Sensitivity of film measured off-axis ratios to film calibration curve using radiochromic film

Sensibilidade das razões fora do eixo central medidas para a curva de calibração de filmes usando filme radiocrômico

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Abstract
Off-axis ratios of conical beams generated with a stereotactic radiosurgery-dedicated LINAC were measured with EBT2 film and stereotactic diode. The sensitivity of both full width at half maximum (FWHM) and penumbras (80-20% and 90-10%, respectively), with respect to the characteristics of the film calibration curve fit, was investigated. In all cases, penumbras resulted to be more sensitive than FWHM. However, these differences were, in general, smaller than the ones found between EBT2 reference values and the stereotactic diode measurements. The larger variation in OAR parameters was found to depend on whether the fit intersected or not the origin. A 1D gamma-index analysis showed this difference can be important in all measured conical beams.

Keywords: small field dosimetry, radiochromic film, penumbra.

Resumo
As razões fora do eixo de feixes cônicos criados com um acelerador de partículas linear (LINAC), dedicado à radiocirurgia estereotáxica, foram medidas com um filme EBT2 e diodo estereotáxico. A sensibilidade da largura a meia altura (FWHM) e das penumbras (80-20% e 90-10%, respectivamente), com relação às características da curva de calibração do filme, foi investigada. Em todos os casos, as penumbras mostraram ser mais sensíveis do que FWHM. Entretanto, estas diferenças foram, em geral, menores do que aquelas encontradas entre os valores de referência do EBT2 e as medidas do diodo estereotáxico. Encontrou-se que a maior variação nos parâmetros da razão fora do eixo depende se o ajuste se intersectava, ou não, à fonte. Uma análise do índice de gamma de 1D mostrou que esta diferença pode ser importante em todos os feixes cônicos medidos.

Palavras-chave: dosimetria de campo pequeno, filme radiocrômico, penumbra.

Introduction

Stereotactic radiosurgery (SRS) requires high precision and accuracy in the calculation of dose distributions, due to the high dose delivered to the target and the near presence of healthy radiosensitive tissues. One of the major concerns in SRS is its dosimetry, because of the lack of lateral electronic equilibrium and steep dose gradients existing in large portions of these fields[1].

Along with tissue-maximum-ratios and total output factors, off-axis ratio (OAR) is one of the most important dosimetric parameters to be determined during the characterization of small radiation fields. OAR is defined as in Eq. 1:

$$OAR(c,r,d)=D(c,r,d)/D(c,0,d) \quad (1)$$

where:
c is the diameter of collimator;
r is the off-axis distance perpendicular to central beam axis, and
d is the depth in water.

The FWHM and the penumbras 80-20% and 90-10% are relevant information derived from the OAR. The penumbra 90-10% is particularly important in SRS because the 90% isodose curve is commonly used for dose prescription (instead of the 80% isodose curve used in radiotherapy).

In small field dosimetry, the choice of the suitable detector is another difficulty. In this sense, radiochromic films are detectors with high-spatial resolution and very interesting properties (tissue-equivalence, dose integration, self-development, small or null dependence with energy

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of radiation), which make them appropriate for dose distribution measurements in megavoltage radiation fields with high-dose gradients[2,3].

However, as relative dosimetry detectors, radiochromic films must be calibrated. This paper investigated the sensitivity of measured OAR to the form and characteristics of the used film calibration curve.

Materials and methods

Radiochromic film EBT2

The recently introduced Gafchromic® EBT2 radiochromic film was used for all measurements. Sheets were cut in 3x3 cm^2 pieces for the calibration curve irradiation, and cut in 4x5 in^2 pieces for the field profiles irradiation. The films were handled in accordance with the procedures outlined in the AAPM TG-55 report[4].

Irradiation protocol

Beam diameters ranging from 4 to 20 mm were produced by conical collimators attached to a dedicated SRS 6 MV linear accelerator (Novalis BrainLAB, Germany). Films were irradiated in liquid water at least 24 hours after they were cut.

The calibration curve was built with 16 equidistant points covering the dose interval from 0 to 560 cGy, and performing three measurements per dose point. The irradiation was performed under SAD technique, 5 cm in depth.

The OAR of each conical collimator were obtained irradiating the film pieces under a SAD geometry, 7.5 cm in depth. The used monitor units were such that the dose delivered was between 400 and 450 cGy for all the cones.

The profile for the cones of 4, 10 and 20 mm were also measured with a stereotactic diode (SFD, IBA-Dosimetry, Germany).

