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OPTIMIZING HEAD AND NECK CANCER RADIOTHERAPY: A DOSIMETRIC COMPARISON OF FF AND FFF BEAMS IN VMAT

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Aim: Head and neck cancer (HNC) is a significant global health concern, with rising incidence rates and a high prevalence in South Asia, particularly in India. Radiation therapy, including advanced techniques like Volumetric-Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiotherapy (IMRT), plays a crucial role in treating HNC. This study aims to compare the dosimetric and biological and second cancer risk estimation differences between flattened (FF) and flattening filter-free (FFF) beams in VMAT treatment plans for HNC, focusing on the impact of 6 MV and 10 MV energies.

Methods: Twenty HNC patients underwent replanning using VMAT on an ELEKTA VERSA HD linear accelerator with 6 MV FF, 6 MV FFF, 10 MV FF, and 10 MV FFF beams. Dosimetric parameters evaluated included dose distribution to planning target volumes (PTVs) and dose delivered to 98% of the target (D98), 50% (D50), and 2% (D2), as well as doses to organs at risk (OARs)., monitor units per segment (MU/Segment), number of MU/cGy, treatment delivery time, conformity index, and homogeneity index, also biological parameters (NTCP and EUD) and second cancer risk estimation were evaluated.

Results: The results showed that 6 MV FFF beams provided slightly better dose-sparing for OARs compared to 6 MV FF, with no significant differences in target volume coverage. Both FF and FFF beams demonstrated comparable conformity indices, but FF beams had better homogeneity indices. FFF beams required more monitor units (MUs) and segments but offered reduced treatment delivery times. For 10 MV beams, FFF showed marginal advantages in dose homogeneity and sparing of normal tissues at lower doses, though it required more MUs and segments, this study found that NTCP and EUD were largely comparable between FF and FFF types, with minor but statistically significant differences for the brainstem (favoring FFF) and heart. Second cancer risks varied slightly by energy and technique 6MV FFF reduced parotid risks (though increased larynx risk).

Conclusion: 6 MV beams, particularly FFF, showed slight advantages in sparing OARs and target volume coverage compared to 10 MV beams. This study highlights the dosimetric comparability of FF and FFF beams in HNC treatment, with FFF offering potential benefits in treatment efficiency and reduced delivery times. This study also shows that FF and FFF types yield comparable radiobiological outcomes, though 6MV FFF beams slightly reduce doses to critical organs without sacrificing efficacy. Both types perform similarly, with minor risk variations by energy.

Keywords: *Head and neck cancer; Volumetric Modulated Arc Therapy (VMAT); Flattening filter (FF); Flattening filter-free (FFF); 6MV; 10 MV*
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1. INTRODUCTION

Head and neck cancer (HNC) ranks as the seventh most prevalent cancer worldwide, with approximately 660,000 new cases diagnosed each year, contributing to nearly half of all cancer-related deaths. The incidence of HNC has been increasing annually. About 55% to 60% of HNC cases occur in South Asia. In India specifically, HNC represents roughly one-third of all cancer diagnoses, following cervical and breast cancer. The majority of HNC patients are male, with around 70% to 75% presenting at advanced stages of the disease [1].

Radiation therapy for head and neck cancers continues to present significant challenges due to the severe side effects experienced by patients. For individuals with cancers located outside the oral cavity who are undergoing definitive treatment aimed at organ preservation, the established standard of care involves concurrent chemoradiation. In the postoperative context, radiation therapy is often employed based on specific risk factors, accompanied by concurrent chemotherapy in cases where there are positive surgical margins or extravasation of cancer cells (ECE) [2].

Radiotherapy is a crucial element in the treatment of head and neck cancers. Volumetric-Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiotherapy (IMRT) are prevalent treatment techniques for head and neck cancers due to their dosimetric advantages, along with the preservation of nearby critical organs, which improves survival and quality of life.

VMAT and IMRT are advanced techniques in radiation therapy used to target cancerous tumors with precision while minimizing damage to surrounding healthy tissues. VMAT delivers radiation by rotating the machine around the patient in one or more continuous arcs. This technique modulates the dose dynamically as the machine moves, allowing for a more complex and conformal dose distribution. As a result, VMAT can be faster, reducing treatment time and patient movement. In contrast, IMRT employs multiple static or non-rotational beams from different angles to deliver radiation.

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The intensity of each beam is adjusted using multi-leaf collimators (MLCs) to shape the dose distribution, which can make IMRT slower compared to VMAT due to the need for precise beam angle adjustments and patient repositioning.

Regarding treatment planning and dosimetry, VMAT planning can be more complex due to the need to optimize dose distribution over a continuous arc. However, it often provides highly conformal dose distributions with fewer beams, potentially offering better sparing of healthy tissues. IMRT, on the other hand, requires the creation of intricate beam arrangements and intensity maps, which can be time-consuming but achieve precise dose distributions. VMAT typically results in shorter treatment times and improved patient comfort due to its continuous arc delivery, whereas IMRT may have longer treatment times. [3], because of the multiple beam angles and adjustments required [4], [5].

Flattening Filter (FF) and Flattening Filter-Free (FFF) are terms related to different configurations of linear accelerators used in external beam radiotherapy. Flattening filter to create a uniform dose distribution across the treatment field, ensuring that the radiation dose is evenly spread over the target area. However, the flattening filter can introduce some variation in the dose distribution, resulting in a dose fall-off at the edges (penumbra) and FF beams have longer delivery time which can lead to decreased patient comfort during treatment [6].

In contrast, FFF (Flattening Filter-Free) does not use a flattening filter, leading to a non-uniform dose distribution with a higher dose rate at the central axis and a dose decreasing towards the edges of the field [7].

Treatment plans need to use more MUs to ensure that the entire target volume receives the appropriate dose, while also effectively sparing surrounding healthy tissues [1].

Additionally, FFF can provide higher dose rates, which can shorten treatment times and improve efficiency. This makes it particularly advantageous for techniques that require high precision and rapid delivery.

This study seeks to quantify and contrast treatment plan differences in terms of dosimetric parameters, radio-biological response, and second primary cancer risk when using conventional flattened versus flattening-filter-free (FFF) photon beams for head and neck malignancies. It further examines how beam energy levels (6 MV and 10 MV) influence these parameters across both irradiation techniques.

2. MATERIALS AND METHODS

Twenty patients with head and neck cancer were included in this study, and underwent replanning with VMAT under ELEKTA VERSA HD using 6MV FF and 6MV FFF also 10MV FF, and 10MV FFF. All 20 patients were treated at the National Cancer Institute (NCI), Cairo, Egypt, the patients all males between the age of 40 and 60 with low grade tumors are selected for this study.

Each patient underwent CT simulation using the Siemens SOMATOM Ratproof Computed Tomography (Siemens Healthineers) with a dedicated protocol, with a 3 mm slice thickness. The simulation was performed head-first in a supine position using a mask for immobilization.

All patients' CT images were transmitted to the Monaco Sim system (ELEKTA MONACO 5.51.10). The physician delineated the target volumes and organs at risk (OARs).

After the delineation of the target and OARs was completed, the CT structure was transferred to the Monaco workstation to design the VMAT planning (FF and FFF) facility for each case using energies 6MV and 10MV in the planning, the prescribed dose 36Gy per 18 fractions of all cases for radical intent. Then it was transferred by the mosaic system to begin radiation delivery.

Using two-photon beams of VERSA HD LINAC, 80 VMAT plans were created by directly changing the original plan radiation energy 6MV (FF beam) to 6MV with FFF beam.

The same thing happened with 10 MV (FF beam) preplanned to 10 MV with FFF beam while maintaining the original plan optimization parameters unchanged. Then the optimization was performed inversely using the original plan parameters and doses were calculated using the Monte Carlo (MC) algorithm.

VERSA HD LINAC is equipped with an agility head with MLC of 5mm (160 leaves) with 6MV FF and 10MV FF. The beam quality for High dose (HD) values for the FFF energies is the same as that of flattened energies. The effective leaf speed is 6.5cm/s which is important for FFF, and dynamic treatment.

All plans were produced with the Monaco treatment planning system (TPS) (ELEKTA MONACO 5.51.10,) this allowed plan evaluation for the PTVs, the relevant organs at risk (OARs) as well as mean dose (D mean), maximum dose (D max.), 95% dose (D95), 98%(D98), 50%(D50), 2% (D2), monitor units per segment (MU/Segment), and the number of MU/cGy in addition to treatment delivery time and conformity index.

