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Performance of Radiation Dosimeters in Gradient Regions at Different Dose Rates of Linear Accelerators

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ABSTRACT

Introduction: This work aimed to evaluate the accuracy of using parallel plane against thimble chambers in beam data commissioning of the high dose gradients region for versa HD linear accelerator performing clinical advanced modulated radiation treatment techniques.

Material and Methods: All clinical commissioning data were collected from Elekta Versa HD for energies of 6 MV, 10 MV, 6 MV FFF, and 10 MV FFF for different field sizes using thimble ionization chamber CC13, some from the pool of the measured data were rescanned using parallel plate chamber PPC05 and Gafchromic films and compared to those collected using the thimble ionization chamber.

Results: The skin doses differences measured by thimble chamber against reference films were (0.8%, 0.5%, 1.2% 4.7%) and for the parallel plane chamber against films were (8.4%, 9.7%, 9%, 12%) for 6 MV, 10 MV, 6 MV FFF, 10 MV FFF, respectively. The parried test-test showed a highly significant difference ($p < 0.001$) between the two chambers in measurements of penumbra regions taking over all the investigated field sizes and depths in both inline and crossline datasets. The parallel plate showed a wider and broader penumbra than the thimble chamber and films.

Conclusion: Robust and consistent scans were obtained for the thimble chamber compared to the parallel plane chamber in the highest dose gradient of buildup and penumbra regions. Using a parallel plane chamber might bring dosimetric clinical uncertainties affecting the modeling of the gradient regions in the treatment planning system.

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Introduction

The main objective of radiation treatment is to cover the tumor target with the prescription dose while ensuring that the organ at risk and healthy tissue receive the minimum dose. To accomplish this, a high level of accuracy and precision are required all through the entire process [1].

According to the IAEA publication [2] a thimble ionization chamber with the volume on the order of 0.1 - 0.2 cm^3 is the most suitable for beam data collection. The measurements in rapidly changing gradients regions as buildup in percentage depth dose (PDD) and penumbra in the beam profile need more accurate detector and it highly recommends the parallel plate chambers for the measurement in this regions.

The impact of the detector volume on penumbra width has been broadly investigated due to its major impact on the beam modeling of radiotherapy treatment planning [3,4].

Profile measurements in high gradient areas require maintaining proper detector and detector orientation. High dose rates may be beneficial for respiratory control or breath-holding treatments, where delivery time is limited [5,6]. Most of the benefits of removing the flat filter increase beam intensity, especially near the central axis. Increasing the intensity reduces treatment time, reduces out-of-field doses, improves beam modeling accuracy, increases dose rates, smooth the X-ray spectrum, head-scattered radiation, and non-uniform beams [7,8]. As a rule, FFF beams provide maximum high dose rates of 1400 MU / min and 2400 MU/min for 6 MVFFF beams and 10 MVFFF beams, respectively [9].

Increased dose rates allow for faster delivery, reduce the impact of patient and/or target movement, and improve patient comfort. [10]. The advantage of FFF beams has been shown clearly in small fields, especially for stereotactic radiotherapy/radiosurgery (SRT / SRS) treatment, which is suitable for volume-modulated arc radiotherapy (VMAT). [11,12]. Treatment planning systems require profiles from very small fields to the maximum field size available to

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model the penumbra and off-axis coefficients of open and wedge-shaped fields. [13].

The Flattening filter free beams had a higher ion recombination correction factor than the beams with the flattening filter [14].

In our previous work [15], we have studied the uncertainty of the parallel plate and thimble ionization chambers readings in terms of photon flux and stability during measurements..

The aim of the present work is to investigate the accuracy of parallel plane ionization chambers in commissioning beam data for linear accelerators against thimble ionization chambers and study the possibility of using Gafchromic films to judge the accuracy of data collected by the two ionization chambers.

Materials and Methods

This work was performed using a Versa HD linear accelerator with 6 MV, 6 MV FFF, 10 MV, 10 MV FFF photon beams. Measurements were made using a water tank Blue Phantom² (IBA, Germany) with a scanning range of 48 × 48 × 41 cm^3.

Photon beams profiles of the energy of 6 MV, 10 MV, 6 MV FFF, and 10 MV FFF were measured of various field sizes of 5x5 cm^2, 10x10 cm^2, 15x15 cm^2, and 20x20 cm^2 using different radiation detectors such as thimble ionization chambers, parallel plane ionization chambers. In-plane and cross-plane profile scans were acquired for the above-mentioned fields at depths of D_{max}, 5 cm, 10 cm, and 20 cm.

The PDD and profile scan were processed with the My QA software version (IBA, Germany). The PDD data were smoothed and normalized to 100% by the value at maximum dose depth (Dmax).

