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ORIGINAL RESEARCH

Dosimetric Analysis of Unflattened (FFFB) and Flattened (FB) Photon Beam Energy for Gastric Cancers Using IMRT and VMAT—a Comparative Study

Manindra Bhushan[1,2] · Girigesh Yadav[1] · Deepak Tripathi[2] · Lalit Kumar[1,3] · Vimal Kishore[4] · Abhinav Dewan[1] · Gourav Kumar[1] · Inderjit Kaur Wahi[1] · Munish Gairola[1]

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Abstract

Purpose To evaluate the feasibility of flattening filter free beam (FFFB) for the treatment of gastric tumors and to review their benefits over 6MV flatten beam (6MV_FFB).

Methods Fifteen patients with histologically proven gastric carcinoma were selected. CT scans with slice thickness of 0.3 cm were acquired and planning target volume (PTV) and organ at risk (OAR) were delineated. Plans were made retrospectively for each patient for the prescription dose of 45 Gy/25 fractions to the PTV. Four isocentric plans were compared in the present study on Varian TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA, USA).

Results PTV D98% was 44.41 ± 0.12, 44.38 ± 0.13, 44.59 ± 0.14, and 44.49 ± 0.19 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. 6MV_FFFB beam minimizes the mean heart dose D_{mean} ($P = 0.001$). VMAT dominates over IMRT when it came to kidney doses V_{12Gy} ($P = 0.02$), V_{23Gy} ($P = 0.015$), V_{28Gy} ($P = 0.011$), and D_{max} ($P < 0.01$). VMAT has significantly reduced the doses to kidneys. It was analyzed that 6MV_FFFB significantly reduces the dose to normal tissues ($P = 0.006$ and $P = 0.018$). VMAT significantly reduces the TMU, which is required to deliver the similar dose by IMRT ($P < 0.01$).

Conclusions Unflattened beam spares the organs at risk significantly to avoid the chances of secondary malignancies and reduces the intra-fraction motion during treatment due to provision of higher dose rate. Hence, we conclude that 6MV unflattened beam can be used to treat gastric carcinoma.

Keywords Gastric carcinoma · Flattening filter free · IMRT · VMAT · Secondary malignancies

Introduction

Gastric carcinomas contribute a large patient population worldwide [1, 2]. The role of radiotherapy with combination of chemotherapy in gastric cancers has already been established [3]. While the incidence of gastric cancer has declined in the past half-century, the trend of adenocarcinoma of the gastric cardia and lower esophagus is increasing in Western population [4–6] and in Eastern population, and gastric carcinoma is very common [7, 8]. Actually, the gastric cancer has shifted towards gastric cardia and GE junction, as well as from squamous cell carcinoma (SCC) to adenocarcinoma. Radiotherapy delivers a highly penetrating radiation beam to kill the cancerous cells. The choice of beam energy has changed a lot with the introduction of advanced treatment techniques. Evolution of megavoltage accelerators galvanized the whole scenario and resulted in omission of the orthovoltage treatment due to provision of photons and electrons of desired energy.

✉ Manindra Bhushan
manindra.drp44@gmail.com

[1] Division of Medical Physics & Department of Radiation Oncology, Rajiv Gandhi Cancer Institute and Research Centre, Sector-5, Rohini, New Delhi 110085, India

[2] Amity School of Applied Sciences, Amity University (AUUP), Noida, India

[3] Dr. APJ Abdul Kalam Technical University, Lucknow, UP, India

[4] Department of Applied Science & Humanities, Bundelkhand Institute of Engineering & Technology, Jhansi, UP, India

Traditionally, high energy photons were considered for the treatment of deep-seated tumors due to their greater penetrating power. But due to drawbacks like wider penumbra and secondary neutron production, photon energy greater than or equal to 10MV is not the common choice for treatment [9].

IMRT is often used currently because of its ability to cover the target and spare the nearby critical organs. Advancement in technology has led to introduction of VMAT which allows continuous delivery of treatment with rotating gantry, fluctuating dose rate, and changing MLC speed with the advantage of modulated intensity map [10]. Several researchers have published the benefits of modulated arc therapy over IMRT in terms of reduced intra-fractional motion and shorter treatment time to improve the treatment accuracy [11–13].

Treatment accuracy plays an important role in cure of such patients, which can be achieved by reducing the treatment time to the optimum level. Delivering the treatment at very high dose rate may help in achieving this goal which is possible after removing the flattening filter from the path of the beam.

Flattening filter is a part of carousal, made up of lead or tungsten, used to filter low energy components, and helps in making the beam more flattened. Removal of flattening filter produces a forwardly directed beam. Usually, 6MV_FFB energy is used for the treatment planning in abdominal malignancies; however, flattening filter free (FFF) 6MV beam is gaining momentum for the treatment of such cases, due to their advantage of higher dose rate than 6MV beam [14–16].

The aim of present study is to evaluate the feasibility of flattening filter free beam (FFFB) for the treatment of gastric carcinoma and to review their benefits over 6MV flatten beam (6MV_FFB).

Material and Methods

CT Simulation and Treatment Preparation

Fifteen patients with completely resected adenocarcinoma of stomach or GE junction with TNM 7th edition stage Ib-IV without distant met, with pre-op cross-sectional imaging, and fulfilled the inclusion criteria: (1) no prior radiation to abdomen, (2) ECOG performance score ≤ 2, (3) written informed consent, and (4) aged 18–70 years were included in the present study.

Orfit casts were made to immobilize the patient during planning computed tomography (CT) scan and for the whole treatment course. Patients were positioned on the flat couch of CT simulator (Somatom Sensation Open, Siemens Medical System) in supine position with hands above the head (to avoid unnecessary dose to healthy tissues) with the help of lasers. Furthermore, radiopaque fiducial markers were placed on the cast to guide the isocenter shift. CT scans with slice thickness of 3 mm were acquired.