Each pair of plans (FF and FFF for the same patient) and FF in both energies (6MV, 10MV), and FFF in both energies (6MV, 10MV) were compared and then the statistical analysis was made Radiobiological models are commonly employed to calculate the outcomes of treatment plans, particularly by utilizing dose-volume histograms (DVH). One such model is Niemierko's EUD-based NTCP mathematical model. To implement these models and generate corresponding program code, MATLAB was selected as the platform. MATLAB is a high-level technical computing language and an interactive environment that facilitates the development and execution of such models.

The risk of radiation-induced secondary cancer is estimated using guidelines from ICRP (International Commission on Radiological Protection) Publication 103.[8]

The calculation is performed in two steps. First, the equivalent dose is calculated by multiplying the absorbed dose (in Gy) by the radiation weighting factor (wR). For photon radiation, wR=1, meaning the equivalent dose (in Sv) is numerically equal to the absorbed dose. Second, the equivalent dose is multiplied by the nominal risk coefficient

(NRC) for the specific organ or tissue, as defined in ICRP 103. This approach provides a standardized method for estimating the long-term risk of secondary cancers following radiation exposure.

For example, if the absorbed dose to the salivary glands is 9.78 Gy, the equivalent dose is 9.78 Sv. Using an NRC of 0.0005 per Sv, the risk of secondary cancer is calculated as 9.78×0.0005=0.004899.78(or 0.489%). This method ensures a standardized approach to estimating long-term risks associated with radiation exposure in radiotherapy.

Statistical analysis

Statistical analysis was done using Excel Microsoft Office 2019 to compare means using a *t*-test and to estimate the significant difference between the two techniques. If the P value < 0.05, then the result was considered statistically significant.

3. RESULTS

The following figures and tables show the mean values of 20 patients replanned 80 VMAT plans with two energies 6 and 10 MV both with the FF and FFF beam type.

Comparison between FF and FFF beam configuration for the energy 6 MV

3.1.1. Comparison between the mean doses of the OARs for both types at 6 MV

Figure 1 compares the mean doses received by organs at risk (OARs) for 20 head and neck (H&N) cancer patients treated with volumetric modulated arc therapy (VMAT) using 6MV flattened filter (FF) and flattening filter-free (FFF) beams.

The brainstem (maximum dose) received the highest dose, with values of 34.53 Gy for the FF beam type and 35.03 Gy for the FFF mode. However, the difference was not statistically significant (p = 0.23). Conversely, the heart (mean dose) received the lowest dose, with 2.6 Gy for the FF mode and 2.2 Gy for the FFF mode, also showing no significant difference (p = 0.20).

It can be noticed that some of the OARs received slightly higher doses in FF mode like the right parotid (mean dose) (9.78Gy for FF mode, 9.5Gy for FFF mode). There is no significant difference where the p-value equals 0.19. The left parotid was (mean dose) (12.36Gy for FF mode, and 12.28Gy for FFF mode) where the p-value is 0.39 which indicates that there is no significant difference between them.

No significant differences were observed in most organs at risk (OARs) between FF and FFF beam types. The right eye (maximum dose) (10.52 Gy FF, 10.04 Gy FFF; p=0.25), right lens (maximum dose) (5.96 Gy FF, 5.9 Gy FFF; p=0.40), right cochlea (mean dose) (19.1 Gy FF, 18.28 Gy FFF; p=0.14), right optic nerve (maximum dose) (14.66 Gy FF, 13.34 Gy FFF; p=0.10), right lung (mean dose) (8.6 Gy FF, 7.75 Gy FFF; p=0.25), left lung (mean dose) (9.75 Gy FF, 8.6 Gy FFF; p=0.25), and oral cavity (mean dose) (7.36 Gy FF, 6.96 Gy FFF; p=0.07) all showed no notable differences.

Similarly, some OARs received slightly higher doses in FFF beam configuration, but without significant differences: left eye (maximum dose) (19.32 Gy FF, 20.72 Gy FFF; p=0.23), left lens (maximum dose) (8.78 Gy FF, 8.82 Gy FFF; p=0.47), left cochlea (mean dose) (20.7 Gy FF, 20.81 Gy FFF; p=0.45), left optic nerve (maximum dose) (17.32 Gy FF, 18.92 Gy FFF; p=0.09), spinal cord (maximum dose) (26.38 Gy FF, 27.33 Gy FFF; p=0.21), larynx (mean dose) (14.52 Gy FF, 14.97 Gy FFF; p=0.19), optic chiasm (maximum dose) (27.66 Gy FF, 28.82 Gy FFF; p=0.29), and esophagus (mean dose) (11.87 Gy FF, 11.91 Gy FFF; p=0.45).

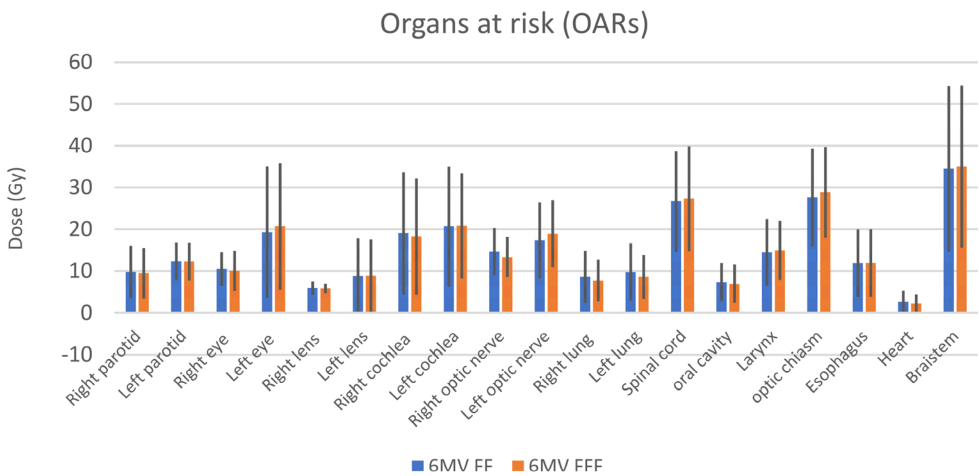

Figure 1. A comparison between the mean doses for the OARs of the H&N patients treated with VMAT technique with the energy 6MV in both FF and FFF types

3.1.2. Comparison between the planning target volumes for both types at 6 MV

Table 1. compares the average PTV volumes for the patients treated using FF and FFF types for 6 MV. The dose delivered to 95% of the target volume was 33.63 Gy for FF and 33.57 Gy for FFF. There is no statistically significant difference between them (p-value was 0.23).

The dose delivered to 98% of the target volume was 33.04 Gy for FF and 32.84 Gy for FFF. There is no significant difference (p-value is 0.08). FFF delivers a slightly lower dose to 98% of the target compared to FF.

The dose received by 50% of the target volume (D50%), which typically represents the central and most intense region of the target, was 35.3 Gy for FF and 35.33 Gy for FFF. The difference was minimal and not statistically significant ($p = 0.34$).

The dose delivered to the 2% of the target volume receiving the highest dose (D2%), representing the maximum dose applied to a small portion of the target, was 36.43 Gy for FF and 36.48 Gy for FFF. This difference was also not significant ($p = 0.21$).

Table 1. A comparison between the mean value of the PTV of the H&N patients treated using the VMAT technique with the energy 6 MV in both FF and FFF types, where SD means standard deviation.

6MV				
Planning target volumes	**FF**	**SD**	**FFF**	**SD**
D95%	33.63	±12.92	33.57	±12.97
D98%	33.04	±12.67	32.84	±12.83
D50%	35.3	±13.46	35.33	±13.54
D2%	36.43	±13.83	36.48	±13.84

3.1.3. Comparison between the dosimetric parameters for both types at 6 MV

Table 2 compares the dosimetric parameters for FF and FFF types. Both types have a perfect conformity index (CI) of 1, indicating that both techniques deliver an equally precise radiation dose to the target, with minimal exposure to surrounding healthy tissues.

The homogeneity index (HI) in the case of FF (0.086) is significantly lower compared to FFF (0.104) with a p-value of 0.023. The number of segments used in FF (259.42) was slightly lower than in FFF (290.69), but the difference was not statistically significant ($p = 0.15$).

However, the monitor units (MU) for FF (1028.6) were significantly lower compared to FFF (1390.6), with a significant difference ($p = 0.0001$).