Gafchromic™ EBT3 film (Ashland, Bridgewater, NJ, USA) with dose range: 0.2 - 10 Gy was held in the slap phantom of relative electron density 1.045 and dimensions of 30x30x30 cm^3 to measure the percentage depth dose (PDD) and beam profiles for 10x10 cm^2 field size at D_{max}, then compare the films with the two chambers for the same field size. Scanning of the film was done using an Epson 11000 XL flat- bed document scanner (version 3.49A) after exposure to 500 MUs. The analysis was done using the MEPHYSTO mc2 software (PTW, Germany) at least 24 hours after irradiation to minimize effects from post-irradiation coloration.

The penumbral width was defined within the central 80% of the full width at half maximum (FWHM) of the processed profile. Within the specified region, flatness is defined as the maximum ratio between any two data points

$$\frac{\text{Dmax}}{\text{Dmin}} \times 100 \qquad (1)$$

D_{max} is the maximum dose and D_{min} is the minimum dose along the profile within the core 80% of the field size.

The symmetry is defined as the maximum ratio between two symmetric data points.

$$\frac{\text{D(x)}}{\text{D(-x)}} \times 100 \qquad (2)$$

Penumbra is defined as the spatial distance between 80% and 20% of the CAX value in the profile scan [16]. For FFF beams, all the profile absolute gradient values are calculated. The maximum gradient (or maximum slope) is then identified as the point of inflection. The penumbra margin is calculated with the renormalized profile at the inflection point which is defined at 50 % of the dose.

Results

The coefficient of variation of the ionization chamber measurements (variance between the three measurements including each measurement point) is 0.1% for the parallel plate chamber and 0.5% for the thimble ionization chamber. In addition, the coefficient of variation for the various settings was 0.12%.

PDDs curves have been divided into two regions of interest to investigate, surface dose at depth =0 and depth of maximum dose. Figure (1) shows the measured values of the surface dose for different energies and various square field sizes with the two ionization chambers. Surface doses are seen to increase almost linearly with increasing field size, surface doses in FFF are generally higher than the FF beams for different field sizes by the two chambers. It was found that the parallel plate PPC05 ionization chamber showed an overresponse in the measurement of surface dose, as shown in figure (2).

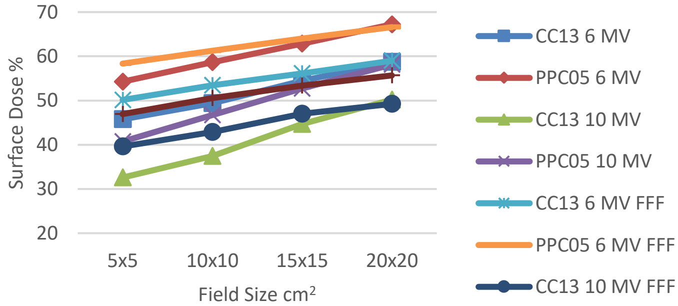

Figure 1. The surface dose with (%) of different energies for the parallel plate PPC05 ionization and the thimble ionization chamber CC13 at different field sizes (cm^2).

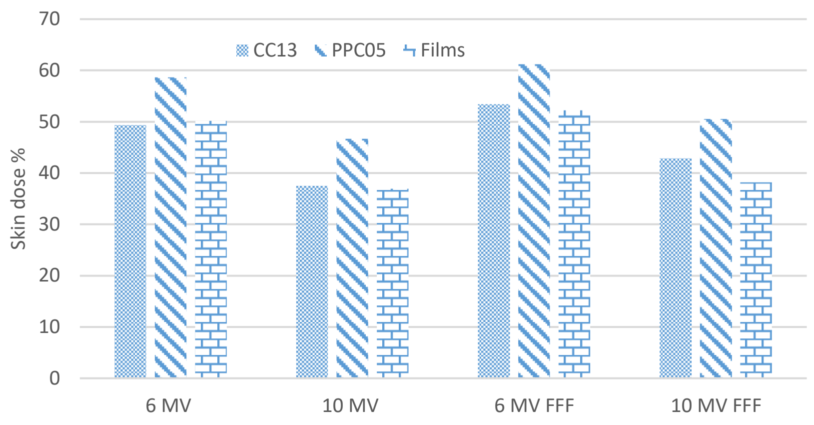

Figure 2. The skin dose of different energies with the parallel plate PPC05 ionization chamber, the thimble ionization chamber CC13, and Gaffchromic films at 10x10 cm^2 field size.

Table 1. D_{max} (mm) of energies 6 MV, 6 MV FFF, 10 MV and 10 MV FFF for the parallel plate PPC05 ionization and the thimble ionization chamber CC13 at different field sizes (cm^2).

