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Original research paper

RADIATION PROTECTION IN RADIOTHERAPY DEPENDS ON UNCERTAINTIES IN SMALL FIELD DOSIMETRY

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Abstract. *Technological improvements in radiotherapy machines using small fields (SF) have improved mechanical accuracy and stability, as well as dosimetric control. Small fields are nonstandard radiation fields, for which reference dosimetry cannot be reliably performed using the existing protocols. Field size definition, difficulties of accurate measurements, modeling of SF dose calculations in Treatment Planning System (TPSs), calibration protocol establishing, reference condition achievements, are some of the challenges in SF Dosimetry. Small and Intensity Modulated Radiation Therapy (IMRT) field dosimetry can be very complex – large perturbation effects could make a significant impact on reference dosimetry procedures and output factors. Comparison between different detectors provides valuable information. The aim of this paper is to evaluate the differences of dose profiles and depth dose measured in the same conditions for standard and non-standard radiation fields. Measurements are performed using detectors with different sensitive volumes. Beam quality as well as symmetry and flatness are analyzed. Results from the measurements show that the differences for SF are obvious at the edge of the profiles and in the penumbra region, as well as in the build-up region into depth dose curves. To avoid the uncertainties, for static SF where reference conditions cannot be met and for IMRT fields where delivery conditions are far removed from calibration conditions, the new formalism should be implemented.*

Key words: *Beam quality, calibration, flatness, small field, symmetry*

1. INTRODUCTION

Radiation therapy is a medical branch for malignant disease treatment using ionizing radiation. The linear accelerator is one of the most common devices in radiotherapy that produces photon and electron radiation beams, directs them to the patient, penetrates into body and irradiates certain volume. High quality radiotherapy treatment implies accurate and precise irradiation of the volume of interest with prescribed radiation dose and in the same time providing maximal protection of healthy organs along the path of ionizing radiation. Great and complicated technical preparation both of the patient and the equipment should be ensured in order to meet this medical requirement. Above all, pretreatment CT scan of patients is necessary in order to define the volume of interest to be irradiated, as well as to determine the exact coordinates for the administration of radiation treatment. The second requirement is to maintain mechanical and geometrical accuracy of the accelerator by which the treatment is being performed. The third requirement refers to dosimetric optimization which implies defining the benchmarks in the treatment planning system as initial conditions in the algorithm for isodose distribution calculation. Furthermore, these parameters are periodically checked and calibrated in order to minimize the uncertainty compared to reference data [1, 2].

According to international recommendations [3, 4], the measurement of dose profiles and depth dose curves should be strictly defined and maintained with the least possible deviation from the reference ones (Figure 1 and Figure 2).

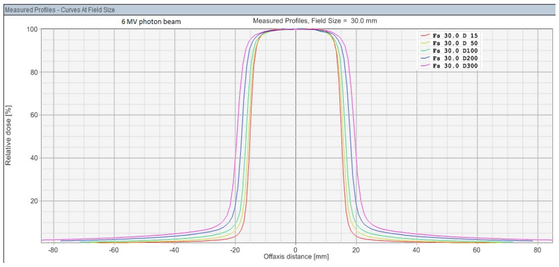

Figure 1. Dose profiles for 6 MV photon beam measured at five different depths in water when the radiation field on the water surface was 3 cm x 3 cm

The analysis of parameters that should be undertaken is based on the quality of radiation beam determined by depth dose curves and symmetry, flatness and penumbra defined by dose profiles. The values of these parameters are directly related to the dose distribution in a given volume.

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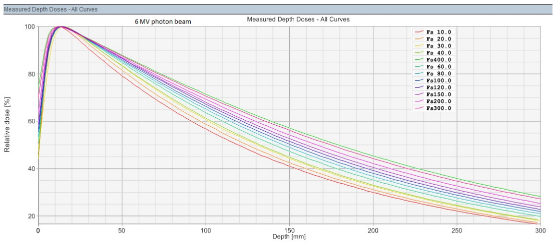


