Evaluation of different physical parameters based on standard photon beam versus flattening filterfreein treatment cancer patients

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Abstract

In radiotheraby, the purpose of using standard photon beam (Flattening Filter; FF) is to convert the forward peaked MV bremsstrahlung photon intensity into uniform intensity pattern for obtaining clinically acceptable beam profile. Recently a number of studies were carried out on existing medical linac by removing the flattening filter to produce the unflat photon beam and demonstrated their feasibility in the implementation of advanced radiotherapy techniques. Flattening Filter Free (FFF) beam have a fundamental physical parameter differences with respect to the standard filter flattened beams, making the generally used dosimetric parameters and definitions not always viable. In this concern, the current paper is a trial to shed further light on studying some dosimetric parameters for use in quality assurance of FFF beams generated by medical linacs in radiotherapy. The main characteristics of the photon beams have been analyzed using specific data generated by a Varian TrueBeamlinac having bothFFF and FF beams of 6 and 10 MV energy. Definitions for dose profile parameters are suggested starting from the renormalization of the FFF with respect to the corresponding FF beam. From this point the flatness concept has been translated into one of “unflatness” and other definitions have been proposed, maintaining a strict parallelism between FFF and FF parameter concepts. In summary, although there are a number of advantages of using a FFF beam especially for advanced radiotherapy techniques there are a few challenges (e.g., criteria for beam quality evaluation and penumbra, establishment of dosimetry methods, and consequences of photon target burn-up) which need to be addressed for establishing this beam as an alternate to the FF beam.

Keywords: Flattening filter free, beam and flattening filter, breast cancer,treatment planning, beam characteristics and multi-leaf collimators.

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1. Introduction

Traditionally, the flattening filter in the X-ray beam path of a linear accelerator produces an almost uniform fluence over a collimated field. This is particularly advantageous for 3D conformal radiation therapy (3D CRT) for practical reasons.

The removal of the flattening filter leads to a radially decreasing fluence distribution and thus to inhomogeneous dose distributions. The advantage of this is its positive influence on the peripheral dose through reduced head scatter andMulti Leaf CollimatorMLC leakage [Vassiliev ON et al (2006)], as well as a considerable increase in the dose rate, which has a beneficial effect on modern therapy methods.

Besides improved shielding in the treatment head **Hall et al. in 2006(Ponisch F et al 2006)**also suggested the use of secondary jaws to track the MLC and removal of the flattening filter as a source of scattered radiation with fluence-modulated radiation therapy (RT). The disadvantage of a non-uniform, conical fluencedistribution can be taken into account with Intensity Modulated Radiotherapy (IMRT)in the optimization algorithm. Recent studies have shown the feasibility of the use of FFF beams for IMRT and Stereotactic Body Radiation Therapy (SBRT) **(Cashmore J ,2008**),(**Parsai EI et al 2007), (Kragl G et al ,2009).**Also, it has been concluded that the decreased variation in scatter factors and beam quality along the field will simplify dose calculation **[Dalaryd M et al ,2010)**. It is often necessary to resort to Field In Field techniques (FiF), which are often also termed forward IMRT techniques, in order to achieve better conformity for the Planning Tumor Volume (PTV) in 3D CRT planning. Additional fields in one angle of incidence (multistatic field) can be used to adapt dose distribution optimally to the anatomy of the patient without the need for a wedge. Several studies for various RT locations have shown that a beneficial dose distribution can be achieved with this method in relation to homogeneity and conformity **(Titt U et al ,2006),(Georg D et al 2010),(Kry SF et al ,2008).** It is also possible to adapt FFF beams in 3D CRT by using this field in field technique.

2. Materials and Methods

2.1. Materials

2.1.1. Linear Accelerator - TrueBeam System

Thelinear accelerator used during the present study isTrueBeam system**(Fig. 1),** the unit which represents a new linac of Varian Medical Systems. It is designed to deliver **FF,** as well as **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. Also, it contains a multiport X-ray filter management system (carousel) that accommodates field flattening filters and open ports. The dosimetry systems of these linacs (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.The accelerator is equipped with asymmetric collimation jaws and a MLC consisting of 120 leaves on each side, allowing a maximum field size of 40×40 cm^2.

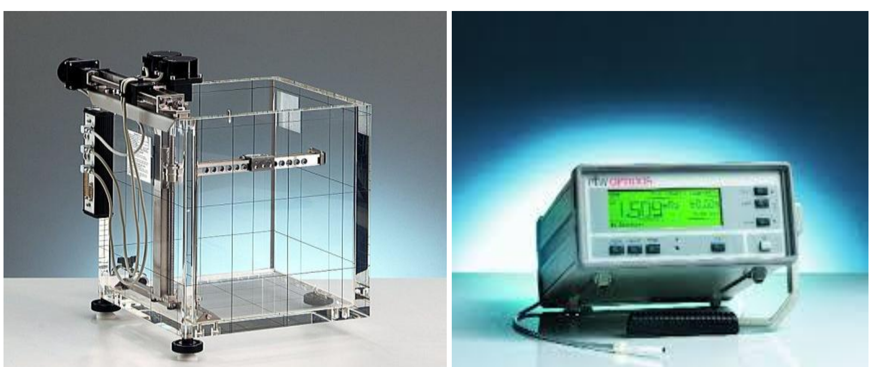
Fig. (1):Linear accelerator - TrueBeam system.