Table 2. A comparison between the dosimetric parameters using the VMAT technique for the energy 6 MV in both FF and FFF types.

6MV				
Dosimetric parameters	**FF**	**SD**	**FFF**	**SD**
Conformity index (CI)	1	Identical	1	Identical
Homogeneity index (HI)	0.086	±0.01	0.104	±0.02
Number of segments	259.42	±179.03	290.69	±215.97
Monitor unit (MU)	1028.6	±341.04	1390.6	±475.58

3.2. Comparison between FF and FFF beam type for the energy 10 MV

3.2.1. Comparison between the mean doses of the OARs for both types at 10 MV

Figure 2 shows a comparison of the mean doses received by the OARs in the twenty H&N patients treated using VMAT of energy 10 MV for FF and FFF beams.

The results indicate that the brainstem (maximum dose) received the highest dose, with 35.26 Gy in FF beam type and 36.33 Gy in FFF beam configuration, showing no significant difference between the two beam types ($p = 0.20$). In contrast, the heart (mean dose) received the lowest dose, with 2.45 Gy in both FF and FFF types, also demonstrating no notable difference ($p = 0.50$).

Some of the OARs received slightly higher doses in the case of using FF beam type, although the differences were not statistically significant: right eye (maximum dose) (10.7 Gy FF, 10.3 Gy FFF; $p = 0.14$), left eye (maximum dose) (20.52 Gy FF, 19.92 Gy FFF; $p = 0.15$), right lens (maximum dose) (6.38 Gy FF, 5.68 Gy FFF; $p = 0.10$), left lens (maximum dose) (9.16 Gy FF, 8.8 Gy FFF; $p = 0.30$), right cochlea (mean dose) (18.78 Gy FF, 18.26 Gy FFF; $p = 0.16$), spinal cord (maximum dose) (27.43 Gy FF, 27.18 Gy FFF; $p = 0.34$), and larynx (mean dose) (15.6 Gy FF, 15.07 Gy FFF; $p = 0.34$).

Conversely, some OARs exhibited slightly higher doses in the case of using FFF beam configuration, also without statistically significant differences: right parotid (mean dose) (10.2 Gy FF, 10.32 Gy FFF; $p = 0.36$), left parotid (mean dose) (12.38 Gy FF, 12.6 Gy FFF; $p = 0.34$), left cochlea (mean dose) (21.48 Gy FF, 21.95 Gy FFF; $p = 0.26$), right optic nerve (maximum dose) (13.52 Gy FF, 14.1 Gy FFF; $p = 0.32$), left optic nerve (maximum dose) (17.66 Gy FF, 18.1 Gy FFF; $p = 0.35$), optic chiasm (maximum dose) (29.62 Gy FF, 30.08 Gy FFF; $p = 0.35$), and esophagus (mean dose) (11.69 Gy FF, 11.92 Gy FFF; $p = 0.16$).

However, significant differences were observed in the right lung (mean dose) (8.5 Gy FF, 8.85 Gy FFF; $p = 0.04$) and left lung (mean dose) (8.85 Gy FF, 10 Gy FFF; $p = 0.041$). The oral cavity (mean dose) (7.03 Gy FF, 7.53 Gy FFF; $p = 0.09$) did not exhibit a statistically significant difference.

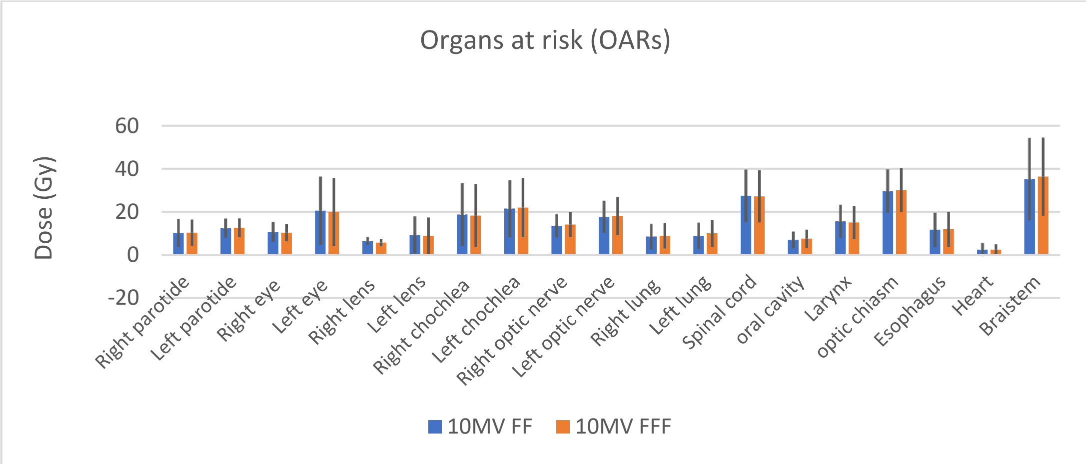

Figure 2. A comparison between the mean doses for the OARs of the H&N patients treated using the VMAT technique of the energy 10 MV in both FF and FFF modes.

3.2.2. Comparison between the planning target volumes for both types at 10 MV

Table 3 compares the average PTV volumes for the patients treated using FF and FFF types for 10 MV. The dose delivered to 95% of the PTV (D95%) was comparable between the two techniques, with no statistically significant difference ($p = 0.11$). The FFF technique delivered a slightly higher dose (33.17 Gy for FF and 33.4 Gy for FFF).

For the dose delivered to 98% of the PTV (D98%), both techniques produced similar results, with no notable difference ($p = 0.17$). The FF technique delivered a slightly higher dose (32.79 Gy for FF and 32.68 Gy for FFF).

The dose to 50% of the PTV (D50%) was slightly higher with the FFF technique (34.97 Gy for FF and 35.21 Gy for FFF and), though the difference was not statistically significant ($p = 0.21$).

The dose received by 2% of the PTV (D2%), representing the highest dose region, was 36.38 Gy for FF and 36.31 Gy for FFF. The difference between the two techniques was minimal and not statistically significant ($p = 0.22$).

Table 3. A comparison between the mean value of the PTV of the H&N patients treated using the VMAT technique with the energy 10 MV in both FF and FFF types.

10MV				
Planning target volumes	**FF**	**SD**	**FFF**	**SD**
D95%	33.17	±13.18	33.4	±12.96
D98%	32.79	±12.80	32.68	±12.67
D50%	34.97	±13.37	35.21	±13.44
D2%	36.38	±13.89	36.31	±13.81

3.2.3. Comparison between the dosimetric parameters for both types at 10 MV

Table 4 shows that both FF and FFF have the same conformity index (1), which indicates that techniques deliver radiation doses that perfectly match the shape of the target volume.

Regarding the homogeneity index, the FFF technique demonstrates a slightly lower value compared to FF (0.1 for FF vs.0.098 for FFF), though the difference is not statistically significant ($p = 0.36$).

In terms of treatment complexity, the FFF technique requires a greater number of segments (271 for FF vs. 328 for FFF), though the difference is not statistically significant ($p = 0.16$). However, FFF requires a significantly higher number of monitor units (MU) compared to FF (1093.8 MU for FF vs. 1579.4 MU for FFF), with a statistically significant difference ($p = 0.02$).

Table 4. A comparison between the dosimetric parameters using the VMAT technique for the energy 10 MV in both FF and FFF types.

10MV				
Dosimetric parameters	**FF**	**SD**	**FFF**	**SD**
conformity index (CI)	1	Identical	1	Identical
homogeneity index (HI)	0.1	±0.02	0.098	±0.02
Number of segments	271	±195.45	328	±243.88
Monitor unit	1093.8	±328.24	1579.4	±823.88

3.3. Comparison between the energies 6 and 10 MV for the FF beam type

3.3.1. Comparison between the mean doses of the OARs

Figure 3 compares the mean doses received by the OARs for 20 H&N patients treated using VMAT of 6 MV and 10 MV with FF beams. Among the OARs, the brainstem (maximum dose) received the highest dose (34.53 Gy for 6 MV FF and 35.26 Gy for 10 MV FF), with no significant difference between the two energies (p = 0.19). Conversely, the heart (mean dose) received the lowest dose (2.6 Gy for 6 MV FF and 2.45 Gy for 10 MV FF), also showing no significant difference (p = 0.25).

