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A method to improve the accuracy of diode *in vivo* dosimetry for external megavoltage photon beams filtered by wedges

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Abstract

Diode *in vivo* dosimetry is widely considered to be an important tool for quality improvement of patient care in external radiotherapy. *In vivo* dose measurements for wedged photon beams require correction factor estimation for difference in wedge angles and field sizes. The diode dosimeters that were used in this study were two different models of PTW products; T60010L and T60010M models were used for ^{60}Co and 6-MV photon beams, respectively. The values of off-axis wedge correction factor were determined at two different physical situations in the wedged and non-wedged directions on the entrance surface of the polystyrene phantom. The wedge correction factor at various depths was then estimated by a proposed method. Results show that the absorbed dose at each depth can be estimated by applying accurate wedge correction factor at depth, on entrance surface dose with negligible probable errors (below 1.2%).

Keywords: *In vivo* dosimetry, Diode dosimeter, Ionization chamber, Off-axis wedge correction factor

Introduction

In vivo dosimetry performed with diodes is a reliable method for patient dose control [1]. The major advantage of diode dosimeter compared with TLD dosimeter is that the results of the measurements are immediately available [2,3]. Uncertainty in dose delivery should, in general, fall within ±5% of the prescribed dose as recommended by the International Commission of Radiological Units and Measurements [4].

It is important to know the dosimetric characteristics of diode dosimeters before choosing them to be used in clinical measurements. Therefore, a set of correction factors has to be established to account for the variations of diode response in situations deviating from the reference conditions [5-7].

Wedge filters are routinely used to modify photon intensities to obtain uniformity of dose in the target volume [5,8,9]. According to previous studies, wedge correction factors of ionization chamber dosimeters in different wedge directions at various off-axis distances were different from those at central beam axis [9,10], while in other studies performed by entrance surface diode dosimeters, no differences between them were considered [3,5,11,12]. Thus, it is necessary to investigate the manner of diode reading variations at different directions of externally wedged fields. In clinical situations, sometimes, it is necessary to determine the delivered dose to the organ at risk placed out of the central beam axis for wedged photon beams. Thus, applying a proper wedge correction factor at depth is obligatory for the estimation of organ-at-risk dose value.

In this paper, the off-axis wedge correction factor (OAWCF) was evaluated in different modes: two modes in the wedged direction (thin and thick edges of wedge) and in the non-wedged direction positions. In previous research, utilization of two dosimeters is mandatory for depth dose evaluation in externally wedged beams [10]. However, this paper presents a systematic study of the influences of external off-axis wedge correction factors on dose value for two ranges of photon energies and then suggests a method for estimating the value of dose in each depth of tissue

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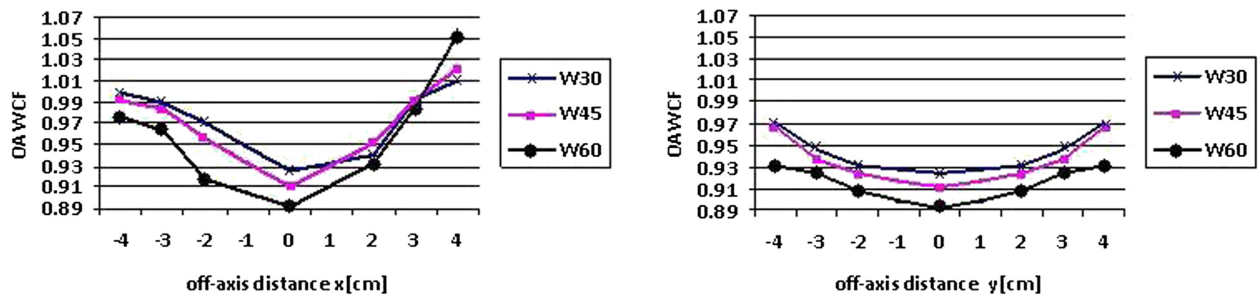

Figure 1 Variations of the OAWCF with 10 × 10-cm^2 fields for ^{60}Co photon beams. They are in the wedged direction (*x*) and in the non-wedged direction (*y*) for three different wedges under reference conditions.

employment in a single diode dosimeter. These estimated absorbed doses are actual values for comparison with the prescribed dose values at each depth of patient tissue. Therefore, our new method can be applied to predict the delivered dose to patient clinical position.