	6MV		6 MV FFF		10 MV		10 MV FFF	
Field size	PPC05	CC13	PPC05	CC13	PPC05	CC13	PPC05	CC13
5x5	14.7	14.7	15	14.7	21.9	22.2	23.5	24.2
10x10	14.6	14.5	14.7	14.6	20.6	22	23.2	22
15x15	14.6	14.5	14.7	14.6	19.5	19.1	22	22
20x20	14.3	14.4	14	14	17.1	17.9	21.9	20.6

a b

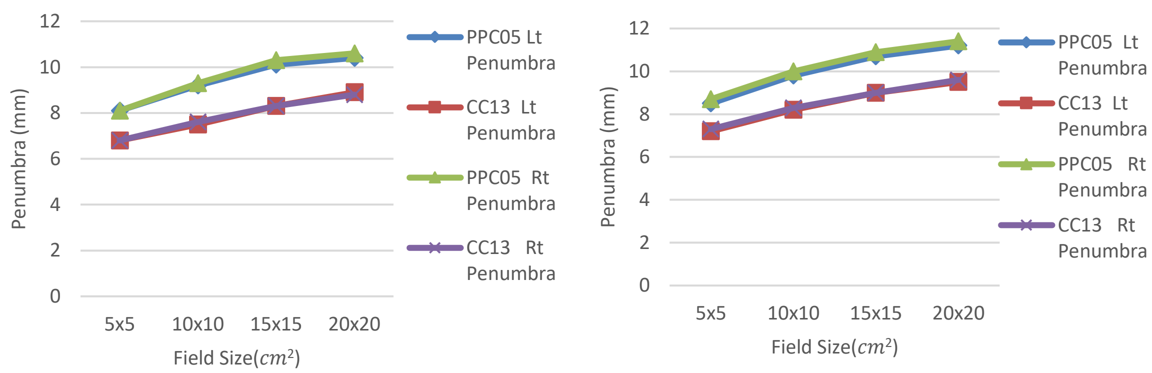

Figure 3. The penumbra width inline (a) and crossline (b) of 6 MV at D_{10} for the parallel plate PPC05 chamber and the thimble ionization chamber CC13 at different field sizes.

The differences between the thimble chamber and films in skin doses for 6 MV was 0.8 % while the parallel plate was 8.4 %. For 10 MV, the thimble chamber showed a 0.5 % difference while the parallel plate was 9.7 %. For 6 MV FFF, the thimble was 1.2 % while the parallel plate was 9 %. For 10 MV FFF, the thimble chamber was 4.7 % while the parallel plate was 12 %.

As shown in table 1, the D_{max} is directly proportional with the collimator scatter effect and meanwhile, the scattering effect decreases with increasing the field size (Podgorsak 2005) [2].

Beam Profiles and Penumbra

The rapid decrease at the edges of the radiation beam is called the penumbra region which is defined as the space between the 80% and 20% relative dose in mm. Figures 3-6 represent the measured penumbra for different photon beams for various square field sizes (5x5, 10x10, 15x15 and 20x20 cm^2) at depths (D_{max}, D_5, D_{10}, D_{20}) cm in water with two ionization chambers CC13 and PPC05.

For FFF beams, all the profile absolute gradient values were measured. The maximum gradient (or maximum slope) was then identified as the point of inflection. The penumbra margin was calculated with the renormalized profile at the inflection point defined at 50% of dose.

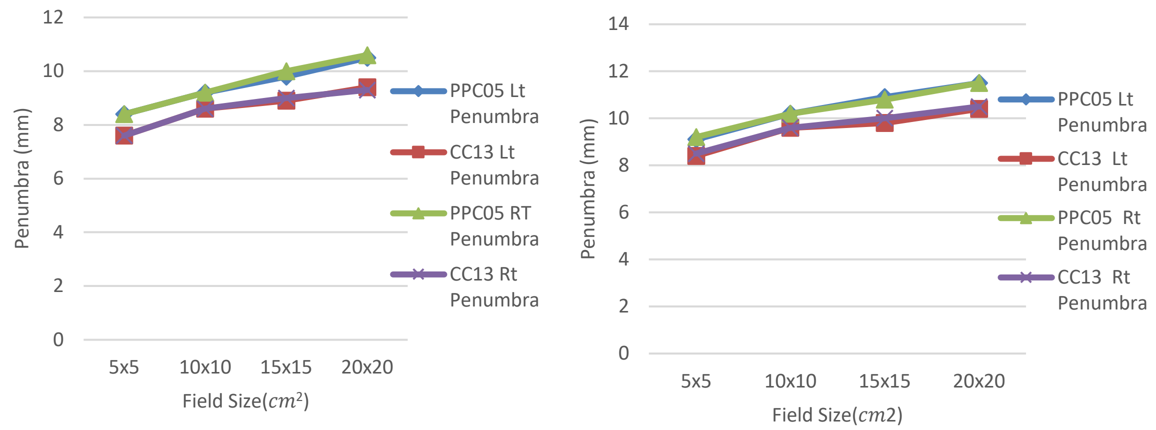

Figure 4. The penumbra width inline (a) and crossline (b) of 10 MV at D_{10} for the parallel plate PPC05 ionization and the thimble ionization chamber CC13 at different field sizes.

