JBUON 2018; 23(5): 1448-1459
ISSN: 1107-0625, online ISSN: 2241-6293 • www.jbuon.com
E-mail: editorial_office@jbuon.com

ORIGINAL ARTICLE

Determination of beam profile characteristics in radiation therapy using different dosimetric set ups

George D. Patatoukas[1], Pantelis Kalavrezos[1,2], Ioannis Seimenis[2], Maria Dilvoi[1], Vasileios Kouloulias[1], Efstathios Efstathopoulos[1], Kalliopi Platoni[1]

[1]2nd Department of Radiology, University Hospital 'Attikon', School of Medicine, National and Kapodistrian University of Athens, Athens, 12462, Greece; [2]Medical School, Demokritus University of Thrace, Alexandroupolis, 68100, Greece

Summary

Purpose: *The purpose of this study was to analyze and to compare results regarding the penumbra size, flatness and symmetry obtained using six different measuring systems.*

Methods: *Beam profile measurements were performed in standard water phantom set-up for two photon beams for various square field sizes and for five electron beams for several applicator sizes at several depths. Six measuring systems were used: three ionization chambers; a Semiflex (31002, PTW), a Markus (23343, PTW) and a Roos (34001, PTW); Two semiconductor detectors; a p-type diode (60008, PTW) and an e-type diode (60017, PTW) and a one dimensional Linear Array (LA48, PTW).*

Results: *Our results indicate that penumbra size determination is strongly dependent on the measuring system. For the photon measurements the diodes showed the narrowest penumbra followed by the LA48, while the largest penumbra was presented by the Semiflex. The unshielded diode overestimates the penumbra in large field sizes and big depths. The parallel plate ionization chambers overestimate the penumbra width of electron beam profiles. The LA48 presents the most symmetric beam profiles.*

Conclusions: *Regarding penumbra size determination, the LA48 can be considered acceptable in terms of accuracy, and is the most time-effective system. It is also adequate for symmetry and flatness measurements. For greatest possible accuracy silicon diode is recommended. Parallel plate ionization chambers are not appropriate for penumbra measurements.*

Key words: *electron, flatness, penumbra, photon, radiotherapy, symmetry*

Introduction

The goal of radiation therapy is to deliver the maximum dose to the tumor region (target) while protecting the adjacent healthy tissues. To achieve this, great accuracy is required throughout the whole procedure. A beam profile is the graphical representation of the relative dose versus the distance from the central axis at a specific depth. The penumbra region, usually defined as the region between the 80% and the 20% relative dose in the beam profile, is an intrinsic characteristic of any beam, whether photon or electron. Therefore, its precise determination, along with the determination of the other beam profile characteristics, like flatness and symmetry, constitutes a vital part in the dosimetric chain of a modern radiation therapy department. Accurate knowledge of the penumbra width is a necessary prerequisite for a correct treatment planning. For example, overestimation of the penumbra width can lead to unnecessary large fields and irradiation of healthy tissues [1].

Results of beam profile measurements may present important variations depending upon the detector used. The choice of the proper radiation detector among a broad range of available systems

Correspondence to: Kalliopi Platoni, PhD. National and Kapodistrian University of Athens, Medical School, Medical Physics Unit of 2nd Dpt of Radiology, Radiotherapy Unit, "Attikon" University Hospital, Rimini 1, 12462, Haidari, Greece.
Tel: +30 6976800124; E-mail:polaplatoni@gmail.com
Received: 27/03/2018; Accepted: 16/04/2018

covering all sizes (regular, mini-, to micro-detectors) and types (ionization chambers, semiconductors etc.) is crucial in order to obtain a beam profile that is the closest possible to the 'real' one. Radiation detectors have an active measuring volume of finite size causing them to have a finite spatial resolution. This limitation is more pronounced in high dose gradient regions, like field edges, and can result in an artificial increase of the penumbra width. This effect, known in the literature as "*the volume averaging effect*", plays a dominant role in the choice of the appropriate detector and has been the subject of many publications [2-6].

Depending on the type of the detector that is used, there are other factors that, along with the volume averaging effect, have an impact on the results and should be considered. For example, the high photoelectric effect cross section of the semiconductor dosimeters (Silicon, Z=14) makes them sensitive in the low energy scattered radiation, which is more intense in large field sizes and big depths [7-11]. When detector arrays are used, the impact of their side material that absorbs the obliquely scattered electrons should also be taken into consideration.

The purpose of this study was to compare and analyze the results concerning penumbra width, flatness and symmetry determination obtained using six different measuring systems: three ionization chambers, two dosimetry diodes, and a linear detector array. The performance in terms of accuracy and time efficiency of these detectors was tested for measurements in various photon and electron beam energies, field or applicator sizes, and depths using two measurement step sizes in two directions. The final purpose was to propose the most suitable among these detectors for beam profile measurements in each case.

Methods

Beam profile measurements were performed for two photon beams (6, 15 MV) using the 4×4, 5×5, 6×6, 8×8, 10×10, 12×12, 15×15, 20×20 and 25×25 cm^2 square field sizes and for five electron beams (6, 9, 12, 16, 20 MeV) using the 6×6, 10×10, 20×20 and 25×25 cm^2 applicators. Measurements were performed at d_{max}(E), 50, 100 and 200 mm for the 6 MV photon fields and at d_{max}(E), 100 and 200 mm for the 15 MV photon fields. All electron beam profiles were measured at R_{100}(E) and R_{80}(E). All measurements were performed for both Gun-Target (GT) and Left-Right (LR) directions in "Attikon" General University Hospital in Athens, using a Varian 2100C linear accelerator (Varian Medical Systems, Palo Alto, CA, USA).

Six different measuring systems were used: a) a Semiflex (31002, PTW-Freiburg, Germany) thimble ionization chamber with a sensitive volume of 0.125 cm^3, open to air. b) A Markus (23343, PTW) vented parallel plate ionization chamber for electron measurements with an active volume of 0.055 cm^3. c) A Roos (34001, PTW) vented parallel plate ionization chamber for electron measurements with an active volume of 0.35 cm^3. d) An one dimensional Linear Array (LA48, PTW) consisting of 47 fluid-filled flat cylinder chambers surrounded by glass-reinforced epoxy resin as wall material. e) A p-type dosimetry silicon diode (60008, PTW) with a 1 mm^2 circular and 2.5 μm thick active volume. f) An e-type shielded dosimetry silicon diode (60017, PTW) with an active volume of 0.03 mm^3.