2.1.2. Dosimetry System

A PTW MP3 water phantom (PTW-Freiburg, Germany) with inner tank dimensions of 694.0×596.0×502.5 mm^3 was used together with a cylindrical semiflex ion-chamber (PTW, type 21010) with an inner cavity volume of 0.125 cm^3**(Fig. 2a).**Also, to compensate for beam output variations, a cylindrical ion-chamber (PTW, type 31010) was used as a reference in the present and all of the following relative dose measurements.

2.1.3. PTW-UNIIDOS Electrometer

For all measurements with the water tank scanning system a PTW-UNIIDOS Electrometer was used and the data collection was governed by the MEPHSTO software from PTW**(Fig. 2b).**



(a) (b)

Fig. (2): MP3 water phantom (a) and PTW-UNIIDOS electrometer (b).

2.1.4. Portal Dosimetry

During the course of the work,portal imaging devices (EPIDs) havebeenused for acquiring megavoltage images during patienttreatment. The larger area of the Digital Megavolt Imagers (DMI) is now square (43x43 cm^2 for single images).

2.2. Methods

2.2.1. Beam Parameters for FFF

For each photon energy, Percentage Depths for Different Field Size(PDD) curves were acquired for 13 square field sizes: 2, 3, 4, 6, 8, 10, 12, 15, 20, 25, 30, 35 and 40 cm. Field size was defined by jaws, not MLC.

Water level was checked periodically with the front pointer: always before the first scan, for X6 and 6FFF additionally at mid-field size. Evaporation can make it necessary to fill up the water tank every 30 minutes or so, depending on room temperature and humidity. The front pointer method can detect changes of the Source-Surface Distance (SSD) in the order of 0.2 mm.

On one hand, theDepth of Maximum Dose(dmax) depths serve as reference depths for the linac output calibration. We calibrate our TrueBeams to deliver 1.0Gy per 100 MU at an SSD of 100 cm in depth of $d_{max}$for the 10 x 10 cm^2 reference field, following the Varian recommendation.

3. Results and Discussion

3.1. D_{max}Results

The following d_{max} depths for the 10 x 10 field were determined:

16 mm for6MV(FF)
14 mm for 6MV (FFF)
26 mm for 10MV (FF)
24 mm for 10MV (FFF)

Figures (3 and 4) show the percentage depths dose for all field size (from 3.0 cm^2 up to 40 cm^2) for 6 MV (FF and FFF). On the other hand, **Fig's. (6 and 7)** show the beam profiles for all field sizes (from 3.0 cm^2 up to 40 cm^2) for 10 MV (FF and FFF).

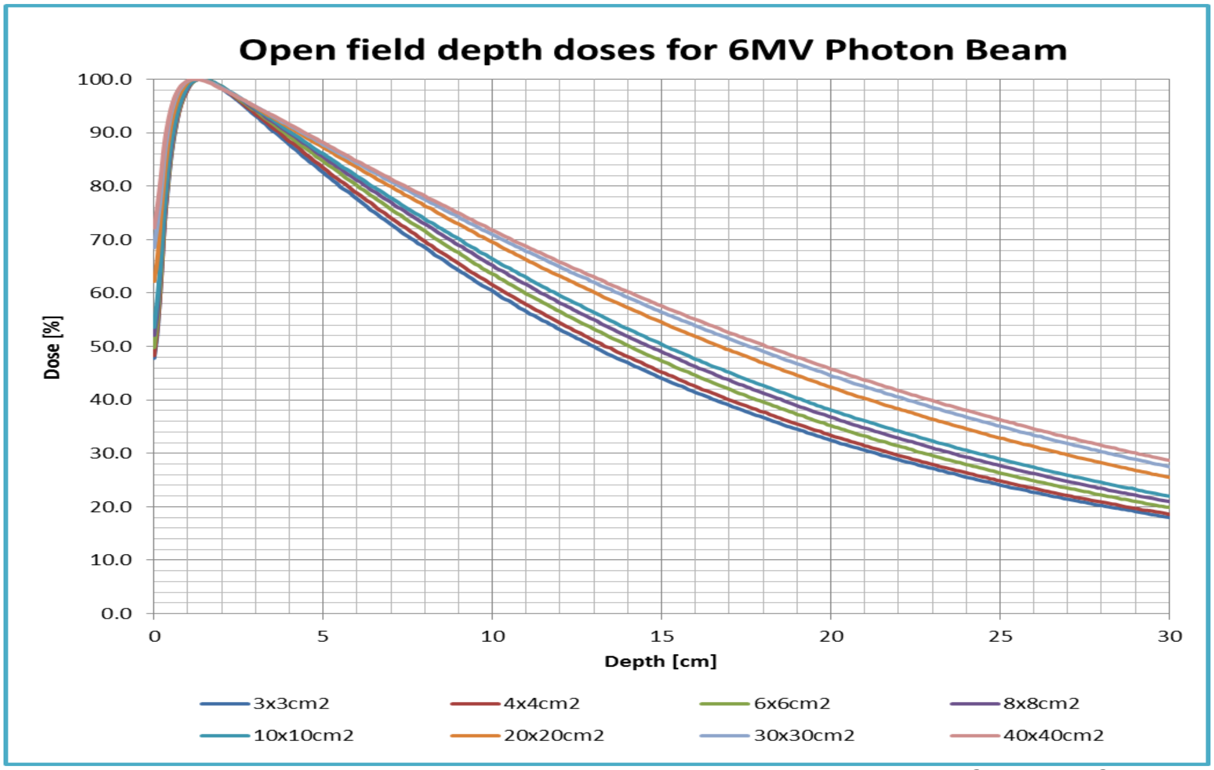


Fig. (3): Percentage Depths Dose for all field size start from $3cm^2$ to $40cm^2$ for 6 MV (FF).

