Original Article

Acceptance criteria for flattening filter-free photon beam from standard medical electron linear accelerator: AERB task group recommendations

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ABSTRACT

Medical electron linear accelerators with the capability of generating unflat photon (flattening filter-free, FFF) beams are also available commercially for clinical applications in radiotherapy. However, the beam characteristics evaluation criteria and parameters are not yet available for such photon beams. Atomic Energy Regulatory Board (AERB) of India constituted a Task Group comprising experts from regulatory agency, advisory body/research and technical institutions, and clinical radiotherapy centers in the country to evolve and recommend the acceptance criteria for the flattening filter-free (FFF) photon beams. The Task Group thoroughly reviewed the literature and inputs of the manufactures/suppliers of the FFF linac and recommended a set of dosimetry parameters for evaluating the characteristics of the unflat photon beam. The recommendations included the evaluation of quality index, degree of unflatness, difference in percentage surface dose between flat and unflat photon beams, percentage depth dose at 10 cm depth, off-axis-ratios and radiation beam penumbra. The recommended parameters were evaluated for FFF photon beams generated by three different models of the linac, and it was observed that recommended evaluation methods are simple and easy to be implemented with the existing dosimetry and quality assurance infrastructure of the linac facilities of the radiotherapy departments. Recommendations were also made for periodic quality control check of the unflat photon beams and constancy evaluation in the beam characteristics.

Key words: Flattening filter free, medical accelerator, photon beam, quality assurance, unflat photo beam

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INTRODUCTION

Standard medical electron linear accelerators (linacs) with flattened photon beams (also called flattening filter photon beam) are in clinical use from past 6 decades for treatment of cancer employing both conventional (e.g. parallel opposed field, box technique) and advanced (intensity-modulated radiotherapy, IMRT; intensity-modulated arc therapy, IMAT; volumetric modulated arc therapy, VMAT, etc.) techniques. The purpose of using flattening filter is to convert the forward peaked MeV bremsstrahlung photon intensity into uniform intensity pattern for obtaining clinically acceptable beam profile.[1] However, recently introduced advanced techniques of radiotherapy are based on the further modulation in the intensity pattern of the flattened photon beam indicating that flattening of initially produced

unflat beam is not necessary for such advanced treatment techniques.[1-3] A number of studies were carried out on existing medical linac by removing the flattening filter (FF) to produce the unflat photon beam and demonstrated their feasibility in the implementation of advanced radiotherapy techniques.[1-11] It was also demonstrated that the removal of the FF results in significant increase in dose rate by a factor of about 2-4, softening of the x-ray spectra leading to reduction in scattered radiation as well as reduction in neutron and photon leakage from the treatment head.[1-12] Encouraged with such findings, manufacturers came forward with a modified version of linac designs incorporating the options of generating both flattened and unflattened photon beam for clinical use. This development has necessitated the modification in the evaluation criteria of the medical linacs before their clinical use. It is well known that the FF in a standard linac acts as an attenuator, beam hardener, and the scatterer. Due to removal of the FF, the dosimetric parameters such as field size definition, beam quality, surface dose, off axis ratio (OAR), beam flatness, symmetry, and penumbra as well as depth dose profiles of unflattened beam differs from flattened beam.

Fogliata *et al*.[12] proposed new definitions for evaluating the beam characteristics of FFF photon beams generated by standard medical linacs for establishment of quality assurance (QA) programs in the clinical environment by modifying the definitions of dosimetry quality control parameters of FF beams. However, evaluating the dosimetry characteristics of FFF photon beam applying their definitions are complex in nature, which requires normalization/re-normalization of beam profiles and finding out the inflexion points by taking derivatives of the beam profiles. Evaluation of dosimetry characteristics of FFF beam as per their definitions requires the use of dedicated software and hence need further review and simplification so that the user can easily implement in the practice.

As of now, no standard acceptance test protocol containing easily implementable definitions of dosimetry parameters is available for unflat photon beam generated by standard medical linacs. The Atomic Energy Regulatory Board (AERB) of India constituted a Task Group (TG) comprising experts from regulatory agency, advisory body/research and technical institutions, and clinical radiotherapy centers in the country to evolve and recommend the acceptance criteria for the flattening filter-free (FFF) photon beams. The Task Group approached manufacturers/suppliers of standard medical linac for obtaining technical details about the technology of their FFF beam linac and their viewpoints in evaluating the characteristics of FFF photon beams. The information received from the manufacturers/suppliers as well as the data available in the literature were thoroughly reviewed and acceptance criteria for FFF photon beam from standard medical linac were evolved. One could think of using the available definitions of beam parameters prescribed for flat photon beams. However, some of the definitions of the beam parameters (e.g., flatness, symmetry, penumbra) prescribed for evaluating the characteristics of flat photon beams are not applicable to unflat photon beams because of significant differences in shape of their beam profiles. The rationale for prescribing the definitions of beam parameters was to make it applicable to the shape of beam profiles of unflat photon beams. This paper presents the evaluation criteria and recommendations of the AERB Task Group constituted for this purpose.