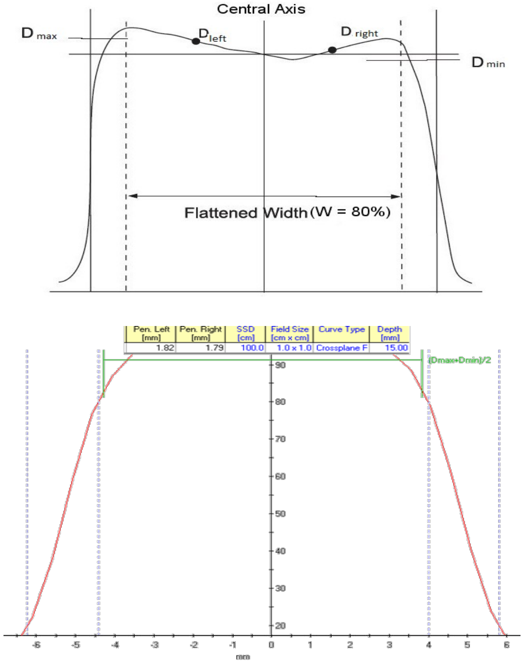
Figure 2. Depth dose distribution in water for different radiation fields

According to the recommendations of the International Atomic Energy Agency (IAEA) and American Association of Physics in Medicine (AAPM) [5-7], the quality of the photon radiation beam (Quality Index - QI) is defined for the field size 10 cm x 10 cm at the phantom surface when SSD = 100 cm. It can be expressed [7] by the equation (1):

$$QI = 1.2661 * PDD_{20,10} - 0.0595 \qquad (1)$$

where $PDD_{20,10}$ is the ratio of the doses measured at depths of 20 cm and 10 cm, expressed as percentages.
It is defined

According to the International Electrotechnical Commission [8] - IEC, flatness is defined as the maximum percentage deviation (D_{max} in Figure 3) of average dose along the central axis at 80% of the profile's width. The symmetry is defined as the percentage dose variation at two points D_{left} and D_{right} (Figure 3) of the dosing profile, spaced at equal distances from the left and right sides relative to the central axis.



Pen. Left [mm]	Pen. Right [mm]	SSD [cm]	Field Size [cm x cm]	Curve Type	Depth [mm]
1.82	1.79	100.0	1.0 x 1.0	Crossplane F	15.00

Figure 3. a) Dose profile shape; b) Penumbra definition

Physical penumbra is defined [4] as the lateral distance between two specific isodose curves at specific depths (2 dose points at the left or right field boundary expressed as the percentage of the central axis dose) between 80% and 20 % of the dose on the central axis (Figure 3b).

The exact determination of these parameters in the treatment planning system is of a particular importance. They affect the calculated dose distribution.

The development of more sophisticated radiotherapy techniques during recent years, such as stereotactic radiotherapy and radio surgery, increases the requirements for higher accuracy in radiotherapy when small radiation fields are used. Studies show that standard detectors are not adequate to determine the parameters for small radiation fields. This paper presents the analysis of dose profiles and depth dose curve measurements performed under equal conditions with three different detectors, each of them with a different sensitive volume.

2. EXPERIMENTAL

2.1. Description of equipment

According to the international recommendation [7, 9], different kinds of dosimeters and electrometers properly calibrated in a primary or secondary laboratory could be used in radiotherapy. Measurements have been performed under clinical conditions, referring to 6 MV photon radiation beam generated by a linear accelerator TRILOGY. Dosimetry equipment includes: water phantom, measuring detectors, electrometer and compatible software Mephysto (produced by PTW) [10, 11].

D1 detector (0.125 Semiflex Chamber Type 31010) is designed by PTW as a waterproof and fully guarded vented cylindrical ionization chamber, 6.5 mm length, with a nominal sensitive 0.125 cm^3 volume. The wall of the sensitive volume is 0.55 mm PMMA (1.19 g/cm^3) and 0.15 mm graphite (0.82 g/cm^3). It is designed for measuring quantities in radiotherapy like absorbed dose to water, air kerma, or exposure.

D2 detector (Dosimetry Diode P Type 60016) is designed by PTW as a waterproof silicon detector, shielded, with a nominal sensitive volume of 0.03mm^3 (1 mm^2 circular, 30 μm thick). It can be used in air, solid state phantoms and in water for high energy photon beam dosimetry. The sensitive volume is disk-shaped and perpendicular to the detector axis. The very high response (175nC/Gy, versus 9nC/Gy and 3.3nC/Gy for D3 and D1 respectively) allows to measure beam profiles with very high resolution and very short dwell time.

