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Comparative Dosimetric Analysis of Flattened (FFB) and Flattening Filter-Free (FFFB) in IMRT for Oropharyngeal Cancer

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ABSTRACT

Introduction: The study compared the conformal radiotherapy doses in Oropharynx and lymph nodes of Head and Neck cases using 6MV flattened filter beam (FFB) and flattening filter-free beam (FFFB) in two phases (PI and PII).

Material and Methods: 25 patients with stage N2 involvement with no metastasis and undifferentiated advanced carcinoma of the Oropharynx were administered with pathological biopsy. 12 patients were staged T3 and other 13 staged T2. planning target volume (PTV) coverage, Organs at Risk (OARs), Monitor unit (MU), Homogeneity Index (HI), and conformity Index (CI) were presented.

Results: Intensity Modulated Radiation Therapy (IMRT) plans in 6 MV FFB and FFFB produced similar PTV coverage in the regions in PI and PII, with no significant variation in prescribed isodose of VRI95%, CI, HI, and MU in both Phases. The minimium dose (Dmin) was lower in FFB, while the maximum dose (Dmax), and maximum isodose (Imax) were significantly ($p<0.05$) lower in FFB. There was no significant variations in the CI and HI in the FFB and FFFB in both phases. FFFB in Dmax, Dmean, volume of the organ receiving dose, V20 and V50 reduced in brainstem, spinal cord, left and right parotid, left and right eye, and both lenses with little discrepancy in some organs, particularly in Dmax and Dmean compared to FFB.

Conclusion: IMRT with FFFB produced a highly conformal plan and homogeneity, spare the OAR's, particularly in the brainstem, right lens, and left lens.

Keywords: Oropharynx, IMRT, FFFB, FFB, OARs

Introduction

The use of Intensity Modulated Radiation Therapy (IMRT) is rapidly becoming essential in the area of Radiation Oncology. IMRT is likely to modify clinical effort aimed at implementing highly conformal non-convex dose distributions. It also plays essential roles in increased dose sparing and conformance as well as delivery of more monitor units (Amoabeng *et al.*, 2023). In the past, the FFB is used in 2D and 3D conformal radiotherapy. However, in the recent years, there have been new techniques developed for the treatment. For instance, IMRT is capable of producing the conformal plans without FFB directly. Consequently, this results in the availability of optimization concept due to the modification of the MLC speed, dose rate, and gantry speed to achieve the planned goals desired

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in the treatment planning system (Suresh and Madeswaran, 2022). It has been observed that in recent times, modern linear accelerators are designed to have 6 MV and 10 MV FFB and FFFB. According to Georg *et al*. (2011), the FFFB has unique features in comparison to FFB, such as fewer head scatter, sharper penumbra, out of field dose decrease, negligible difference in energy spectrum associated with off-axis position, dosimeter response to high ion recombination, beam on time (BOT) reduction, fewer multileaf collimator (MLC) leakage, little electron contamination, better dose calculation quality reliability, decrease in structure shielding demand and bringing down neutron level impurity in higher energies (>10 MV). The use of FFFB was aimed at decreasing the duration of treatment delivery since removing the FFB causes an increment in the dose rate to up to two to four times proportion (Cashmore, 2008). Studies aimed at investigating the effect of FFFB on the number of radiotherapy requirements have been carried out in the past to include contaminant particle, surface dose, among other factors (Kry *et al.*, 2005; Kry *et al.*, 2007; Pichandi *et al.*, 2014; Yani *et al,* 2020; Suresh and Madeswaran, 2022).