The technology of FFF beam linacs

Currently two vendors, namely M/s Varian Medical Systems, USA (TrueBeam System) and M/s Siemens Medical Solutions, Germany (PreScision package for upgrading their existing linac models of PRIMUS, ONCOR, and ARTISTE for generating unflat photon beams), are supplying electron medical linacs which are having capabilities of generating high-intensity unflat photon beams.

TrueBeam system is a new linac of Varian Medical Systems, which is designed to deliver flattened (FF), as well as flattening filter-free (FFF) photon beams. It represents a new platform of Varian linacs, where many key elements including the waveguide system, carousel assembly, beam generation, and monitoring control system differ from the preceding CLINAC series. TrueBeam system of M/s Varian Medical Systems is supplied to the user in two different versions, namely TrueBeam and TrueBeam STx. TrueBeam is a general purpose linac while TrueBeam STx is a special purpose linac, which is used for stereotactic irradiations. These linacs are capable of producing stable, high-intensity beam output (high dose rate) over a wide X-ray energy spectrum. It also contains a multiport X-ray filter management system (carousel) that accommodates field flattening filters and open ports. The dosimetry systems of these linacs (i.e., monitor chamber) are capable of accurately processing a wide range of ionization per pulse. The maximum dose rates of TrueBeam system are 1400 and 2400 MU/min for 6 MV (labeled as 6XFFF) and 10 MV (labeled as 10XFFF) X-rays, respectively.

M/s Siemens Medical Solutions introduced a new option called PreScision package for upgrading their existing linac models of PRIMUS, ONCOR, and ARTISTE for generating unflat photon beams. The PreScision feature supports stereotactic radiosurgery (SRS) as well as stereotactic radiotherapy (SRT) using the conventional linac and subsystems for the delivery of precision dose to tumors using high-intensity unflat photon beams. The PreScision option can be used for operating the linac up to the dose rate of 2000 MU/min for nominal unflat photon beam energy of 7 MV (labeled as 7UF). The quality index of unflattened 7UF photon beam is similar to quality index of 6 MV flattened photon beam.

Recommendations

As the FFF photon beams (i.e. unflattened photon beam) are capable of delivering dose to patients at a very high dose rates in comparison to filtered photon beams (flattened photon beam, FF), the Task Group strongly recommended that treatment using unflattened photon beams should necessarily be carried using properly commissioned radiotherapy treatment planning system (TPS) and record and verify system through a networked arrangement. Manual treatment planning and dose calculation shall not be adopted in clinical use of these photon beams. The intention of the TG for making this recommendation is to avoid the manual calculations of monitor unit by the hospital physicist even for conventional treatments using unflat photon beam. So far, MU calculation methods are prescribed for flat photon beam only. If a medical physicist uses these calculation method for unflat photon beam the error in calculated values may be far beyond the tolerance of medical dosimetry. Because the TPS (e.g., AAA algorithm) gives the results comparable to measured values from the FFF beam.[2]

It is well established that beam parameters such as beam energy, off-axis ratio, flatness, symmetry, penumbra, surface dose affects beam characteristics of FF beams and therefore same is expected for FFF beam as well.[13,15] Therefore, for pre-commissioning evaluation and quality control purposes of unflattened photon beams, the Task Group recommended the generation of following data sets/parameters:

Beam energy

Nominal beam energy along with measured TPR20/10 values for 10 cm × 10 cm collimator setting shall be recorded for all available unflattened photon beam energies.

Surface dose

Surface dose shall be measured for collimator settings of 10 cm × 10 cm and 20 cm × 20 cm and compared with the corresponding nominal flattened photon beam energy.

Field size, flatness, symmetry, and penumbra for unflattened photon beam with field size less than 10 cm × 10 cm

For medical electron linear accelerators capable of producing unflattened photon beam with field size less than 10 cm × 10 cm, the dosimetric parameters such as field size, flatness, symmetry, and penumbra shall be measured and evaluated following the methods applied for flattened photon beams as recommended by International Electrotechnical Commission (IEC 60976, 2008). Accordingly, the flat region of a beam profile along major axes for field sizes less than 10 cm × 10 cm is defined by subtracting 1 cm from either side of the beam profile. For example, for a beam profile of field size 5 cm × 5 cm, the flat region is considered to be the central 3 cm of the beam profile.