Contouring and Dose Prescription

After acquisition of CT scans, Digital Imaging and Communications in Medicine (DICOM) images were sent through Varian ARIA network server and hence to Eclipse Treatment Planning System (Eclipse version 11.0.34, Varian Medical Systems, Palo Alto, CA, USA). Planning target volume (PTV) and organs at risk (OARs) were delineated on SOMAVISION System (Varian Medical Systems, Palo Alto, CA, USA) on axial slices.

Target volumes were based on INT-0116 protocol, taking into consideration pre-operative tumor, gastric bed, site of anastamosis, and regional lymph nodes at risk [17]. Different OARs such as the bowel, common lung, heart, bilateral kidneys, liver, and spinal cord were contoured. All the OARs were delineated as per Radiation Therapy Oncology Group (RTOG) guidelines [18]. All the plans were made for each patient for the prescription dose of 45 Gy in 25 fractions to the PTV keeping 1.8 Gy as fractional dose [19].

Treatment Planning

Four isocentric plans were compared in the present study. Varian TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA, USA), equipped with flattened as well as unflattened beam and integrated with 120 high-definition multi-leaf collimator (HDMLC) leaves (characterized by a spatial resolution of 2.5 mm at isocenter for the central 32 leaves and 5 mm in the outer 28 leaves), was used for the treatment planning delivery.

Removing the flattening filter from the beam path increases the dose rate up to 1400 MU/min for 6MV and 2400 MU/min for 10MV beam with reduction in mean radial energy (TPR20/10: 6MV 0.667, 6MV(FFF) 0.631, 10MV 0.738, 10MV(FFF) 0.692), taking beam quality index TPR20/10 as a measure of beam energy.

IMRT, as we know, delivers higher dose to the target without increasing unwanted exposure. IMRT plans were made using seven gantry angles 60°, 100°, 135°, 180°, 215°, 260°, and 300° with collimator 0°, selecting 6MV_FFB and 6MV_FFFB as photon beam energy. IMRT utilized dose-volume optimization (DVO) algorithm

to optimize the intensity map and analytical anisotropic algorithm (AAA) for final fluence generation.

VMAT is the next generation treatment technique of IMRT. VMAT plans were generated using dual-arc technique as clockwise arc 181°–179° and anti-clockwise arc 179°–181° with collimator 0°, selecting 6MV_FFB and 6MV_FFFB beam for different plans respectively. VMAT utilizes progressive resolution optimization (PRO) algorithm to determine the optimal combination of beam weight and shape and final dose calculation is carried out by AAA.

All the plans were optimized in such a way that 95% volume of PTV should be covered with 100% prescription dose. Dose more than 110% was considered as a "hot-spot" and dose less than 93% of prescription dose to more than 1% of PTV volume was considered as a "cold-spot."

Evaluation Parameters

Quantec protocol [20] was used to evaluate the doses to critical structures from cumulative dose-volume histogram. The evaluation parameters used were

- PTV: $D_{95\%}$, $D_{98\%}$, $D_{50\%}$, $D_{2\%}$, $D_{107\%}$, $D_{110\%}$, Homogeneity Index (HI), Conformity Index ($CI_{95\%}$)
- Common lung:V_{20Gy}, V_{40Gy}, D_{max}, D_{mean}
- Heart: V_{30Gy}, V_{25Gy}, D_{max}, D_{mean}
- Right kidney: V_{12Gy}, V_{20Gy}, V_{23Gy}, V_{28Gy}, D_{max}, D_{mean}
- Left kidney: V_{12Gy}, V_{20Gy}, V_{23Gy}, V_{28Gy}, D_{max}, D_{mean}
- Combined kidney: V_{12Gy}, V_{20Gy}, V_{23Gy}, V_{28Gy}, D_{max}, D_{mean}
- Liver: D_{max}, D_{mean}, $D_{>700cc}$
- Spinal cord: D_{max}, $D_{<2cc}$
- Bowel: V_{15Gy}, V_{45Gy}, D_{max}, D_{mean}

Total monitor units (MUs) and integral dose (body-PTV; for the normal healthy tissues other than PTV) were also evaluated.

Conformity Index ($CI_{95\%}$) is defined as ratio of volume of PTV within 95% isodose line and total volume of PTV [21], i.e.,

$$CI = \text{PTV volume within } 95\% \text{isodose line} / \text{Volume of PTV}$$

Ideally, CI should be equal to 1.0 which indicates the better dose conformality of the plan.

Homogeneity Index (HI) is a parameter of homogeneous dose distribution inside the PTV and is defined in ICRU83 [22] as,

$$HI = (D_2 - D_{98})/D_{50}$$

Ideal value of HI should be zero. This indicates a sharp dose fall between the neck region and tail region of the PTV dose-volume histogram (DVH).

To evaluate lower dose contributions, integral dose (ID) [23] was calculated for normal healthy tissues, using the formula

$$\text{Integral dose (ID)}_{(\text{Body}-\text{PTV})} = \text{Mean dose (Gy)} \times \text{Volume } (\text{cm}^3)$$

Statistical Analysis

Data were analyzed using paired *t* test, available with SPSS Software 20.0 (SPSS Inc., Chicago, IL, USA). Data was analyzed by applying the standard statistical tests using SPSS Statistics 22.0 (SPSS Inc., Chicago, IL, USA). One-way ANOVA test was used if the distribution of difference between the four groups was normally distributed. Post hoc comparison using Tukey HSD test helped to determine as to which plan among the sample differed. Otherwise, non-parametric Kruskal-Wallis test was used for comparison of means between each plan. A *P value* of < 0.05 was considered statistically significant.