D3 detector (Dosimetry Diode SRS Type 60018) is also PTW designed as a waterproof silicon detector, unshielded, disk-shaped perpendicular to the detector axis. Its outer diameter is 7 mm and the entrance window is 0.3 mm RW3, 0.27 mm epoxy. The water-equivalent window thickness is 1.31 mm with total window area density of 140 mg/cm^2. The sensitive volume is 0.3 mm^3 (1 mm^2 circular 250 μm thick). The SRS diode is with extremely high resolution.

The TANDEM electrometer is a dual channel therapy electrometer designed for fast scanning measurements in the motorized water phantom with measuring intervals of 10 ms. It is calibrated in electrical current (A) according to IEC 60731 with 10 fA resolution. This dual channel device accepts ion chambers and solid state detectors to be connected. The chamber voltage for both channels is individually programmable in 50 V increments up to 400 V with reversible polarity. In conjunction with a TBA therapy beam analyzer, MEPHYSTO software controls TANDEM for fast and accurate beam data acquisition. A trigger input synchronizes measurements with external signals.

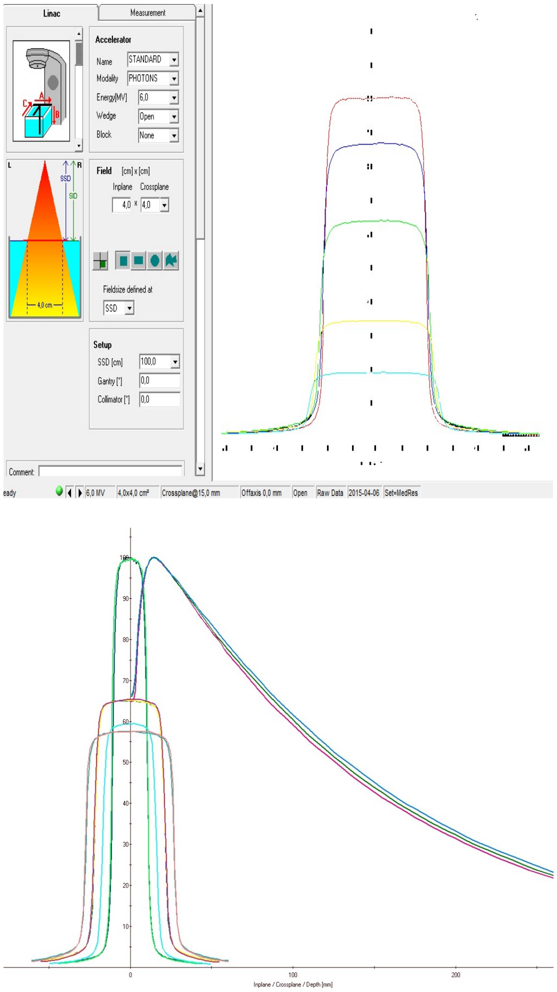
Water phantom MP3 is designed by PTW as a remote-controlled 3D acrylic water tank with 20 mm thick walls and a scanning range of 50 x 50 x 40.8 cm^3, suitable for measuring radiation field sizes of up to 40 cm x 40 cm. The phantom comes complete with a high-precision electromechanical lifting carriage to allow its height adjustment; 3D moving mechanism driven by three calibration-free, high-speed stepper motors; as well as an electronic device (TBA Control Unit) for an automatic control of the detector position into the water phantom via RS232 interface. It provides detector positioning accuracy true to 0.1 mm.

"MEPHYSTO mc^2" is a beam analyzing software for beam data acquisition and analysis with a PTW Water scanning system. It is equipped with all essential tools that allow performing dosimetry tasks related to accelerator commissioning as well as beam quality control.

