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Investigation of physical penumbra definition in treatment planning

H. Alipour*, K. Hadad, R. Faghihi

Department of Nuclear Engineering, Faculty of Mechanical Engineering, Shiraz University, Shiraz, Iran

► ***Technical note***

****Corresponding authors:***
Dr. Hajar Alipour,
Fax: *+ 98 71 3613 3152*
E-mail:
halipour@shirazu.ac.ir

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ABSTRACT

Background: Due to the small size of the beamlets in IMRT (intensity modulated radiotherapy), physical penumbra is one of the important dosimetric parameters and small changes in the penumbra have a notable impact on the results. The physical penumbra width is defined as the lateral distance between two specified isodose curves at a specified depth of phantom. In this study, after demonstrating the inconsistency of conventional physical penumbra definition for non-uniform MLC (multileaf collimator) fields, two new dosimetric parameters proposed that are suitable for MLC fields. ***Materials and Methods***: Physical penumbra evaluation was obtained using IAEA (international atomic energy agency) phase space data for a Varian IX and EGS (electron gamma shower)nrc Monte Carlo code package. These measurements have been performed in water phantom at an SSD of 100 cm and a depth of 5 cm. ***Results:*** With conventional definition, physical penumbra width for all MLC setups on right and left sides of isodose curves (parallel to X and Y axes) are not equal. With a novel beam penumbra parametrization, the effect of MLC setup is taken into consideration. ***Conclusion:*** The conventional definition of physical penumbra for non-uniform MLC setups is not comprehensive. For such cases, surface penumbra and uniformity index parameters are demonstrated to be more suitable and indicative of the field non-uniformity. It is also shown that for an idle treatment planning system, the uniformity index approaches unity.

Keywords: *Physical Penumbra, Dosimetric Parameters, DOSXYZnrc, EGSnrc, CTV.*

INTRODUCTION

During the past 40 years, medical linacs have gone through five distinct generations; in the second generation, symmetric jaws and electron cones; in the third generation, motorized wedge; asymmetric or independent collimator jaws; in the fourth generation dynamic wedge; electronic portal imaging device; multileaf collimator are used. The latest accelerators, photon beam intensity modulation with multileaf collimator equipped with full dynamic conformal dose delivery are produced with multileaf collimators [1]. In IMRT because of small size of the beamlets, dosimetric parameters determination such as the physical penumbra is important and small changes in the penumbra will have a notable impact on result [2]. The desirability to incorporate MLC penumbra into treatment planning beam data depends on the planning system's capabilities. To acquire accurate data in the penumbra region, beam profiles should be measured with special precision [3]. The conventional physical penumbra definition is a one dimensional quantity indicative of the lateral distance between two specified isodose curves at a specified depth of the phantom [2, 4]. Physical penumbra have been evaluated with different methods by various investigators [5, 6].

The effect of different MLC setups on the physical penumbra as the important factor was evaluated, physical penumbra measurements in two directions (X and Y axes) were performed. Factors assessed are impact of the field shape and the position of the end of the leaves in the physical penumbra in two directions (X and Y axes). Surface of two isodose curves (20% and 80%) in reference depth of the phantom (e.g. in our study at z=5 cm) and X-Y plane was calculated, based on this result and Considering the importance of the physical penumbra in radiation therapy protocols, it is necessary to review the conventional definition of physical penumbra, which is a one-dimensional dosimetric parameter and suitable for rectangular fields. In this review, the non-uniformity of the field shape to the physical penumbra must be seen.

In this study by using EGSnrc code first, physical penumbra width according to current definition for different setup MLC are obtained. Due to the lack of conclusiveness in the current definition for IMRT applications, novel beam penumbra parametrization is proposed. In the new dosimetric parameters as two dimensional and comprehensive definitions, the dosimetric field nonuniformity is included in the definition.

Surface penumbra and uniformity index as the new dosimetric parameters defined and for each MLC set up evaluated.

MATERIALS AND METHODS

EGSnrc Monte Carlo simulation package is used to evaluate physical penumbra. EGSnrc is MC code for electrons and photons transport with energy between 40 KEV to several TEV [8]. BEAMnrc and DOSXYZnrc are part of EGSnrc package for LINAC simulation and dose evaluation respectively [9, 10].

A. EGSnrc Validation

As the beam incident on a phantom, the absorbed dose varies with depth. There is an initial region that absorbed dose increases with depth (build up region) and then it decreases with depth [11].

Using the IAEA phase space data for Varian IX LINAC and the Millennium 120 leaf MLC specifications [11, 12].

EGSnrc validation was carried in 3 steps:

In the first step, IAEA phase space data for Varian IX LINAC just above MLC in z=46 cm together with modified MLC with 5×5 field size was modelled in BEAMnrc to produce the new phase space data at z=100 cm .