Kry *et al*. (2005) and Kry *et al.* (2007) assessed the risk rate of 2.9 % and 5.1 in treatment energies with the use of 6 MV and 18 MV IMRT planning in the second cancer malignancy. They suggested that while FFFB reduced risk to 0.9 %, the use of FFB gives a risk rate is 2.9 % . Yani *et al.* (2020) in their research reported that, the type of neutrons produced by FFB and FFFB nodes in the head Linac Elekta InfinityTM 10-MV photon were of similar energy. However, significant differences were observed in their neutron intensity. It was concluded, that although the neutrons produced from the head Linac as a result of photoneutron interactions of high-energy photons quantity were similar in FFB and FFFB, the FFB produce a larger quantity of neutrons. Suresh and Madeswaran (2022) also concluded that a reduced D700cc, V10Gy, and Dmean of the liver minus gross tumor volume region was produced in 6 and 10 MV VMAT FFB and FFFB in comparison to 3DCRT and DCA plans. It was further observed that FFFB, in combination with VMAT, produces highly conformal plan with better conformity number, and reduced Paddick gradient index in comparison to 3DCRT and DCA. They suggested that FFFB needs higher monitor units to achieve the plan in all the techniques, though it reduces the BOT and the body-PTV mean dose in the non-tumour volume. From the aforementioned, it was obvious that while FFFB offers potential benefits (higher dose rate, lower out-of-field dose), its comparative dosimetric performance for complex head-and-neck IMRT, particularly in a two-phase approach, requires further investigation to inform clinical implementation.

2.0 Materials and Method

Patient Selection

Twenty-five patients within the age range of 19-86 years were randomly selected with undifferentiated advanced carcinoma of the Oropharynx at the NSIA, Lagos University Teaching Hospital Cancer Centre in Lagos, Nigeria. All patients were administered with pathological biopsy and staged according to the American Joint Committee on Cancer (AJCC) guidelines. 12 patients selected from the 25 patients were staged T3, while the other 13 patients were staged T2. All the patients had stage N2 advanced carcinoma of the Oropharynx involvement with no metastatis (M0).

Imaging and Delineation

All patients were simulated in a supine position fixated to the couch with a thermoplastic head-neck/shoulder mask on a 16-slice computed tomography (CT) simulator (Optima 580; GE Healthcare, Waukesha,WI, USA). Images were obtained from the patient's skull vertex to the mid-chest with a slice thickness of 2.5 mm. The planning target volume (PTV) included the CTV with 3-5 mm extensions in all dimensions to account for patient setup error and motion uncertainties. MR Imaging was obtained for better soft tissue delineation in position similar to CT within immobilization after CT scan. A CT-MRI fusion aided in contouring of target volumes according to the ICRU 62 report. The MRI fusion is a weighted sequence with contrast and fat suppression. All volumes were contoured in two phases . Phase I included the primary tumor (Oropharynx) and lymph nodes while Phase 2 included only the primary tumor. Organs at risk,

such as the parotids, eyes, lenses, spinal cord, and brainstem were contoured according to the Radiation Therapy Oncology Group (RTOG) atlas for contouring normal tissues (Søren *et al.,* 2010).

Treatment Planning

Patients with unresected tumor and post-operative radiotherapy received a prescribed total dose of 70G/35fx delivered in phases of Phase I (54 Gy/27fx) and Phase II (16 Gy/8fx). IMRT plans using 6 MV FFFB and FFB from the Halcyon and Vital beam machine, respectively, were generated in the Eclipse treatment planning system (Varian Medical System; version 15.6.05) for each patient. Equally spaced beam arrangement was used at angles 0, 40, 80,120 etc. using 7 - 9 beams. The beam angle arrangement was implemented on Halcyon and Vital beam machine systems. Optimization objectives were set to achieve 95% coverage to the target volume and meet a tolerance dose to the OARs bearing in mind that a maximum dose of 107% must not be exceeded, as presented in Table 1. Dose calculation was done with Analytical Anisotropic Algorithm (AAA) on the Eclipse TPS, and Dose constraints were based on the Quantitative Analyses of Normal Tissue Effects in the Clinic recommendation (Søren, 2010).