2.2. *Description of measurements*

Measurements were performed by using three different detectors sequentially for several radiation fields (square fields from 1 cm^2 to 100 cm^2), under identical geometry of the system: linear accelerator – water phantom – detector system. The photon beam leaves the accelerator gantry and shapes a certain radiation field on the water surface. Water phantom is placed directly under a photon radiation beam, the water surface is perpendicular to the direction of the radiation beam and source-skin-distance is 100 cm. The detector is placed on the rail in the water phantom so that the geometrical center of the sensitive volume is matched with the radiation field center. D1 is positioned parallel to the water surface and D2, D3 are perpendicular. The rail has an automatically accommodated movement. The detector is forced to move according to pre-set conditions: in depth, along the central radiation beam in order to present the depth dose curve, or at a specific depth (50 mm or 100 mm), perpendicular to the central radiation beam in order to present the dose profile representative for the certain depth.

The electrometer displays the signals from the irradiated detector in real time. This system is connected to the software (Figure 4) which processes the signals and calculates the values of the parameters of interest: symmetry, flatness, penumbra on the left and right side and quality of radiation beam. For the comparative analyses of the respective measurements, the curves obtained by different detectors referring to the same field and measuring depth are presented in the same graph.



Accelerator
Name STANDARD
Modality PHOTONS
Energy[MV] 6,0
Wedge Open
Block None

Field [cm] x [cm]
Inplane Crossplane
4,0 x 4,0

Fieldsize defined at SSD

Setup
SSD [cm] 100,0
Gantry [°] 0,0
Collimator [°] 0,0

Comment:

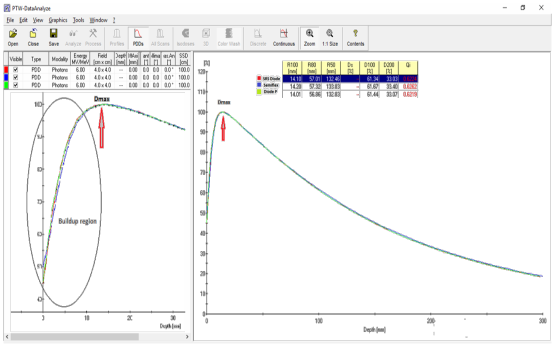
eady 6,0 MV 4,0x4,0 cm² Crossplane@15,0 mm Offaxis 0,0 mm Open Raw Data 2015-04-06 Set+MedRes

Figure 4. Software display of measurement results

3. RESULTS AND DISCUSSION

Measurements of dose profiles performed with three different detectors - D1, D2 and D3, are made for several radiation fields: 10 cm x 10 cm; 5 cm x 5 cm; 4 cm x 4 cm; and 3 cm x 3 cm, 2 cm x 2 cm and 1 cm x 1 cm, at two different depths in water (5 cm and 10 cm). Also, measurements of depth dose curves for the same radiation fields are performed.

Measuring parameters such as the quality of radiation beam, symmetry, flatness, and penumbra region are analyzed. Some of the results for dose profiles and penumbras are shown in Figure 5 to Figure 8. The measured values with three different detectors for the depth dose – the quality of radiation beam, dose profile for standard fields and dose profile for small radiation fields are presented in Table 1, Table 2 and Table 3, respectively.



	Visible	Type	Modality	Energy MV/MeV	Field [cm x cm]	Depth [mm]	OffAxis [mm]	ant [°]	llima [°]	as.An [°]	SSD [cm]
🟥	☑	PDD	Photons	6.00	4.0 x 4.0	---	0.00	0.0	0.0	0.0 °	100.0
🟦	☑	PDD	Photons	6.00	4.0 x 4.0	---	0.00	0.0	0.0	0.0 °	100.0
🟩	☑	PDD	Photons	6.00	4.0 x 4.0	---	0.00	0.0	0.0	0.0 °	100.0

	R100 [mm]	R80 [mm]	R50 [mm]	Ds [%]	D100 [%]	D200 [%]	Qi
🟥 SRS Diode	14.10	57.01	132.46	-	61.34	33.03	0.6224
🟦 Semiflex	14.20	57.32	133.83	-	61.67	33.40	0.6262
🟩 Diode P	14.01	56.86	132.83	-	61.44	33.07	0.6219