In the second step, using DOSXYZnrc and the new phase space generated in the first step, dose distribution (3ddose file) in a water phantom of 40×40×20 cm^3 with voxel size of 4×4×2 mm^3 was obtained.

In the third step, using the DOSXYZnrc output (3ddose file) and STATDOSE utility of EGSnrc, depth doses data were obtained (table 1).

For validation of MLC modelling, data obtained was compared with the measured values of PDD (percent depth dose) for Varian LINACs based on IAEA TRS 398 protocol [13], (table 1).

As evident in table 1, Varian IX modelling with EGSnrc code has produced dosimetric parameters which are in good agreement with IAEA TRS 398 protocols.

B: Isodose curve measurement

An isodose chart for a given beam consists of a family of isodose curves usually drawn at equal increments of percent depth dose, representing the variation in dose as a function of depth and transverse distance from the central axis [14].

In this study isodose curve for different field shape obtained.

In the first step, IAEA phase space data for Varian IX LINAC just above MLC in z=46 cm together with modified MLC with 25 cm^2 field size with different MLC setup (5 cases study) is modelled in BEAMnrc to produce the new phase space data at z=100 cm .

In The second step, using DOSXYZnrc and the new phase space generated in the first step, dose distribution (3ddose file) in a water phantom of 40×40×20 cm^3 with voxel size of 4×4×2 mm^3 is obtained.

In the third step, using the DOSXYZnrc output (egslst file) and dosxyz - show utility of EGSnrc, isodose curve plotted. By using the excel software and 3ddose data for 5 cases surface penumbra and uniformity index calculated.

Table 1. Values of depth dose data Varian IX derived from Millennium 120 Leaf MLC and values of dosimetric parameters for Varian linacs based on the IAEA TRS 398 protocol, SSD= 100, field size 5×5 linac model.

	R100 mm	R_{50} mm	R80 mm	D100 %	D200 %
Varian IX	16.7	156.3	56.8	65	34.6
IAEA TRS 398 protocol	16.04	153.8	56.1	67.29	38.7

RESULTS

A. Isodose curves

Isodose curve for five cases study (z=5cm) with different MLC setups by using dosexyz_show plotted.

B. Physical penumbra in X and Y direction

The physical penumbra width is defined as the lateral distance between two isodose curve at a specified depth) lateral distance between 80% and 20% isodose line [15]. Based on this definition, the physical penumbra evaluations for five cases study are performed. Physical penumbra is evaluated in two directions (X and Y axes) (table 2). The impact of the position of the leaves and field shape on the physical penumbra in two directions is assessed.

C. Uniformity Index (UI) and Surface Penumbra

Specifies beam flatness in terms of a uniformity index. For Photon beam, to be consistent with the penumbra dosimetric parameter, the uniformity index is defined as:

$$UI = \frac{\text{Area of 20\% isodose curve}}{\text{Area of 80\% isodose curve}} \qquad (1)$$

At reference depth (ICRU 24) of phantom (e.g. in our study at z=5 cm).

Surface between two isodose curve (20% and 80%) in specified depth of Phantom (z=5 cm) and X-Y plane was calculated, surface penumbra defined as the surface between two isodose curve (20% and 80%) in specified depth of phantom (z= reference) and X-Y plane and calculated.

$$SP = Surface\ area\ of\ 20\%\ isodose - Surface\ area\ o80\%\ isodose \qquad (2)$$

Table 3 represents the Uniformity Index and Surface Penumbra for five case studies.