All photon beam profile measurements were performed with the LA48, the Semiflex ionization chamber and the 60008 and 60017 diodes. Electron beam profile measurements using the 6×6, 10×10 and 25×25 cm^2 applicators were performed with the LA48, the Semiflex, Roos and Markus ionization chambers and the 60017 diode. Additional measurements with the 20×20 cm^2 applicator were performed with the LA48.

All measurements were obtained with standard water phantom geometry (MP3, PTW) using water as medium. The voltage was set at 0V for the diode measurements, at +200V for the Roos measurements and at +300V for the Markus measurements and at +400V for the Semiflex measurements.

For the ionization chamber and for the diode measurements two different measurement steps were used (step A and step B). The idea was to decrease step size the further away the detector moves from the central axis and the closer it moves to the gradient region of the profile. Step A is smaller by a factor of 4 with respect to step B, as shown in Table 1.

For the LA48 measurements the 1 mm and 2 mm resolution step was used. The measurement time was set at 0.1 sec for the ionization chambers and the diodes and at 1sec for the LA48.

The diodes were positioned parallel to the beam axis, while all the other detectors were positioned perpendicularly to the beam axis. For the purpose of this work a PTW TANDEM Dual-Channel Electrometer, a MULTIDOS multi-channel dosimeter and an ME48 extender for the measurements taken with the LA48 were

Table 1. The two different steps, step A (left) and step B (right), that were used in the ionization chamber and diode measurements respectively. Shown here for a 10x10 cm2 square field

	STEP A	*STEP B*
Distance from CAX (mm)	*Step size (mm)*	*Step size (mm)*
-96.7	0.5	2
-60.0	0.3	1.2
-40.0	1	4
0	1	4
40	0.3	1.2
60	0.5	2
96.7	0.5	2

also used. All measurements were analyzed using the PTW MEPHYSTO mc^2 software.

Results

All penumbra size measurements refer to the lateral distance between the points of 80% and 20% relative dose in mm. The mean value between the left-side and right-side penumbra was calculated for each profile. The presented results refer to measurements performed using the step A (1 mm resolution for the LA48) and in the GT direction unless stated otherwise.

Photon beam penumbra measurements

Tables 2 and 3 summarize the measured values for the penumbra size for the two studied photon beams. The results were in excellent agreement with theory as the penumbra width showed an increase with increasing beam energy, depth and field size, as expected.

The order of magnitude of the penumbra width (mm) was another indication of the accuracy of the readings. It is evident from the tabulated data that the diodes (6008 and 60017) always presented the smallest penumbra values with respect to ioniza-

Table 2. Penumbra readings for the 6MV photon beam

	Field (cm^2)/Detector	*LA48*	*Semiflex*	*60008*	*60017*
	4x4	3.96	5.03	2.88	2.83
	5x5	4.00	5.11	2.95	2.92
	6x6	4.04	5.16	3.03	2.96
	8x8	4.15	5.35	3.06	3.07
D_{max}	10x10	4.24	5.37	3.12	3.15
	12x12	4.23	5.39	3.14	3.15
	15x15	4.28	5.54	3.20	3.22
	20x20	4.38	5.55	3.23	3.31
	25x25	4.37	5.63	3.28	3.37
	4x4	4.28	5.37	3.2	3.22
	5x5	4.35	5.51	3.31	3.34
	6x6	4.40	5.61	3.36	3.44
	8x8	4.58	5.83	3.53	3.64
50mm	10x10	4.74	5.99	3.63	3.78
	12x12	4.77	6.08	3.68	3.88
	15x15	4.87	6.27	3.81	3.94
	20x20	5.05	6.52	3.97	4.20
	25x25	5.26	6.59	4.11	4.53
	4x4	4.53	5.77	3.56	3.58
	5x5	4.72	6.00	3.73	3.77
	6x6	4.86	6.33	3.89	3.94
	8x8	5.17	6.70	4.15	4.39
100mm	10x10	5.44	6.95	4.44	4.71
	12x12	5.64	7.23	4.61	4.98
	15x15	5.89	7.52	4.97	5.63
	20x20	6.35	8.08	5.52	6.66
	25x25	6.79	8.54	6.13	7.44
	4x4	5.10	6.34	4.04	4.09
	5x5	5.32	6.90	4.35	4.43
	6x6	5.69	7.10	4.70	4.85
	8x8	6.27	8.08	5.37	5.53
200mm	10x10	6.91	8.69	6.16	7.14
	12x12	7.55	9.75	7.03	8.26
	15x15	8.69	11.20	8.68	10.79
	20x20	10.71	13.42	12.35	16.88
	25x25	12.98	17.50	16.05	20.51

tion chambers (Semiflex and LA48) regardless of the photon energy studied. In general this holds true with respect to the field size as well as with respect to the depth of measurement. It was more prominent at small field sizes. What is of interest is that for the 6 MV beam at greater depths (of the order of 200mm) and at field sizes 20×20 and 25×25 cm^2, it appeared that the above observation did not hold anymore, and the LA48 exhibited the tightest penumbra. In addition the Semiflex ionization chamber seemed to measure a penumbra size smaller than the 60017 but not from the 60008 diode.

Electron beam penumbra measurements

Tables 4-8 represent the measured values for the penumbra width for the five electron beams that were studied. In general, the penumbra size increased with increasing energy, as expected, with the exception of the 12 MeV beam where results from all measuring systems depicted a slight reduction. Additionally, the penumbra size increased with increasing the depth of measurement, again as expected. Furthermore, with respect to applicator size it seemed that greater applicator size did not always lead to greater penumbra size. This phenomenon was observed at the transition from the 10×10 cm applicator size to the 25×25 cm for all the detectors for both R_{100} and R_{80} depths at all energies studied.