Quality Assurance Analysis

Arc Check (Sun Nuclear Corporation) phantom [24] was used to acquire beam profiles and absolute dose at the isocenter of the plans during exposure in QA mode of Linac. Arc Check phantom is equipped with helical detector grid which increases the sampling rate and reduces over-shadowing of detectors. It consists of over 1300 SunPoint diode detectors at the physical depth of 2.9 cm from the surface with 1.0 cm interspacing among detectors. The criterion for gamma evaluation [dose to agreement (DTA)/dose difference (DD)] was 3.0 mm/3.0% and for absolute dose measurement, variation of ± 3.0% was acceptable.

Results

Target Coverage

Dose to 98% volume ($D_{98\%}$) was 44.41 ± 0.12, 44.38 ± 0.13, 44.59 ± 0.14, and 44.49 ± 0.19 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively [Figs. 1 and 2]. Data showed a

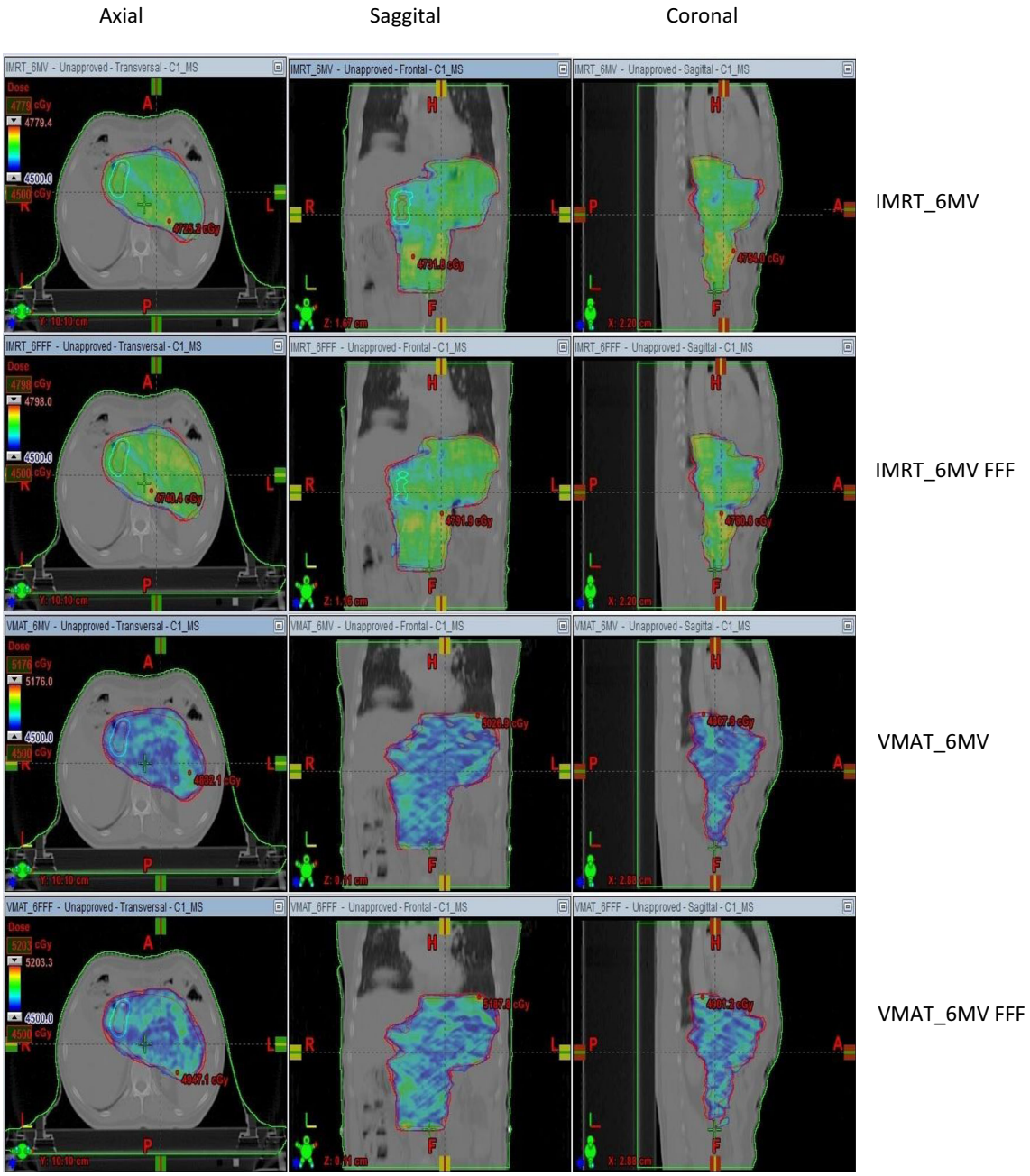

Fig. 1 Coverage of planning target volume (PTV) with 45 Gy

significant difference for 6MV_FFFB ($P = 0.02$ and $P = 0.002$) plans over 6MV_FFB plans. Dose to 2% volume ($D_{2\%}$) was 46.65 ± 0.37, 46.64 ± 0.34, 47.19 ± 0.55, and 47.53 ± 0.61 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively.

To evaluate the "cold-spots," dose $D_{<93\%}$ was measured and reported as 0.09 ± 0.08, 0.11 ± 0.09, 0.01 ± 0.02, and 0.03 ± 0.04% for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. There was a significant difference among IMRT and VMAT plans, as VMAT plans lowered the cold-spot ($P = 0.008$ and $P = 0.003$) [Table 1].