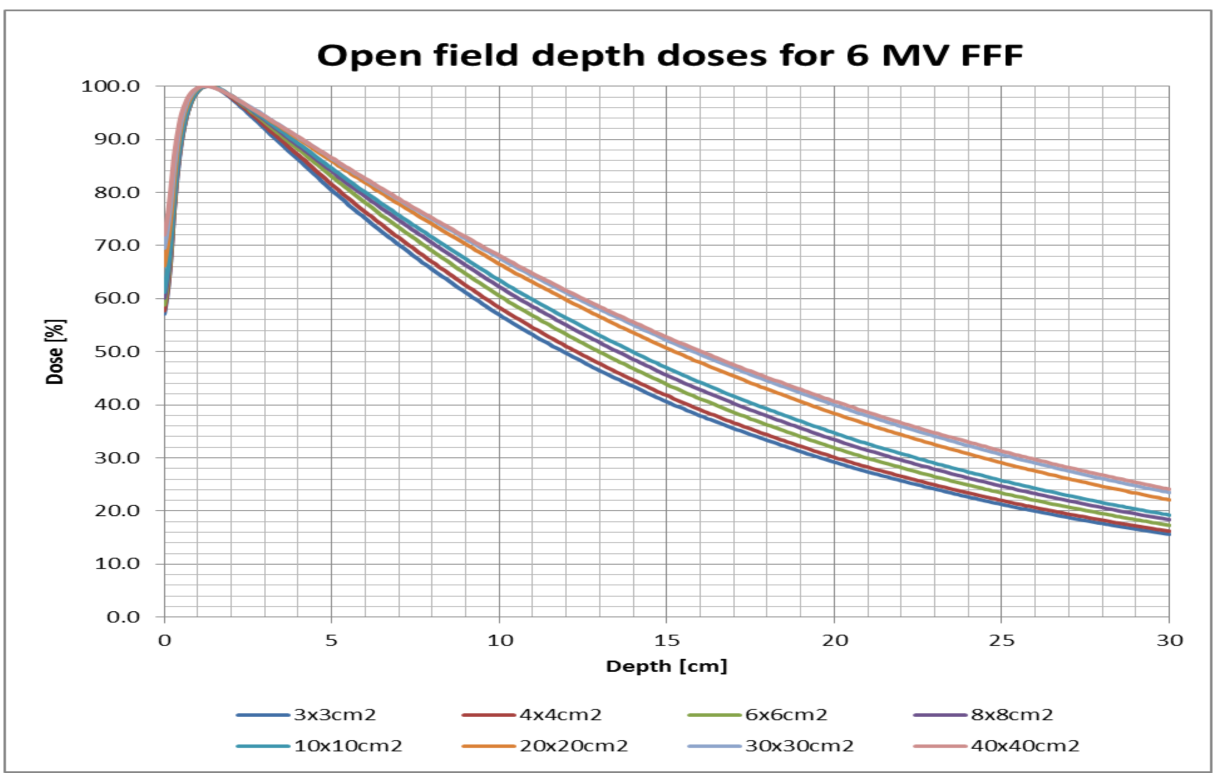


Fig. (4): Percentage Depths Dose for All field size start from $3cm^2$ to $40cm^2$ for 6 MV (FFF)

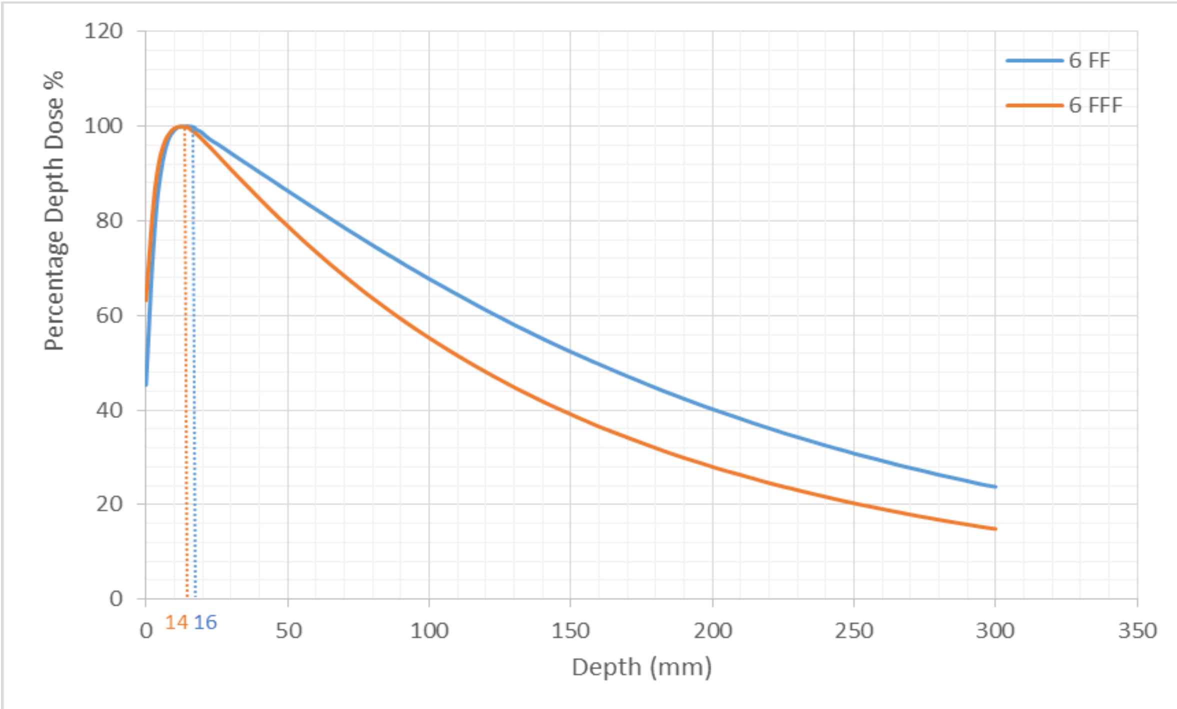


Fig. (5) Comparison between PDD% Curve of (6FF& 6FFF) at Field size 10 x 10 cm^2 and at SSD 100 cm.

