.decimal®
The benchmark for custom radiation therapy

121 Central Park Place
Sanford, Fl 32771
1-800-255-1613
www.dotdecimal.com

The Advantages of Compensator-Based IMRT using Flattening Filter Free Beams

By Ken Cashon, M.S., DABR, .decimal, Inc.

Key Points

- Flattening filter free (FFF) beams have less variation in off-axis beam hardening
- FFF have less scatter introduced into the field and may be easier to model accurately in the TPS
- Since the flattening filter is removed, the dose rate on the machine is very highfor example, 1400MU/min for 6MV
- Modulation of the beam at such a high dose can be done with compensator based IMRT
- Using compensators with high dose rate can be an optimal combination to reduce treatment times, for example with breath hold techniques
- Patient throughput is improved with less “on the table” time

Contents

Table of Contents

Introduction / Previous Work

In order to mitigate the effect of high-energy Bremsstrahlung photons being emitted primarily in the forward direction and thus to make a therapeutic beam more homogeneous, a cone-shaped flattening filter has been a staple of the medical linear accelerators for many years.

The use of the flattening filters created flat profiles and made it possible to treat patients based only on hand calculations or minimal treatment calculations. However, early investigations of the use of flattening filter free (FFF) beams for stereotactic radiosurgery and IMRT delivery techniques were promising, since these techniques did not require homogenous flat beams.

Many articles have been published on the characteristics of the dosimetry of flattening filter free machines[1-6]. Some characteristics of these beams are described below.

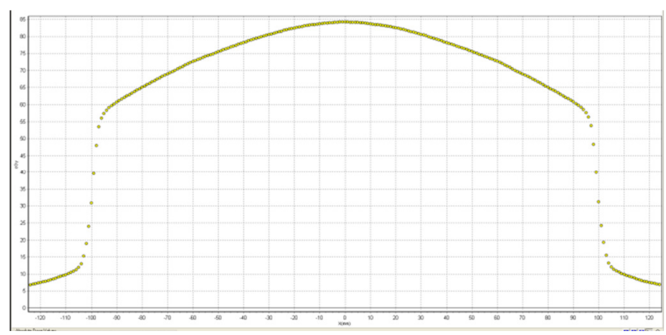

Figure 1 6MV FFF Beam Profile

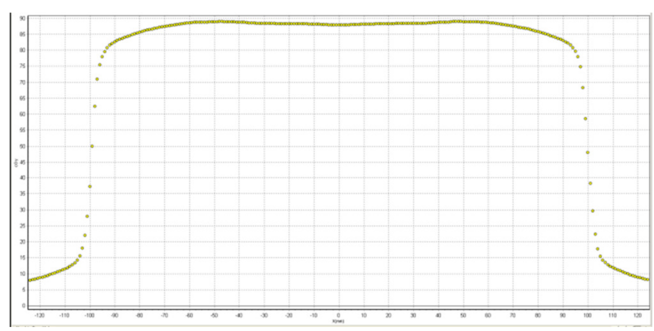

Figure 2 6MV Flattened Beam Profile

Energy Spectrum Changes

With the flattening filter in the beam, the photon energy spectrum is progressively softening from the center to the periphery of the field due to the changing thickness of the intervening flattening filter. Characterizing these off-axis energy spectra creates additional complexity in the dose calculations.

Without the filter, the beam is no longer hardened and thus has a spectrum shifted towards lower energy compared to a conventional beam. For 6MV photons, the FFF beam tends to appear as a conventional 4-5MV beam, and the 10MV as a 8MV beam.

Scatter Reduction

The use of a flattening filter contributes greatly to the variation of the source of head scatter in a beam. In particular, for FFF beams, the variation in in-air output factors for field sizes between 3x3 to 40x40 is around 3%, whereas the variation with conventional beams is more than 8% for 6MV beams.