It appears that the diode consistently gave the smallest penumbra size regardless of electron energy or applicator size. It was followed by Semiflex and LA48 ionization chambers. The widest penumbra was measured with the Markus and Roos parallel plate ionization chambers. At greater applicator sizes and depths, the diode and the LA48 array seemed to converge to similar values while the Semiflex chamber deviated by a small factor.

Flatness histograms for photon measurements

Figure 1(A, B) presents graphically the flatness value for a reference field 10×10 cm^2 at D_{max} (1.5 cm and 3 cm respectively) for the two photon beams studied. In terms of absolute flatness all measured values were well within the suggested limits. Overall, the 15 MV beam appeared to ex-

Table 3. Penumbra results for the 15 MV photon beam

	Field (cm^2)/Detector	*LA48*	*Semiflex*	*60008*	*60017*
D_{max}	4x4	4.47	5.78	3.34	3.35
	5x5	4.50	5.95	3.39	3.43
	6x6	4.56	5.94	3.49	3.47
	8x8	4.63	6.12	3.57	3.65
	10x10	4.77	6.20	3.63	3.77
	12x12	4.86	6.26	3.73	3.91
	15x15	4.86	6.44	3.77	3.99
	20x20	4.99	6.52	3.89	4.1
	25x25	4.99	6.60	3.92	4.18
100mm	4x4	5.05	6.48	3.92	4.08
	5x5	5.16	6.66	4.12	4.37
	6x6	5.22	6.70	4.22	4.42
	8x8	5.53	7.00	4.47	4.67
	10x10	5.60	7.19	4.57	4.97
	12x12	5.72	7.33	4.80	5.10
	15x15	5.93	7.59	5.00	5.4
	20x20	6.08	7.82	5.25	5.83
	25x25	6.28	7.95	5.38	5.96
200mm	4x4	5.47	6.86	4.55	4.68
	5x5	5.72	7.29	4.76	5.12
	6x6	5.99	7.53	5.03	5.21
	8x8	6.35	8.00	5.47	5.77
	10x10	6.73	8.52	5.87	6.53
	12x12	7.06	8.74	6.18	6.95
	15x15	7.54	9.37	6.79	7.65
	20x20	8.15	9.99	7.47	8.64
	25x25	8.57	10.98	8.25	9.68

Table 4. Penumbra results for the 6MeV electron beam

	Detector/ Applicator (cm²)	*LA48*	*Markus*	*Roos*	*Semiflex*	*60017*
	6x6	10.84	12.44	15.12	10.97	9.74
R_{100}	10x10	10.99	12.98	15.33	11.12	10.04
	25x25	10.95	12.53	15.33	11.08	9.88
	6x6	12.33	13.97	16.70	13.32	12.36
R_{80}	10x10	12.48	14.21	16.82	13.66	12.70
	25x25	12.39	14.66	16.84	13.62	12.80

Table 5. Penumbra results for the 9MeV electron beam

	Detector/ Applicator (cm²)	*LA48*	*Markus*	*Roos*	*Semiflex*	*60017*
	6x6	12.02	13.35	15.50	11.38	10.38
R_{100}	10x10	12.17	13.57	15.80	11.57	10.63
	25x25	12.27	13.47	16.13	11.78	10.84
	6x6	15.23	17.25	19.05	16.34	15.40
R_{80}	10x10	15.04	17.06	18.83	16.47	15.32
	25x25	15.74	17.61	19.58	16.83	15.78

Table 6. Penumbra results for the 12MeV electron beam

	Detector/ Applicator (cm²)	*LA48*	*Markus*	*Roos*	*Semiflex*	*60017*
	6x6	13.41	14.17	16.09	12.27	11.52
R_{100}	10x10	14.08	15.17	17.39	13.61	12.51
	25x25	13.44	14.24	16.76	12.66	11.79
	6x6	19.16	20.71	21.78	19.73	18.79
R_{80}	10x10	19.46	21.06	23.02	20.29	19.30
	25x25	19.29	20.62	22.68	20.04	19.01

Table 7. Penumbra for the 16 MeV electron beam

	Detector/ Applicator (cm²)	*LA48*	*Markus*	*Roos*	*Semiflex*	*60017*
	6x6	12.53	13.11	15.05	11.65	10.83
R_{100}	10x10	13.92	14.52	16.59	13.22	12.23
	25x25	12.51	13.03	15.44	11.62	10.97
	6x6	22.53	23.99	24.53	22.44	21.77
R_{80}	10x10	23.61	25.49	26.39	24.05	23.06
	25x25	23.11	24.93	26.03	23.21	22.96

Table 8. Penumbra readings for the 20 MeV electron beam

	Detector/ Applicator (cm²)	*LA48*	*Markus*	*Roos*	*Semiflex*	*60017*
	6x6	17.01	17.41	18.85	15.92	15.52
R_{100}	10x10	18.88	19.61	21.13	18.11	17.43
	25x25	17.98	18.86	20.26	16.96	16.28
	6x6	26.12	26.06	26.19	24.06	23.74
R_{80}	10x10	26.82	27.88	29.35	26.87	26.39
	25x25	27.33	28.22	29.72	27.03	27.07

hibit a less flat profile compared to the 6MV beam regardless of the measuring system.

More in particular, the 60008 diode gave the flattest beam profile for the lowest energy and the LA48 for the highest energy. The least flat beam profile was displayed by the Semiflex for the low energy and by the 60017 diode for the higher one; however, there did not seem to be a particular pattern followed.