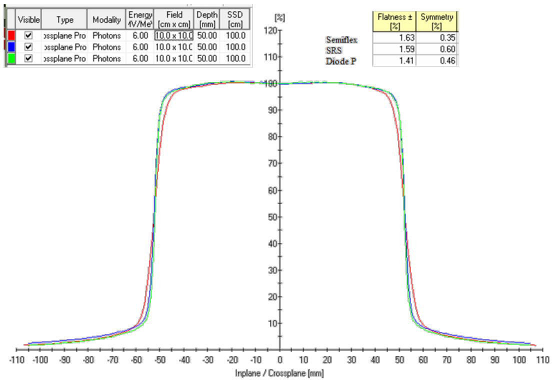
Figure 5. Depth dose distribution for radiation field 4 cm x 4 cm, measured by three different detectors

Figure 5 shows the depth dose curves relating to 4 cm x 4 cm radiation field. There are almost no deviations and the quality of radiation beam has been observed, irrespective of the measuring detector used for measuring of depth dose curves.

Table 1. Depth dose – Quality of radiation beam

Photons 6 MV	Depth dose –Quality of radiation beam (QI)					
	10cm x 10cm	5 cm x 5 cm	4 cm x 4 cm	3 cm x 3 cm	2 cm x 2 cm	1 cm x 1 cm
PDD$_{20/10}$ D1:	0.575	0.554	0.546	0.545	0.53	0.534
QI	0.670					
PDD$_{20/10}$ D2:	0.575	0.553	0.545	0.541	0.532	0.537
QI	0.669					
PDD$_{20/10}$ D3:	0.570	0.554	0.542	0.541	0.532	0.536
QI	0.667					

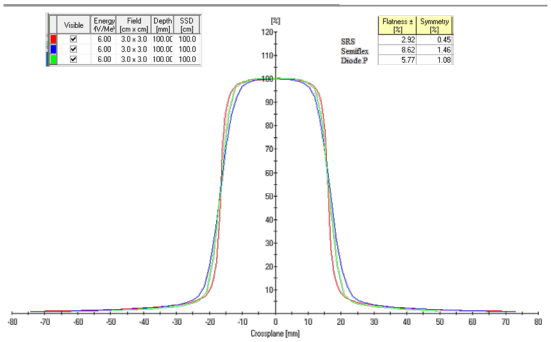
It could be concluded from the depth dose analyzes presented in Table 1 that the quality of the radiation beam is constant for particular field size, irrespective of the used detector. The differences appear only in the "build-up" region, for depth doses smaller than the depth of dose maximum (Figure 5).



	Visible	Type	Modality	Energy MV/MeV	Field [cm x cm]	Depth [mm]	SSD [cm]
🟥	☑	ossplane Pro	Photons	6.00	10.0 x 10.0	50.00	100.0
🟦	☑	ossplane Pro	Photons	6.00	10.0 x 10.0	50.00	100.0
🟩	☑	ossplane Pro	Photons	6.00	10.0 x 10.0	50.00	100.0

	Flatness ± [%]	Symmetry [%]
Semiflex	1.63	0.35
SRS	1.59	0.60
Diode P	1.41	0.46

Figure 6. Dose profiles of 10 cm x10 cm radiation field measured by three different detectors



	Visible	Energy MV/MeV	Field [cm x cm]	Depth [mm]	SSD [cm]
🟥	☑	6.00	3.0 x 3.0	100.00	100.0
🟦	☑	6.00	3.0 x 3.0	100.00	100.0
🟩	☑	6.00	3.0 x 3.0	100.00	100.0

	Flatness ± [%]	Symmetry [%]
SRS	2.92	0.45
Semiflex	8.62	1.46
Diode P	5.77	1.08

Figure 7. Dose profile of 3 cm x 3 cm radiation field measured by three different detectors

Dose profiles performed at 5 cm depth in water, relating to 10 cm x 10 cm radiation field, measured by the three detectors in series, are presented in Figure 6. Strong concurrence between the curves can also be visually observed. The differences in symmetry and flatness values measured with three detectors respectively are negligible. Figure 7 presents the dose profiles obtained by three detectors in series at 10 cm depth in water for a small (3 cm x 3 cm) radiation field. There is a significant difference between the curves, especially relating to the profile measured by D1, particularly at points at the radiation field's edges and the penumbra region. This is a result of the fact that the smaller the distance from the central beam to the field's edge, the smaller the distance to which the scattered (secondary) electrons can "travel" so that the equilibrium of scattered electrons has been disturbed [12; 13]. Also, there are great deviations in measured parameters relating to this detector (Table 3), because the sensitive volume of detector D1 is the greatest one.