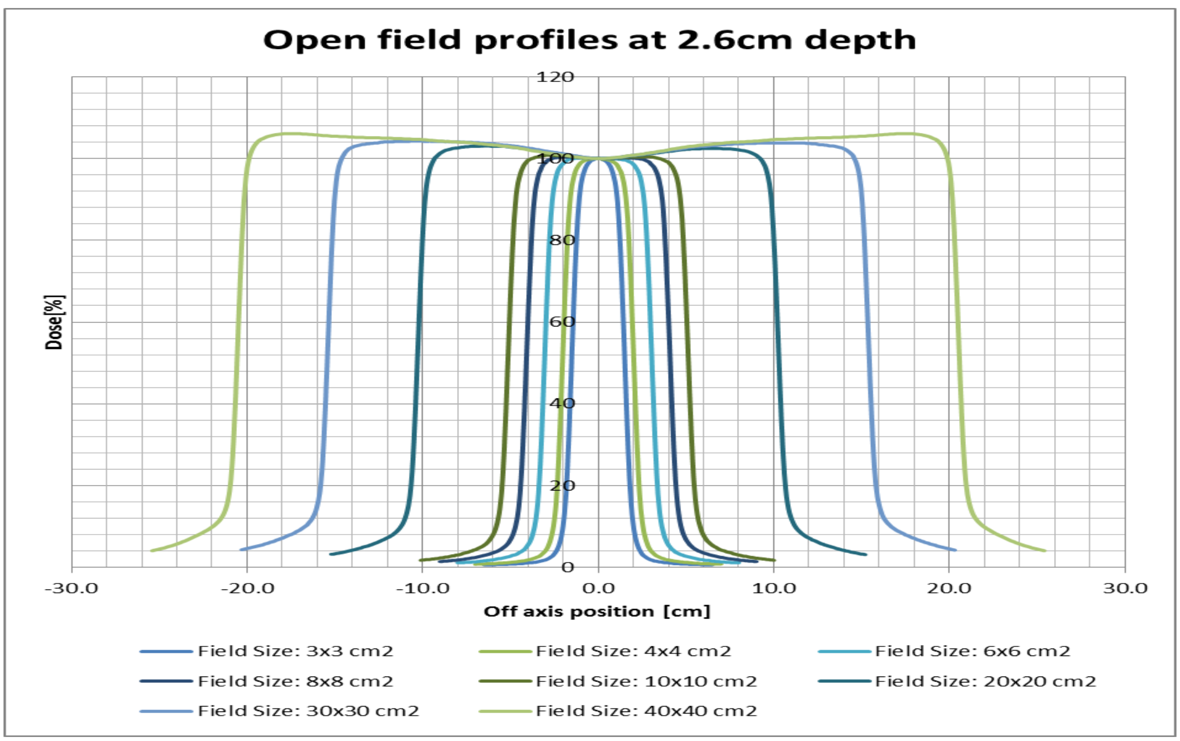


Fig. (6): Beam Profiles for All field size start from $3cm^2$ to 40 cm^2 for 10 MV (FF) at depth 26.0 mm.