Flatness histograms for electron measurements

Figure 2 (A-E) shows the beam flatness values for all electron beams and all measuring systems for a 'reference' applicator size of 10×10 cm² at R_{100} (different for each beam). The LA48 gave the flattest beam profile for the lower energy and the 60017 diode for the other four as shown in Figure 3. The Semiflex also displayed low flatness values in all cases while the Roos displayed the less flat

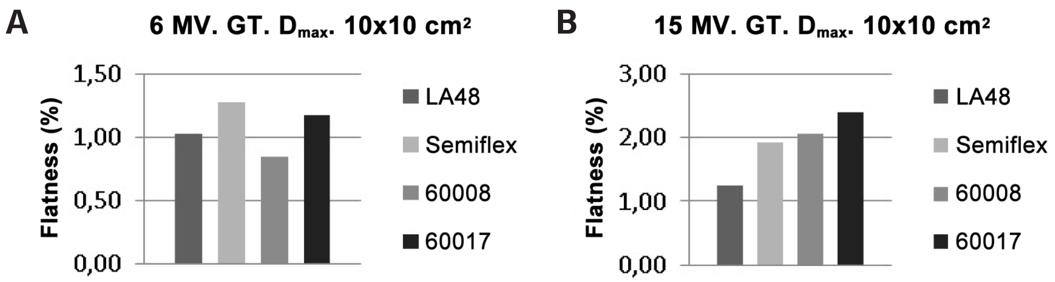

Figure 1. Beam flatness values in gun-target direction for **(A)** 6MV and **(B)** 15 photon beams at d_{max} for a 10×10 cm² field size.

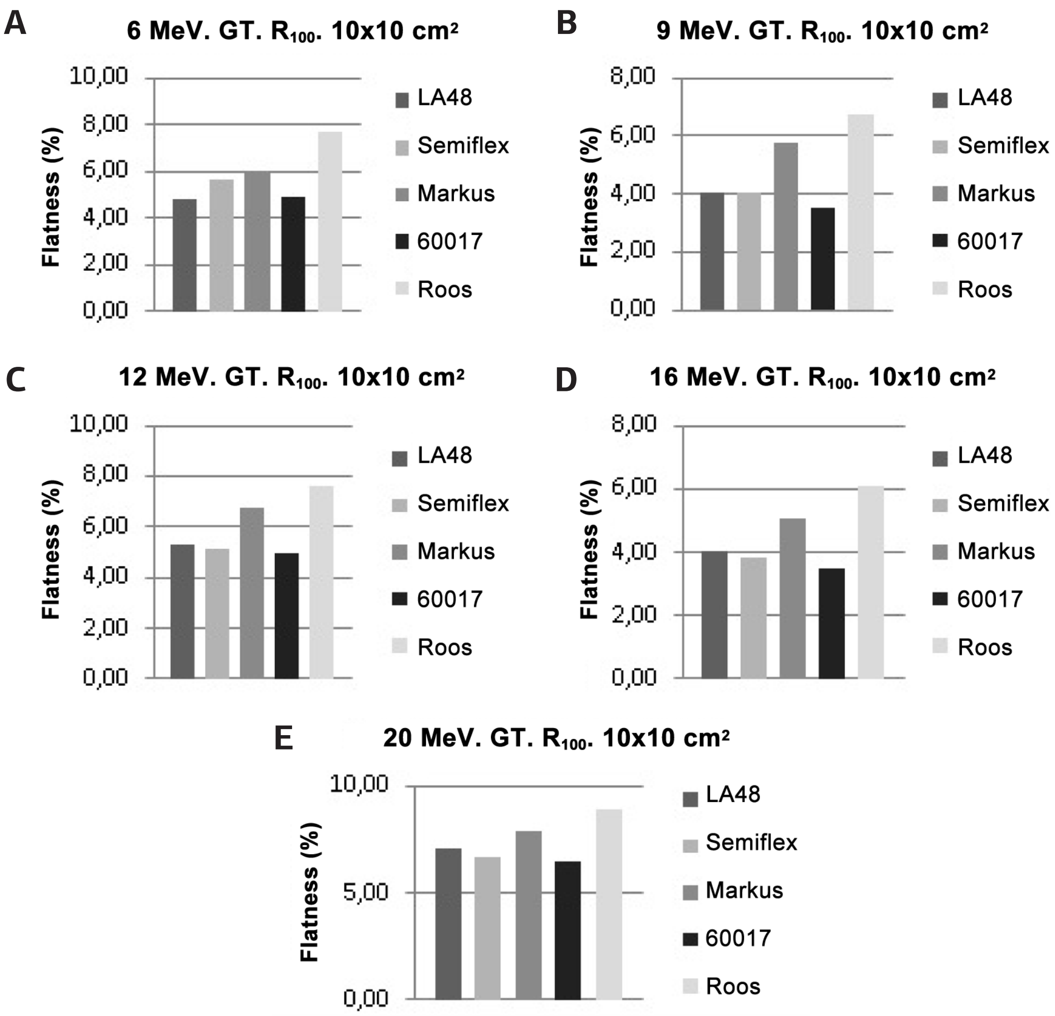

Figure 2. Beam flatness values in gun-target direction for five electron beams (6, 9, 12, 16, 20 MeV) at R_{100} for a 10×10 cm² applicator size **(A-E)**.

beam profiles followed by the Markus chamber. There appeared to be an obvious similarity with the penumbra results for the electron measurements. The detectors that gave wider penumbra also gave higher flatness values.

Symmetry histograms for photon measurements

Symmetry results for the two photon beams are depicted graphically in Figure 3A and B. In terms of absolute symmetry values both beams appeared to have highly symmetrical profiles at the reference field studied (10×10 cm² field, at D_{max}).

The 60008 diode gave the most symmetric profile for the low energy and the LA48 gave by far the most symmetric profile for the high one as shown in Figure 3. The least symmetric values are given by the 60017 diode in both cases. Symmetry variation appeared to be greater at the higher photon energy beam.