Organs at Risk

Common Lung

Volume receiving 20 Gy dose, i.e., V_{20Gy} of common lung, was 8.48 ± 3.68, 8.13 ± 3.34, 7.84 ± 3.18, and 7.68 ± 2.98%

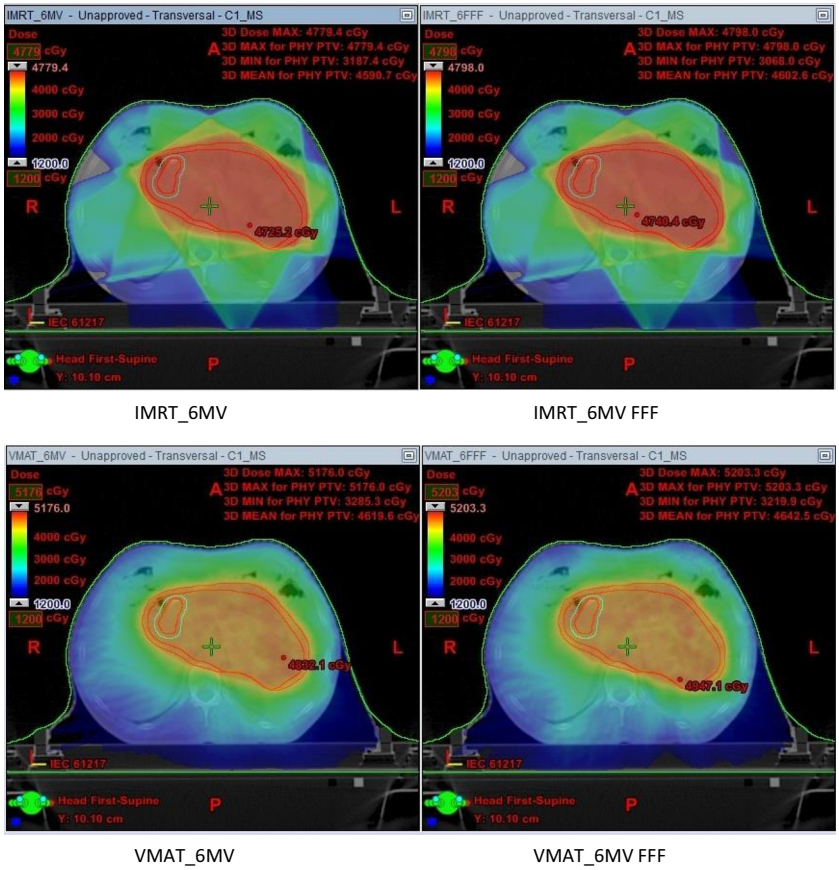

Fig. 2 Low dose 12 Gy covering PTV

for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. Data showed significant reduction in IMRT 6MV_FFFB (P = 0.035) and VMAT 6MV_FFB (P = 0.044) plans in comparison to other techniques [Table 3].

Heart

Maximum dose (D_{max}) was 46.28 ± 1.44, 46.32 ± 1.46, 48.19 ± 1.76, and 48.66 ± 1.46 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT

Table 1 Evaluation parameters for PTV and corresponding P values

Structure	Parameter	Treatment modality				P values					
		IMRT 6MV	IMRT 6FFF	VMAT 6MV	VMAT 6FFF	IMRT 6MV vs IMRT 6FFF	IMRT 6MV vs VMAT 6MV	IMRT 6MV vs VMAT 6FFF	IMRT 6FFF vs VMAT 6MV	IMRT 6FFF vs VMAT 6FFF	VMAT 6MV vs VMAT 6FFF
PTV	D_2 (Gy)	46.65 ± 0.37	46.64 ± 0.34	47.19 ± 0.55	47.53 ± 0.61	0.836	0.002	0.001	0.001	0.001	0.004
	D_{50} (Gy)	46.02 ± 0.27	46.07 ± 0.26	46.13 ± 0.55	46.18 ± 0.46	0.185	0.489	0.276	0.66	0.385	0.701
	D_{98} (Gy)	44.41 ± 0.12	44.38 ± 0.13	44.59 ± 0.14	44.49 ± 0.19	0.02	0.02	0.143	0.001	0.063	0.002
	D_{max} (Gy)	47.34 ± 0.46	47.29 ± 0.49	49.46 ± 1.16	49.72 ± 1.09	0.831	0.001	0.001	0.001	0.001	0.016
	D_{mean} (Gy)	46.11 ± 0.69	45.89 ± 0.36	45.99 ± 0.24	46.21 ± 0.36	0.262	0.538	0.525	0.284	0.015	0.005
	$D_{<93\%}$ (%)	0.09 ± 0.08	0.11 ± 0.09	0.01 ± 0.02	0.03 ± 0.04	0.008	0.006	0.003	0.004	0.002	0.103
	HI	0.05 ± 0.01	0.05 ± 0.01	0.06 ± 0.01	0.07 ± 0.02	0.82	0.029	0.003	0.01	0.002	0.002
	CI	0.95 ± 0.001	0.95 ± 0.001	0.95 ± 0.001	0.95 ± 0.001	0.726	0.343	0.758	0.279	0.168	0.678

6MV_FFFB respectively. Data showed a significant reduction of maximum doses in IMRT plans ($P < 0.01$). However, 6MV_FFFB beam minimizes the mean dose D_{mean} ($P = 0.001$) as the reported dose was 10.01 ± 3.71, 9.75 ± 3.61, 10.03 ± 3.84, and 9.51 ± 3.73 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively [Table 3].