Comparison of the measured parameters for the standard field sizes indicates a strong matching of the dose profiles, as well as an insignificant difference in the measurement parameters referring to the same radiation field. For smaller radiation fields, the differences are getting greater.

Table 2. Dose profile for standard fields

Photons 6 MV	Measured parameters for field 5 cm x 5 cm		Measured parameters for field 10 cm x 10 cm	
	Symmetry (%)	Flatness (%)	Symmetry (%)	Flatness (%)
D1 (d=5cm)	0.82	0.36	0.36	1.63
D1 (d=10cm)	0.96	0.36	0.44	1.73
D2 (d=5cm)	0.86	1.61	0.46	1.41
D2 (d=10cm)	0.51	1.63	0.46	1.41
D3 (d=5 cm)	0.51	1.51	0.51	1.31
D3 (d=10cm)	0.66	1.56	0.45	1.32

Table 3. Dose profile for small radiation fields

Photons 6 MV	Measured parameters for field 4cm x 4 cm		Measured parameters for field 3 cm x 3 cm	
	Symmetry (%)	Flatness (%)	Symmetry (%)	Flatness (%)
D1 (d=5cm)	0.98	5.93	0.95	10.6
D1 (d=10cm)	1.4	6.06	1.19	10.77
D2 (d=5cm)	0.64	2.12	1.18	8.99
D2 (d=10cm)	0.42	2.34	2.76	8.28
D3 (d=5 cm)	0.28	1.84	0.18	4.52
D3 (d=10cm)	0.35	2.17	0.52	4.63

Table 4. Dose profile for small radiation fields

Photons 6 MV	Measured parameters for field 2 cm x 2 cm		Measured parameters for field 1 cm x1 cm	
	Symmetry (%)	Flatness (%)	Symmetry (%)	Flatness (%)
D1 (d=5cm)	0.95	10.6	2.89	14.88
D1 (d=10cm)	1.19	10.77	4.72	15.10
D2 (d=5cm)	1.18	8.99	2.44	10.73
D2 (d=10cm)	2.76	8.28	2.94	11.65
D3 (d=5 cm)	0.18	4.52	0.61	8.88
D3 (d=10cm)	0.52	4.63	1.14	9.22

Table 5. Penumbra measured by Diode P detector

Field size Depth	10x10	8x8	6x6	4x4	3x3	2x2	1x1
50mm	3.25	3.6	3.45	3.26	3.11	3.03	2.83
100mm	4.2	3.9	3.63	3.36	3.39	3.22	3.02

Measuring parameters referring to dose profiles, symmetry and flatness of small radiation fields depend on the applied detector. According to the results that can be found in available literature [14, 15, 16], the smaller radiation field, the greater the influence of the sensitive volume's size of measuring detector upon the result.

If we analyze penumbra 80-20% obtained from one detector presented in Table 4, it is obvious that the penumbra dimension is dependent on the field size and the depth of the profile. Penumbra is as small as the field size is, and as small as the measuring depth is.

Dose profiles for the same radiation field size, obtained at the same depth, show that the penumbra dimension depends on the detector type. Detector 1 (D1) always presents the biggest penumbra and detector 3 (D3) presents the smallest one. Penumbra differences for the 3x3 radiation field are presented in Figure 8.