Scanning protocol

Film digitization was carried out using a commercial document scanner Epson Perfection V750 Pro, by means of the SilverFast (LaserSoft Imaging, USA) scanning software, 72 hours after they were immersed in water (Aldelaijan[5]). The scanning resolution was 300 dpi, and 48-bits color depth (RGB mode), although only the red channel was used for the analysis.

Analysis

Images were first filtered with a Wiener filter (7x7) in a homemade Matlab (Mathworks Inc., USA) routine. Another routine gave the fit parameters of the selected calibration model, with its respective χ^2. Fifty profiles, 3 cm long around the centroid of the cone image, were averaged to obtain a single OD beam profile.

The reference fit was chosen based on the recommendations made by Bouchard et al.[6], who listed the minimum requirements of a suitable fit function:

- the function intersects the origin;
- the function is strictly increasing;
- the function has zero or one inflection point in the domain of interest;
- if there is an inflection point, it occurs between 0 and $0.5OD_{máx}$.

We analyzed the impact over the OAR of varying the following parameters in the calibration curve:

Analytical expression for the fit.

Number and distribution of experimental points.

Intersection (or not) with origin.

The behavior of the EBT2 film sensitivity is derived from multiple hit theory and assumed to be on the form of a series of dose powers[6]. Different calibration curves were used, which did not meet the above criteria and applied to the measured OAR to evaluate their effect.

Uncertainty analysis

Uncertainty analysis was mainly based on the approach made by Devic et al.[7]. The uncertainty in the dose determined from an OD and the calibration curve takes into account contributions derived from: OD determination; LINAC output instability and calibration fit uncertainty (χ^2). Variations in film-to-film response, the noise of the ROI used for the average pixel value determination, and the electronic noise of scanner contribute to the OD uncertainty.

1D Gamma Index

We compared the gamma index (Γ) between the profiles obtained with the reference curve, and a profile found with the same reference curve does not cross the origin. The latter for the cones of 4 and 20 mm, and allowing a dose difference of 1% in combination with a distance to agreement of 2 mm.

Results and Discussion

Different fits

We chose as a reference calibration fit, the curve with smaller χ^2, and which satisfied the requirements that have already been described. Table 1 shows the analytical form and parameters of different curves used for the intercomparison.

All beam profile data were normalized to the central axis and the beam penumbra was characterized by extracting the beam fall-off widths between 90-10% and 80-20% of dose. Table 2 shows the reference values of these parameters; we also include the values measured using a stereotactic diode SFD.

Implementing different fits to calibration data, we found that the variation of FWHM is always smaller than 1.6% among fits, for all the cone diameters and the penumbras are even more sensitive (Figure 1). For example, there is a difference of 5% between the 80-20% penumbras of the fits *'s1'* and *'log3'* for the cone of 7.5 mm. A similar situation is found for the penumbra 90-10% (4.6% difference between *'s2'* and *'log3'*). In general, *'s1'* underestimates, and *'s2'* and *'poli6'* overestimate the values of the penumbras relative to *'log3'*.

Number and distribution of dose points used for the calibration curve fit

Here, we fit a calibration curve of the form *'log3'* for different sets of images: one set – reference set – consisting of 16 equidistant points in the interval (0,560 cGy); a set of nine equidistant points; a set of 12 points with detail in low doses region; a set of 12 points with emphasis in high doses region. The percentage difference in all of the OAR parameters determined with the four sets resulted always less than 2.3% relative to the reference set, being the set of 12 points (high doses region) that expressed the largest difference. Table 4 shows that the use of a set with detail in high doses results in more slightly closer-to-reference set FWHM and penumbra values than using a set with emphasis in low doses.

Intersection with origin

The Figure 1 shows the variation in FWHM and penumbras after fitting two curves of the form *'log3'* (passing and not through origin) to the experimental data set of 16 equidistant points. Again, the FWHM is relatively insensitive to this variation. However, both penumbras are underestimated by the noncrossing (0,0) fit, at least in 4%.

Based on the results, it is interesting to see how the differences among OAR parameters obtained with diverse film calibration curves are smaller than the ones between 'log3'-values and the stereotactic diode measurements. This variation can be as large as 14% for the penumbra 90-10% in the 4 mm cone.

1D Gamma Index

The *'log3'* is the reference fit curve to the calibration data. From the previous sections, it can be perceived that the same form of fit, when it does not cross the origin, offers one of the largest differences in the values of the OAR parameters. That is the reason why we decided to compare, through the 1D gamma index, the two beam dose profiles obtained with the last mentioned fits. Figure 2 shows the shape of the smallest and biggest collimators' profiles normalized to the beam axis dose.

