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Research Article

The Effects of Flattened and Flattening-Filter-Free Beam on Treatment Plans

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Abstract

We investigated the dosimetric and biological differences between the flattened and flattening-filter-free (FFF) beam plans for the 6 and 10 MV photon beams from the Varian TrueBeam system. One hundred and four treatment plans were created for 13 cases involving 3 different cancer sites: head & neck, lung and prostate. Significant dose sparing was obtained with FFF beams for the head & neck cases, especially for cases with large field sizes (≈16×20 cm^2). Overall, the FFF beams provide similar target coverage as the flattened beams. Additionally, the FFF beams resulted in improved dose sparing to organs at risk compared to the conventional flattened beams, for both static intensity modulated radiotherapy and volumetric modulated arc therapy plans.

Keywords: Treatment Planning; Flattening-Filter-Free; Intensity-Modulated Radiotherapy

Introduction

Flattening filters have been used for decades to provide uniform beam profiles. With the rapid developments of intensity-modulated radiotherapy (IMRT), the flattening filter is no longer an indispensible component of a modern radiotherapy system. CyberKnife [1] and Tomotherapy [2] use unflattened beam to deliver acceptable dose distribution. In recent years, the potential application of the flattening-filter-free (FFF) beam in modern linac system is being explored. Removal of the flattening filter from the path of the photon beam leads to significant changes in several physical characteristics of a conventional beam [3]. Compared to the flattened beams, the FFF beams have: (1) increased dose rate [4-7], (2) decreased external scatter from the flattening filter [8], (3) reduced neutron contamination for the high energy beam (>10 MV) [9-11], and (4) improved dose calculation accuracy [3]. However, the non-uniform beam profile of the FFF beam requires higher monitor unit (MU). Additionally, the soft spectrum of the FFF beam is likely to increase the dose to organs-at-risk (OARs). Several groups [11-15] have investigated the benefits of FFF beam. Most of them focused on the time efficiency obtained by the FFF beam compared to the flattened beam. The dosimetric and biological differences between the flattened and FFF beams are still unclear. In this work, we evaluated these differences for clinical treatment plans between the flattened and FFF beams.

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Materials and Methods

Thirteen patients with three different cancer sites (head and neck (5 patients), lung (4 patients), and prostate (4 patients)) were randomly selected. A case number was used to refer to each plan. TrueBeam STx linac (Varian Medical Systems, Palo Alto, CA) was commissioned on the Eclipse™ treatment planning system based on the clinical golden data[16]. Beam energies were 6 and 10 MV. An Anisotropic-Analytical-Algorithm (AAA) was used to calculate the dose distribution for both static IMRT and volumetric modulated arc radiotherapy (VMAT) plans. The dose calculation grid was 2.5 mm for all treatment plans. Beam modalities consisted of flattened and FFF beams. High definition (120 leaves) multi-leaf collimator (MLC) was used to modify the beam fluence for all treatment plans. The widths of the MLC were 2.5 mm and 5 mm in the center and peripheral region, respectively. In order to make a reasonable comparison, all optimization parameters, such as, arc number, beam angle, optimization weight, were kept identical for the flattened and the corresponding FFF beam plans. For the VMAT plans, maximum dose rates of the FFF beam (1400 MU/min for 6 MV and 2400 MU/min for 10 MV) were used to design the plans. For static IMRT plans (sliding window), the dose rate was 600 MU/min for both flattened and FFF beam plans. For sliding window static IMRT plans, the speed limit of the MLC may impact the dose to OARs for high dose rate. It is more likely for large field sizes (e.g.). Reducing the dose rate can eliminate the impact of the interplay effect of the MLC to dose distribution. For VMAT plans, however, this problem does not exist because the Eclipse software will automatically select the dose rate it can use to deliver the radiation. For each patient, 8 treatment plans were designed.

An in-house-developed Matlab (Math Works, Natick, MA) code based on the CERR software [17] was used to read the DICOM data extracted from Eclipse to statistically analyze the results. All planning evaluation parameters (e.g. maximum dose, mean dose, and volume) for each organ were benchmarked with the Eclipse treatment planning software. Excellent agreement was obtained for all treatment plans.

Biological metrics was based on the dose-volume-histogram (DVH). It consisted of biological effective dose (BED) [18], equivalent uniform dose (EUD), tumor control probability (TCP), and normal tissue complication probability (NTCP) values. Gay and Niemierko's model [19,20] was used to perform calculations. Values of biological parameters (α/β, TD_{50}, TCD_{50}, a, and γ_{50}) were selected from the published references [19-24]. The biological parameters of OARs are summarized in Table 1.

Table 1. Biological parameters used for OARs to calculate NTCP values.

Organ	Endpoint	α/β	a	γ_{50}	TD_{50}
Brainstem	Necrosis	3	5	3	60
Ear (mid/ext)	Acute serous otitis	10	31	3	40
Ear (mid/ext)	Chronic serous otitis	3	31	4	65
Esophagus	Perforation	3	19	4	68
Heart	Pericarditis	3	3	3	50
Lens	Cataract	3	3	1	18
Lung	Pneumonitis	3	1	2	24.5
Optic nerve	Blindness	3	25	3	65
Parotid	Salivary function (<25%)	3	0.5	4	46
Spinal cord	White matter necrosis	3	13	4	70

Results

For all cases, the FFF beam provided similar target coverage as the flattened beam. Significant dose sparing to OARs was obtained for the head and neck cases, especially for cases with large field sizes (≈16×20 cm^2). The statistical analysis results are shown in Table 2. For each cancer site, in general, the FFF beam provides improved dose sparing compared to the flattened beam. Overall, the FFF beam provides lower mean and maximum dose to OARs, leading to improvement in dose sparing compared to the flattened beam, for both static IMRT and VMAT plans. For critical organs such as brainstem and parotid, the reduction in the mean dose reached up to 14% and 9%, respectively. The reduction in maximum dose was as much as 10% and 5%, respectively. In lung cases, the larynx had the most apparent dose sparing from the FFF beam plans. The mean dose reduction of the FFF beam reached to 8%, that led to decreased NTCP values compared to the flattened beam. For prostate cases, the dose sparing of the FFF beam was not clinically significant for both static IMRT and VMAT plans.