While most OARs received slightly higher doses in the 10 MV FF beam type, the differences were not statistically significant. These include the right parotid gland (mean dose) (9.78 Gy for 6MV FF, 10.2 Gy for 10MV FF; p = 0.08), left parotid gland (mean dose) (12.36 Gy for 6MV FF, 12.38 Gy for 10MV FF; p = 0.47), right eye (maximum dose) (10.52 Gy for 6MV FF, 10.7 Gy for 10MV FF; p = 0.35), and left eye (maximum dose) (19.32 Gy for 6MV FF, 20.52 Gy for 10MV FF; p = 0.14). Similarly, the left lens (maximum dose) (8.78 Gy for 6MV FF, 9.16 Gy for 10MV FF; p = 0.29), left cochlea (mean dose) (20.7 Gy for 6MV FF, 21.48 Gy for 10MV FF; p = 0.18), and left optic nerve (maximum dose) (17.32 Gy for 6MV FF, 17.66 Gy for 10MV FF; p = 0.39) showed no significant differences.

Additionally, the spinal cord (maximum dose) (26.68 Gy for 6MV FF, 27.43 Gy for 10MV FF; p = 0.12), larynx (mean dose) (14.52 Gy for 6MV FF, 15.6 Gy for 10MV FF; p = 0.09), and optic chiasm (maximum dose) (27.66 Gy for 6MV FF, 29.62 Gy for 10MV FF; p = 0.18) also exhibited no significant differences. Notably, the right lens (maximum dose) showed a statistically significant difference (5.96 Gy for 6 MV FF, 6.38 Gy for 10 MV FF; p = 0.03).

A few OARs received slightly higher doses in the 6 MV FF beam type, but these differences were not statistically significant: right cochlea (mean dose) (19.1 Gy for 6MV FF, 18.78 Gy for 10MV FF; p = 0.29), right optic nerve (maximum dose) (14.66 Gy for 6MV FF, 13.52 Gy for 10MV FF; p = 0.13), right lung (mean dose) (8.6 Gy for 6MV FF, 8.5 Gy for 10MV FF; p = 0.35), left lung (mean dose) (9.75 Gy for 6MV FF, 8.85 Gy for 10MV FF; p = 0.18), oral cavity (mean dose) (11.87 Gy for 6MV FF, 11.69 Gy for 10MV FF; p = 0.26), and esophagus (mean dose) (11.78 Gy for 6MV FF, 11.69 Gy for 10MV FF; p = 0.11).

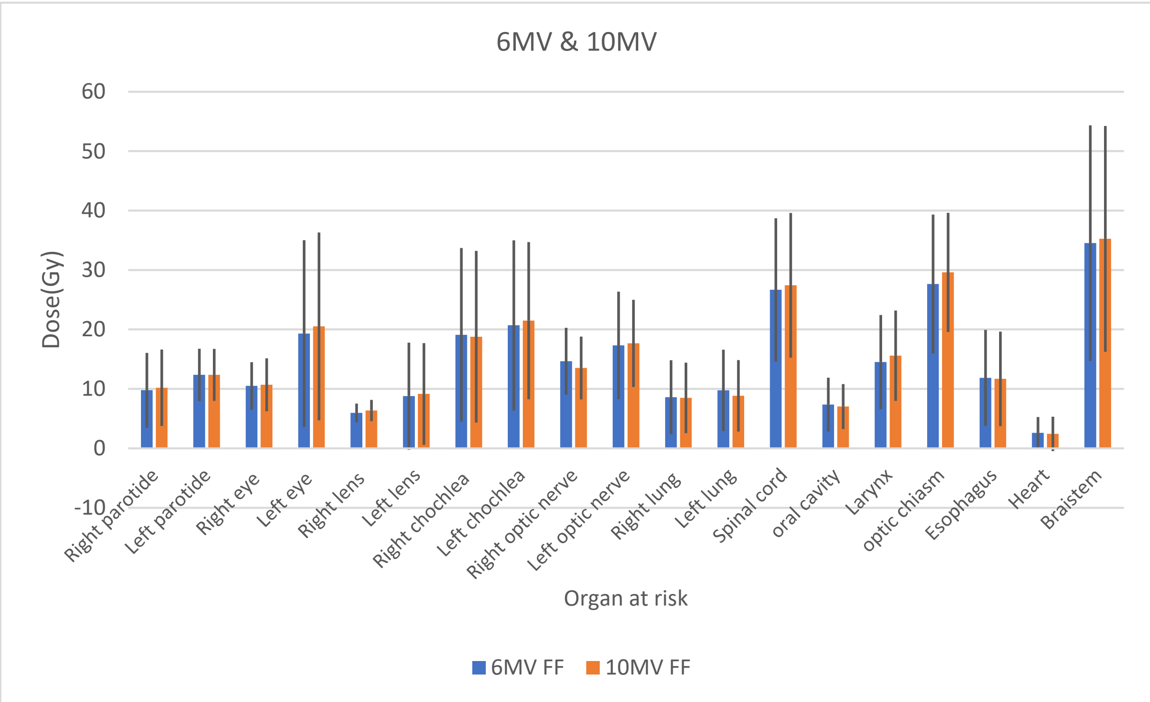

Figure 3. A comparison of the mean doses for the OARs of the H&N patients treated with VMAT technique with the FF beam type in both energies 6 MV and 10 MV.

3.3.2. Comparison between the mean values of the planning target volumes for FF beam type at 6 MV and 10 MV

The planning target volumes (PTV) treated with VMAT flattening filter (FF) beams at both 6 MV and 10 MV energies were analyzed. The dose received by 95% of the PTV (D95%) was nearly the same for both energies, with a significant difference (p = 0.009), as the 10 MV FF beam showed a slight reduction (33.17 Gy) compared to the 6 MV FF beam (33.63 Gy). Similarly, the dose to 98% of the PTV (D98%) was slightly reduced for the 10 MV beam (32.79 Gy) compared to the 6 MV FF beam (33.04 Gy), with a significant difference (p = 0.02).

The dose received by 50% of the PTV (D50%) was very similar between the two energies. The 6MV beam delivered a slightly higher dose (35.3 Gy) compared to the 10 MV FF beam (34.97 Gy), with no significant difference (p = 0.14). The dose received by 2% of the PTV (D2%), representing the highest dose region of the target, was nearly the same for both energy levels, with the 6 MV beam delivering a slightly higher dose (36.43 Gy) compared to the 10 MV FF beam (36.3 Gy), with no significant difference (p = 0.24). Overall, the 6 MV FF beam tends to deliver slightly higher doses to the PTV compared to the 10 MV FF beam.

Table 5. A Comparison between the mean value of the PTV of the H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FF beam configuration

Planning target volumes	6MV		10MV	
	FF	SD	FF	SD
D95%	33.63	±12.92	33.17	±13.18
D98%	33.04	±12.67	32.79	±12.80
D50 %	35.3	±13.46	34.97	±13.37
D2 %	36.43	±13.83	36.38	±13.89

3.3.3. Comparison between the dosimetric parameters for the FF beam type at 6 MV and 10 MV

A conformity index value of 1 indicates perfect alignment between the dose and the target volume for both 6MV and 10MV beams. In this case, the 6 MV FF beam demonstrates a slightly better homogeneity index (0.086) compared to the 10 MV FF beam (0.1), with a significant difference ($p = 0.04$) between the two energies.

Regarding the number of segments, the 10 MV FF beam requires slightly more segments (271) compared to the 6 MV FF beam (259.42), with no significant difference ($p = 0.3$). Additionally, the 10 MV FF beam requires more monitor units (1093.8 MU) than the 6 MV FF beam (1028.6 MU), with no significant difference ($p = 0.19$). Overall, while the 6 MV FF beam shows slightly better homogeneity and higher doses to small volumes, both energies exhibit similar dosimetric characteristics.

Table 6. A comparison between the dosimetric parameters using the VMAT technique in both energies 6 MV and 10 MV with FF beam type

Dosimetric parameters	6MV		10MV	
	FF	SD	FF	SD
conformity index	1	Identical	1	Identical
homogeneity index	0.086	±0.01	0.1	±0.02
Number of segments	259.42	±179.03	271	±195.45
Monitor unit	1028.6	±341.04	1093.8	±328.24

3.4. Comparison between the energies 6 and 10 MV for the FFF beam configuration

3.4.1. Comparison between the mean doses of the OARs

Figure 4 compares the OARs for 20 head and neck (H&N) patients treated with 6 MV and 10 MV using the VMAT technique with FFF beams. The brainstem (maximum dose) received the highest dose (35.03 Gy for 6MV FFF, 36.33 Gy for 10MV FFF), with no significant difference between the two energies ($p = 0.18$). The heart (mean dose) received the lowest dose (2.2 Gy for 6MV FFF, 2.45 Gy for 10MV FFF), also showing no significant difference ($p = 0.17$).