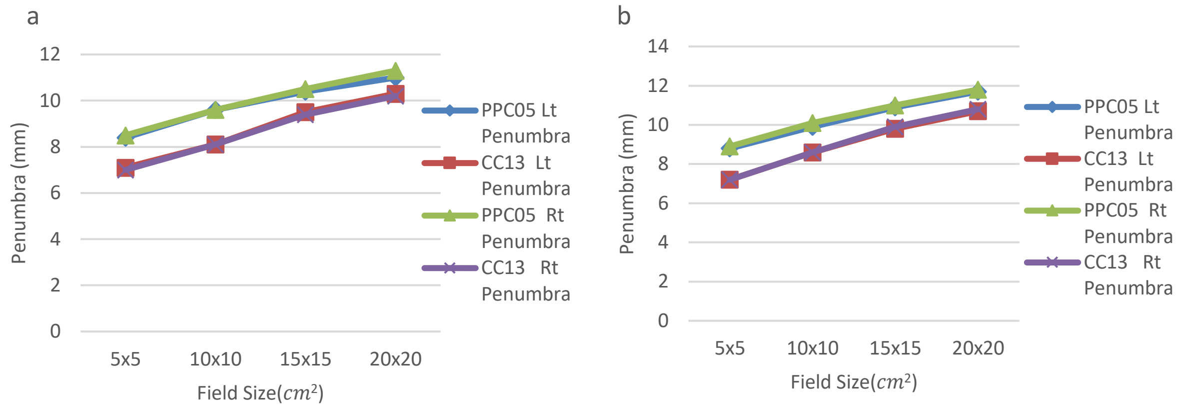

Figure 5. The penumbra width inline (a) and crossline (b) of 6 MV FFF at D_{10} for the parallel plate PPC05 ionization and the thimble ionization chamber CC13 at different field sizes.

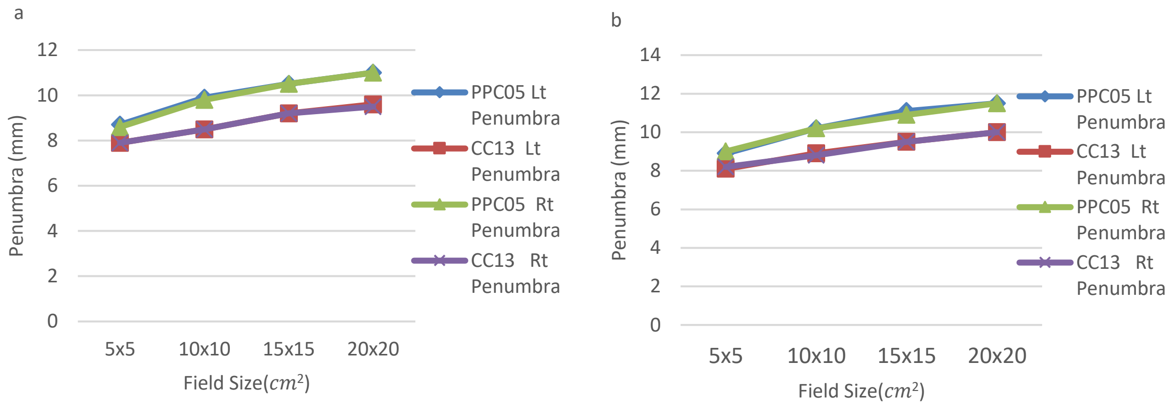

Figure 6. The penumbra width inline (a) and crossline (b) of 10 MV FFF at D_{10} for the parallel plate PPC05 ionization and the thimble ionization chamber CC13 at different field sizes.

Measurements of PPC05 provided wider penumbra and higher flatness values. The paired t-test results showed a highly significant difference ($p<0.001$) between the two chambers in measurements of penumbra regions taking over all the investigated field sizes and depths in both inline and crossline datasets. The mean differences in all instances were not greater than 1.65 ±0.19 mm as in 6 MV inline measurements while very small as shown in 10 MV crossline measured 0.82 ±0.22 mm, as shown in figure (7).