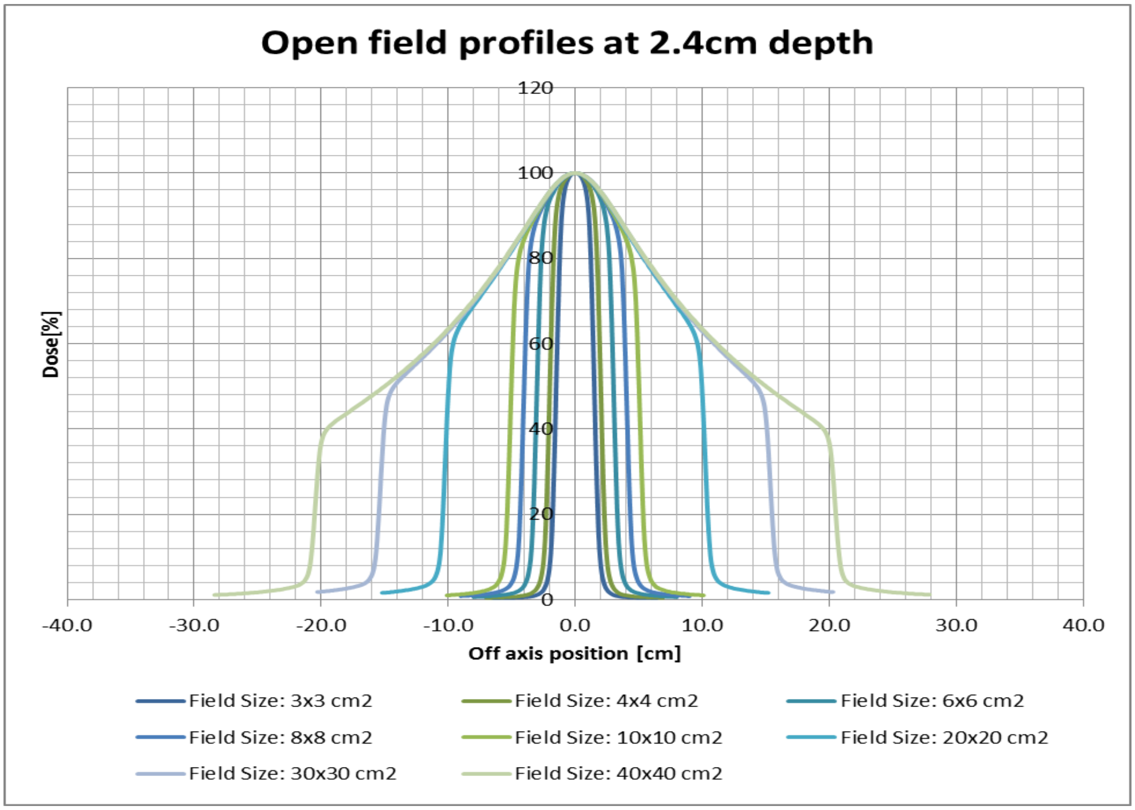


Fig. (7): Beam profiles for all field size start from 3cm^2 to 40 cm^2 for 10 MV (FFF) at depth 24.0 mm

The magnitude of contaminating electrons of FFF beam is relatively small and as a consequence the depth of dose maximum shows weak dependence on field size variation. Lateral dose profiles of FFF beam differ significantly from the FF beam. The central peak in the lateral profiles of FFF beam is pronounced only for medium to large field sizes. The higher the energy the more pronounced is the central peak. The shape of the lateral beam profile of a FFF beam changes slightly with depth due to a significantly reduced off-axis softening effect and hence the depth--dose characteristic remains almost constant across the field even for large field sizes.

Optimizations of Dose Distribution.

The larger area of theDigital Megavolt Imagers(DMI) is now square (43x43 cm for single images). This offers the possibility to image larger field lengths at the same imaging distance. Resolution is also slightly improved. Image size is now 1280x1280 px for single images.

3.1.2 Case Study–6 MV (FFF)

For the second flattening filter free energy, 6FFF, portal dosimetry results also improved dramatically. Outside theComplete Irradiation Area Outline(CIAO), profiles measured with aS1000 were often to low compared to calculation using EPIQA(EPIQA is a non-transit commercial software that can convert a dosimetricimage acquired by an EPID into a dose map, and to compare the dose map with a reference dose distribution). This problem does not exist anymore.

- Here is an example of IMRT plan 5 fields of the breast, 6FFF, 1400 MU/min, again measured at isocenter distance**(Fig. 8).** With the 2%/2mm criterion, the gamma agreement index for both arcs is approximately 100% over the whole detector area.
- As shown in **Fig. (9),** a significant difference between dose distribution for6MV (FFF) in target coverage and doses for organs at risk versus 6 MV (FF) due to difference in depth of maximum dose and applicability for good distribution with FFF beam.

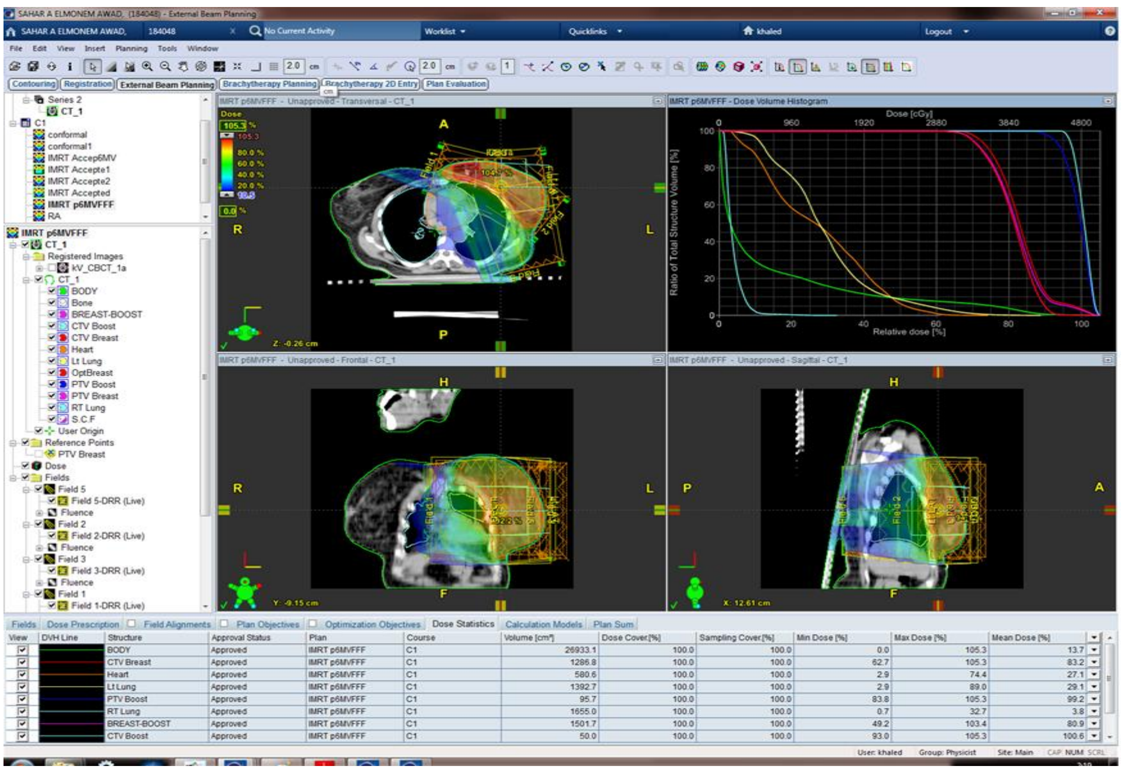


Fig. (8) Breast plan for 6 MV FFF.