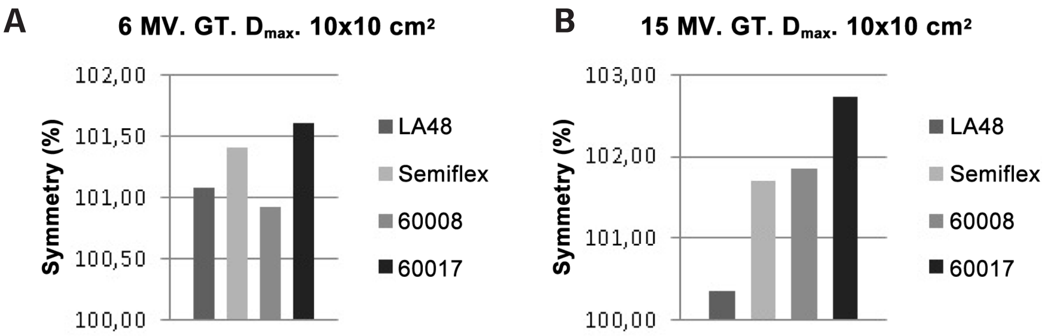

Figure 3. Gun-Target symmetry histograms for **(A)** 6 and **(B)** 15 MV photon beams at d_{max} for a 10×10 cm² field size.

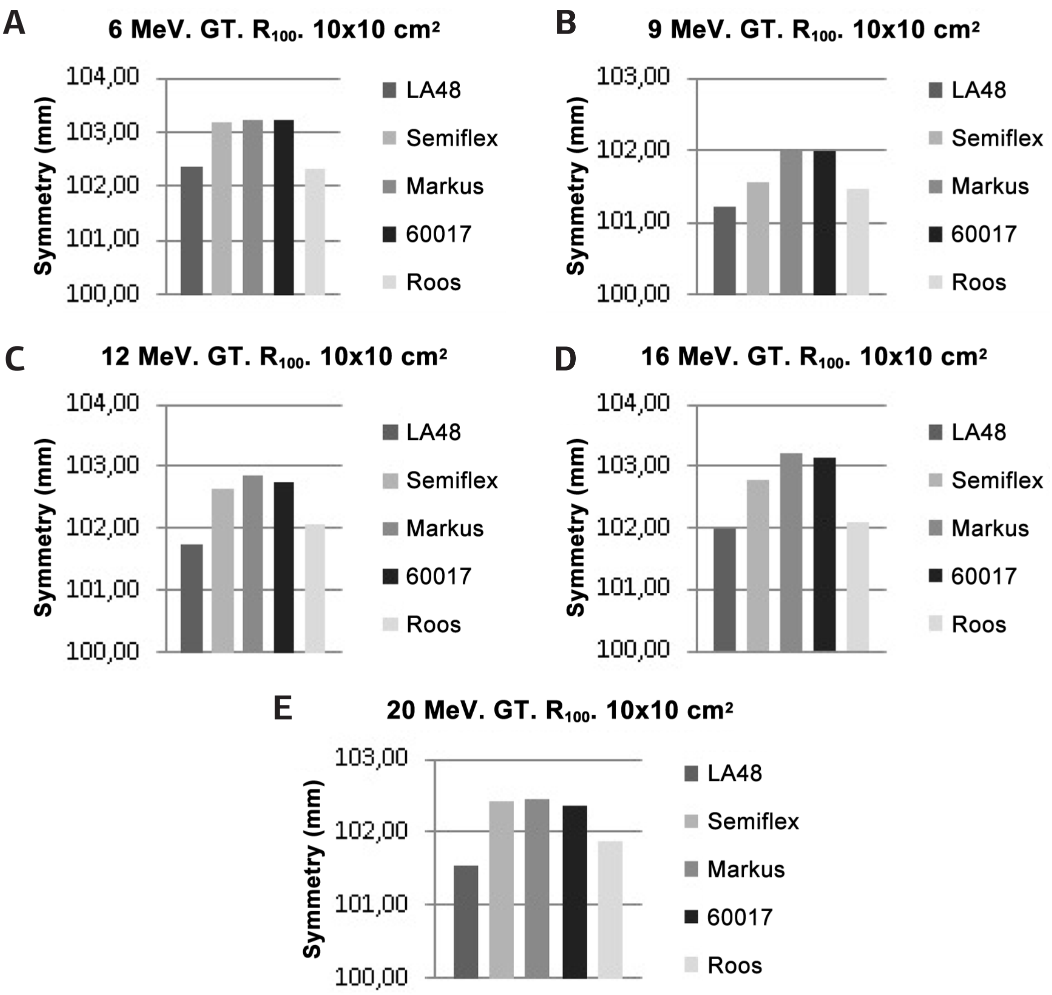

Figure 4. Gun-Target symmetry histograms for 5 electron beams (6, 9, 12, 16, 20 MeV) at R_{100} for a 10×10 cm² applicator size **(A-E)**.

Symmetry histograms for electron measurements

Figure 4 (A-E) displays the measured symmetry values for all the available electron beams using all the available detectors.

The Roos chamber gave the most symmetric beam profile for the lowest energy (6MeV) and the LA48 for the other four energies. The least symmetric values are given in all cases by the Markus. Another point that was apparent is that symmetry variation based upon the different measuring systems was small –and always within limits-regardless of the measuring system.

In general, there was a variation in the flatness and symmetry results. An overall observation is that the LA48 displayed in general the most symmetric beam profiles.

Figure 5 presents the diagram of the penumbra width versus the sensitive detector volume for both photon energies and for the 10×10 cm^2 field at D_{max}. Three detector volumes are displayed: 60008 diode (0.003 mm^3), 60017 diode (0.03 mm^3) and Semiflex (0.125 mm^3). The LA48 was excluded because it consisted of 47 ion chambers. The horizontal axis is in logarithmic scale.

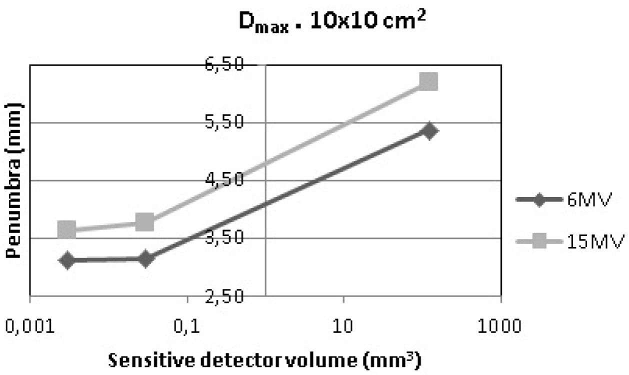

Figure 5. The penumbra size as a function of the sensitive detector volume for two photon beams at D_{max} for a 10×10 cm^2 applicator size.