Liver

VMAT plans have reduced the mean dose D_{mean} ($P = 0.022$) and $D_{>700cc}$ ($P = 0.001$) as they were reported as 26.61 ± 3.23, 26.67 ± 3.17, 26.42 ± 3.16, and 26.33 ± 3.21 Gy and 23.87 ± 5.05 24.06 ± 5.13, 22.64 ± 5.01, and 22.36 ± 4.95 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively [Table 3].

Spinal Cord

Both the parameters evaluated D_{max} [Fig. 3] and $D_{<2cc}$ were 33.72 ± 2.09, 33.77 ± 2.29, 31.45 ± 1.71, and 32.21 ± 2.93 Gy and 30.83 ± 2.18, 29.53 ± 4.79, 29.41 ± 1.69, and 30.09 ± 2.74 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. It was observed that VMAT reduces D_{max} ($P = 0.002$) and $D_{<2cc}$ ($P = 0.001$) significantly [Table 3].

Kidneys

VMAT dominates over IMRT when it came to kidney doses V_{12Gy} ($P = 0.02$), V_{23Gy} ($P = 0.015$), V_{28Gy} ($P = 0.011$), and D_{max} ($P < 0.01$) [Fig. 2]. VMAT significantly reduced the doses to kidneys [Table 2].

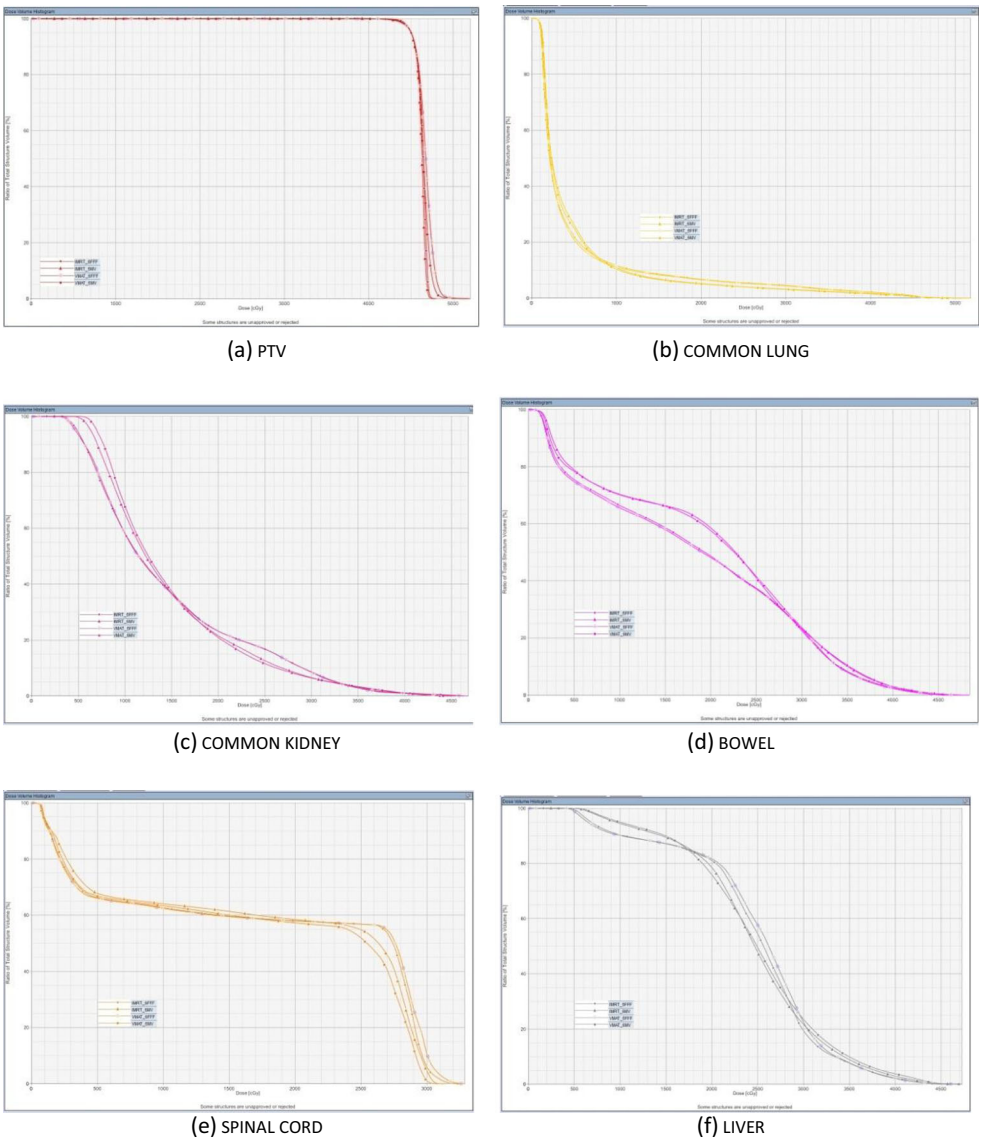

Fig. 3 Dose-volume histogram (DVH). **a** PTV. **b** Common lung. **c** Common kidney. **d** Bowel. **e** Spinal cord. **f** Liver