In case, the beam flatness for unflattened photon beams of field sizes less than 10 cm × 10 cm are greater than ± 3% tolerance (i.e., beyond the acceptable tolerance for flattened photon beam), the field size, flatness, symmetry, and penumbra for such field sizes shall be evaluated using criteria recommended for the unflattened photon beams.

Off-axis ratio

The off-axis ratio at ± 3 cm lateral distance from central axis at 10 cm depth for 10 cm × 10 cm collimator setting shall be measured and indicated for all the available unflattened photon beam energies.

Depth dose profiles

Depth dose profiles for 5 cm × 5 cm, 10 cm × 10 cm and 20 cm × 20 cm collimator setting shall be measured. The depth of maximum dose (dm) and percentage depth dose (PDD) at 10 cm depth shall be indicated for all the available unflattened photon beam energies.

Beam profiles

Beam profiles for 20 cm × 20 cm collimator setting at 10 cm depth in isocentric setup (SAD) for all the available unflattened photon beam energies shall be measured and the profile shall be analyzed to evaluate the following parameters:

Field size

The field size(s) shall be defined by collimator settings only. For verifying the constancy of the beam profiles along major axes (cross-plane and in-plane), the separation between inflection points (IPs) shall be recorded. Inflection point shall be identified as per its mathematical definition. However, for practical purposes, it can be approximated as the mid-point on either side of the high gradient region (sharply descending part) of the beam profile. Its location can be identified as follows [Figure 1]: Locate starting point (S) and end point (E) of high gradient region of the beam profile. The vertical separation between S and E is the height (h) of the high gradient region of the beam profile. Inflection point is located at h/2 on the beam profile from either location (S or E).

Symmetry

Symmetry shall be evaluated following the methods recommended for flattened photon beams by International Electrotechnical Commission (IEC 60976, 2008).

Degree of unflatness

To quantify the degree of unflatness, the lateral distance from the central axis at 90%, 75% and 60% dose points on either side of the beam profile shall be recorded along major axes for all the available unflattened photon beam energies [Figure 2]. If we apply the definitions of flatness of flat photon beam for evaluating the flatness of unflat photon beams of field size greater than 10 cm × 10 cm, the flatness value may be 10-40%, which may be much

higher than the recommended tolerance for this parameter. Accordingly, new definitions have been provided.

Penumbra

For determining radiation beam penumbra, dose value at IP shall be taken as reference dose value (RDV). Points Pa and Pb, which are located at 1.6 and 0.4 times of RDV, respectively, shall be identified [Figure 1]. Lateral separation between Pa and Pb on either side of the profile will be the measure of the radiation beam penumbra. The penumbra along major axes shall be indicated for all the available unflattened photon beam energies.

While measuring beam profile of unflat photon beam, the user should ensure that the dosimetric device/radiation field analyzer (RFA) system used for this purpose will work reliably in high dose rate operation (1000–3000 MU/min) of the linac.

Periodic QA Tests

The Task Group recommended that periodic QA tests shall be carried out on daily/monthly basis and proper records should be maintained to verify the constancy in the performance of the linac in comparison to baseline data of the given parameter generated at the time of acceptance testing/clinical commissioning. Quality control dosimetry device such as 2D array can be used for generating the beam profile in this case.

Energy check

The TPR20/10 should be measured for 10 cm × 10 cm collimator setting,

Measurements of OAR

The OAR should be measured at ± 3 cm for 10 cm × 10 cm collimator setting,

Measurements of profiles

The beam profiles should be measured using multiple detector system/any other suitable device for 20 cm × 20 cm collimator setting.