Discussion

In our investigation, the head and neck cases showed the most apparent differences between the flattened and FFF beams in both static IMRT and VMAT plans. Compared to two other cancer sites, some head and neck cases in our study required relative large field sizes (≈16×20 cm^2) to cover the target. The noticeable dose sparing of the FFF beam compared to the flattened beam could be explained by the peak beam profiles of the FFF beam.

Table 2. Relative dosimetric and biological ratios (FFF/flattened) for all clinical cases.

Head and neck cases (n=5)						
VMAT						
	6 MV			**10 MV**		
OAR	**Mean Dose Ratio**	**Max Dose Ratio**	**NTCP Ratio**	**Mean Dose Ratio**	**Max Dose Ratio**	**NTCP Ratio**
Left Cochlea	0.97±0.02	0.96±0.02	0.56±0.22	0.95±0.06	0.94±0.04	0.53±0.51
Larynx	0.98±0.02	1.00±0.01	0.87±0.23	0.97±0.04	1.00±0.02	0.89±0.25
Cord	0.96±0.01	1.00±0.02	0.73±0.25	0.98±0.03	1.00±0.03	0.97±0.60
Brainstem	0.87±0.11	0.90±0.13	0.50±0.47	0.86±0.09	0.91±0.11	0.45±0.37
Right parotid	0.91±0.06	0.95±0.04	0.25±0.22	0.92±0.03	0.95±0.03	0.21±0.14
Right submandibular	0.94±0.04	0.98±0.01	0.53±0.13	0.93±0.02	0.98±0.04	0.48±0.34
IMRT						
Left cochlea	0.97±0.01	0.98±0.02	0.74±0.25	0.96±0.04	0.99±0.06	0.98±1.04
Larynx	0.98±0.01	1.00±0.00	0.98±0.12	0.98±0.02	1.01±0.02	0.94±0.29
Cord	0.97±0.01	0.98±0.01	0.70±0.16	0.97±0.02	0.99±0.01	0.71±0.19
Brainstem	0.91±0.02	0.96±0.06	0.73±0.40	0.88±0.05	0.92±0.09	0.56±0.48
Right parotid	0.97±0.02	1.01±0.01	0.53±0.29	0.95±0.04	0.98±0.02	0.45±0.46
Right submandibular	0.97±0.02	0.98±0.02	0.74±0.17	0.97±0.03	0.98±0.03	0.72±0.37
Lung cases (n=4)						
VMAT						
Cord	0.99±0.01	1.01±0.01	1.20±0.18	0.98±0.01	1.00±0.02	0.92±0.2
Larynx	0.95±0.06	1.00±0.02	0.84±0.65	0.94±0.00	1.01±0.02	0.76±0.21
Lungs	0.99±0.01	1.01±0.02	0.94±0.06	1.00±0.01	1.03±0.02	1.00±0.17
IMRT						
Cord	0.98±0.02	1.00±0.01	0.85±0.21	0.97±0.01	0.98±0.01	0.65±0.17
Larynx	0.94±0.05	0.99±0.02	0.79±0.53	0.92±0.04	0.98±0.02	0.48±0.26
Lungs	0.98±0.01	1.01±0.01	0.88±0.06	0.98±0.00	1.01±0.00	0.83±0.02
Prostate cases (n=4)						
VMAT						
Bladder	0.96±0.04	1.02±0.01	0.71±0.34	0.98±0.02	1.01±0.00	0.91±0.23
Right Hip	0.97±0.02	0.97±0.02	0.57±0.23	0.96±0.04	0.96±0.04	0.52±0.42
Left Hip	0.97±0.02	0.99±0.01	0.64±0.24	0.97±0.04	0.99±0.03	0.79±0.48
IMRT						
Bladder	0.99±0.02	1.00±0.00	0.98±0.38	0.99±0.02	1.00±0.00	0.94±0.29
Right Hip	0.98±0.02	1.00±0.01	0.84±0.29	0.98±0.01	0.98±0.02	0.84±0.22
Left Hip	0.98±0.02	1.00±0.02	0.86±0.24	0.99±0.01	1.00±0.02	0.87±0.21

For small field sizes (e.g. ≈ 6×6 cm^2), the differences in the beam profiles between the flattened and the FFF beams are minor. However, for large field sizes (e.g. ≈ 20 ×20 cm^2), the FFF beam provides lower dose to the out-of-field region compared to the flattened beam for both 6 and 10 MV beams.

Conclusion

In this work, we investigated the dosimetric and biological differences between the flattened and FFF beams in 13 clinical cases. Significant dose sparing was obtained with FFF beams for head and neck cases, especially for cases with large field sizes (≈16×20 cm^2). In general, the FFF beam can provide similar target coverage as the flattened beam with improved dose sparing to OARs.

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