Table1: Dose Planning Objectives

Structures	Planning Objectives
PTV 16 (phase 2)	V16Gy ≥ 95%
PTV54 (phase 1)	V54Gy ≥ 95%
Spinal Cord	Max 50Gy
Lens	Max: 7Gy
Chiasm/ Optic nerves	Max: 55Gy
Brainstem	Max < 56Gy
Eyes	Mean < 35Gy
Parotids	Mean < 20Gy (1 gland)
Larynx	Mean ≤ 44Gy
Cochlea	Mean dose < 45Gy
Oral Cavity	Mean < 50Gy

Plan Evaluation

A plan summation was generated from both phases (I & II) and analysed on the DVH. The data acquired from the analysis included the maximum dose (D_{max}), minimum dose (D_{min}), mean dose (D_{mean}), and dose reaching the following percentage volume of the PTV were recorded: V2%, V5%, V50%, V95%, V98% and V99% denoted by $D_{2\%}$, $D_{5\%}$, $D_{50\%}$, $D_{95\%}$, and $D_{99\%}$. Also, the maximum isodose in the target (I_{max}) and the reference isodose reaching V95% of the PTV were recorded. The target coverage and doses to OARs (spinal cord, brainstem, parotids, eyes, and lenses) were analyzed to evaluate treatment plans for all cases. The Homogeneity Index (HI) and conformity Index (CI) were calculated according to the definition proposed by ICRU Report 83, (2010) as follows. Also, the doses to the OARs were analyzed.

Conformity Index (CI)

The Conformity Index (CI) is a measure of how well the dose delivered conforms well to the target volume. It is denoted according to Loic Feuvret *et al.* (2006) that:

$$CI = \frac{TV}{V_{RI}}$$

where:

V_{RI} = volume of the PTV receiving 95% of the prescribed dose

TV = Volume covered by the reference isodose.

The ideal value for CI is 1. The closer the CI is to 1, the more conformal the dose is to the target volume which indicates t

Homogeneity Index (HI)

This shows how the dose is been distributed about the target volume. It is denoted by:

$$HI = \frac{D2\,\% - D98\,\%}{D50\,\%}$$

where $D_{2\%}$, $D_{50\%}$, and $D_{98\%}$ are the dose given to 2%, 50%, and 98% volume of the PTV respectively. For HI, the ideal value is 0. The value of HI closer to zero is considered to be more homogeneous.

Two-tailed T-test was used for statistical comparison of FFB and FFFB with the significance level set at 0.05. P-values < 0.05 were considered statistically significant, corresponding to a 95% confidence level. The statistical analyses were performed using Microsoft Excel spreadsheet 2016.

Results

IMRT Plans for the FFB and FFFB of both phases (PI and PII) for all twenty five patients were generated and comparative dosimetric outcome were recorded as presented in Table 2 and Figure 1 and 2 (for the PTV). It was observed that there were no significant difference between the FFB and FFFB plans for the mean dose (D_{mean}) and doses getting to 2%, 5%, 50%, 95%, 98%,99% of the PTV denoted by $D_{2\%}$, $D_{5\%}$, $D_{50\%}$, $D_{95\%}$, $D_{98\%}$ and $D_{99\%}$,respectively in PI. Furthermore, there was no significant variations in the volume that received 95% of the prescribed isodose ($VRI_{95\%}$), CI, HI and MU (Monitor unit) also in PI. The dose coverage of the PTV and machine output were quite the same in both plans. The minimum dose (D_{min}), maximum dose (D_{max}), I_{max} (dose reaching 2 cm^3 of the PTV, same as D_{max}) were similar in FFB in comparison to FFFB ($p<0.05$, though with negligible reduction in FFB as presented in Table 2.