Experimental setup

The investigations were performed using ^{60}Co and 6-MV photon beams generated by Theratron 780C ^{60}Co (Best Theratronics, Ontario, Canada) and Varian Clinac 2100C (Varian Medical Systems, Palo Alto, CA, USA) machines, respectively. T60010L model (p-type diodes for 1 to 5 MV of photon energies range) and T60010M model (p-type diodes for 5 to 13 MV of photon energies range) of PTW diode dosimeter products (PTW, Freiburg, Germany) were used for ^{60}Co and 6-MV photon beams, respectively. Calibration process was done individually for each diode against an ionization chamber dosimeter (TM31013 and TM30010 models of PTW ionization chamber products were used as the reference dosimeters for ^{60}Co and 6MV photon beams, respectively). In order to calibrate the p-type diodes, the procedure reported by previous papers was followed [2,3,5,13-15]. The calibration was performed with the diode positioned on the entrance surface of the polystyrene phantom, with a 15-cm thickness at the center of a 10 × 10-cm^2 field size. The ionization chamber was then inserted into the phantom at the buildup depth ($d_{\mathrm{m,en}}$). ^{60}Co and 6-MV photon beams were used at source-to-skin distances of 80 and 100 cm, respectively. The dose calibration factor (F_{cal}) was determined as the ratio of the absorbed dose measured by the ionization chamber (D) at the buildup depth and the reading of the surface diode (R) under reference conditions:

$$F_{\mathrm{cal}} = \left(\frac{D}{R}\right). \tag{1}$$

The correction factors (CF) for nonstandard irradiation conditions at the entrance surface of the phantom were defined as follows:

$$\mathrm{CF} = \left[(D/R)_{\mathrm{meas}}/(D/R)_{\mathrm{ref}}\right], \tag{2}$$

where $(D/R)_{\mathrm{meas}}$ was the calibration factor measured in the actual geometry and $(D/R)_{\mathrm{ref}}$ was the calibration factor under reference conditions [2,3,6]. Therefore, the OAWCF was determined as follows:

$$\begin{aligned}\mathrm{OAWCF} &= \left[(D/R)_{\text{wedged beam}}/(D/R)_{\text{open beam}}\right]\\ &= \left[\left(D_{\text{wedged beam}}/D_{\text{open beam}}\right) \div \left(R_{\text{wedged beam}}/R_{\text{open beam}}\right)\right]. \end{aligned} \tag{3}$$

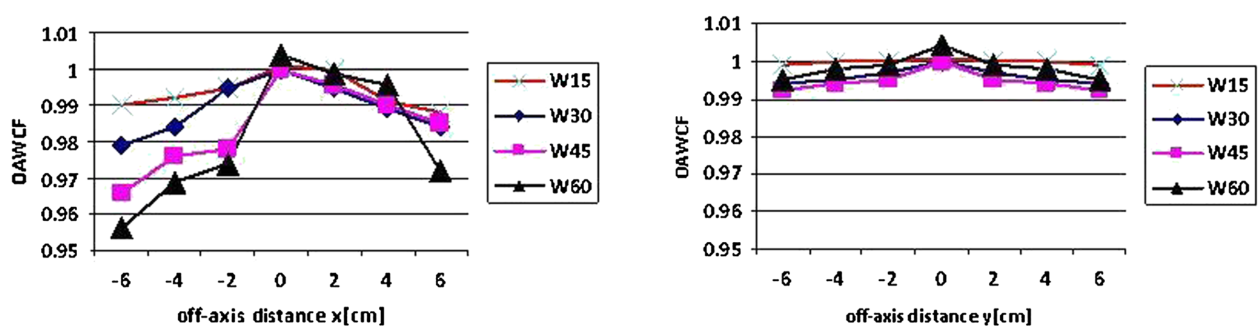

Figure 2 Variations of the OAWCF with 15×15 cm^2 fields for 6-MV photon beams. They are in the wedged direction (*x*) and in the non-wedged direction (*y*) for four different wedges under reference conditions.