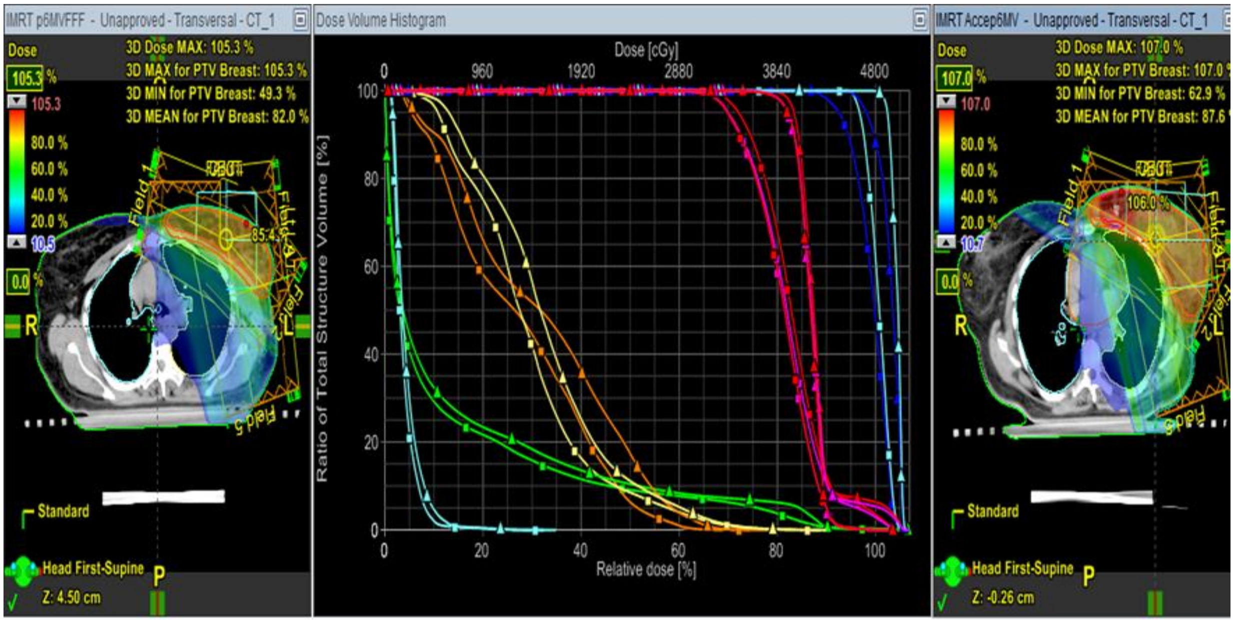


Fig. (9) Comparison for two dose distribution for breast cancer, plotted at 6MV (FFF) and 6 MV (FF).

3.1.2 Case Study– 10 MV (FFF)

The following example shows palliative treatment of single arc, 10FFF energy, 2400 MU/min and 2357.2 MU total, planned with Eclipse 13.6 (AAA 13.6.23). This plan verified with Portal dosimetry for single fraction in palliative case**(Fig. 10).**