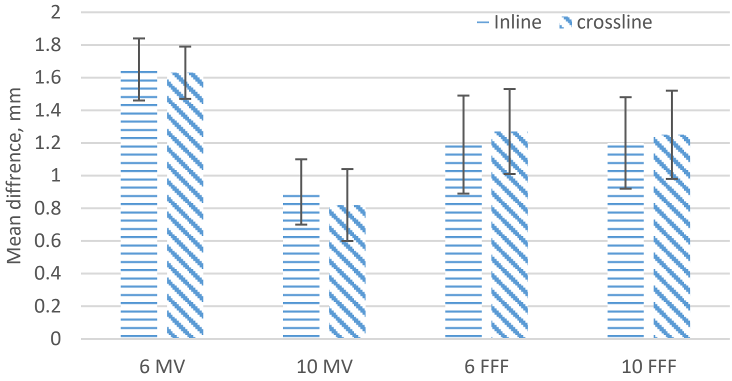

Figure 7. Mean differences of the measurements performed using PPC05 and CC13 chambers for the penumbra regions in inline and crossline dataset at 6 MV and 10 MV with and without flattening filter. Error bars represents 1 stander deviation.

Table 2. Profile analysis of 6 MV and 10 MV for field size 10x10 cm2 at Dmax by the parallel plate PPC05 ionization chamber, the thimble ionization chamber CC13 and gaffchromic film.

For 6 MV						
Detector	Depth	Scan type	Flatness	Symmetry	Left Penumbra	Right Penumbra
CC13	1.5 cm	Crossline	102.60%	101.50%	6.6 mm - 6.7 mm	
PPC05	1.5 cm	Crossline	103.20%	101.00%	8.2 mm - 8.2 mm	
Film	1.5 cm	Crossline	104%	101.90%	6 .1 mm - 6.2 mm	
For 10 MV						
CC13	2.3 cm	Crossline	103.50%	100.20%	8.2 mm - 8.3 mm	
PPC05	2.3 cm	Crossline	104.90%	100.50%	9.0 mm - 9.0 mm	
Film	2.3 cm	Crossline	104%	101%	7.5 mm - 7.6 mm	

Table 3. Profile analysis of 6 MV FFF and 10 MV FFF for field size 10x10 at Dmax by the parallel plate PPC05 ionization chamber, the thimble ionization chamber CC13 and gaffchromic film.

6 MV FFF					
Detector	Depth	Scan type	Symmetry	Left Penumbra	Right Penumbra
CC13	1.5 cm	Crossline	101.10%	7.1 mm - 7.1 mm	
PPC05	1.5 cm	Crossline	100.70%	8.8 mm - 8.8 mm	
Film	1.5 cm	Crossline	101.20%	6.5 mm - 6.6 mm	
10 MV FFF					
CC13	2.3 cm	Crossline	101.00%	9.4 mm - 9.3 mm	
PPC05	2.3 cm	Crossline	100.60%	11.0 mm - 10.8 mm	
Film	2.3 cm	Crossline	101.20%	8.6 mm- 8.5 mm	

The thimble chamber CC13 showed the narrowest penumbra after the Gaffchromic films, while the largest penumbra was presented by the parallel plate chamber, see tables 2-3.

For 6 MV, the CC13 showed the closest result to the films, the difference between the CC13 and films was 8% (0.5 mm), while the difference between the parallel plate and the films was 33% (2 mm). For 10 MV, the difference between the CC13 and films was 9.2% (0.7 mm), while the difference between the parallel plate and the films was 19.2% (1.5 mm).

For 6 MV FFF, the difference between the CC13 and films was 8.3% (0.6 mm) while the difference between the parallel plate and the films was 34.3% (2.3 mm). For 10 MV FFF, the difference between the CC13 and films was 9.3% (0.8 mm) while the difference between the parallel plate and the films was 27.4% (2.4 mm).

Figures (8-9) show the intervals of local dose differences addressed the different behavior of FFF beams compared to FF beams for the high dose gradient of the penumbra regions.

The figures show a new approach and simply viewing to figure out the beam characteristic differences of FFF beams and the ability of CC13 chamber to distinguish between different high energies (10 MV and 10 MV FFF) as shown in 8b vs 9b, while the PPC05 showed less ability to define the beam characteristics differences for the same energy level.