Table 2 Evaluation parameters for kidneys and corresponding *P* values

Structure	Parameter	Treatment modality				*P* values					
		IMRT 6MV	IMRT 6FFF	VMAT 6MV	VMAT 6FFF	IMRT 6MV vs IMRT 6FFF	IMRT 6MV vs VMAT 6MV	IMRT 6MV vs VMAT 6FFF	IMRT 6FFF vs VMAT 6MV	IMRT 6FFF vs VMAT 6FFF	VMAT 6MV vs VMAT 6FFF
Right kidney	V_{12} (Gy)	41.74 ± 7.08	40.63 ± 6.59	44 62 ± 9.19	48.09 ± 10.57	0.016	0.055	0.003	0.02	0.003	0.009
	V_{20} (Gy)	20.57 ± 4.58	20.36 ± 4.54	19.33 ± 3.91	20.07 ± 4.37	0.211	0.094	0.618	0.158	0.768	0.134
	V_{23} (Gy)	16.39 ± 4.55	16.39 ± 4.46	13.64 ± 3.08	13.92 ± 3.76	0.988	0.013	0.054	0.009	0.043	0.572
	V_{28} (Gy)	9.12 ± 3.58	9.09 ± 3.28	6.54 ± 2.32	6.56 ± 2.71	0.825	0.03	0.055	0.02	0.04	0.959
	D_{max} (Gy)	42.17 ± 2.03	41.99 ± 2.09	41.76 ± 2.09	41.71 ± 2.09	0.122	0.687	0.664	0.83	0.81	0.784
	D_{mean} (Gy)	13.27 ± 1.68	13.03 ± 1.62	13.09 ± 1.74	13.44 ± 1.97	0.005	0.376	0.53	0.67	0.123	0.027
Left kidney	V_{12} (Gy)	50.82 ± 6.26	49.44 ± 5.51	50.05 ± 7.64	54.71 ± 11.11	0.001	0.67	0.168	0.735	0.086	0.039
	V_{20} (Gy)	24.71 ± 5.87	24.06 ± 5.65	21.31 ± 4.42	21.44 ± 3.65	0.002	0.008	0.035	0.027	0.077	0.839
	V_{23} (Gy)	20.06 ± 6.28	19.58 ± 6.16	15.89 ± 4.61	16.23 ± 3.75	0.017	0.008	0.035	0.018	0.062	0.669
	V_{28} (Gy)	13.48 ± 5.62	12.37 ± 5.99	9.22 ± 4.16	9.64 ± 3.56	0.2	0.015	0.028	0.039	0.126	0.516
	D_{max} (Gy)	45.34 ± 0.93	45.29 ± 0.93	43.95 ± 1.34	43.86 ± 1.72	0.521	0.1	0.007	0.1	0.007	0.779
	D_{mean} (Gy)	15.24 ± 1.74	14.92 ± 1.65	14.68 ± 1.24	15.15 ± 1.32	0.1	0.095	0.835	0.45	0.629	0.03
Combined kidney	V_{12} (Gy)	46.28 ± 4.56	45.66 ± 3.45	47.53 ± 6.67	51.61 ± 9.74	0.388	0.382	0.02	0.232	0.026	0.013
	V_{20} (Gy)	22.64 ± 1.48	22.22 ± 1.51	20.36 ± 1.33	20.93 ± 1.99	0.002	0.004	0.079	0.013	0.17	0.26
	V_{23} (Gy)	18.23 ± 2.07	17.98 ± 2.07	14.78 ± 1.82	15.18 ± 2.14	0.002	0.001	0.015	0.001	0.023	0.507
	V_{28} (Gy)	11.31 ± 2.71	10.73 ± 3.12	7.97 ± 2.41	8.19 ± 2.34	0.132	0.004	0.011	0.015	0.052	0.641
	D_{max} (Gy)	43.76 ± 1.15	43.65 ± 1.09	43.95 ± 1.33	43.88 ± 1.73	0.15	0.699	0.833	0.54	0.687	0.844
	D_{mean} (Gy)	14.26 ± 0.96	13.98 ± 0.91	13.94 ± 0.99	14.35 ± 1.23	0.1	0.145	0.779	0.866	0.254	0.016