The average Γ along the profile is 8.5 for the cone of 4 mm, and 2.4 for the one of 20 mm. The mayor contribution to these out-of-tolerance values comes from the low dose regions, where the Γ can easily

Table 1. Parameters of the different fits used for film calibration experimental points

Fit name	Analytical form	Fit parameters	χ^2 [cGy]
'log3'	$D(OD)=a_1Log_{10}[OD+1] + a_2Log_{10}[OD+1]^2 + a_3Log_{10}[OD+1]^3$	a_1=2406.33 a_2=-5965.03 a_3=175960.50	0.44
's1'	$D(OD)=-a_1Ln[1-OD/b]$	a_1=419.74 b=0.45	1.07
's2'	$D(OD)=-a_1Ln[1-OD/b] -a_2Ln[1-OD/b]^2$	a_1=506.48 a_2=-182.95 b=0.59	1.01
'poli6'	$D(OD)=a_1OD+a_2OD^2+a_3OD^3+a_4OD^4+a_5OD^5+a_6OD^6$	a_1=933.45 a_2=337.55 a_3=4669.05 a_4=1765.65 a_5=4228.97 a_6=-6717.24	0.63

Table 2. Measured OAR parameters [mm] for *reference fit 'log3'*

Cone diameter	FWHM (EBT2)	FWHM (SFD)	Penumbra 80-20% (EBT2)	Penumbra 80-20% (SFD)	Penumbra 90-10% (EBT2)	Penumbra 90-10% (SFD)
4	3.87	3.91	1.41	1.35	2.59	2.26
6	5.71		1.58		2.99	
7.5	7.54		1.71		3.29	
10	10.07	10.12	1.88	1.71	3.84	3.23
12.5	12.41		2.10		4.38	
15	14.87		2.11		4.38	
17.5	17.16		2.18		4.62	
20	19.88	20.00	2.18	1.93	4.70	4.05

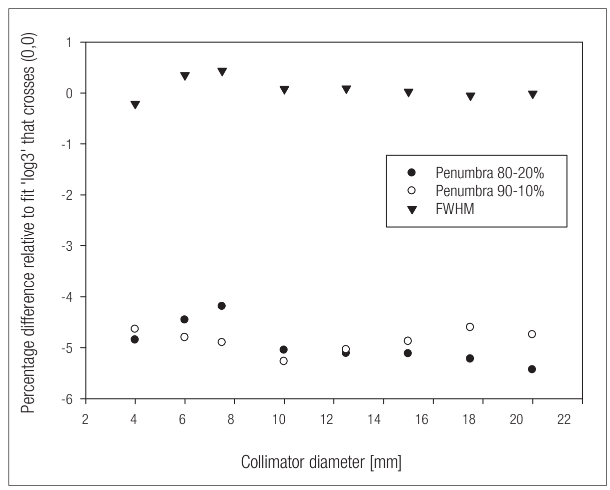

Figure 1. FWHM and penumbras variation depending on the calibration fit 'log3' crossing or not the origin.

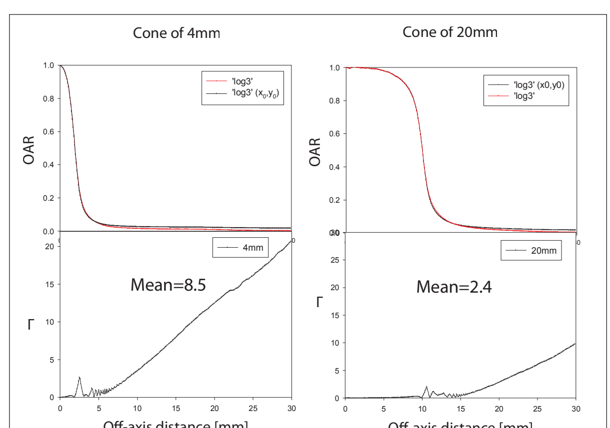

Figure 2. Gamma index for comparing off-axis ratios between a beam dose profile obtained with a fit of the form 'log3' and another of the same form, but it does not cross the origin.