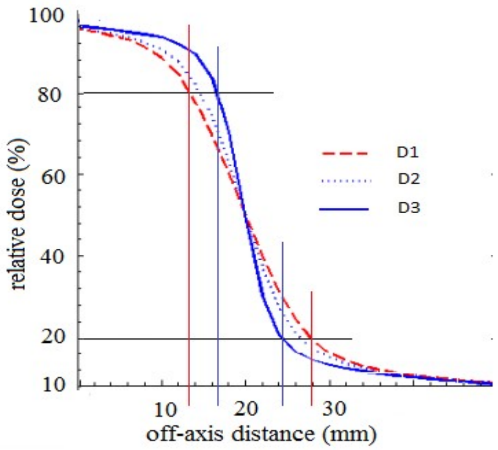


Figure 8. Penumbras for 3x3 cm radiation field measured by three different detectors

The three detectors analyzed in this paper are largely similar. They are all invented by same manufacturer and are recommended for radiotherapy measurements. For standard dimensions of the radiation fields used in conventional radiotherapy, there are no significant differences in the curves performed with different detectors. By reducing the dimensions of the radiation field below 4 cm, the length of the first detector (D1) becomes comparable to the dimension of the radiation field. Means, the length of 6.5 mm is placed centrally in a field of 1 cm or 2 cm width. The diodes (D2 and D3 detectors) have a cross-sectional area of 1 mm^2, which means that the diameter of 1.1 mm is centrally positioned in the radiation field. This explains the difference in the shape of the profile curves to the edges of the small field and in the penumbra region.

Table 6. Differences in penumbra measured with different detectors

Field sixe (cm^2)		1x1	2x2	3x3	4x4	5x5	10x10
Δ_{left}	(mm)	0.99	2.04	3.6	3.64	3.62	3.67
	(%)	9.9	10.2	12	9.1	7.2	3.67
Δ_{right}	(mm)	1.04	2.18	3.52	3.69	3.6	3.79
	(%)	10.4	10.9	11.7	9.2	7.2	3.79

The absolute values of these differences are not dramatically big (table 5, Δ_{left} and Δ_{right} in mm), but it should be taken into consideration that the 3 mm difference for the 10x10 field is 3% of the radiation field dimension and just a 1 mm difference for the 1x1 field is 10% of that radiation field dimension. This is one more reason why a smaller volume detector should be used for small field dosimetry. The accuracy of penumbral measurements in radiotherapy is very important.

Dose planning computers require accurate data to adequately model beams which are used to calculate patient dose distributions. Smaller detectors, having spatial resolutions as low as 1 mm, provide minimal error for the penumbra dose assessment.

4. CONCLUSIONS

This paper presents the accuracy of dose profiles and depth dose measurements for standard and non-standard radiation fields.

Measurements and analysis of the quality of radiation beam show that it is constant for a particular field size, irrespective of the used detector. The differences appear only in the "build-up" region, for depth doses smaller than the depth of dose maximum.

Measuring parameters referring to dose profiles, symmetry and flatness of small radiation fields depend on the applied detector. Dose profiles for the same radiation field size, obtained at the same depth, show that the penumbra dimension depends on the detector type. Penumbra is as small as the field size, and as small as the measuring depth. The absolute values of these differences are not huge, but if we consider the differences versus the field size, the relative values of the differences should become up to 10% and more.

The measurements and analysis presented in the paper lead to the conclusion that a smaller volume of the measuring detector provides more accurate signals in the penumbra region, and the volume effect is negligible when the detector's size is several times smaller than the size of the radiation field.

As the size of the sensitive volume of the measuring detector directly affects the parameters of small radiation fields (4 cm x 4 cm and smaller), dosimetry for standard radiation fields is not sufficient. In this case, dosimetry of small fields could be implemented, which is not typical for standard radiant fields

Ensuring accurate measurement of dose distribution for small fields (especially at the radiation field's edges and the penumbra region) is a particular interest of contemporary radiotherapy techniques such as stereotactic radiotherapy and radiosurgery, given the fact that the whole radiation treatment is conducted using small fields. When carrying out this treatment, a number of small fields at different angles were used, so the contribution of each field has been superposed into their penumbra regions. For the fields smaller than 3 cm, the field is practically composed merely of penumbra. The distance between 80% and 20% dose is very small. It increases the isodose curve and volume effects in the penumbra region.

Therefore, in order to avoid major uncertainties, dose profiles and depth dose curves of small fields should be measured by a detector with a small sensitive volume. Dosimetric uncertainties in small field dosimetry include many other factors important for accurate measurements. International standards regarding dosimetry of small fields are developing permanently and different uncertainties in small field dosimetry are still the subject of scientific research.

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