Considering the selected parameter in the Phase II case, there were no significant differences in the D_{max}, D_{mean}, $D_{2\%}$, $D_{5\%}$, $D_{50\%}$, $D_{95\%}$, $D_{98\%}$, $D_{99\%}$, I_{max}, $VRI_{95\%}$, CI and HI between the two plans. However, there was a significant decrease in D_{min} and MU for the FFB plan compared to the FFFB plan ($p<0.05$) as shown in Table 2. The Conformity index (CI) for PI appeared to be more conformal in FFFB with a mean of 0.989 ± 0.01 in comparison to FFB with mean of 0.987 ± 0.01. These results are rather quite close and were of no statistical significance with p=0.518. Conformity Index for PII appears to be of the same value with means of 0.982 ± 0.02 and 0.982 ± 0.02 for FFB and FFFB, respectively, with no statistical significance (p=0.598). Although, there is no statistical significance ($p>0.05$) between HI in FFB and FFFB for PI and PII, it was observed that the HI in PI, with mean of 0.066 ± 0.020 and 0.068 ± 0.015 for FFB and FFFB respectively, indicated more homogeneity in FFFB than in FFB. Likewise in PII with mean of 0.074 ± 0.029 and 0.075 ± 0.026 for FFB and FFFB respectively. Figure 1 shows the dose distribution in an axial and coronal view for FFFB and FFB for a particular head and neck of a cancer patient. The PTV size and DVH were used to evaluate the treatment plans in order to achieve adequate sparing of the OARs. The dose to PTV and OAR's doses in all cases considered as summarized in Table 3 and Figure 3.

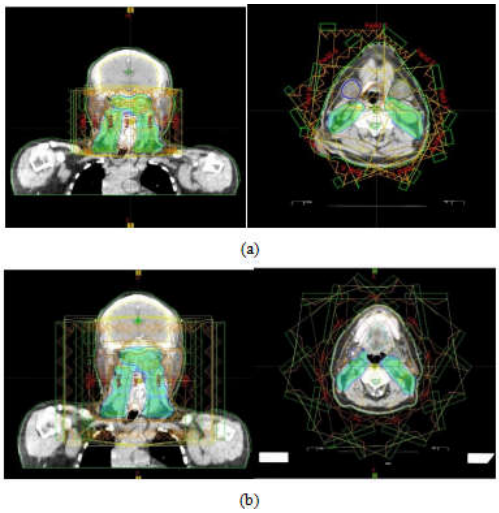

Figure 1: Dose distribution for axial and coronal view in (a) FFFB, and (b)FFB.

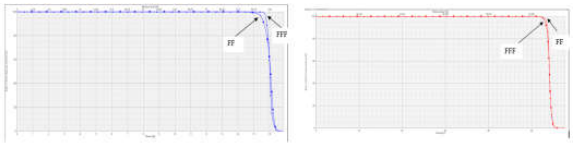

Figure 2: PTV comparison for P1 and PII for FF and FFF beam

The parameters considered in evaluating the dose to the organs at risk were the mean dose to the organ (D_{mean}), maximum dose received by the organ (D_{max}), volume of the organ receiving dose of 20Gy measured in cm^3 (V_{20}), and volume of the organ receiving dose of 50Gy measured in cm^3 (V_{50}) . The Dmean for Brainstem and Dmax/Dmean for Lenses are statistically significant ($p<0.05$) in FFFB compared to FFB for the brainstem. For the left parotid and right parotid, D_{max}, D_{mean}, and V_{20} reduced in FFFB in comparison to FFB. The value of V_{50} decreased in FFB for the left parotid and right parotid, but it was of no significance ($p>0.05$). The left eye showed a reduced dose for V_{20} and V_{50} values for

FFFB than in FFB, but D_{max} and D_{mean} were reduced in FFB with no significance ($p>0.05$). The right eye had a reduced value for all parameters except D_{max} for FFB compared to FFFB. For both lenses, there were reduced doses for all parameters for FFFB compared to FFB,. although V_{20} and V_{50} for both lenses appeared to be approximately null which shows no volume of the lenses received close to 20Gy but left lens had 0.01 ± 0.05 for V_{20}. Results from the total plan sum show that there was a significant decrease ($P<0.05$) in D_{max} to the lenses for FFFB compared to FFB. The D_{mean} for FFFB was also significantly reduced ($P<0.05$) compared to FFB for the brainstem, left lens, and right lens. All other parameters recorded were statistically not significant ($p>0.05$). FFFB spares the brainstem and lenses relatively more when compared to FFB. The Monitor unit (MU), which signifies the machine output and the beam-on time, was reduced in FFB compared to FFFB for both phases (2093.50 vs 2144.63 for P1 and 1237.88 vs 1443.95 for PII). There was a significant decrease in the MU for PII ($p=0.0063$) unlike P1($p=0.495$).