Table 3. FWHM and penumbras percent difference (relative to FWHM and penumbras obtained with 'log3') depending on the kind of fit selected

Cone diameter	FWHM			Penumbra 80-20%			Penumbra 90-10%		
	s1	s2	poli6	s1	s2	poli6	s1	s2	poli6
4	1.55	0.75	0.38	0.79	-1.78	-0.69	-1.41	-4.56	-2.51
6	0.38	0.26	0.09	3.48	0.19	0.30	0.42	-2.87	-1.60
7.5	-0.13	0.01	-0.02	4.92	1.15	0.70	2.19	-1.80	-1.11
10	0.53	0.29	0.13	2.20	-0.85	-0.15	-0.27	-3.68	-2.01
12.5	0.44	0.24	0.11	2.43	-0.66	-0.04	0.04	-3.23	-1.76
15	0.45	0.24	0.11	1.69	-1.16	-0.29	-0.46	-3.56	-1.91
17.5	0.46	0.23	0.11	0.46	-1.97	-0.70	-1.25	-3.95	-2.09
20	0.36	0.18	0.09	1.06	-1.67	-0.53	-0.82	-3.70	-1.93

Table 4. FWHM and penumbras percent difference (relative to FWHM and penumbras obtained with 'log3') depending on the number and distribution of points in calibration data

Cone diameter	FWHM			Penumbra 80-20%			Penumbra 90-10%		
	9 pts	12 pts (LD)*	12 pts (HD)**	9 pts	12 pts (LD)	12 pts (HD)	9 pts	12 pts (LD)	12 pts (HD)
4	-0.30	-0.30	0.07	1.52	0.83	-0.22	2.28	1.29	-0.33
6	-0.38	-0.33	0.08	1.15	0.59	-0.16	1.81	0.97	-0.26
7.5	-0.36	-0.30	0.07	0.98	0.49	-0.14	1.73	0.93	-0.25
10	-0.20	-0.18	0.04	1.52	0.85	-0.22	2.34	1.34	-0.35
12.5	-0.19	-0.17	0.04	1.63	0.95	-0.25	2.20	1.27	-0.33
15	-1.4E-03	-1.3E-03	3.1E-04	0.02	0.01	-2.5E-03	0.02	0.01	-3.4E-03
17.5	-9.7E-04	-9.6E-04	2.2E-04	0.02	0.01	-3.0E-03	0.02	0.01	-3.7E-03
20	-9.0E-04	-8.6E-04	2.0E-04	0.02	0.01	-2.9E-03	0.02	0.01	-3.7E-03

*12 pts (LD), 12 points with detail in low doses; **12 pts (HD), 12 points with detail in high doses.

reach values of 10. Nevertheless, averaging the gamma-index in the profile region, where dose is higher than 5%, the one in the beam axis, for the 20 mm cone it results in Γ=0.26 (96% of the points satisfy the acceptance criterion), and for the 4 mm cone it results in Γ=0.53 (with 81% of the points passing the acceptance criterion).

Conclusions

OAR of conical beams generated with a SRS-dedicated LINAC were measured with EBT2 film. The sensitivity of the FWHM and penumbras 80-20% and 90-10%, with the characteristics of the film calibration curve, was investigated. In all the cases, penumbras resulted to be more sensitive than FWHM to the kind of fit. However, these differences were, in general, much smaller than the ones found between EBT2 reference *'log3'*-values and the stereotactic diode measurements.

The largest differences in OAR parameters were found between curves that intersected (and not) the origin. A 1D gamma analysis showed this difference can be significant, because, for example, 19% of the points in the 4 mm-cone profile did not pass the acceptance criteria.

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References

1. Das IJ, Ding GX, Ahnesjö A. Small fields: Nonequilibrium radiation dosimetry. Med Phys. 2008;35(1):206-15.
2. Ramani R, Lightstone AW, Mason DL, O'Brien PF. The use of radiochromic film in treatment verification of dynamic stereotactic radiosurgery. Med Phys. 1994;21(3):389-92.
3. Wilcox EE, Daskalov GM. Evaluation of Gafchromic EBT film for Cyberknife dosimetry. Med Phys. 2007;34(6):1967-74.
4. Niroomand-Rad A, Blackwell CR, Coursey BM, Gall KP, Galvin JM, McLaughlin WL, et al. Radiographic film dosimetry: Recommendations of AAPM Radiation Therapy Committee Task Group 55. Med Phys. 1998;25(11):2093-115.
5. Aldelaijan S, Devic S, Mohammed H, Tomic H, Liang LH, DeBlois F, et al. Evaluation of EBT2 model Gafchromic film performance in water. Med Phys. 2010;37(7):3687-93.
6. Bouchard H, Beaudon G, Carrier JF, Kawrakow I. On the characterization and uncertainty analysis of radiochromic film dosimetry. Med Phys. 2009;36(6):1931-46.
7. Devic S, Seuntjens J, Sham E, Podgorsak EB, Schmidtlein C, Kirov AS, et al. Precise radiochromic film dosimetry using a flat-bed document scanner. Med Phys. 2005;32(7):2245-53.