Table 3 Evaluation parameters for OARs and corresponding *P* values

Structure	Parameter	Treatment modality				*P* values					
		IMRT 6MV	IMRT 6FFF	VMAT 6MV	VMAT 6FFF	IMRT 6MV vs IMRT 6FFF	IMRT 6MV vs VMAT 6MV	IMRT 6MV vs VMAT 6FFF	IMRT 6FFF vs VMAT 6MV	IMRT 6FFF vs VMAT 6FFF	VMAT 6MV vs VMAT 6FFF
Common lung	V_{20} (Gy)	8.48 ± 3.68	8.13 ± 3.34	7.84 ± 3.18	7.68 ± 2.98	0.035	0.044	0.105	0.193	0.281	0.575
	V_{40} (Gy)	1.62 ± 1.39	1.59 ± 1.36	1.54 ± 1.39	1.41 ± 1.25	0.06	0.293	0.156	0.509	0.203	0.271
	D_{max} (Gy)	45.86 ± 1.67	45.82 ± 1.63	46.83 ± 2.91	47.14 ± 3.15	0.741	0.168	0.086	0.113	0.058	0.17
	D_{mean} (Gy)	6.34 ± 1.88	6.21 ± 1.78	6.39 ± 1.94	6.23 ± 1.87	0.01	0.449	0.379	0.06	0.923	0.151
Heart	V_{30} (Gy)	5.93 ± 2.69	5.99 ± 2.46	6.31 ± 3.61	5.94 ± 2.94	0.784	0.452	0.989	0.575	0.915	0.461
	V_{25} (Gy)	10.16 ± 4.53	9.79 ± 4.13	10.14 ± 6.61	9.63 ± 6.19	0.08	0.982	0.539	0.736	0.876	0.379
	D_{max} (Gy)	46.28 ± 1.44	46.32 ± 1.46	48.19 ± 1.76	48.66 ± 1.46	0.619	0.001	0.001	0.001	0.001	0.085
	D_{mean} (Gy)	10.01 ± 3.71	9.75 ± 3.61	10.03 ± 3.84	9.51 ± 3.73	0.001	0.942	0.016	0.203	0.219	0.05
Liver	D_{max} (Gy)	46.52 ± 0.91	46.63 ± 0.77	47.77 ± 1.24	47.93 ± 1.43	0.175	0.001	0.001	0.001	0.001	0.287
	D_{mean} (Gy)	26.61 ± 3.23	26.67 ± 3.17	26.42 ± 3.16	26.33 ± 3.21	0.238	0.224	0.064	0.09	0.022	0.392
	$D_{>700cc}$ (Gy)	23.87 ± 5.05	24.06 ± 5.13	22.64 ± 5.01	22.36 ± 4.95	0.099	0.002	0.001	0.001	0.001	0.096
Spine	D_{max} (Gy)	33.72 ± 2.09	33.77 ± 2.29	31.45 ± 1.71	32.21 ± 2.93	0.698	0.001	0.21	0.002	0.214	0.401
	$D_{<2cc}$ (Gy)	30.83 ± 2.18	29.53 ± 4.79	29.41 ± 1.69	30.09 ± 2.74	0.318	0.001	0.499	0.931	0.804	0.399
Bowel	V_{15} (Gy)	31.07 ± 8.88	30.69 ± 9.14	30.21 ± 9.21	38.32 ± 9.17	0.034	0.086	0.388	0.287	0.372	0.346
	V_{45} (Gy)	26.67 ± 10.99	26.27 ± 11.06	25.37 ± 11.44	25.26 ± 11.59	0.017	0.057	0.08	0.177	0.195	0.593
	D_{max} (Gy)	46.45 ± 0.64	46.38 ± 0.76	47.45 ± 1.16	47.69 ± 1.66	0.386	0.005	0.009	0.001	0.003	0.455
	D_{mean} (Gy)	19.84 ± 3.57	19.55 ± 3.58	19.64 ± 3.82	19.38 ± 3.89	0.001	0.541	0.233	0.744	0.635	0.052
ID	(in Gy-cm^3)	168.03 ± 32.76	166.77 ± 32.91	167.24 ± 32.98	165.12 ± 32.19	0.006	0.653	0.171	0.784	0.409	0.018
TMU	(in MU)	1416.7 ± 224.75	1722.2 ± 411.58	492.5 ± 32.13	588.1 ± 41.89	0.003	0.001	0.001	0.001	0.001	0.001

Bowel

6MV_FFFB beam helps in lowering the V_{15Gy} ($P = 0.034$), V_{45Gy} ($P = 0.017$), and mean dose D_{mean} ($P = 0.001$) of bowel. V_{15Gy} reported was 31.07 ± 8.88, 30.69 ± 9.14, 30.21 ± 9.21, and 38.32 ± 9.17 Gy for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively [Table 3].

Integral Dose

For normal healthy tissues, ID reported was 168.03 ± 32.76, 166.77 ± 32.91, 167.24 ± 32.98, and 165.12 ± 32.19 Gy-cm^3 for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. It was analyzed that 6MV_FFFB significantly reduced the dose to normal tissues ($P = 0.006$ and $P = 0.018$) [Table 3].

Total Monitor Unit

It was noticed that total monitor units (TMUs) were 1416.7 ± 224.75 MU, 1722.2 ± 411.58 MU, 492.5 ± 32.13 MU, and 588.1 ± 41.89 MU for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. Observations clearly state that VMAT significantly reduced the TMU, which is required to deliver a dose to IMRT ($P < 0.01$) [Table 3].

QA Evaluation

The analyzed data demonstrated that all the plans were within the permissible limits [25] and dosimetrically tolerable but VMAT plans were superior to IMRT plans in terms of variability. VMAT plans were more consistent in treatment delivery [Table 4].

Evaluated values of dose to agreement (DTA) were 89.4 ± 6.4, 87.2 ± 4.6, 99.6 ± 0.6, and 96.6 ± 2.5 for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively. Similarly, gamma indexes were 94.9 ± 5.0, 94.4 ± 2.9, 99.8 ± 0.3, and 99.4 ± 0.8 for IMRT 6MV_FFB, IMRT 6MV_FFFB, VMAT 6MV_FFB, and VMAT 6MV_FFFB respectively [Fig. 4].

Discussion

Like earlier published researches [26–28], our study also demonstrated comparable PTV dose coverage, conformity, and homogeneity between traditional flattened beam and flattening filter free beam for both the techniques, i.e., IMRT and VMAT.

Use of fixed and multiple gantry angles may help to generate an optimum plan with the help of fluence modulation, but there are chances of missing the optimum gantry angle. VMAT advances the technology of intensity modulation by addition of rotational delivery for treatment planning [29].

Simultaneously changing multi-leaf position and dose rate helps to achieve the optimum solution with VMAT. Dual-arc VMAT plan showed some advantage over IMRT in gynecological malignancies [30–32].

This study demonstrated that 6MV_FFB and 6MV_FFFB provided similar dose coverage, homogeneity, and conformity whether they are used with IMRT or VMAT. *Daniel* et al. found similar results while using hypofractionated VMAT using flattening filter free beam in prostate cancers [33, 34].

Homogeneous photon fluence across the treatment field covering PTV is the priority of treatment planning. Flattening filter was introduced to deliver homogeneous dose coverage. *Fu* et al. reported that flattened and unflattened beams resulted in comparable dose coverage, omitting the requirement of uniform beam when dealing with smaller treatment fields [35].

Although the PTV coverage was comparable, inhomogeneity or cold-spots were reduced with VMAT due to rotational nature of the treatment.

For the critical structures like the common lung, heart, liver, and kidneys, mean dose reduced significantly with VMAT unflattened beam. This may be possible due to non-deposition of unnecessary dose to the area outside the PTV. Reduced low-dose region of kidney and bowel with 6MV FFF lowers the risk of secondary cancers [36].