Another key scattering reduction attribute with FFF is the out of field dose near the treatment field (<3cm from the field edge). This small effect may be beneficial in reducing certain risks in secondary induced cancers from primary radiation treatments.

Increased Dose Rate

Since the flattening filters are composed of medium to high-Z materials and can be a few centimeters thick at the central axis, they greatly reduce the dose rate of the machine. For example, the Varian TrueBeam™ has the maximum dose rate of 1400 MU/min for 6MV FFF beams, and 2400 MU/min for 10MV FFF beams, an increase by a factor of about 2.3 and 4, respectively, over conventional treatment techniques. Other machines, such as HiArt Tomotherapy, are also designed without a flattening filter and can achieve dose rates close to 900MU/min.

Benefits of a Higher Dose Rate

There are many reasons to use higher dose rates. Obviously, this shortens the treatment time. For the patient, that means less time on the table and for the institution, a potential increase in throughput. There may also be radiobiological advantages as well.

This treatment time reduction should be particularly pronounced for the hypofractionated treatments such as Stereotactic Body Radiation Therapy (SBRT) which deliver more MUs per fraction.

A number of publications have shown the ability to use MLC – based IMRT with FFF beams but also commented on the limitation of delivering at high dose rates due to the limitation of the leaf speeds of the MLC leaves themselves.

The purpose of this white paper is to show the advantages of compensator-based IMRT using an FFF beam from a Varian TrueBeam™ linear accelerator. With the high dose rate, inversely planned SBRT beams could be delivered in a very short time, possibly using a voluntary breath hold technique. One can think of this as delivering doses in "snapshots". The use of breath hold will remove any issues with interplay between the aperture shape changes and target movement, and could potentially allow a reduction in normal tissue irradiation by essentially limiting the ITV to a single phase.

Beam Modeling and Initial Characteristics for Compensators

In order to commission compensator-based IMRT several issues need to be addressed. Inherent in all compensators is a beam hardening effect since the filter itself preferentially attenuates the lower energy photons from the beam's spectrum. In addition, compensators alter the amount of scattered radiation in the beam.

In order to characterize the attenuation characteristics of the compensator material, measurements were made for various thicknesses and field sizes. The effective linear attenuation coefficient μ (LAC) was determined. This was previously done on a conventional flattening filter machine and repeated for the 6MV FFF beam.

The methodology for performing these measurements has previously been reported.[8] Measurements were made for various field sizes, and brass slab thicknesses. The value for LAC was determined using the following equation[8]:

$$\mu = -\left[\frac{\ln I/I_0}{x}\right]$$

Equation 1 Calculation of Effective LAC[8]

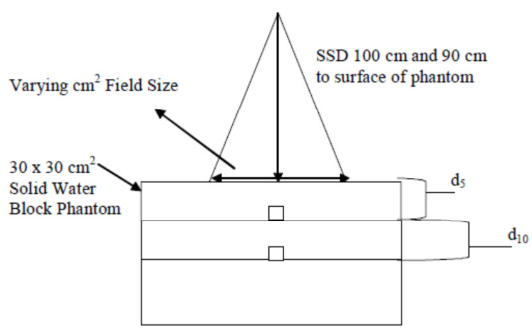

Figure 3 Effective LAC Measurement Arrangement[8]

Effective LAC data typically show a large variation with field size. It will also change drastically with energy, decreasing in nature with increases in energy.

In Pinnacle, for example, the calculation is done to handle the attenuation and hardening of the beam as it propagates through the compensator, knowing the dimensions of the compensator and the density of the material. In order to account for the increase in scatter a separate parameter in the beam model can be adjusted to boost the primary TERMA. This parameter is called the Modifier Scatter Factor (MSF).