Qualifying the recommended acceptance criteria

Recommended QA parameters were measured on three different models of the medical linear accelerators having capabilities of generating FFF photon beam in addition to FF photon beam. Beam profiles and depth dose curves of both FF and FFF photon beams were measured using 3D-RFA (Blue phantom, IBA, Sweden) using CC13 ionisation chamber (sensitive volume of 0.13 cc). The measurement accuracy was within 1%. The ionization chambers/dosimetry diodes used for flat photon beam dosimetry are also useful in unflat photon beam dosimetry. However, care should be taken about the current range of electrometers. Majority of vendors have come out with a communication that their existing dosimetry instruments are also suitable for dosimetry of unflat photon beams. The user should verify the suitability of the dosimetry system before measurements of the required beam parameters. The measured beam profiles were analyzed for evaluating the symmetry, degree of unflatness, radiation beam penumbra, and OARs applying the definitions recommended by the Task Group. The depth dose curves were analyzed for determining depth of dose maximum, percentage depth dose at 10 cm depth and the difference in percentage surface dose. The quality indices ($TPR^{20,10}$) for 6 and 10 MV flat and unflat photon beams were measured using reference dosimetry phantom. The measured values are shown in Table 1. The data given in Table 1 is determined from the measured profiles of unflat photon beams as the numerical values of the quoted parameters are more important than the beam profiles. The measured quality index for corresponding flat photon beam energy has been indicated in the parentheses. This exercise provided the confidence that the recommended dosimetry parameters can easily be measured and documented for characterizing the FFF photon beam.

It is also expected that the user will use these definitions for generating the values of recommended dosimetry parameters on periodic basis to ascertain the constancy

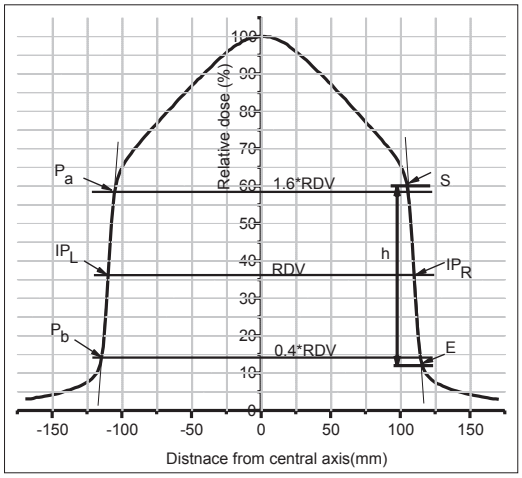

Figure 1: Schematic diagram for determining inflection point and penumbra

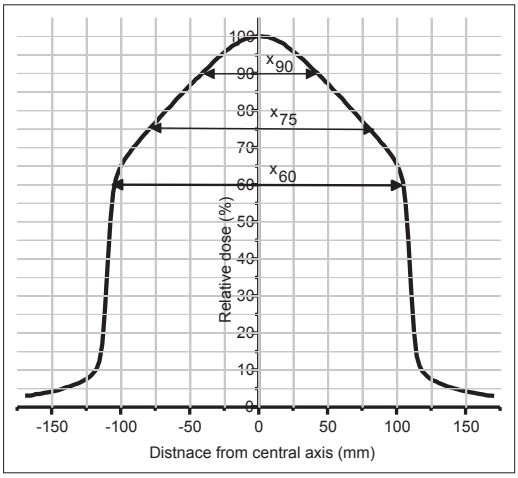

Figure 2: Schematic diagram for determining degree of unflatness

in the performance of the medical linac in the FFF mode of operation. A format for recording the values of the parameters required for assessing the constancy in the characteristic parameters of FFF photon beam was also prescribed [Table 2]. Usually, the collimator setting for defining a nominal field size is calibrated with respect to lateral separation between 50% dose points on the beam profile of a flattened photon beam. However, in case of FFF beam, the separation between the IPs can be a measure of radiation field size for unflattened photon beams, which can be compared with the collimator setting used for generating the beam profile. The user should also record these data and verify the constancy of the beam size with respect to collimator setting.

Summary and conclusions

The AERB Task Group constituted to evolve and recommend the acceptance criteria for the FFF photon beams thoroughly reviewed the literature available and technical details provided by the manufactures/suppliers about the characteristics of unflat photon beams. Based on the review of available information and deliberations among the members and invitees, the Task Group prescribed the definitions of dosimetry parameters required for evaluating

Table 1: Measured values of recommended parameters on three different models of medical electron linear accelerators capable of generating unflat photon beams