Gulliford et al. stated that the reduction in rectal volume receiving dose less than 30 Gy in the treatment of prostate cancer lowers the late rectal toxicities by 10–18% [37].

Our data demonstrated an increase in monitor units for FFF beams compared to normal routine flattened beam (6MV_FFB) which may be due to non-flat profile of FFF beam. *Daniel* et al. reported that integral dose for open field

Table 4 Arc Check Data Analysis

Plan modality	Gamma index (GI)	DTA (at 3%, 3.0 mm; threshold 20%)
IMRT_6MV_FFFB	94.4 ± 2.9	87.2 ± 4.6
IMRT_6MV_FFB	94.9 ± 5.0	89.4 ± 6.4
VMAT_6MV_FFFB	99.4 ± 0.8	96.6 ± 2.5
VMAT_6MV_FFB	99.8 ± 0.3	99.6 ± 0.6

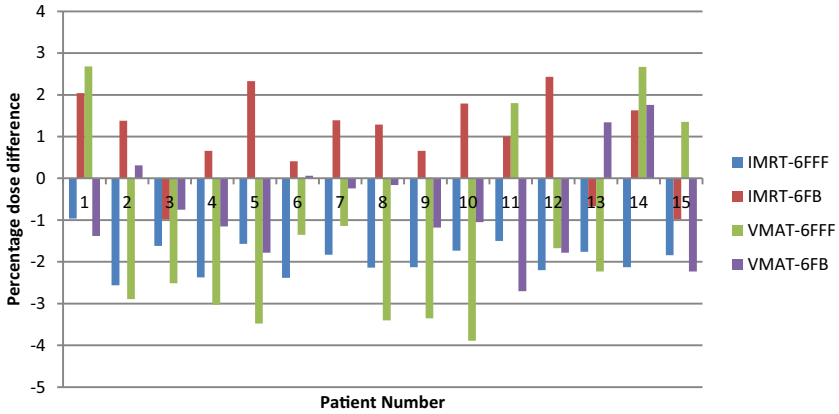

Fig. 4 Variation of absolute dose between TPS calculation and ion chamber measurements

using FFF beam resulted in lesser dose than for a flattened beam for 100 MU.

In fact, in our study, IMRT 6MV_FFFB showed 21.56% increase in TMU and VMAT 6MV_FFFB followed the same pattern with 19.4% increase as compared to flat 6MV_FFB beam. Our study also stated that there was a slight reduction in integral dose, despite the increase in MUs. This may be due to the fact that FFF beam delivered lesser dose outside the planning target or region of interest due to missing scatter from flattening filter and also from reduced head scatter [38, 39].

It was found that integral dose to healthy tissues was reduced with FFF beams. Reason for this may be the reduced collimator and head scatter and hence the reduced out-of-field dose. Reduced dose to healthy tissues may lead to reduced risk of long-term radiation-induced complications, i.e., secondary malignancies, especially for young and adult patients [40].

Kragl et al. demonstrated reduction in Linac head leakage by 52% for 6MV FFF beam for IMRT prostate treatment [41]. *Cashmore* et al. found similar results after removal of unwanted head scatter dose and hence up to 70% reduction in integral dose [42]. Elimination of beam hardening components from flattening filter softens beam quality of FFF beams and hence increases the superficial dose. This demonstrated the PDD distribution of 6MV_FFF beam similar to 4MV flattened beam [43].

Delivering high dose with accuracy is a challenge in radiotherapy. For flattened beam with limited output and dose rate (MU/min), higher dose needed more time to deliver and hence, organ motion comes into picture. FFF beam showed advantage of shorter treatment delivery time due to higher dose rate. If the gantry is running with maximum speed, 6MV can deliver 600 MU in 1 min but 6MV FFF beam can deliver 1400 MUs in the same time period.

Most of the investigators have raised their concern about organ motion in abdominal region. But the margins for PTV to account for organ motion are a critical problem in radiotherapy [44, 45].

Although TMU increased slightly in FFF, yet unfiltered beam made lesser treatment time possible with availability of higher dose rate. Our data demonstrated that the time required to deliver the same dose is 5.62 times higher in IMRT 6MV, 2.93 times higher in IMRT 6MV FFF, and 1.95 times higher in VMAT 6MV when compared with VMAT 6MV FFF.

As the gastric carcinoma is the fourth most common in male and fifth most common in females worldwide [46] and the role of radiotherapy is already proven, the necessity is to deliver the radiation safely and accurately.

Spruijt et al. reported 10% reduction in total treatment time and 31% reduction in beam-on time [47]. Our findings also supported the above facts. Arc Check measurements showed better concordance with unflattened beam with volumetric modulation which may be due to the conformal delivery of VMAT plans.

Limitations

Major limitation of our study was that the numbers of patient included in the study were less. Although the plans were generated to achieve optimum output, our dosimetric study was based on planning and not on clinical results. *Loan Hoffmann* et al. stated that the algorithms of treatment planning system overestimated the penumbra width and hence resulted in more deviation in the low-dose region [48]. Despite these limitations, we realize that our study will help to understand the behavior of unflattened beam in abdominal malignancies.

Conclusion

VMAT plans provided comparable dose coverage as IMRT. The benefit of 6MV_FFFB beam adds to the advantage of VMAT with respect to treatment volume coverage and OAR sparing. Unflattened beam spared the organs at risk significantly to minimize chance of secondary malignancies and reduce the intra-fraction motion during treatment due to the

provision of higher dose rate. Hence, we conclude that 6MV unflattened beam can be used to treat gastric carcinoma.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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