It is recommended to review a previous publication from Moffitt Cancer Center [7] for details on the systematic commissioning process for compensators in the Pinnacle treatment planning system. To summarize some of the key points, the beam spectrum is adjusted to best fit the open field PDDs, since beam hardening is accounted for in the planning process. The lateral profiles are adjusted to best fit the beams with a 2 cm brass slab. The best absolute dose agreement is achieved when relative output factors (S_{cp}) are measured with a 2 cm brass slab in the beam. The effective LAC is adjusted by changing the density of the compensator material used in the planning process. In addition, the MSF is adjusted to produce the best compromise in terms of dosimetric agreement for a matrix of field sizes and attenuator thicknesses.

For the FFF beams, similar modeling can be done, but there are some significant differences. The numerical values of the best fit parameters are different. While the lateral beam profiles were very successfully modeled with a cone approach before, the shape of the FFF beam profile necessitated the use of the explicit incident fluence modeling in Pinnacle. Also, the output factors are less variable than the values for the conventional 6MV beam.

In addition to Pinnacle, Eclipse has similar corrections for beam hardening and scattering conditions with the FFF beam.

End to End Tests: q.d™ and TG-119 Plans

.decimal, Inc. (Sanford, FL) has created a QA process known as q.d™. Before a customer can order solid compensators from .decimal, Inc., the clinic must satisfactorily complete the q.d™ process, with the idea that completing this process will reduce variation and errors, and improve throughput and efficiency. The q.d™ process establishes a baseline for the dosimetric performance of the clinic's compensator-based IMRT planning and delivery.

After the modeling and some assessment of the mechanical aspects of the machine, a pre-defined 7-field IMRT plan designed on a standard head/neck phantom (CIRS, Norfolk, VA) with challenging pre-defined regions-of-interest (ROI) and dose objectives is created. Dose objectives are specified for each ROI (targets and sensitive structures). Once the optimized plan is finalized, the compensator parameters are electronically transmitted to .decimal® for manufacturing.

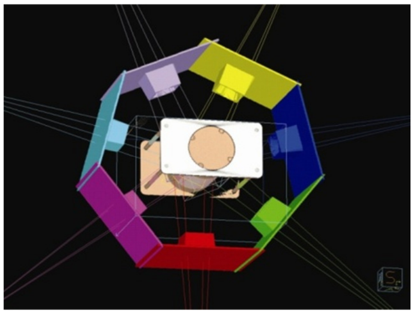

Figure 4 q.d Plan on CIRS Phantom

Once the facility receives the compensators, beam-by-beam IMRT QA dose comparison is made with the MapCHECK diode array (Sun Nuclear Corporation, Melbourne, FL). Finally the phantom, with an ion chamber placed in the high dose target region, is treated with the actual beam angles and the composite measured dose is compared to the treatment plan.

For the purpose of this study, this q.d™ process was done for both a conventional beam and an FFF beam. The results were compared.

In addition to the q.d™ process, plans were created using the AAPM TG-119 tests. This report provides a suite of ROIs and dose objectives. Appropriate plans were optimized and compensators were generated and manufactured. In this report, preliminary results from the prostate case are reported.

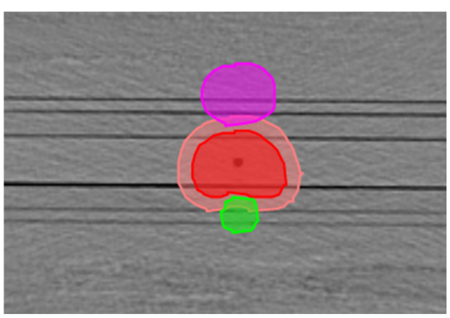

Figure 5 TG119 Prostate Test Case

Results and Discussion

The effective linear attenuation coefficient data for the FFF model and the conventional model are shown in Table 1 and Table 2 respectively.