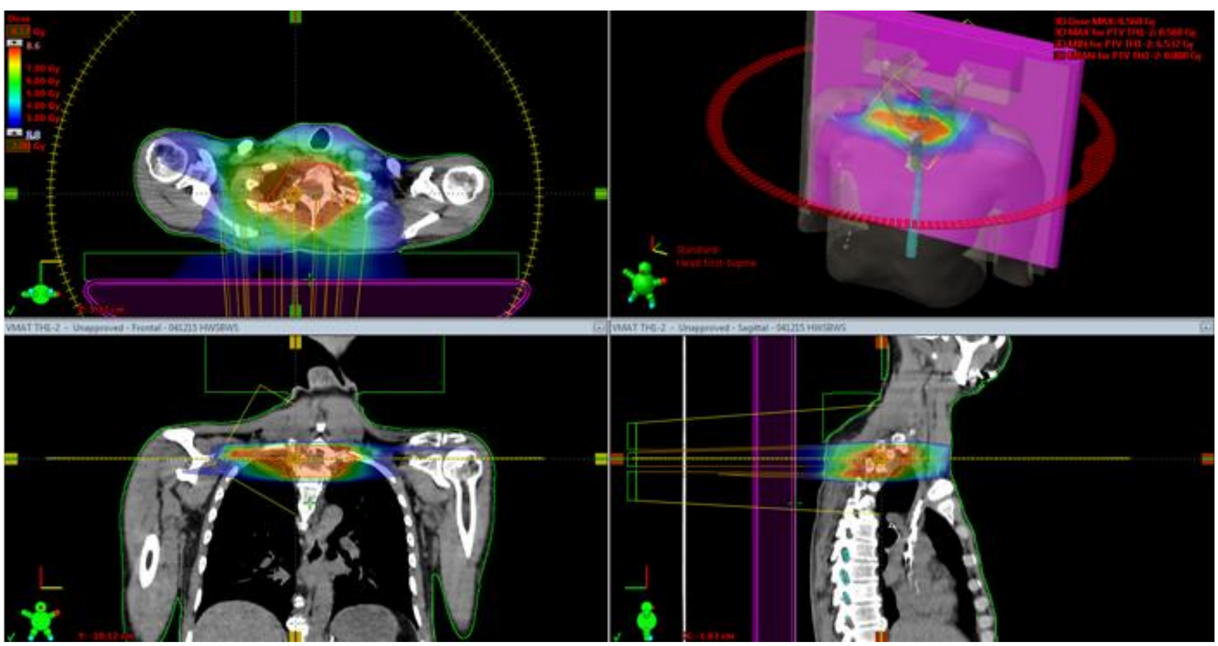


Fig. (10): Example for dorsal lesion for 10 MV FFF beam and dose distribution using VMAT technique(single ARC).

A verification plan was calculated using the Portal Dose Image Prediction (PDIP) algorithm. The arc was measured with the DMI imager at isocenter distance and analyzed using the 3%/3mm DTA Gamma criterion.

-Volumetric Arc Therapy (VMAT) or RapidArc® Radiotherapy technique is an advanced form of IMRT that delivers a precisely-sculpted 3D dose distribution with a 360-degree rotation of the gantry in a single or multi-arc treatment, RapidArc uses a dynamic multileaf collimator (MLC), variable dose rate, and variable gantry speed to generate IMRT-quality dose distributions.

- The current dosimetry protocols which are followed for output measurement of photon beams from medical Linear accelerator requires a beam quality correction factor. This beam quality correction factor is related to the quality index [%DD(10) or TPR_{10}^{20}] of the photon beam. As the reference conditions for measuring the quality index of the photon beam is given with reference to the FF beam it cannot be directly applied for the FFF beam. There is a need to revise the existing dosimetry protocols for the FFF beam. The conventional definition of beam penumbra is not applicable to the FFF beam requiring a modification in the definition. The primary electrons have been reported to penetrate through the high Z thin targets used for generating bremsstrahlung photons posing a potential risk for producing high surface doses if not removed.

In the case of FF linac, the electrons penetrating through the thin bremsstrahlung targets are efficiently removed by the FF. In a FFF linac, an additional thin metal plate in front of the monitor chamber is used to remove the primary electrons penetrating through the bremsstrahlung target. The material and the thickness of this plate need to be optimized maintaining the advantage of the FFF beam and giving due consideration to the incidence of bremsstrahlung target breaks.

3.2 Discussions

The advanced beam therapy techniques, such as radiotherapy where inhomogeneous dose distributions are applied and intensity-modulated radiotherapy (IMRT) where varying fluence pattern across the beam are delivered, have stimulated the increasing interest in operating standard linac in a flattening filter free (FFF) mode.A standard linac can therefore be used for generating photon beams either with flattening filter (FF beam) or without flattening filter (FFF beam). A number of Monte Carlo and experimental studies dealing with characteristics, dosimetric aspects, and radiation protection issues of FFF photon beams generated by mechanically removing the flattening filter of existing standard linacs of different makes and models have been reported in the recent past.Studies related to treatment planning and dose delivery of various clinical cases using FFF beams demonstrate their clinical suitability and superiority over FF photonbeams.A review of the properties of FFF photon beams summarizing the findings of different investigators has also been published recently.

Very recently, [Hrbacek J et al (2011)],reported the measured dosimetric characteristics of unflattened photon beams generated by a new model of a standard linac (TrueBeamSTx, Varian Medical Systems) capable of generating both flattened and unflattenedclinical photon beams.It is well known that the flattening filter in a standard linear accelerator acts as an attenuator, the beam hardener and the scatterer. Obviously, the removal of the FF results in an increase in dose rate, softening of the x-ray spectra, and reduction in head scattered radiation, and the non-uniform beam profile. The reported dose rate of FFF beams is about 2 - 4 times higher than that of the FF beams, i.e., FFF linear accelerator can typically be operated at a dose rate higher than 10 Gry/min under the normal operating conditions applied for FF linear accelerator . The increased dose rate decreases the dose delivery time, especially for hypo-fractionated SRT, and is thought to be useful in managing the intra-fractional target motion.

The softening of the x-ray spectra affects the depth as well as lateral dose distribution at all depths and results in increased surface dose and slight shifting of the depth of maximum dose toward the surface. The lateral transport is reduced, which may result in greater control over gradients with the field and at target boundaries. The head scatter variation for an unflattened beam is typically about 1.5% as against about 8% of the flattened beam for the field sizes in the range of 3×3 up to 40×40 cm^2.

As a result a simple model for dose calculation of irregular treatment fields would be sufficient for the FFF beam. Moreover, due to the absence of the collimator exchange effect, it would not be necessary to account whether the upper or lower secondary collimator is defining the long side of the rectangular beam. The decreased head scatter and hence the reduced head leakage also results in decreased far field Peripheral Dose(PD) to the patient.

The near field PD is also less due to the combined effects of softer photon beam spectra, increased dose per pulse, and reduced collimator transmission.While treating the patients by radiotherapy (IMRT) with a 6 MV FFF beam, the integral dose to nearby healthy tissue and the whole-body integral dose respectively were found significantly higher than the FF beam and the use of higher FFF beam energy was suggested as the remedy of the problem (e.g., using 10MV instead of 6 MV) [Vassiliev ON et al (2006)]. This is due to the fact that 10 MV unflattened depth dose characteristics are similar to those for a 6 MV flattened beam. The use of a FFF beam over a FF beam is a natural choice for IMRT treatments. However, leaf travel time for creating a large number of optimized segments for static IMRT and the leaf speed for the dynamic and rotational IMRT are the limiting factors in dose delivery efficiency by IMRT.