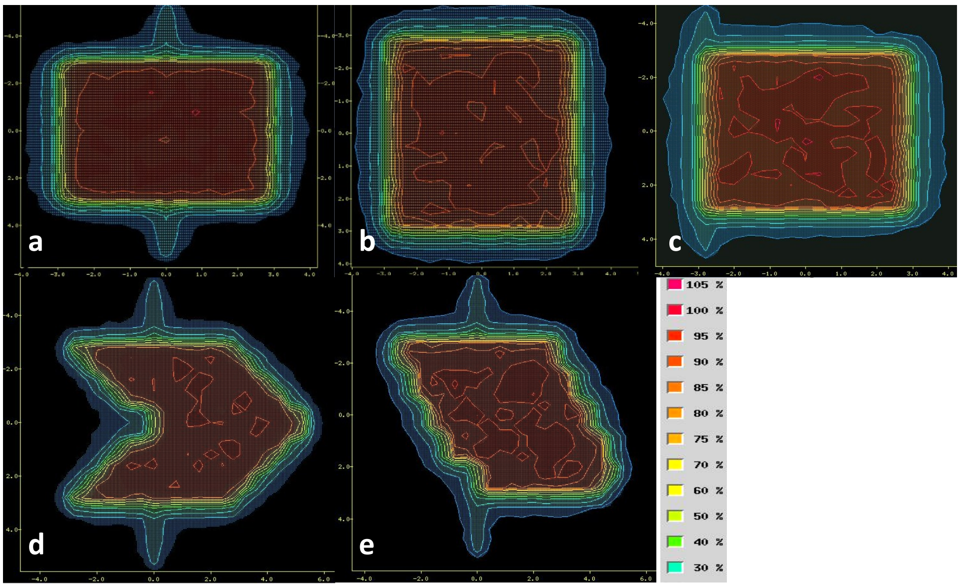

Figure 1. Beams of view of isodose curves measured for square field 5×5, Position of the contact of the closed leaves at (a) X=0. (b) X=-2.5. (c) X=-10. (d) And (e) irregular fields of 25 cm2, Position of the contact of the closed leaves at X=0.

Table 2. Physical penumbra based on the conventional definition, in X and Y directions, SSD=100 cm, Field size=25 cm2 for the case studies presented in figure 1.

Case study	Y-physical penumbra (mm) (At the top of the profile)	Y-physical penumbra (mm) (At the bottom of the profile)	X-physical penumbra (mm) (To the right of the profile)	X-physical penumbra (mm) (To the left of the profile)	position of the end of the closed leaves
Figure 1.a	10.83	9.70	5.08	4.77	X=0
Figure 1.b	5.47	5.05	4.92	3.97	X= -2.5
Figure 1.c	5.48	4.83	4.99	4.92	X= -10
Figure 1.d	20.95	21.31	2.37	6.17	X=0
Figure 1.e	17.46	7.60	5.53	5.52	X=0

Table 3. Uniformity Index and Surface Penumbra for the cases presented in figure 1.

Case study	Surface Penumbra (Cm^2)	Uniformity index	Aria of 80% isodose curve (Cm^2)	Aria of 20% isodose curve (Cm^2)	position of the end of the closed leaves
Fig 1.a	12.35	1.41	29.76	42.10	X=0
Fig 1.b	12.36	1.42	29.31	41.67	X= -2.5
Fig 1.c	13.10	1.46	28.56	41.66	X= -10
Fig 1.d	13.50	1.49	27.35	40.85	X=0
Fig 1.e	13.47	1.49	27.46	40.93	X=0

DISCUSSION

Since CTV (clinical tumor volume) to PTV (planning tumor volume) margin recipe is based on beam penumbra and random and systematic errors [16], physical penumbra is an important parameter in IMRT related TPS (treatment planning system) and medical dosimetry. Kehwar *et al.* (2006) [17] evaluated changes in the dosimetric characteristics of the Varian Millennium 80-leaf multileaf collimator in a radiation field. The results of this study suggest that while one collects linear accelerator beam data with a MLC, the effects of the positions of the MLC leaves play an important role in physical penumbra of 3D conformal radiation therapy and intensity-modulated radiotherapy. Klein *et al.* (2001) [18] studied the effects of tissue heterogeneities on penumbra and the resultant field definition.

Van den Wollenberg W *et al.* (2018) [19] proposed a novel general beam penumbra parametrization for the MR-Linac. The novel parametrization works on general FF (flattening filter) and FFF (free flattening filter) beams.

To define a parameter, the constraints under which the parameter is valid must be clearly specified. The results presented in this study demonstrate that the conventional physical penumbra definition when applied in IMRT, is not Comprehensive definition. The observations are as follows:

1. Based on the result presented in table 2, physical penumbra width (X axis) on right is not equal to penumbra width on left side of isodose curve. The same phenomenon is observed for the physical penumbra width on Y-axis.
2. Meanwhile, penumbra width on the X and Y axes are different. This result is important since in physical penumbra definition there is not any reference to its measurement position. For different radiation field shapes the phenomena of asymmetric physical penumbra is demonstrated in figures 1-a to 1-e.
3. In MLC, the end-leaf position affects the physical penumbra width. As demonstrated in Figures 1a to 1-c, the position of the end of the closed leaves is different and the physical penumbra is different as well. This result is important since in physical penumbra definition there is not any reference to the position of the end of the closed leaves despite its effect on the physical penumbra width.

These problems are due to the definition of the physical penumbra as a one-dimensional parameter, therefore the novel beam penumbra parametrization is proposed. Based on the case studies presented in this paper (figure 1), two new dosimetric parameters are proposed to be substituted for the physical penumbra namely uniformity index and surface penumbra. The surface penumbra complements the conventional one-dimensional penumbra by including the nonuniformity in any direction of dosimetric field. Uniformity index for electron is defined in a reference plane and at a reference depth as the ratio of the areas inside the 90% and 50% isodose lines [20]. The uniformity index (UI), which is an indicative of the dosimetric field nonuniformity are evaluated and illustrated in table 3. As evident, cases 1.*a* and 1.*b* have the lowest UI, which indicate the lower nonuniformity and sharpness of the dosimetric field edges.

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