LAC	Brass Slab Thickness			
Field Size	1 cm	2 cm	3 cm	7 cm
5x5	0.4055	0.3916	0.3826	0.3576
10x10	0.4064	0.3912	0.3808	0.3530
20x20	0.3940	0.3776	0.3663	0.3366

Table 1 Effective Attenuation Coefficients for 6MV FFF

% diff	Brass Slab Thickness			
Field Size	1 cm	2 cm	3 cm	7 cm
5x5	12.3%	10.2%	9.1%	6.1%
10x10	14.4%	10.9%	9.6%	6.6%
20x20	14.5%	12.5%	11.1%	8.1%

Table 2: Percent difference between effective attenuation coefficient for 6MV-FFF and 6MV-Conventinonal beams.

Note the substantial differences in the values of the LAC parameters for the FFF beam and the conventional beam. This is a clear indication of the softening of the beam due to the removal of the flattening filter, where the effective energy is lower and the corresponding LAC values are increased.

The q.d™ data for the conventional plan and for the FFF plan were analyzed. All seven fields were compared to their respective planar dose calculation using the Mapcheck software (version 5.01.03). The gamma analysis was performed with both the local and global dose-error normalization. Also, the "measurement uncertainty" feature in the Mapcheck software was turned off for this comparison.
For the FFF beam plan (1400 MU/min) the average percentage of the points passing the IMRT gamma analysis (see Table 3) was 100 % for γ(3%/3mm) and 98.6% for γ(2%/2mm) using global dose-error normalization and 99.1% for γ(3%/3mm) and 95.1% for γ(2%/2mm) using local normalization. The conventional plan (600 MU/min) had an average of 99.4 % passing rate for γ(3%/3mm) and 97.0% for γ(2%/2mm) global dose-error normalization and 97.8 % for γ(3%/3mm) and 91.5% for γ(2%/2mm) using local normalization. This shows an improvement in agreement for the strictest criteria of almost 4% from the conventional compensator plan to the FFF compensator plan. This dosimetry

improvement can be explained at least in part by the removal of the off-axis variation of the effective LAC in the FFF beam.

	Global Normalization		Local Normalization	
Criteria	γ(3/3) < 1	γ(2/2) < 1	γ(3/3) < 1	γ(2/2) < 1
FFF	100	98.6	99.1	95.1
Conventional	99.4	97	97.8	91.5

Table 3 Percent points passing IMRT Gamma Analysis

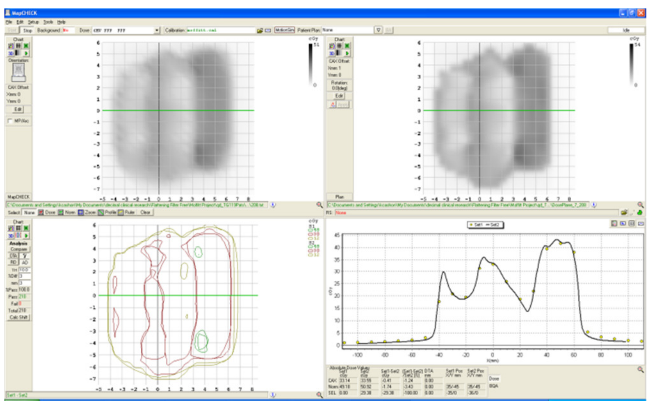

Figure 6 Typical IMRT Gamma Analysis

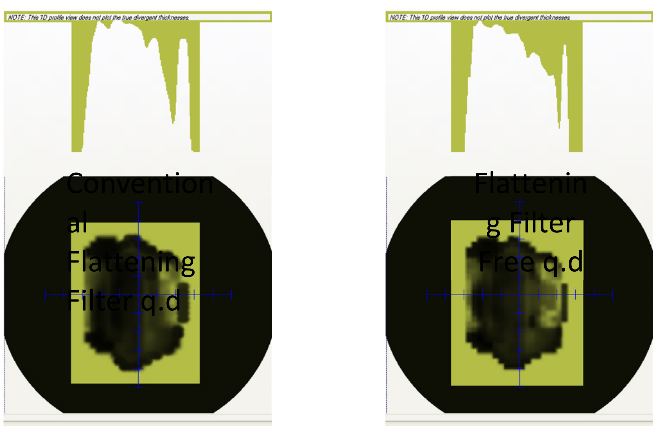

Figure 7 Side by Side view of Conventional Comp versus FFF Comp Parts

For the TG-119 Mock Prostate case the average γ(2%/2mm) passing rate with local normalization was 99.4% (range 98.4-100%).