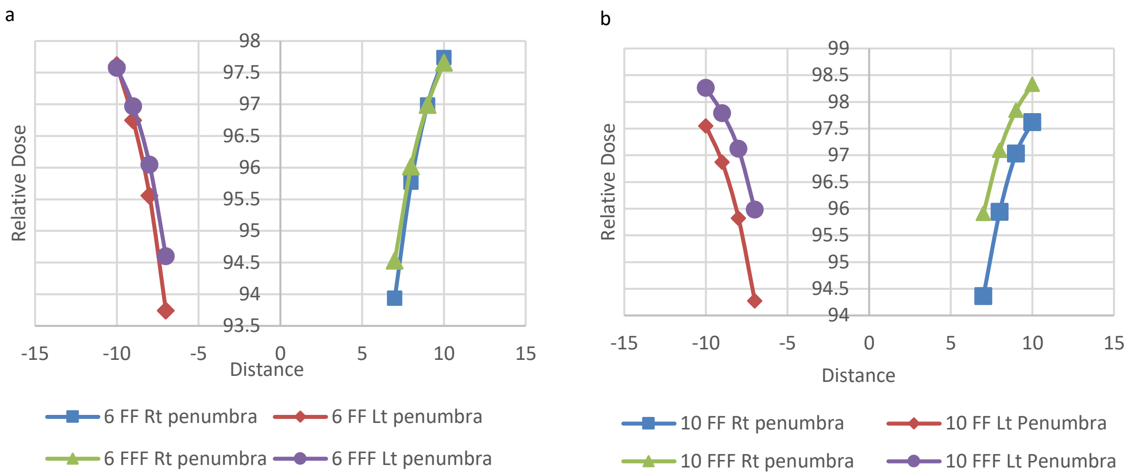

Figure 8. The local doses intervals show the differences between (a) 6 MV FF and 6 MV FFF and (b) 10 MV FF and 10 MV FFF beams in penumbra region for CC13 chamber at depth 10 for 10x10 field size.

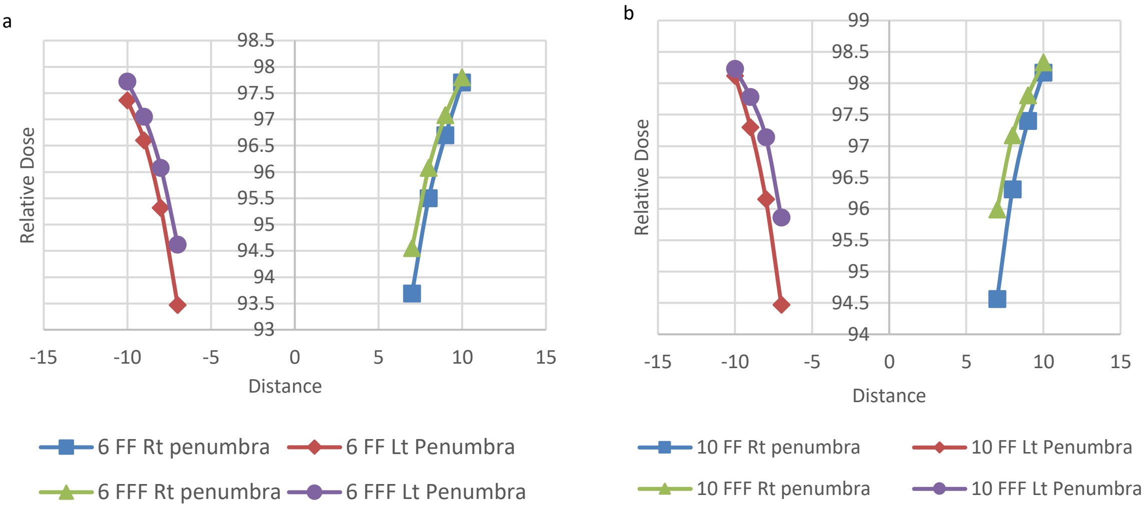

Figure 9. The local doses intervals show the differences between (a) 6 MV FF and 6 MV FFF and (b) 10 MV FF and 10 MV FFF beams in penumbra region for PPC05 chamber at depth 10 for 10x10 field size.

Discussion

From the PDDs curve we can notice that the removal of flattening filter causes a significant rise in the surface dose for FFF beam compared to the FF beam, which can be explained by the large amounts of low energies in FFF beams which are no longer filtered out with the flattening filter. The results were in a good agreement with the previous studies as the skin dose showed an increase with increasing the field size, and decreases with increasing the energy. [17,18]

Conventional beams have a hardened beam spectrum. That is, it tends to contain small amounts of low-energy X-ray radiation, resulting in lower surface doses. On the other hand, FFF beams contain a large amount of low-energy photons. These are no longer filtered out by the flattening filter.

It was found that the skin doses taken by the thimble chamber were more reasonable closer with the skin doses taken by reference films, while the parallel plate PPC05 ionization chamber showed an overresponse in the measurement of surface dose, as shown in figure (2).

The overresponse in surface dose regions detected by the plane-parallel chamber agreed with Das et al 2008 [1] who reported that the plane-parallel chambers showed an overresponse in the buildup region and especially at the surface. However, according to Apipunyasopon et al 2012 [19] who investigated the percentage depth dose in the build-up region and the surface dose for the 6-MV photon beam from a Varian linear accelerator, the thimble ionization chamber showed an overresponse in the measurement of surface dose.