Figure 6 presents the diagram of the penumbra width versus the sensitive detector volume for three electron energies (6, 12, 20 MeV) and for the 10×10 cm^2 applicator at R_{100}. Four detector volumes are displayed: 60017 diode (0.03 mm^3), Semiflex (0.125 mm^3), Markus (55 mm^3) and Roos (350 mm^3).

Discussion

The quality assurance program of a radiotherapy department remains the main aspect for the quality of treatment as well as for the security of delivered dose, while it is definitively essential and crucial for research and clinical practice [12].

In our department we have already published several reports regarding dosimetric procedures as well as quality controls for either simulation or new whole or semi-body electron-based techniques [13-16]. Under this scope, the penumbra region together with flatness and symmetry constitute fundamental characteristics for photon and electron beams [17]. Their accurate determination is vital in the dosimetric chain of a radiotherapy department.

Photons

Based upon the results it is apparent the penumbra width increases with increasing detector volume. These results are in agreement with the literature and with the predictions of the volume averaging effect. The latter has been investigated by many authors [2-6] and some of them have concluded that an increase of 1 cm in the active diameter of the detector results in an increase of 0.5 cm in the penumbra width [2,5]. The penumbra displayed by the LA48 becomes even tighter because

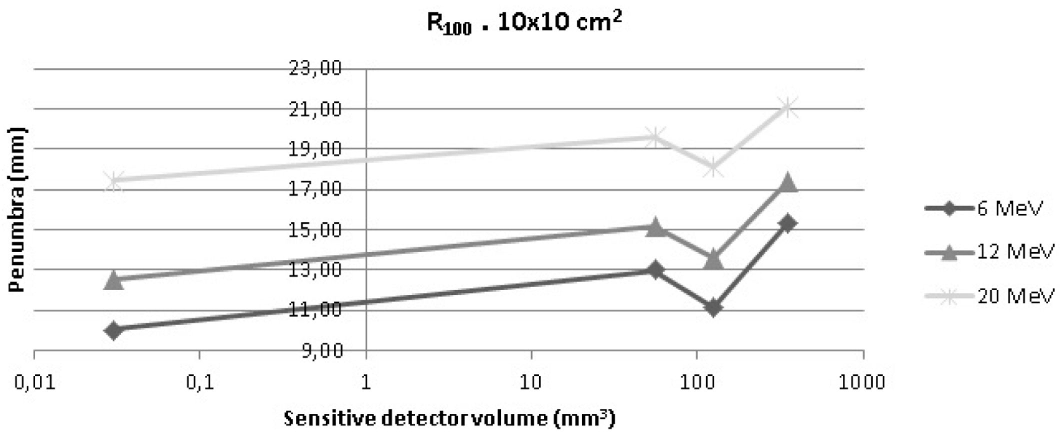

Figure 6. Penumbra size as a function of the sensitive detector volume for three electron beams at R_{100} for a 10×10 cm^2 applicator size.

its side material absorbs the obliquely scattered electrons before they enter detectors' active volume, a behavior well documented in the literature [18-20].

The diodes are more sensitive to low energy scattered radiation than the ionization chambers due to their high Z material (silicon) which gives them a high cross-section for the photoelectric effect. This effect is responsible for the progressive relative increase of the penumbra size displayed by the diodes at the depths 50, 100 and 200 mm, especially for the larger field sizes. It was expected that this increase would be more important for the 60017 diode which lacks a shielding that could absorb an important portion of the scattered radiation. Similar results for an unshielded diode have been reported elsewhere [21]. The overresponse of the semiconductor dosimeters in scattered radiation has been underlined by many authors [7-11]. Gersh et al. suggest that this overresponse can be as high as 10%. The reason that the diode results are less affected by depth and field size increase when the 15 MV energy was used is that the scattering decreases with increasing energy, as the beam becomes more directional.

Electrons

What is evident from the electron beam measurements is that the penumbra width increases with increasing detector volume, except for the case that the Semiflex gives a narrower penumbra than the Markus, even though the later has a smaller volume. This is not strange because of the larger active diameter of the Markus. The investigation of the change of the penumbra width with increasing detector volume would be more accurate if all the detectors had the same shape and material and differ only in volume.

The Roos ionization chamber displays the widest penumbra for all energies and applicator sizes, followed by the Markus ionization chamber. This was expected since these are parallel plate ionization chambers, mainly designed for absolute dosimetry. Their shape (large active diameter) causes a deteriorating effect on spatial resolution of measurements. The LA48 and the Semiflex follow. The former produces wider penumbra areas for measurements at the depth R_{100} and the later at R_{80}. This could be attributed to the absorption of the obliquely scattered electrons by the side material of the linear array. Possibly, there are more of those electrons as we go deeper in water because of increased scattering. Finally, the 60017 diode displays the narrowest penumbra in almost all cases. The fact that the silicon diodes present the best lateral resolution as well as the spatial blurring of the Markus chamber have also been pointed out elsewhere [22].

As the energy increases, the percentage differences in the penumbra size displayed by the different detectors decreases considerably. For example, the difference between the Roos chamber and the 60017 diode has decreased from about 50% at 6 MeV to about 20% at 20 MeV at R_{100}. This can be explained by the fact that the absolute penumbra width increases in higher energies making the technical differences between the detectors less important.

Another effect that is observed in our results and is more prominent at electron energies higher than or equal to 12 MeV is that the penumbra width decreases slightly from the 10×10 cm^2 to the 25×25 cm^2 cone. This effect was displayed by all detectors. A similar effect was found by Du Plessis et al. [23] but in this work an MLC was used, so comparisons are not safe. However, it is obvious that at higher energies the primary beam plays the dominant role and therefore the scatter factor, which increases with increasing field (cone) size, is not so important. This applies especially for the electron beams, where the scattered electrons have a very small range and therefore the scattered induced increase in penumbra has a limit no matter how large the cone gets. After noticing this effect, complementary measurements were performed with a 20×20 cm^2 cone using the LA48. The results showed that the mentioned reduction of the penumbra width is linear.