Parameters	*Energies (MV)*	*Collimator setting (cm^2)*	*Measured values on FFF linac*		
			Varian TrueBeam	*Varian TrueBeam STx*	*Siemens ONCOR PreScision*
Beam quality* ($TPR_{20/10}$)	6XFFF/7UF	10×10	0.633 (0.667)	0.630 (0.671)	0.682
	10XFFF	10×10	0.709 (0.737)	0.704 (0.743)	-
Difference in % surface dose (PSD) between flat and unflat beams of similar nominal photon beam energy	6XFFF/7UF	10×10	8.74	8.10	1.23
		20×20	5.21	4.90	1.13
	10XFFF	10×10	8.27	7.70	-
		20×20	2.07	2.00	-
Off axis ratio: Cross-plane	6XFFF/7UF	10×10	0.947 (−3 cm) 0.949 (+3 cm)	0.940 (−3 cm) 0.942 (+3 cm)	0.924 (−3 cm) 0.908 (+3 cm)
	10XFFF	10×10	0.907 (−3 cm) 0.903 (+3 cm)	0.895 (−3 cm) 0.900 (+3 cm)	-
Off axis ratio: In-plane	6XFFF/7UF	10×10	0.944 (−3 cm) 0.942 (+3 cm)	0.935 (−3 cm) 0.933 (+3 cm)	0.917 (−3 cm) 0.909 (+3 cm)
	10XFFF	10×10	0.906 (−3 cm) 0.908 (+3 cm)	0.900 (−3 cm) 0.899 (+3 cm)	-
Depth of dose maximum (d_m) (mm)	6XFFF/7UF	5×5	15.1	13.5	21.0
		10×10	14.7	13.6	20.3
		20×20	14.1	12.4	19.5
	10XFFF	5×5	24.3	22.4	-
		10×10	23.5	22.0	-
		20×20	23.1	20.9	-
Percentage depth dose at 10 cm depth	6XFFF/7UF	5×5	60.3	59.6	66.0
		10×10	64.2	63.6	68.6
		20×20	67.2	66.6	70.7
	10XFFF	5×5	69.6	68.7	-
		10×10	71.8	71.0	-
		20×20	73.2	72.6	-
Symmetry (%)**	6XFFF/7UF	20×20	0.13	0.2	0.1
	10XFFF	20×20	0.32	0.7	-
Separation between IP_L and IP_R (cm)**	6XFFF/7UF	20×20	19.95	19.96	19.81
	10XFFF	20×20	19.90	19.94	-
Lateral width at 90% dose level ($X_{90\%}$) (cm)**	6XFFF/7UF	20×20	9.95	9.82	7.40
	10XFFF	20×20	6.52	6.44	-
Lateral width at 75% dose level ($X_{75\%}$) (cm)**	6XFFF/7UF	20×20	17.30	17.22	14.30
	10XFFF	20×20	12.69	12.68	-
Lateral width at 60% dose level ($X_{60\%}$) (cm)**	6XFFF/7UF	20×20	19.40	19.36	18.70
	10XFFF	20×20	19.27	18.20	-
Radiation beam Penumbra (P_b-P_a) (mm)**	6XFFF/7UF	20×20	7.0	9.4	11.0
	10XFFF	20×20	7.2	9.1	-

*Values given in the parentheses are for corresponding flat photon beam energy. **Data are from the cross-plane profile. TPR: Tissue phantom ratio, PSD: Percentage surface dose, IP: Inflection point, FFF: Flattening filter-free

Table 2: Format for recording the values for constancy verification of separation between inflexion points, degree of unflatness, symmetry and radiation beam penumbra (IP_L and IP_R are the locations of left and right inflection points on the beam profile, respectively; $X_{90\%}$, $X_{75\%}$, and $X_{60\%}$ are lateral widths at 90%, 75%, and 60% dose levels, respectively). These parameters should be evaluated for 20 cm ×20 cm collimator setting

Nominal beam energy (MV)	*Measurement plane*	*Separation between IP_L and IP_R (cm)*	*$X_{90\%}$ (cm)*	*$X_{75\%}$ (cm)*	*$X_{60\%}$ (cm)*	*Tolerance*	*Symmetry*		*Penumbra (mm)*	
							Measured	*Tolerance*	*Measured*	*Tolerance*
6FFF/7UF	In-plane					±2 mm*		±2%*		±2 mm*
	Cross-plane									
10FFF	In-plane					±2 mm*		±2%*		±2 mm*
	Cross-plane									

*Variation from the baseline values.

the characteristics of the FFF photon beams. Measurements were carried out on three different models of the medical linacs, capable of generating FFF photon beams for clinical applications, to evaluate the recommended dosimetry parameters and assess the simplicity in implementing the recommendations. This exercise provided the confidence that the recommended definitions and evaluation procedures are simple in nature, which can easily be implemented by the medical physicists in the hospitals. It is therefore expected that the recommended dosimetry parameters can easily be implemented during acceptance testing of the FFF photon beam with the existing infrastructure available at medical linac facility of the radiotherapy departments. The Task Group also prescribed parameters for periodic quality control check of the FFF photon beam, which will help in ascertaining the constancy in the performance of medical linacs in FFF mode of operation.

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