The percentage surface doses observed with CC13 dosimeter with the field sizes of 5×5 cm^2, and 10×10 cm^2 were about 50% and 55%, while in our measurements were 46.9% and 50.5%, respectively. Imae T et al 2020 [20] described the differences between the surface and build-up doses of the Elekta and Varian linacs. There are many differences between the two linacs, for example, the head design, the positions of the collimator jaws and the MLC. For a given x-ray field size, Elekta linacs provide a smaller solid angle from a measurement point toward the flattening filter ,therefore a smaller number of low energy scattered particles reaches the measurement point.

The literature different results led us to conclude that the measurement of surface dose from different linear accelerators using different dosimeters is institutional experience and should be specifically performed for each institution based.

We noticed from our results that the lowest value of D_{max} is obtained for the largest field size (20x20) having the lowest value of scattering effect. The difference in D_{max} for different energies scored more values rather than the difference in D_{max} measured with different dosimeters especially with field size increases. For field size 10x10 cm^2, the parallel plate chamber was closer to the films in the D_{max} values than the thimble chamber.

Even though it was expected that the parallel plate ionization chambers with smaller active volume than CC13 would give better and narrow penumbra, the relatively large active diameter has caused a deteriorating effect on the spatial resolution of the measurements. Recently, Patatoukas et al 2018 [21] mentioned that if all detectors have the same shape and material, and vary only in the volumes, then the investigation of the change in penumbra width with increasing volume of the detector will be more accurate.

Compared to conventional photon beams, FFF beams have many different properties. They have different beam profiles,higher dose rates, different photon energy spectra, and different head scattering characteristics. In addition, the characteristics of FFF beams include sharper penumbra, less head scatter, and lower doses outside the field.

FFF beams have different characteristics compared to conventional flattened beams. These differences depend on whether the energy of the electrons hitting the bremsstrahlung target has been increased. The penumbra shoulder for FFF beams was found sharper than that of flattened beams. The FFF penumbra has been found to be comparable to or broader than the penumbra for flattened beams. In general, however, these differences are small between the FFF and the FF beams between the three detectors CC13, PPC05 and Gaffchromic films.

The results showed that the penumbra width increases with increasing beam energy because of an increase in the range of laterally scattered electrons. It also showed an increase with increasing depth and field size.

The parallel plate also showed the best symmetry with all energies. This is because of its geometry that easily allows to adjust it for measurements, while the thimble ionization chamber showed the best flatness. The accurate measurements of the penumbra width should be considered in clinical practice to avoid unnecessary radiation exposure to the healthy tissues.

Our investigations using different ionization chambers in the recent clinical practice of the free flattening filter beams in advanced radiotherapy techniques will open a new horizon to understand the behavior of characterizations of the FFF beams for the clinical implementation, in addition introducing this kind of new practice into radiation therapy with a well understanding its characteristics.

Conclusion

The uncertainties in the ion chamber readings in terms of photon flux and stability during measurements for the parallel plate and thimble ionization chambers were very low similar to the uncertainties associated with ion chamber localization and positioning. The results of the surface doses showed an increase with increasing the field size, and decreases with increasing the energy. Surface doses in FFF are higher than the FF beams for different field sizes by the two chambers due to the FFF beams contain larger amounts of low-energy photons since these are no longer filtered out by the flattening filter.

The skin doses taken by the thimble chamber were more close to the skin doses than those taken by reference films. The parallel plate PPC05 ionization chamber showed an overresponse in the measurement of surface dose. Therefore, we recommend the use of the thimble chamber when attempts are made to address the skin dose.

The wider penumbra obtained by the parallel plane chamber PPC05 could affect the modeling of the treatment planning system and disturb the dose distribution accuracy , which might lead to undesired clinical implications.

There was a significant difference between the parallel plate chamber and the thimble chamber in the penumbra regions over all the investigated field sizes and depths in both inline and crossline beam scans. Future work is therefore warranted to investigate thoroughly the performance of the parallel plate ionization chamber versus highly accurate radiation dosimeters such as semiconductor dosimeters, diamond chambers, and Gafchromic films.