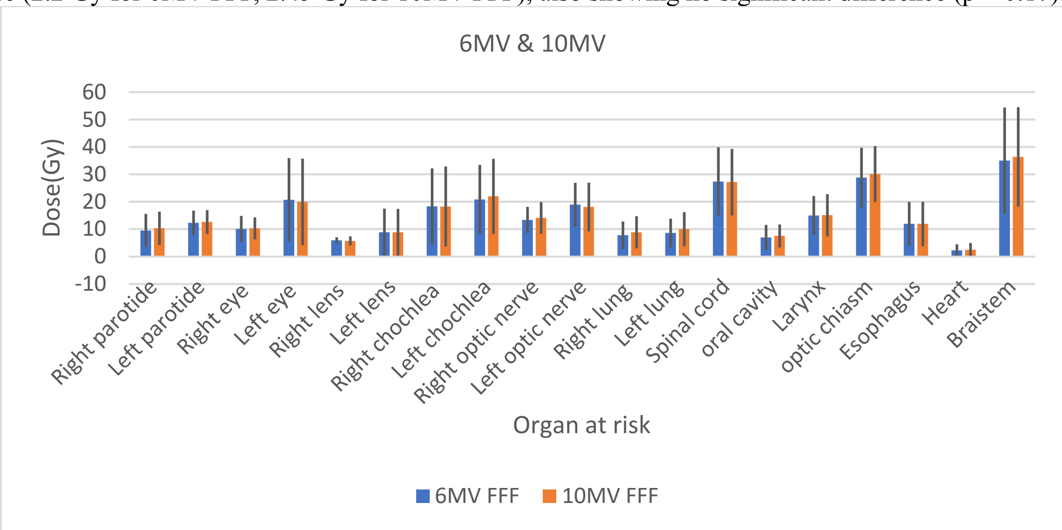

Figure 4. A comparison of the mean doses for the OARs of the H&N patients treated with VMAT technique with the FFF beam type in both energies 6 MV and 10 MV

Most OARs received slightly higher doses in the 10MV FFF beam type. The right parotid gland (mean dose) (9.5 Gy for 6MV FFF, 10.32 Gy for 10MV FFF) showed a significant difference ($p = 0.03$), while the left parotid gland (mean dose) (12.28 Gy for 6MV FFF, 12.6 Gy for 10MV FFF; $p = 0.23$) did not show a significant difference. Other OARs with no significant differences include the right eye (maximum dose) (10.04 Gy for 6MV FFF, 10.3 Gy for 10MV FFF; $p = 0.35$), left cochlea (mean dose) (20.81 Gy for 6MV FFF, 21.95 Gy for 10MV FFF; $p = 0.14$), right optic nerve (maximum dose) (13.34 Gy for 6MV FFF, 14.1 Gy for 10MV FFF; $p = 0.27$), right lung (mean dose) (7.75 Gy for 6MV FFF, 8.85 Gy for 10MV FFF; $p = 0.15$), left lung (mean dose) (8.5 Gy for 6MV FFF, 10 Gy for 10MV FFF; $p = 0.14$), larynx (mean dose)

(14.97 Gy for 6MV FFF, 15.07 Gy for 10MV FFF; p = 0.44), optic chiasm (maximum dose) (28.82 Gy for 6MV FFF, 30.08 Gy for 10MV FFF; p = 0.20), and esophagus (mean dose) (11.91 Gy for 6MV FFF, 11.92 Gy for 10MV FFF; p = 0.46).

A few OARs received slightly higher doses in the 6MV FFF beam type, but these differences were not significant: left eye (maximum dose) (20.72 Gy for 6MV FFF, 19.92 Gy for 10MV FFF; p = 0.28), right lens (maximum dose) (5.9 Gy for 6MV FFF, 5.69 Gy for 10MV FFF; p = 0.29), left lens (maximum dose) (8.82 Gy for 6MV FFF, 8.8 Gy for 10MV FFF; p = 0.48), right cochlea (mean dose) (18.28 Gy for 6MV FFF, 18.26 Gy for 10MV FFF; p = 0.48), left optic nerve (maximum dose) (18.92 Gy for 6MV FFF, 18.1 Gy for 10MV FFF; p = 0.25), and spinal cord (maximum dose) (27.33 Gy for 6MV FFF, 27.18 Gy for 10MV FFF; p = 0.36).

3.4.2. Comparison between the mean values of the planning target volumes for FFF beam configuration at 6 MV and 10 MV

From Table 7, one can notice that the dose to 95% of the PTV (D95%) was slightly lower for the 10 MV FFF beam (33.4 Gy) compared to the 6 MV FFF beam (33.57 Gy), with no significant difference (p = 0.13). Similarly, the dose to 98% of the PTV (D98%) was also slightly lower for the 10 MV FFF beam (32.68 Gy) compared to the 6 MV FFF beam (32.83 Gy), showing no significant difference (p = 0.18). The dose to 50% of the PTV (D50%) was very similar between the two energies, with a marginal difference (35.33 Gy for FFF 6 MV, 33.21 Gy for FFF 10 MV) and no significant difference (p = 0.14).

The dose to the 2% of the PTV (D2%), which represents the highest dose region within the target volume, was slightly lower with the 10 MV FFF beam (36.31 Gy) compared to the 6 MV FFF beam (36.48 Gy). This difference was statistically significant (p = 0.01).

Overall, the results indicate that the 6 MV FFF beam delivers slightly higher doses to the PTV compared to the 10 MV FFF beam, particularly in the highest dose region.

Table 7. A Comparison between the mean value of the PTV of the H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FFF beam type.

planning target volume	6MV		10MV	
	FFF	SD	FFF	SD
D95%	33.57	±12.97	33.4	±13.18
D98%	32.84	±12.83	32.68	±12.80
D50%	35.33	±13.54	35.21	±13.37
D2%	36.48	±13.84	36.31	±13.89

3.4.3. Comparison between the dosimetric parameters for the FFF beam type at 6 MV and 10 MV

From Table 8, The conformity index (CI) for both 6 MV and 10 MV with FFF beams is 1, indicating perfect alignment between the dose and the target volume. The 10 MV FFF beam demonstrates a slightly better homogeneity index (HI) of 0.098 compared to 0.104 for the 6MV FFF beam, with no statistically significant difference (p = 0.19).

The 10 MV FFF beam uses slightly more segments (328) compared to the 6 MV FFF beam (290.69), with no statistically significant difference (p = 0.22). Additionally, the 10 MV FFF beam requires more monitor units (1579.4 MU) compared to the 6 MV FFF beam (1390.6 MU), though this difference is not significant (p = 0.09).

In terms of delivery time on the Elekta linac using the VMAT technique for 20 head and neck cases, the FFF beam configuration generally showed reduced delivery times compared to the FF beam type. The FF technique took about 3 minutes to 3 minutes and 20 seconds, while the FFF beam configuration was approximately a minute shorter, ranging from 2 minutes to 2 minutes and 20 seconds.

Table 8. A comparison between the dosimetric parameters using the VMAT technique in both energies 6 MV and 10 MV with FFF beam type.

Dosimetric parameters	6MV		10MV	
	FFF	SD	FFF	SD
conformity index (CI)	1	Identical	1	Identical
homogeneity index (HI)	0.104	±0.02	0.098	±0.02
Number of segments	290.69	±215.97	328	±243.88
Monitor unit	1390.6	±475.58	1579.4	±823.88

3.5. Biological parameters NTCP (%) and EUD (Gy) for the OARs

3.5.1 Comparison between the mean values of biological parameter (NTCP) of the organs at risk for both types at 6 MV.

From Table 9, the spinal cord, esophagus, and heart showed identical values. The NTCP values of the brainstem were higher compared to the other organs in both types. They also in case of using the FFF technique, it was slightly lower than that in case of using FF, and there was a statistically significant difference, where the p-value is 0.0005.

Table 9. A Comparison between the mean value of the NTCP (%) the H&N patients treated using the VMAT technique with the energy 6 MV in both FF and FFF types.