Direction of measurement

The Semiflex was the only detector that displayed a wider penumbra in the Left-Right direction in comparison with the Gun-Target direction. For example, for the 6 MV photon energy at d_{max} and for the 10×10 cm^2 field, the penumbra produced by the Semiflex is 8.6% wider than the corresponding penumbra measured in the GT direction. On the other hand, the penumbras produced by the LA48, the 60008 diode and the 60017 diode are 10.1%, 20.5% and 20% narrower, respectively. Considering a subset of electron measurements (6 MeV, R_{100}, 10×10 cm^2), the penumbra produced by the Semiflex in the LR direction is 1.7% wider than the corresponding penumbra measured in the GT direction. On the other hand the penumbras produced by the LA48, the Markus, the 60017 diode and the Roos are 2.3%, 2.8%, 2.7% and 0.8% narrower respectively.

This is based on the fact that the Semiflex, unlike all the other detectors, has different dimensions in the GT and in the LR direction, the larger one being in the LR, because of its shape and positioning perpendicular to the beam. This creates worse spatial resolution in this direction, increasing the penumbra width. The difference in the behavior of the LA48 and the diodes when the direction is changed during the photon beam measurements may be explained by the fact that the water phantom was rotated by 90 degrees in order to take measurements with the LA48 in the LR direction and positioning errors may have been induced.

Flatness and symmetry measurement

Flatness and symmetry measurements present considerable variation. These results may be influenced by many factors, including the daily 'output status' of the linear accelerator, making it risky to interpret them based on the characteristics of the detectors. However, the following two remarks can be made.

Firstly, for the electron beam measurements, the detectors that give large penumbra also give higher flatness values. For example, for the 6 MeV electron beam, for the 10×10 cm^2 applicator at R_{100} the flatness values for the LA48, the Semiflex, the Markus, the Roos and the 60017 diode are 4.80%, 5.62%, 5.99%, 4.92% and 7.68%, respectively.

Secondly, the LA48 displays generally the most symmetric beam profiles. For example, for the 15 MV photon beam, for the 10×10 cm^2 field at D_{max}, the symmetry values for the LA48, the Semiflex, the 60008 diode and the 60017 diode are 100.34%, 101.7%, 101.85% and 102.73%, respectively. This is due to the fact that measurements at the left and the right area of the beam profile are taken simultaneously when using the LA48. This eliminates possible beam variations that may occur during the time that all other detectors need to go from one point of measurement to its symmetric one.

Step of measurement

As it was expected, when the bigger step was used, all detectors produced wider penumbras due to worse spatial resolution. On the other hand, the results indicate that the change in the step of measurement is not enough to radically alter the results concerning penumbra width. We consider two examples, one for a photon measurement and one for an electron measurement.

For the 6 MV photon beam, at D_{max}, for the 10×10 cm^2 field when we used the step A (1 mm resolution for the LA48), the Semiflex presented a penumbra 26.7% wider than the LA48, 72.1% wider than the 60008 diode and 70.5% wider than the 60017 diode. When we used step B (2 mm resolution for the LA48), these values were 22.6%, 66.8%, 58.6%, respectively.

For the 6 MeV electron beam, at R_{100}, for the 10×10 cm^2 field when we used step A (1 mm resolution for the LA48), the Roos presented a penumbra 18.1% wider than the Markus, 37.9% wider than the Semiflex, 39.5% wider than the LA48, and 52.7% wider than the 60017 diode. When we used step B (2 mm resolution for the LA48), these values were 21.2%, 38.4%, 38.4% and 52.6%, respectively.

Therefore, time saving should be the first thing to consider when choosing the step of measurement in clinical practice. From the two steps used in this work, step B presents an acceptable accuracy and provides quicker measurements. Finally, a drawback of the use of LA48 is that it is impossible to apply different step size for different regions of the beam profile.

Time efficiency

The LA48 offered considerable time saving during measurements in comparison with all other detectors. It needed about 25 seconds to measure one beam profile with the best possible resolution, regardless of field size dimensions. All other detectors needed about 2.5 minutes to measure one beam profile of a 10×10 cm^2 field with step A and even more for larger field sizes. This time saving of the LA48, which has been pointed out by other authors as well [14], can be of great importance for a modern radiotherapy department.

On the other hand, a disadvantage of the LA48 is that the user needs to rotate the water phantom in order to take measurements in both directions. The extra time needed for this is by far regained when using the LA48 for measurements, but it may also induce uncertainties.

Limitations and future work

The most important limitation of this work is that one cannot be sure which detector provides the closest to the true values for the penumbra width, the flatness and the symmetry in every measurement. For this reason, and taking under consideration the volume averaging effect which is dominant, we are obliged to assume that the closest to the 'real' penumbra width is the smallest one. In small field sizes and depths this is displayed by the diodes. The same assumption has been made by other authors too [5] while others have used deconvolution [24] or extrapolation methods [2,4] to obtain the real penumbra width and others have compared the detector obtained values with values generated by Monte Carlo simulations [7,25].

Another limiting factor is that we did not investigate all the parameters that may have an impact on the performance of a detector in relative dosimetry measurements. Two parameters, which require further investigation, are the SSD, which in this work was kept constant at 100 cm, and the dose-rate, which was also kept constant at 240 MU/min. A slightly decreasing response of the LA48 with increasing dose-rate has been reported [18].

The next step point towards entering these results in a Treatment Planning System and using the calculated dose distribution is to investigate the differences concerning the irradiation of healthy tissues using different detectors for relative dosimetry measurements.

The results of the measurements performed for this work are in good agreement with the existing literature, including the recent work of Benmakhlouf et al. [20]. The volume effect and the sensitivity of the silicon diodes in scattered radiation appear to play an important role in the penumbra width measured by the detectors.