References

1. Das IJ, Cheng CW, Watts RJ, Ahnesjö A, Gibbons J, Li XA, et al. Accelerator beam data commissioning equipment and procedures: report of the TG-106 of the Therapy Physics Committee of the AAPM. Medical physics. 2008 Sep;35(9):4186-215.
2. Podgorsak EB. Radiation oncology physics. Vienna: IAEA. 2005 Jul; 123-271.
3. Khan FM, Gibbons JP. Khan's the physics of radiation therapy. Lippincott Williams & Wilkins; 2014.
4. Gersh JA, Best RC, Watts RJ. The clinical impact of detector choice for beam scanning. Journal of applied clinical medical physics. 2014 Jul;15(4):174-93.
5. Mahmoudi A, Geraily G, Shirazi A. Penumbra reduction technique and factors affecting it in

radiotherapy machines‒Review study. Radiation Physics and Chemistry. 2019 Apr 1;157:22-7.
6. Yan G, Fox C, Liu C, Li JG. The extraction of true profiles for TPS commissioning and its impact on IMRT patient-specific QA. Medical physics. 2008 Aug;35(8):3661-70.
7. Farrukh S, Ilyas N, Naveed M, Haseeb A, Bilal M, Iqbal J. Penumbral dose characteristics of physical and virtual wedge profiles. International Journal of Medical Physics, Clinical Engineering and Radiation Oncology. 2017;6(02):216.
8. Narayanasamy G, Saenz D, Cruz W, Ha CS, Papanikolaou N, Stathakis S. Commissioning an Elekta Versa HD linear accelerator. Journal of applied clinical medical physics. 2016 Jan;17(1):179-91.
9. Shende R, Gupta G, Patel G, Kumar S. Commissioning of TrueBeam TM medical linear accelerator: quantitative and qualitative dosimetric analysis and comparison of flattening filter (FF) and FLATTENING FILTER FRee (FFF) beam. International Journal of Medical Physics, Clinical Engineering and Radiation Oncology. 2016;5(01):51.
10. Yarahmadi M, Allahverdi M, Nedaie HA, Asnaashari K, Vaezzadeh SA, Sauer OA. Improvement of the penumbra for small radiosurgical fields using flattening filter free low megavoltage beams. Zeitschrift für Medizinische Physik. 2013 Dec 1;23(4):291-9.
11. Xiao Y, Kry SF, Popple R, Yorke E, Papanikolaou N, Stathakis S, et al. Flattening filter-free accelerators: a report from the AAPM Therapy Emerging Technology Assessment Work Group. Journal of applied clinical medical physics. 2015 May;16(3):12-29.
12. Sharma SD. Unflattened photon beams from the standard flattening filter free accelerators for radiotherapy: advantages, limitations and challenges. Journal of Medical Physics/Association of Medical Physicists of India. 2011 Jul;36(3):123.
13. Ding GX, Duggan DM, Coffey CW. Commissioning stereotactic radiosurgery beams using both experimental and theoretical methods. Physics in Medicine & Biology. 2006 May 4;51(10):2549.
14. Hentihu FK, Ryangga D, Pawiro SA. The impact of flattening filter free (FFF) photon beams to ion recombination correction factor. InJournal of Physics: Conference Series 2019 Jun 1 (Vol. 1248, No. 1, p. 012062). IOP Publishing.
15. Khalil MS. Evaluation of the Characteristics of Ionization Chambers Used for Commissioning in High Dose Rate Linacs. ARCHIVOS DE MEDICINA. 2019;4(1):1.
16. Pönisch F, Titt U, Vassiliev ON, Kry SF, Mohan R. Properties of unflattened photon beams shaped by a multileaf collimator. Medical physics. 2006 Jun;33(6Part1):1738-46.
17. Manavalan M, Duraisamy M, Subramani V, Godson HF, Krishnan G, Venkataraman M, et al. Analysis of various dosimetric parameters using multiple detectors in the cyberknife® robotic radiosurgery system. International Journal of Radiation Research. 2020 Jul 1;18(3):437-47.
18. Singh A, Saini A, Pahwa S, Kumar A, Dora T, Chhabra A, et al. Surface dose variations in 6 and 10 MV flattened and flattening filter-free photon beams. Journal of Medical Physics. 2017;42(suppl. 1):198-9.
19. Apipunyasopon L, Srisatit S, Phaisangittisakul N. An investigation of the depth dose in the build-up region, and surface dose for a 6-MV therapeutic photon beam: Monte Carlo simulation and measurements. Journal of radiation research. 2013 Mar 1;54(2):374-82.
20. Imae T, Takenaka S, Watanabe Y, Aoki A, Matsuda K, Sasaki K, et al. Surface and build-up dose comparison between Elekta 6 MV flattening filter and flattening-filter-free beams using an advanced Markus ionization chamber and a solid water-equivalent phantom. Journal of Applied Clinical Medical Physics. 2020 Dec;21(12):334-9.
21. Patatoukas GD, Kalavrezos P, Seimenis I, Dilvoi M, Kouloulias V, Efstathopoulos E, et al. Determination of beam profile characteristics in radiation therapy using different dosimetric set ups. JBUON. 2018 Sep 1;23(5):1448-59.