	NTCP	
	6MV FF	6MV FFF
Spinal cord	0	0
esophagus	0	0
Heart	0	0
Brainstem	1.9	1.7

3.5.2 Comparison between the mean values of biological parameter (NTCP) of OARs for both beam types at 10 MV

From Table 10, it can be noticed that the heart and esophagus had identical values, but the spinal cord and brainstem had different values, where in the spinal cord, there was no statistically significant difference (p-value = 0.2), unlike the brainstem, which had slightly higher values. Also, FFF had a lower value. There was a significant difference, where the p-value is 0.

Table 10. Comparison between the mean value of the NTCP (%) of the H&N patients treated using the VMAT technique with the energy 10 MV in both FF and FFF beam types.

	NTCP	
	10MV FF	10MV FFF
Spinal Cord	0.00018	0.00026
esophagus	0	0
Heart	0	0
Brainstem	1.75	0.54

3.5.3 Comparison between the mean values of biological parameter (NTCP) of organ at risk between the energies 6 and 10 MV for the FF beam type

According to Table 11, the heart and esophagus exhibited identical values across both techniques. In contrast, the spinal cord showed slightly higher values with the 10 MV FF technique, although this difference was not statistically significant (p = 0.2). The brainstem presented different values between techniques, with the 10 MV FF technique yielding a slightly lower value, which was statistically significant (p = 0.0005).

Table 11. Comparison between the mean value of the NTCP (%) the H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FF beam configuration.

	NTCP	
	6MV FF	10MV FF
S. cord	0	0.00018
esophagus	0	0
Heart	0	0
Brainstem	1.9	1.75

3.5.4 Comparison between the mean values of biological parameter (NTCP) of organ at risk between the energies 6 and 10 MV for the FFF beam type

Table 12 shows that the heart and esophagus demonstrated identical values across both techniques. The spinal cord exhibited a slightly higher value in the 10 MV FFF beam type; however, this difference was not statistically significant (p = 0.2). In contrast, the brainstem showed a lower value in the 10MV FFF beam type, with the difference reaching statistical significance (p = 0.00000332).

Table 12. Comparison between the mean value of the NTCP (%) of H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FFF beam configuration.

	NTCP	
	6MV FFF	10MV FFF
S. cord	0	0.00026
esophagus	0	0
Heart	0	0
Brainstem	1.7	0.54

3.5.5 Comparison between the mean values of biological parameter (EUD) of organ at risk for both types at 6 MV

Figure 5 demonstrates that the variations between the FF and FFF techniques were marginal, with the FFF approach producing marginally reduced doses in all examined organs at risk (OARs). Nonetheless, for the spinal cord and esophagus, the observed discrepancies lacked statistical significance (p = 0.07 and p = 0.2, respectively). Conversely, pronounced differences were noted for the heart and brainstem, both exhibiting statistically significant deviations ($p = 0.0$ in each case). This hypothesizes that while the two techniques deliver largely similar doses to most OARs, the FFF beam type may lead to slightly reduced exposure for certain critical structures, particularly the heart and brainstem.

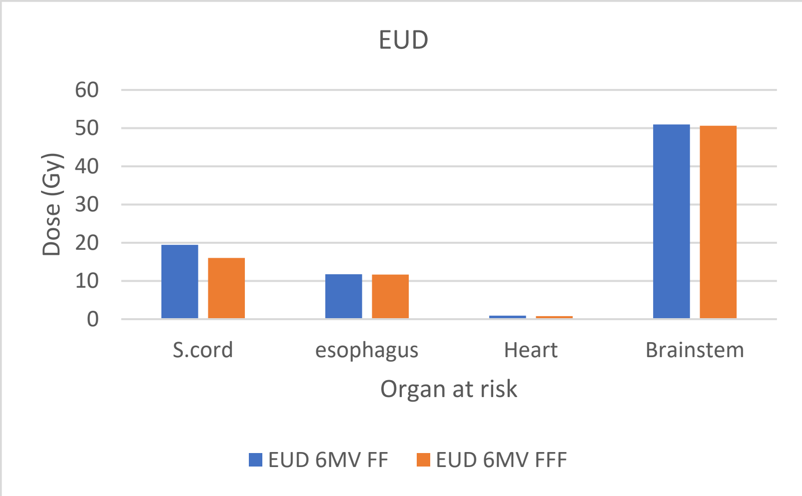

Figure 5. A Comparison between the mean value of the EUD of H&N patients treated using the VMAT technique with the energy 6 MV in both FF and FFF types.

3.5.6 Comparison between the mean values of the biological parameter (EUD) of the organ at risk for both beam configurations at 10 MV

Figure 6 presents the Equivalent Uniform Dose (EUD) delivered to various organs at risk (OARs) using the 10MV FF and 10MV FFF techniques. Overall, the differences in EUD between the two techniques are minimal. For the spinal cord and esophagus, the EUD values are nearly identical, indicating no significant variation between FF and FFF beam configurations ($p = 0.4$ and $p = 0.2$, respectively). In contrast, the heart shows a noticeable reduction in EUD with the FF technique, although the absolute dose remains very low for both techniques. The brainstem exhibits the highest EUD among all OARs, with a significantly lower value observed in the FF beam configuration compared to FFF ($p = 0.0$). This suggests that while both techniques offer comparable protection for most OARs, the FF technique may offer improved sparing of critical structures such as the brainstem and heart.

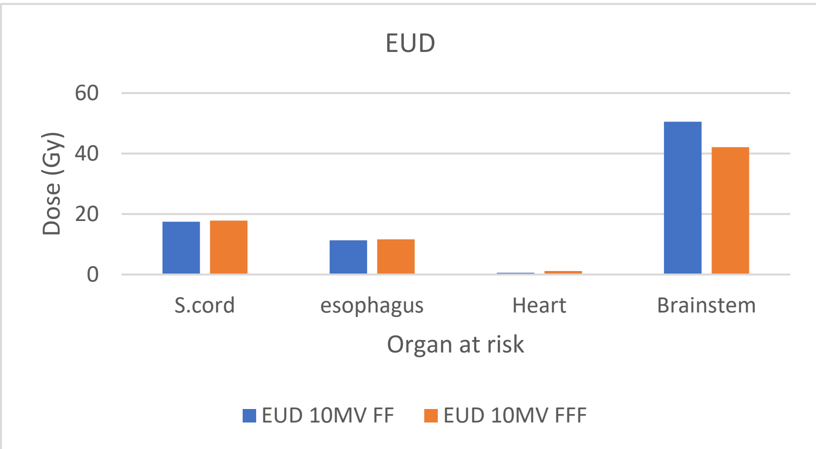

Figure 6. A Comparison between the mean value of the EUD of H&N patients treated using the VMAT technique with the energy 10 MV in both FF and FFF beam types.

3.5.7 Comparison between the mean values of biological parameter (EUD) of organ at risk between the energies 6 and 10 MV for the FF beam type

Figure 7 compares the Equivalent Uniform Dose (EUD) delivered to various organs at risk (OARs) using the 10MV FF and 6MV FF techniques. The the 10MV FF energy yielded slightly lower EUD values than 6MV FF across all OARs. For the spinal cord and esophagus, no significant differences were observed between the two techniques ($p = 0.13$ and $p = 0.24$, respectively). In contrast, the heart and brainstem exhibited significant reductions in EUD with the 10MV FF technique, with p-values of 0 and 0, respectively. These findings suggest that while both photon energies provide comparable sparing for certain OARs, the 10MV FF technique may offer improved dose reduction for critical structures such as the heart and brainstem.

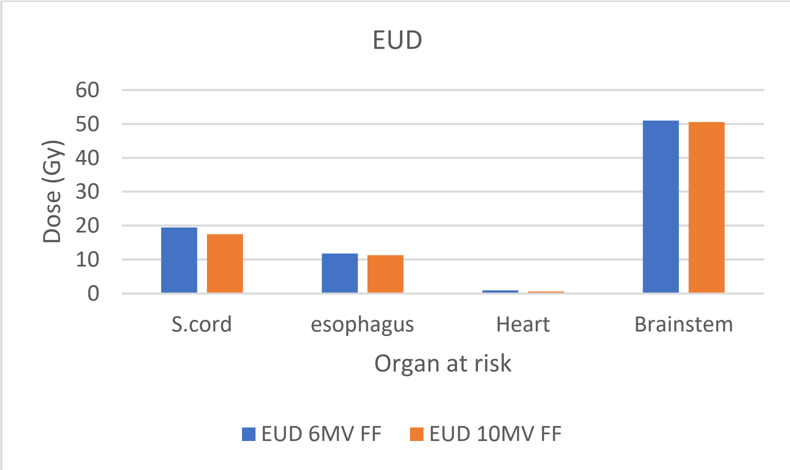

Figure 7. Comparison between the mean value of the EUD of H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FF beam type.