Table 2: Dosimetric outcomes for the PTV between FFB and FFFB for phases I and II

Parameters	Phase I			Phase II		
	FFB	FFFB	P-value	FFB	FFFB	P-value
D_{min} (Gy)	37.744 ± 6.223	40.892 ± 5.276	0.0042	11.218 ± 2.662	12.296 ± 1.591	0.0371
D_{max} (Gy)	57.372 ± 0.723	57.934 ± 0.543	0.0087	16.953 ± 0.249	17.086 ± 0.436	0.2779
D_{mean}(Gy)	54.187 ± 0.177	54.157 ± 0.294	0.6930	16.051 ± 0.082	16.063 ± 0.162	0.8401
$D_{2\%}$ (Gy)	55.568 ± 0.346	55.711 ± 0.303	0.1029	16.476 ± 0.147	16.531 ± 0.184	0.3945
$D_{5\%}$(Gy)	55.296 ± 0.316	55.453 ± 0.353	0.1165	16.399 ± 0.118	16.430 ± 0.159	0.5668
$D_{50\%}$ (Gy)	54.290 ± 0.179	54.310 ± 0.415	0.8588	16.087 ± 0.080	16.068 ± 0.125	0.6992
$D_{95\%}$ (Gy)	52.810 ± 0.490	52.748 ± 0.704	0.6797	15.602 ± 0.233	15.574 ± 0.253	0.7784
$D_{98\%}$ (Gy)	51.986 ± 0.938	52.047 ± 0.745	0.7383	15.286 ± 0.442	15.327 ± 0.364	0.7682
$D_{99\%}$ (Gy)	51.471 ± 1.751	51.429 ± 0.966	0.9084	14.978 ± 0.617	15.077 ± 0.507	0.5622
I_{max} (Gy)	55.967 ± 0.537	56 .189 ± 0.353	0.0450	16.515 ± 0.198	16.582 ± 0.237	0.3712
$VRI_{95\%}$ (cm^3)	470.1525 ± 216.526	470.733 ± 216.522	0.6095	199.387 ± 143.837	200.208 ± 146.474	0.5328
CI	0.987 ± 0.011	0.989 ± 0.010	0.518	0.982 ± 0.017	0.982 ± 0.020	0.598
HI	0.066 ± 0.020	0.068 ± 0.015	0.692	0.074 ± 0.029	0.075 ± 0.026	0.288
MU	2093.50 ± 691.69	2144.63 ± 507.77	0.495	1237.88 ± 495.16	1443.95 ± 452.40	0.0063

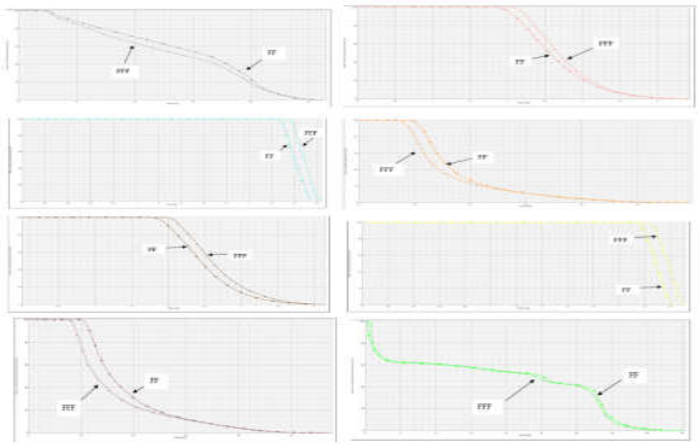

Figure 3: DVH of OAR for FF and FFF beam (brainstem, spinal cord, parotids, eyes, lenses)

