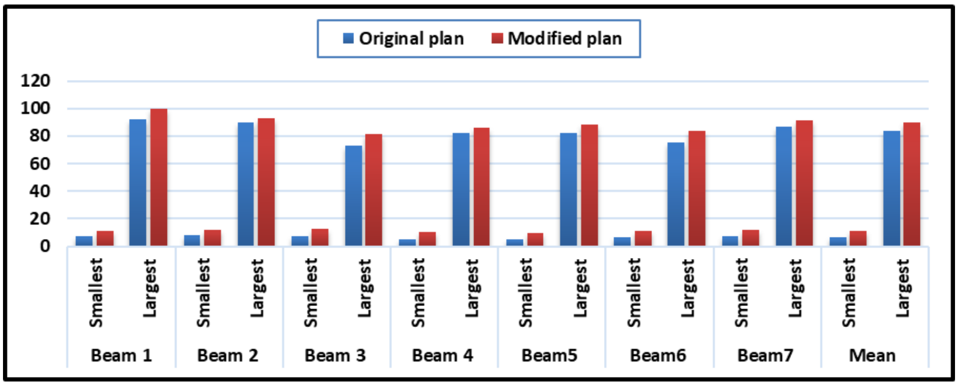


Figure (6): Comparison between the studied groups regarding segment area

Figure (7) shows that no significant difference between original and modified plans regarding total amount of radiation in spinal cord, brain stem, optic chiasma, left & right optic nerve, left & right cornea, left & right lens, left & right parotid as well as comparted ($p>0.05$) . There was no significant difference between original and modified plans regarding PTV70 or PTV60 ($p>0.05$) as given in table 5.

There was no significant difference between original and modified plans regarding total amount of radiation in spinal cord, brain stem, optic chiasma, left & right optic nerve, left & right cornea, left & right lens, left & right parotid as well as comparted ($p>0.05$) as shown in figure 7.

Table 5: PTV according to plan in head & neck cancer patients.

		Original plan (N = 35)	Modified plan (N = 35)	Test value	P-value
PTV 70	Mean± SD	96.44± 3.07	97.16± 2.75	T= 1.043	0.301 (NS)
	Range	86.49- 100.0	88.46- 99.99		
PTV 60	Median (IQR)	98.41 (96.80- 99.19)	98.71 (96.8- 99.48)	ZMWU= 0.628	0.530 (NS)
	Range	91.09- 100.0	93.24- 100+.0		

P value< 0.05 is significant, P value< 0.01 is highly significant, SD: Standard deviation, IQR: Interquartile range, ZMWU = Mann- Whitney U test, T: Student T test.

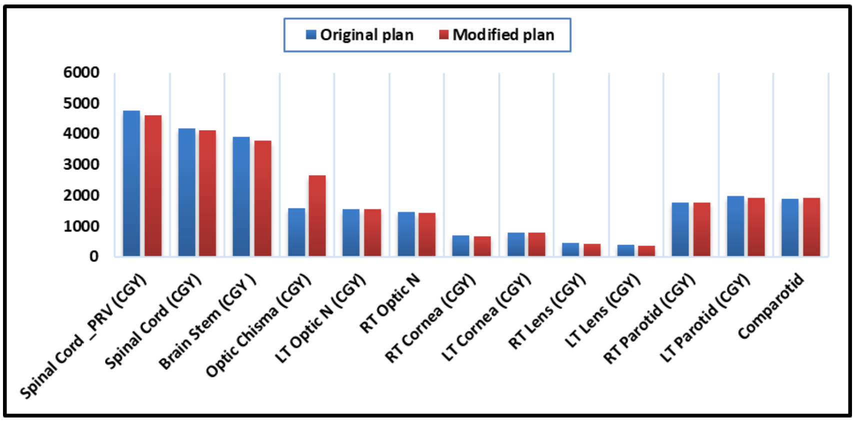


Figure (7): Comparison between the studied groups regarding total amount of radiation in different (OAR)

IV. Conclusion

This study highlights the advancements achieved with a modified IMRT treatment planning approach for head and neck cancer. The patient cohort comprised a higher proportion of males compared to females, reflecting typical demographic trends. The modified plan demonstrated superior performance by significantly reducing optimization and delivery times compared to the original plan. Additionally, the smallest segment areas for all beams showed notable improvements, further optimizing the treatment process. Importantly, the dosimetry analysis revealed no significant differences between the original and modified plans in terms of target volume coverage (PTV70 and PTV60) or radiation exposure to critical structures, including the spinal cord, brainstem, optic chiasma, optic nerves, cornea, lens, and parotid glands. This indicates that the modified plan maintained the same level of safety and effectiveness as the original. These findings suggest that the modified IMRT approach not only enhances treatment efficiency but also maintains clinical precision and safety. By reducing treatment planning and delivery times, this method has the potential to improve the therapeutic ratio, reduce toxicity, and address inefficiencies in current IMRT workflows. The implementation of such innovative strategies may also contribute to cost reduction while ensuring high-quality patient care. Future research should focus on broader clinical applications to further validate these results and refine the approach.

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