Hence, for effective and efficient use of the FFF beam, the technology of current MLC needs to be modified. Further, the intensity of the FFF beam abruptly decreases with the off-axis distance for large open fields ($\geq10\times10$ $cm^{\mathbf{2}}$) which necessitates the off-axis distance-dependent modulation for delivering uniform dose to the tumor. While executing the off-axis distance-dependent modulation by dynamic MLC larger monitor units are required which increase the gross head leakage and lessen the advantage of using the FFF beam. This effect is significant in dynamic IMRT of off-axis targets and large volume targets and while dealing with such clinical cases a modified FFF beam is required [Tyner E et al (2009)].

4 Conclusions

From the experimental work, results, analysis, and discussions, it could be concluded that flattening filter free plan configuration yielded an acceptable improvement in treatment efficiency on advanced radiotherapy techniques. Although, there are a few challenges (e.g., criteria for beam quality evaluation and penumbra, establishment of dosimetry methods, and consequences of photon target burn-up) which need to be addressed for establishing this beam as an alternate to the FF beam.

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الملخص باللغة العربية

تقييم العوامل الفيزيائية المختلفة للشعاع الفوتونى المرشح والغير مرشحفى علاج مرضى السرطان

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يعتبر العلاج الاشعاعى أحد الأفرع الرئيسية لعلاج الأورام السرطانيةوذلك اعتمادا على اسلوب العلاج بالأشعة المؤينة والتى تشتمل على الفوتونات والالكترونات والبروتونات والجسيمات الثقيلة. هذا وينقسم العلاج الاشعاعى الى علاج اشعاعىعن بعد (خارجى) وعلاج اشعاعىعن قرب (داخلى). وفى هذا الصدد فان المحور الرئيسى للدراسة المعروضة هو العلاج الاشعاعى عن بعد (الخارجى) باستخدام الفوتونات والتى بدأ استخدامها الفعلى منذ اكتشاف العالم رونتجن لاشعة الفرملة (ا لأشعة السينية) عام 1895. اما حديثا، فأن هناك أسلوب متطور للعلاج الاشعاعى يعتمد على التغير فى شدة الاشعاع الفوتونى، مما لايحتم ويلغى ضرورة استخدام مرشح التسطيح للشعاع الفوتونى ليجعل شدتة موحدة. وعلى ذلك فان الدراسات الحديثة بدأت تستخدم العلاج الاشعاعى بدون مرشح بواسطة المعجل الخطى .

وفى هذا الصدد، فقد اهتمت الدراسة بعمل تقييم للخصائص الفيزيائية المختلفة للطاقات الفوتونيه العديده ذات المرشح ومقارنتها بالطاقات الفوتونيه الغير مرشحة فى علاج مرضى السرطان .

تم خلال الدراسة قياس منحنيات نسبة جرعة العمق للطاقات المختلفة (6.0 and 10MV) للفوتونات ومع مساحات الحقول الاشعاعية المختلفة من $3.0 \times 3.0\ cm^2$ وحتى $40 \times 40\ cm^2$. كما امتدت الدراسة الى عملمقارنة بين جميع النتائج التى تم الحصول عليها فى حالة استخدام مرشح التسطيح وفى حالة ازالة المرشح، حيث ثبت وجود اختلاف كبير بين المنحنيات للحالتين وان عمق اقصى جرعة فى حالة ازالة المرشح قد قلت بمقدار 2.0 mm عن مثيلتها فى حالة وجود مرشح التسطيح وذلك عند الطاقتين المستخدمتين، مما يعنى ان عمق أقصى جرعة يعتمد على وجود مرشح تسطيح من عدمة. اضافة الى ذلك فقد تم تسجيل ارتفاع نسبة جرعة السطح فى حالة غياب المرشح عند الطاقتين عن مثيلتها فى الحالة العادية وان الجرعة تقل بعد نقطة (d_{max})عند الطاقتين عن مثيلتها فى الحالة العادية مما يفيد فى تقليل جرعة الاشعاع للأنسجة السليمة . وجدنا ايضا ان جرعة السطح لا تتغير باختلاف مساحة الحقل الاشعاعى المستخدم كما هو الحال مع عمق اقصى جرعة فى حالة غياب المرشح عن الحالة العادية .

وبدراسة شكل الشعاع الفوتونى فى الحالتين وعند الطاقات 6.0 and 10 MV ومع جميع مساحات الحقول الاشعاعية وعند اعماق مختلفة نجد اختلاف كبير وواضح جدا بين الشكلين للحالتين، حيث تم تسجيل تكوين شكل مخروطى

لمنحنى الشعاع الفوتونى فى حالة غياب المرشح وتظهر بوضوح عند الحقول الاشعاعية المتوسطة الى الكبيرة وعند الطاقات العالية وانخفاض الجرعة عند أطراف الحقل مما يفيد فى انخفاض الجرعة الاشعاعية للأنسجة السليمة .

- هناك عدة مزايا من ازالة مرشح التسطيح للشعاع الفوتونى خاصة بالنسبة لتقنيات العلاج الاشعاعى المتقدمة ولكن يوجد بعض التحديات الموجودة على سبيل المثال معايير تقييم جودة الشعاع الفوتونى وتعريف شبة الظل .