3.5.8 Comparison between the mean values of biological parameter (EUD) of organ at risk between the energies 6 and 10 MV for the FFF beam type

Figure 8 evaluates the dose distribution between 10MV FFF and 6MV FFF for selected organs at risk (OARs). The esophagus and brainstem exhibited slightly lower doses with the 10MV FFF technique, whereas the heart and spinal cord received marginally lower doses with 6MV FFF. No significant differences were observed between the two energies for the spinal cord and esophagus ($p = 0.2$ for both). In contrast, statistically significant differences were found for the heart and brainstem, with p-values of 0 and 0, respectively. These results indicate that while the two FFF energies perform similarly for some OARs, the choice of energy may influence dose sparing in critical structures such as the heart and brainstem.

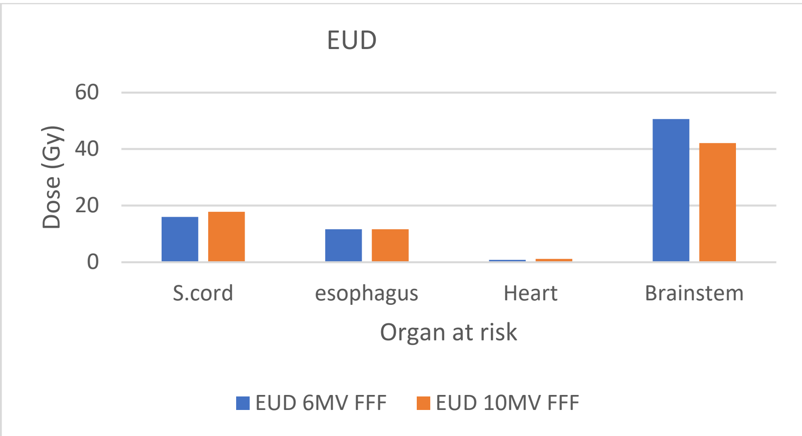

Figure 8. Comparison between the mean value of the EUD of H&N patients treated using the VMAT technique in both energies 6 MV and 10 MV with FFF beam type.

3.6 Second cancer risk estimation (%) for OARs of 20 patients:

3.6.1 Comparison between the mean values of Second cancer risk estimation of organ at risk for both beam types at 6MV.

Table 13 demonstrates subtle but notable differences between the two techniques. Both parotid glands received slightly lower doses in FFF beam type, with statistically significant differences observed (right parotid: $p = 0.00049$; left parotid: $p = 0.0013$). In contrast, the larynx showed reduced dose exposure in FF beam configuration, though this difference was also statistically significant ($p = 0.0005$). These findings suggest that while both techniques achieve clinically acceptable dose distributions, the choice between FF and FFF beam configurations may impact specific anatomical structures differently.

Table 13. Comparison between the mean value of the second cancer risk estimation (%) of H&N patients treated using the VMAT technique in the energy 6MV in both FF and FFF beam types.

OAR	6MV FF	SD	6MV FFF	SD
Right parotid	0.49	±0.31	0.48	±0.30
Left parotid	0.62	±0.22	0.61	±0.22
Larynx	0.73	±0.39	0.75	±0.35

3.6.2 Comparison between the mean values of Second cancer risk estimation of organ at risk for both beam types at 10MV.

Table 14 reveals consistent dose variations between the techniques. Both parotid glands demonstrated slightly higher doses in FFF beam type (right parotid: $p = 0.002$; left parotid: $p = 0.002$), while the larynx received marginally higher doses in FF beam type ($p = 0.0002$). All three comparisons showed statistically significant differences. These findings suggest that while absolute dose differences are modest, they may warrant consideration in clinical applic±ations where these organs are particularly at risk.

Table 14. Comparison between the mean value of the second cancer risk estimation (%) of H&N patients treated using the VMAT technique in the energy 10MV in both FF and FFF beam configurations.

OAR	10MV FF	SD	10MV FFF	SD
Right parotid	0.51	±0.32	0.52	±0.3
Left parotid	0.62	±0.65	0.63	±0.58
Larynx	0.78	±0.38	0.75	±0.38

3.6.3 Comparison between the mean values of Second cancer risk estimation of organ at risk between the energies 6 and 10MV for the FF beam type.

Table 15 demonstrates differential dose distribution patterns between the techniques. While the left parotid showed identical doses for both modalities, the 10MV FF technique yielded slightly higher doses to both the right parotid ($p = 0.0001$) and larynx ($p = 0.0002$), with these differences reaching statistical significance. These findings indicate that while some structures may receive equivalent doses regardless of technique, others exhibit energy-dependent variations that may warrant consideration in treatment planning.

Table 15. Comparison between the mean value of the second cancer risk estimation (%) of H&N treated using the VMAT technique in both energies 6 MV and 10 MV with FF beam configuration.

OAR	6MV FF	SD	10MV FF	SD
Right parotid	0.49	±0.31	0.51	±0.32
Left parotid	0.62	±0.22	0.62	±0.65
Larynx	0.73	±0.39	0.78	±0.38

3.6.4 Comparison between the mean values of Second cancer risk estimation of organ at risk between the energies 6 and 10MV for the FFF beam type

Table 16 reveals distinct dose distribution patterns between the evaluated techniques. While the larynx demonstrated identical dose values for both modalities, both parotid glands exhibited slightly elevated doses with statistically significant differences (right parotid: $p = 0.0001$; left parotid: $p = 0.0005$). This differential effect suggests that while laryngeal dose remains consistent regardless of technique selection, parotid gland doses show technique-dependent variations that may influence clinical decision-making, particularly in cases where parotid sparing is prioritized.

Table 16. Comparison between the mean value of the second cancer risk estimation (%) of H&N treated using the VMAT technique in both energies 6 MV and 10 MV with FFF f.

OAR	6MV FFF	SD	10MV FFF	SD
Right parotid	0.48	±0.30	0.52	±0.3
Left parotid	0.61	±0.22	0.63	±0.58
Larynx	0.75	±0.35	0.75	±0.38

4. DISCUSSION

This study presents the dosimetric and biological differences in treatment plans using flattened (FF) and flattening-filter-free (FFF) beams in the treatment of Head and Neck Cancer, focusing on the influence and impact of energy (6 MV and 10 MV beams) on volumetric modulated arc therapy (VMAT) plans. While extensive research has been conducted on Varian FFF beams (Varian Medical System, Palo Alto, CA, USA), limited literature is available on Elekta FF beams (Elekta Oncology Systems, Crawley, UK) for this specific site.

Previous studies, such as those by Gasic et al. [9] and Ji et al. [10], have explored the potential of using FFF beams for various treatment sites, including the head and neck, brain, prostate, and lung cancer. Our findings align with these studies, demonstrating that the 6 MV FFF beam offers a slightly improved dose-sparing effect for most organs at risk (OARs) compared to the 6 MV FF beam. This improvement means that the 6 MV FFF beam can more efficiently reduce the radiation dose delivered to critical surrounding tissues, as supported by Kumar et al. [1].

According to the results of this study, the planning target volumes (PTV) for both 6 MV FF and FFF beams showed very similar dose distributions, with only minor variations. This indicates that FFF VMAT plans provide comparable results to FF VMAT plans, as reported by Kumar et al. [5] and Manna et al. [11]. Both techniques exhibited equal conformity index (CI), but the FF beam had a better homogeneity index (HI). Additionally, FFF beams required significantly higher monitor units (MUs) due to their conic shape dose distribution, necessitating compensation through a greater number of smaller segments and MUs, as observed in previous studies (Lechner et al. [13], Vassiliev et al. [14], and Sun et al. [15]).

Regarding the delivery time, the FFF beam type generally showed reduced times compared to the FF beam configuration. This reduction in delivery time leads to less machine operating time, ultimately lowering the treatment cost, and this is agreed with a study by Thomas et al. [16].

For the 10 MV FF beam, a more noticeable advantage in reducing the radiation dose delivered to critical structures was observed, with a statistically significant difference in the dose to the lungs. Both 10 MV FF and FFF beam plans delivered similar dose distributions, with FFF slightly outperforming FF in terms of dose to 95% and 50% of the target volume. However, the differences between the plans were not significant.