Table 3: Dosimetric parameters to various OARs

PARAMETERS	FFB	FFFB	P-VALUE
Brainstem			
D_{MAX}(GY)	30.78±21.47	29±20.45	0.3210
D_{MEAN}(GY)	16.17±13.51	14.42±11.28	0.0406
$V_{20}(CM^3)$	10.91±11.13	9.16±10.15	0.0724
$V_{50}(CM^3)$	0.08±0.27	0.05±0.16	0.6950
Spinal Cord			
D_{MAX}(GY)	41.60±7.99	40.42±6.72	0.2351
D_{MEAN}(GY)	19.71±8.66	19.43±8.11	0.5213
$V_{20}(CM^3)$	13.95±9.52	9.16±10.15	0.3634
$V_{50}(CM^3)$	0.08±0.31	0	0.3298
Left parotid			
D_{MAX}(GY)	56.51±13.09	56.35±13.86	0.8418
D_{MEAN}(GY)	21.27±8.99	20.29±8.43	0.1571
$V_{20}(CM^3)$	10.35±6.41	9.48±5.86	0.1111
$V_{50}(CM^3)$	1.50±2.45	1.67±2.52	0.1773
Right parotid			
D_{MAX}(GY)	47.94±25.14	48.41±24.92	0.4200
D_{MEAN}(GY)	16.46±10.85	16.23±10.15	0.7170
$V_{20}(CM^3)$	8.29±7.06	7.60±6.14	0.1797
$V_{50}(CM^3)$	0.77±0.95	1.02±1.27	0.0902
Left eye			
D_{MAX}(GY)	23.68±27.30	24.79±26.98	0.4150
D_{MEAN}(GY)	7.83±9.33	7.85±7.94	0.9888
$V_{20}(CM^3)$	1.24±2.07	0.89±1.57	0.2266
$V_{50}(CM^3)$	0.14±0.32	0.13±0.32	0.8043
Right eye			
D_{MAX}(GY)	16.52±18.57	17.25±18.29	0.3705
D_{MEAN}(GY)	6.84±7.43	5.83±5.16	0.3367
$V_{20}(CM^3)$	0.49±1.08	0.37±0.69	0.3987
$V_{50}(CM^3)$	0.01±0.02	0	0.3332
Left lens			
D_{MAX}(GY)	6.54±6.86	4.57±3.76	0.0367
D_{MEAN}(GY)	5.52±5.92	3.71±3.00	0.0405
$V_{20}(CM^3)$	0.01±0.05	0	0.3319
$V_{50}(CM^3)$	0	0	0.3332
Right lens			
D_{MAX}(GY)	5.86±6.08	4.09±3.35	0.0325
D_{MEAN}(GY)	5.08±5.27	3.50±2.80	0.0360
$V_{20}(CM^3)$	0	0	0.3332
$V_{50}(CM^3)$	0	0	0

Discussion

A key consideration of this study is the use of two different linac platforms (VitalBeam and Halcyon). Therefore, observed differences are attributable to a combination of the flattening filter status and inherent machine characteristics, including MLC design and beam spectra. Despite these differences, our data suggests that within the context of their respective platforms, Halcyon (FFF) and VitalBeam (FF) can produce IMRT plans with comparable PTV coverage and homogeneity for oropharyngeal cancer. A numerically lower doses to several OARs with the Halcyon/FFF system was observed, with

statistically significant reductions in mean brainstem dose and lens doses. Whether these reductions are primarily due to the FFF mode, the Halcyon's MLC design, or a combination, requires further investigation on a single platform. The result of this investigation is in line with Yan et al. (2016) which compared FFB and FFFB for head and neck, lungs, and prostate cancer.