Investigation for the remainingTG-119 test plans are currently being evaluated but preliminary indications are that highly modulated beams also show exceptionally good agreement between measured and calculated dose.

These results demonstrate dosimetric viability of using compensator-based IMRT with FFF beam from the Varian TrueBeam™ accelerator. The associated high dose rate considerably lowers the beam on time and has the potential of increasing the patient throughput for the machine's IMRT delivery. A study to investigate these potential in under investigation currently.

Conclusion

Flattening filter free beams have been shown to have many dosimetric benefits for patient care.

- Less variation in the off-axis beam hardening results from the lack of the flattening filter.
- Less scatter is introduced into the field and certain parameters are less sensitive to geometry changes such as field size.
- Since the flattening filter is removed, the very high dose rate is achieved, in this case 1400 MU/min for 6MV.

After modeling the FFF beam for compensators using techniques described for standard compensator beams, the agreement with the beam model was excellent. It may be that modeling a FFF beam is easier than a conventional beam since there is less variation in beam characteristics across the field, as explained above.

Future work includes the other TG-119 cases, as well as some clinical plans. The beam-per beam comparison will be supplemented by the composite measurements with a 3D diode array. This will allow direct dosimetric comparison with the FFF VMAT data already collected by the authors. In addition, due to the reduction in the effective energy of the 10MV beam to a 8MV beam, investigations of the change in neutron production will be done. Finally, modeling using the Varian Eclipse treatment planning system will be performed and published.

Varian TrueBeam™ Flattening Filter Free treatment beams produce very high dose rates.

The ability of the MLC – based IMRT to take full advantage of these high dose rates is limited by the mechanical constraints such as MLC leaf speed. In contrast, "snap shot" compensator-based IMRT takes better advantage of the FFF dose rate and may be more suitable for cases such as breath hold

[1]J. Cashmore, "The characterization of unflattened photon beams from a 6 MV linear accelerator," Phys. Med. Biol. **53**, 1933–1946 (2008)
[2]G. Kragl, S. af Wetterstedt, B. Knausl, M. Lind, P. McCavana, T. Knoos,
[3]B. McClean, and D. Georg, "Dosimetric characteristics of 6 and 10MV unflattened photon beams," Radiother. Oncol. **93**, 141–146 (2009).
[4]F. Pönisch, U. Titt, O. N. Vassiliev, S. F. Kry, and R. Mohan, "Properties of unflattened photon beams shaped by a multileaf collimator," Med. Phys. **33**, 1738–1746 (2006).
[5]U. Titt, O. N. Vassiliev, F. Ponisch, L. Dong, H. Liu, and R. Mohan, "A flattening filter free photon treatment concept evaluation with Monte Carlo," Med. Phys. **33**, 1595–1602 (2006).
[6]S. Stathakis, C. Esquivel, A. Gutierrez, C. R. Buckey, and N. Papanikolaou, "Treatment planning and delivery of IMRT using 6 and 18 MV photon beams without flattening filter," Appl. Radiat. Isot. **67**, 1629–1637 (2009)
[7]D. Opp, K. Forster,V. Feygelman, "Commissioning compensator-based IMRT on the Pinnacle treatment planning system", J Appl Clin Med Phys **12**, 310-325, (Spring 2011).
[8]Bartrum T, Bailey M, Nelson V, Grace M. Linear attenuation coefficients for compensator-based IMRT. Australas Phys Eng Sci Med. **30**(4):281–87 (2007).

For more information on this, please contact .decimal® at 1.800.255.1613.