Both 6 MV and 10 MV FF plans showed very similar dose distributions and coverage, with slight differences in sparing OARs. The 6 MV FF plan demonstrated better dose homogeneity and a statistically significant difference for the right lens compared to the 10 MV FF plan. The 10 MV FF plan required more segments and higher MUs, leading to increased treatment time and cost.

Therefore, the differences in dose distribution between the 6 MV FFF and 10 MV FFF beams are minor, with the 6 MV FFF beam delivering slightly higher doses at each percentile than the 10 MV FFF beam. Both configurations yield comparable dosimetric results, with the 10 MV FFF beam offering marginally better dose homogeneity but requiring a higher number of segments and MUs.

Previous research has shown that variations in dose can have a substantial impact on radiobiological factors related to NTCP Srivastava et al. [17], potentially influencing the quality of radiotherapy. As a result, assessing NTCP is a critical component when comparing the two technologies, Aly et al. [7], Wu et al. [18].

The biological parameter (NTCP) results were identical for all OARs across techniques and energies except for the spinal cord, though this difference was not statistically significant ($p>0.05$). These findings align with Aras et al. [19] who found FF and FFF beams produced similar results, and Kang et al. [20] who reported minimal radiobiological differences. However, the brainstem showed significant differences ($p<0.05$) across all techniques and energies, with FFF beam type demonstrating reduced values compared to FF, consistent with Wu et al. [18].

For the EUD, no significant difference was observed between FFF (Flattening-Filter-Free) and FF (Flattening-Filter) beam types in the spinal cord and esophagus across all energy levels. However, statistically significant differences were noted for the heart and brainstem in all beam types, as well as when comparing energy levels also the results were lower in FFF but both beam configurations yields comparable results.

For the second cancer risk estimation, statistically significant differences were observed across all comparisons for the left parotid, right parotid, and larynx except for two cases: (1) the left parotid risk was identical between 6MV FF and 10MV FF, and (2) the larynx risk was identical between 6MV FFF and 10MV FFF.

Overall, 6MV FFF beam type slightly reduced the risk to the parotids (supported by Alvarez et al. [21] and Treutwein et al. [22, 23]) but increased the risk to the larynx. Conversely, 10MV FFF beam type increased the parotid risk while reducing the larynx risk. When comparing energies, 10MV exhibited a slightly higher second cancer risk in the parotids than 6MV, particularly in FFF beam configuration. For the larynx, the risk was similar between the two energies in FFF beam type but higher with 10MV in FF beam type.

10MV shows a slightly higher risk in some OARs, but again, the difference is very small, the choice between FF/FFF or 6MV/10MV should prioritize target coverage and normal tissue sparing rather than second cancer risk, given the minimal differences observed

This study contributes valuable insights by comparing both techniques (flattening filter and without the flattening filter) at both energy levels (6 MV and 10 MV) in head and neck cancer treatments using the VMAT technique on the Elekta Versa. However, it is important to note that these findings are based on planning data.

5. CONCLUSIONS

This study provides a comprehensive analysis of the dosimetric and biological and second cancer risk estimation differences between flattened (FF) and flattening-filter-free (FFF) beams and the impact of using both 6 MV and 10 MV energies for Head and Neck Cancer treatment plans using Volumetric Modulated Arc Therapy (VMAT). Our findings indicate that both FF and FFF techniques yield comparable biological and dosimetric outcomes in terms of sparing organs at risk (OARs) and target volume coverage, and second cancer risk estimation.

For the 6 MV FFF beam, there is a slight improvement in dose-sparing for OARs, while the 6 MV FF beam provides a better homogeneity index. The 6 MV FFF configuration required more monitor units and segments (with statistically significant differences) but offered reduced delivery times, leading to more efficient treatment and lower operational costs.

In contrast, the 10 MV FFF beam showed marginally better dose homogeneity and a slight advantage in sparing normal tissue at lower doses. The 10 MV FFF slightly outperformed FF in terms of dose coverage to 95% and 50% of the target volume. The 10 MV FFF plan required additional segments and monitor units (with statistically significant differences), resulting in a slight decrease in treatment time and cost.

It can be concluded that when comparing the impact of the energies, results were very comparable, with a slight advantage for the 6 MV over the 10 MV in sparing OARs and planning target volume coverage, as well as in dosimetric parameters.

Also, this study demonstrates that while radiobiological outcomes between FF and FFF beam types are largely comparable, FFF beams, particularly at 6MV, offer slight advantages in reducing doses to critical structures such as the brainstem and parotids without compromising treatment efficacy. Overall, both FF and FFF beam configurations provided similar outcomes, with minor variations in risk based on energy levels. These results suggest that FFF techniques, particularly at 6MV, offer a feasible approach to reducing dose to critical organs while maintaining treatment efficacy, without significantly altering the overall second cancer risk profile.

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ОПТИМІЗАЦІЯ ПРОМЕНЕВОЇ ТЕРАПІЇ РАКУ ГОЛОВИ ТА ШИЇ: ДОЗИМЕТРИЧНЕ ПОРІВНЯННЯ ПРОМЕНІВ FF ТА FFF У VMAT

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Мета: Рак голови та шиї (РГШ) є значною глобальною проблемою охорони здоров'я, зі зростанням захворюваності та високою поширеністю в Південній Азії, особливо в Індії. Променева терапія, включаючи передові методи, такі як об'ємно-модульована дугова терапія (VMAT) та інтенсивно-модульована радіотерапія (IMRT), відіграє вирішальну роль у лікуванні РГШ. Це дослідження має на меті порівняти дозиметричні та біологічні відмінності в оцінці ризику раку, а також вторинної оцінки між сплющеними (FF) та сплющеними пучками без фільтра (FFF) у планах лікування HNC за допомогою VMAT, зосереджуючись на впливі енергій 6 MV та 10 MV. **Методи:** Двадцять пацієнтів з HNC пройшли повторне планування з використанням VMAT на лінійному прискорювачі ELEKTA VERSA HD з пучками потужністю 6 MV FF, 6 MV FFF, 10 MV FF та 10 MV FFF. Оцінювані дозиметричні параметри включали розподіл дози на об'єми планової мішені (PTV) та дозу, що доставляється до 98% мішені (D98), 50% (D50) та 2% (D2), а також дози на органи, що знаходяться в групі ризику (OAR), одиниці моніторингу на сегмент (MU/сегмент), кількість MU/cGy, час проведення лікування, індекс відповідності та індекс однорідності, а також були оцінені біологічні параметри (NTCP та EUD) та вторинна оцінка ризику раку. **Результати:** Результати показали, що 6-мегавольтні пучки FFF забезпечили дещо кращу економність дози для OAR порівняно з 6-мегавольтними FF, без суттєвих відмінностей у покритті цільового об'єму. Як пучки FF, так і FFF продемонстрували порівнянні показники конформності, але пучки FF мали кращі показники однорідності. Пучки FFF вимагали більше моніторних одиниць (MU) та сегментів, але пропонували менший час проведення лікування. Для 10-мегавольтних пучків FFF показав незначні переваги в однорідності дози та щадінні нормальних тканин при нижчих дозах, хоча й вимагав більше MU та сегментів. Це дослідження показало, що NTCP та EUD були значною мірою порівнянні між типами FF та FFF, з незначними, але статистично значущими відмінностями для стовбура мозку (на користь FFF) та серця. Ризики вторинного раку дещо відрізнялися залежно від енергії та техніки. 6-мегавольтний FFF знизив ризики привушних залоз (хоча збільшив ризик гортані). **Висновок:** 6-мегавольтні пучки, особливо FFF, показали незначні переваги у щадінні OAR та покритті цільового об'єму порівняно з 10-мегавольтними пучками. Це дослідження підкреслює дозиметричну порівнянність пучків FF та FFF у лікуванні раку голови та шиї, причому FFF пропонує потенційні переваги в ефективності лікування та скороченні часу проведення опромінення. Це дослідження також показує, що типи FF та FFF дають порівнянні радіобіологічні результати, хоча пучки FFF потужністю 6 MV дещо знижують дози на критичні органи без шкоди для ефективності. Обидва типи працюють подібно, з незначними варіаціями ризику залежно від енергії.

Ключові слова: *рак голови та шиї; об'ємно-модульована дугова терапія (VMAT); фільтр зі сплющенням (FF); безфільтровий фільтр зі сплющенням (FFF); 6 MV; 10 MV*