Conclusion

The Halcyon system operating in FFF mode can generate highly conformal IMRT plans for head and neck cancer. The potential for reduced dose to certain OARs, alongside the operational benefits of the Halcyon platform (e.g., fast treatment delivery), may make it a valuable option. A controlled comparison on a single machine capable of both modes is warranted to isolate the specific effect of the flattening filter.

Conflict of Interest

Authors declare that, as regards the publication of this article, there are no conflict of interest.

References

Amoabeng, K. A., Marthinsen, A. B. L., Hasford, F., Tagoe, S. N. A., Anaafi, E., Pokoo-Aikins, M., and Dery, T. B. (2023). Assessment of monitor units and gamma pass rate for 6 MV and flattening filter free (FFF) beams in volumetric modulated arc therapy (VMAT). International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 12: 1–8.

Cashmore, J. (2008). The characterization of unflattened photon beams from a 6 MV linear accelerator. *Physics in Medicine & Biology*, 53: 1933–1946.

Georg, D., Knoos, T., and McClean, B. (2011). Current status and future perspective of flattening filter-free photon beams. *Medical Physics*, 38(3): 1280–1293.

ICRU. (2010). Prescribing, recording, and reporting photon-beam intensity-modulated radiation therapy (IMRT). *Journal of ICRU*, 10(1): 12–20.

Kry, S. F., Salehpour, M., Followill, D., Stovall, M., Kuban, D. A., and White, R. A. (2005). The calculated risk of fatal secondary malignancies from intensity modulated radiation therapy. *International Journal of Radiation Oncology Biology Physics*, 62(4): 1195–1203.

Kry, S. F., Titt, U., Ponisch, F., Vassiliev, O. N., Salehpour, M., and Gillin, M. (2007). Reduced neutron production through use of a flattening-filter-free accelerator. *International Journal of Radiation Oncology Biology Physics*, 68(4): 1260–1264.

Kumar, R., Yadav, H. P., Thaper, D., Kamal, R., Gupta, A., and Kirti, S. (2021). Efficacy and toxicity of SBRT in advanced hepatocellular carcinoma with portal vein tumor thrombosis: A retrospective study. *Reports of Practical Oncology and Radiotherapy*, 26(4): 573–581.

Loïc, F., Georges, N., Jean-Jacques, M., and Pierre, B. (2006). Conformity index: A review. *International Journal of Radiation Oncology Biology Physics*, 64(2): 333–342.

Pichandi, A., Ganesh, K. M., Jerin, A., Balaji, K., and Kilara, G. (2014). Analysis of physical parameters and determination of inflection point for flattening filter free beams in medical linear accelerator. *Reports of Practical Oncology and Radiotherapy*, 19: 322–331.

Bentzen, S. M., Constine, L. S., Deasy, J. O., Eisbruch, A., Jackson, A., Marks, L. B., Ten Haken, R. K., and Yorke, E. D. (2010). Quantitative analyses of normal tissue effects in the clinic (QUANTEC): An introduction to the scientific issues. *International Journal of Radiation Oncology Biology Physics*, 76(3): S3–S9.

Suresh, T., and Madeswaran, S. (2022). The dosimetric comparison of different SBRT techniques for treatment of liver cancer using flattened and flattening filter free beam. *Iranian Journal of Medical Physics*, 19: 371–382.

Yani, S., Dirgayussa, I. G. E., Rhani, M. F., Soh, R. C. X., Haryanto, F., and Arif, I. (2016). Monte Carlo study on electron contamination and output factors of small field dosimetry in 6 MV photon beam. *Smart Science*, 4(2): 87–94.

Yani, S., Budiansah, I., Lestari, F. P., Tursinah, R., Rhani, M. F., and Haryanto, F. (2020). Investigation of neutron contamination of flattening filter and flattening filter-free 10 MV photon beams in Elekta InfinityTM accelerator. *Iranian Journal of Medical Physics*, 17: 126–132.