Roos and Markus parallel-plate electron ionization chambers may be not the best choice for relative dosimetry measurements. The Semiflex, although is considered to be the gold standard, seems to overestimate the penumbra width in photon measurements. The diodes offer the best accuracy in small field sizes and depths but tend to overestimate the penumbra width as the field size and/or the depth increase. Especially the 60017 unshielded diode should not be used for photon measurements in large field sizes (>15×15 cm^2) combined with big depths (>100 mm). The latter appears to be the most reliable type of detector to measure differences between the GT and the LR penumbras. The LA48 is acceptable in terms of accuracy for both photon and electron measurements in all energies, depths and field sizes and it is associated with considerable time-saving efficiency compared to all other measuring systems. Changes in the step of measurement do not alter the results significantly. In general, the results for flatness and symmetry display a variation but it is safe to conclude that the LA48 appears the best choice for symmetry measurements.

In any case, further dosimetric studies stand in need for the extraction of safe results.

Conflict of interests

The authors declare no conflict of interests.

References

1. Yuen J, Hardcastle N, Metcalfe P. A study into the relationship between the measured penumbra and effective source size in the modeling of the Pinnacle RTPS. Australas Phys Eng Sci Med 2011;34:233-41.
2. Dawson DJ, Schroeder NJ, Hoya JD. Penumbral measurements in water for high energy x rays. Med Phys 1986;13:101-4.
3. Benítez EM, Casado FJ, García-Pareja S, Martín-Viera JA, Moreno C, Parra V. Evaluation of a liquid ionization chamber for relative dosimetry in small and large fields of radiotherapy photon beams. Rad Meas 2013;58:79-86.
4. Laub WU, Wong T. The volume effect of detectors in the dosimetry of small fields used in IMRT. Med Phys 2003;30:341-7.
5. Garcia-Vicente F, Bejar M J, Perez L, Torres J. Clinical impact of the detector size effect in 3D-CRT. Radiother Oncol 2005;74:315-22.
6. Gonzalez-Castano Z, Pena ZFJ, Sanchez-Doblado Z, Hartmann GH, Gomez ZF, Leal ZA. The change of response of ionization chambers in the penumbra and transmission regions: impact for IMRT verification. Med Biol Eng Comput 2008;46:373-80.
7. Scott AJD, Nahum AE, Fenwick JD. Using a Monte Carlo model to predict dosimetric properties of small radiotherapy photon fields. Med Phys 2008;35;4671-84.
8. Gersh JA, Best RCM, Watts RJ. The clinical impact of detector choice for beam scanning. J Appl Clin Med Phys 2014;15:4801.
9. Akino Y, Gautam A, Coutinho L, Würfel J, Das IJ. Characterization of a new commercial single crystal diamond detector for photon- and proton-beam dosimetry. J Radiat Res 2015;56:912-8.
10. Metcalfe P, Kron T, Elliott A, Wong T, Hoban P. Dosimetry of 6-MV x-ray beam penumbra. Med Phys 1993;20:1439-45.
11. Ralston A, Liu P, Warrener K, McKenzie D, Suchowerska N. Small field diode correction factors derived using an air core fibre optic scintillation dosimeter and EBT2 film. Phys Med Biol 2012;57:2587-2602.
12. Kouloulias VE. Quality assurance in radiotherapy. Eur J Cancer 2003;39:415-22.
13. Diamantopoulos S, Thalassinou S, Efstathopoulos E et al. In vivo dosimetry in the field junction area for 3D-conformal radiation therapy in breast and head & neck cancer cases: A quality assurance study. JBUON 2016;21:1104-12.

14. Platoni K, Diamantopoulos S, Dilvoi M et al. First application of hemi-body electron beam irradiation for Kaposi sarcoma at the lower extremities in children. JBUON 2018;23:268-72.
15. Diamantopoulos S, Kantemiris I, Patatoukas G et al. Theoretical and experimental determination of scaling factors in electron dosimetry for 3D-printed polylactic acid. Med Phys 2018. doi: 10.1002/mp.12790.
16. Platoni K, Diamantopoulos S, Panayiotakis G et al. First application of total skin electron beam irradiation in Greece: setup, measurements and dosimetry. Phys Med 2012;28:174-82.
17. Kouloulias VE1, Poortmans P, Antypas C, Kappas C, Sandilos P. Field flatness and symmetry of photon beams: review of the current recommendations. Technol Health Care 2003;11:283-8.
18. Martens C, DeWagter C, De Neve W. The value of the LA48 linear ion chamber array for characterization of intensity-modulated beams. Phys Med Biol 2001;46:1131-48.
19. Korevaar E. Influence of the detector size used for beam data acquisition on the shape of the pencil beam kernel in Cadplan. Department of Radiation Oncology, University Hospital Zürich, 2001. http://www.uni-ulm.de/~jsalk/cug/contrib/korevaar/detector-v2.pdf [accessed 13/4/2017].
20. Richmond ND, Kermode RH. A practical method of measuring electron isodose curves using a linear detector array for validation of treatment planning system data. Med Dosim 2002;27:25-7.
21. Griessbach I, Lapp M, Bohsung J, Gademann G, Harder D. Dosimetric characteristics of a new unshielded silicon diode and its application in clinical photon and electron beams. Med Phys 2005:32:3750-4.
22. Scherf C, Peter C, Moog J et al. Silicon Diodes as an Alternative to Diamond Detectors for Depth Dose Curves and Profile Measurements of Photon and Electron Radiation. Strahlenther Onkol 2009;185:530-6.
23. du Plessis FC, Leal A, Stathakis S, Xiong W, Ma CM. Characterization of megavoltage electron beams delivered through a photon multi-leaf collimator (pMLC). Phys Med Biol 2006;51:2113-29.
24. Sibatal CH, Mota HC, Beddar AS, Higginsjl PD , Shin KH. Influence of detector size in photon beam profile measurements. Phys Med Biol 1991;36:621-63.
25. Gonzalez W, Lallena AM, Alfonso R. Monte Carlo simulation of the dynamic micro-multileaf collimator of a LINAC Elekta Precise using PENELOPE. Phys Med Biol 2011;56:3417-31.
26. Benmakhlouf H, Andreo P. Spectral distribution of particle fluence in small field detectors and its implication on small field dosimetry. Med Phys 2017;44:713-24.