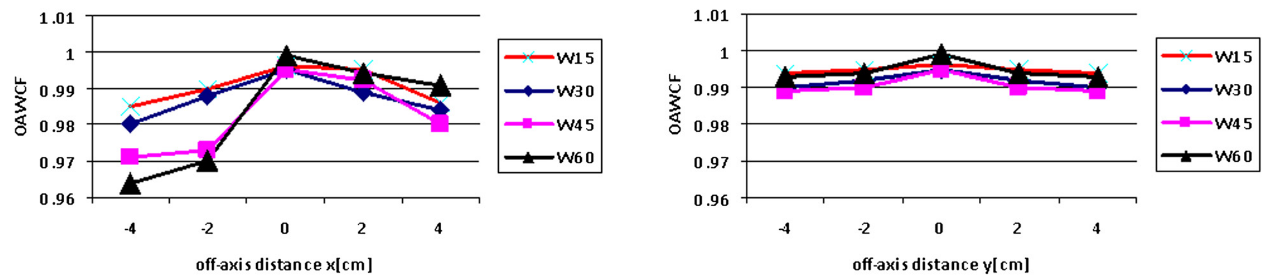

Figure 3 Variations of the OAWCF with 10 × 10-cm^2 fields for 6-MV photon beams. They are in the wedged direction (x) and in the non-wedged direction (y) for four different wedges under reference conditions.

For non-reference conditions of field size ($a \times a$), the OAWCF was given as follows:

$$\mathrm{OAWCF} = \left[\left(D_{[\text{wedged beam},a\times a]}/D_{[\text{open beam},10\times10]}\right) \div \left(R_{[\text{wedged beam},a\times a]}/R_{[\text{open beam},10\times10]}\right)\right]. \quad (4)$$

Depth transmission (T_d) was estimated as the ratio of absorbed dose measured at any depth (D_d) and absorbed dose that was measured at buildup depth (D_m) [8,10,16]. Therefore,

$$T_d = \frac{D_d}{D_m} = (\text{Percentage depth dose})_d = \mathrm{PDD}_d. \quad (5)$$

To obtain OAWCF at any depth, OAWCF can be multiplied by T_d , and it is now called OAWCF_d [10]:

$$\mathrm{OAWCF}_d = \mathrm{OAWCF} \times \mathrm{PDD}_d. \quad (6)$$

According to other investigations, PDD_d values of wedged fields in all directions at different off-axis distances are approximately equal to those of open fields at central beam axis [9,10,17]. Thus, PDD_d values of open-field sizes at central beam axis were used in the given formulas.

In the dose calculation process, the target dose was deduced from the diode reading with the application of a proper calibration factor (F_{cal}) which is corrected with OAWCF_d [4].

In this study, all diode and ionization chamber measurements were done three times, and their average values were reported as the dose number to reduce statistical errors.

To check the accuracy of the proposed method, depth dose values at different off-axis points inside the phantom were measured directly with an ionization chamber dosimeter. Calculated doses were acquired from surface diode readings corresponding to each point (after applying required OAWCF_d), and dose verification was done by comparison of these dose values [10].

Results

Off-axis wedge correction factor

OAWCF was determined for ^{60}Co and 6-MV photon beams. Firstly, the data for 30°, 45°, and 60° wedged fields of ^{60}Co energy in a maximum square field size were adjusted such that they can be opened using these wedges (10 × 10-cm^2 field size). Figure 1 shows the estimated OAWCF as a function of the off-axis distance in the wedged direction and in the non-wedged direction for the mentioned wedges, using a 10×10-cm^2 field size for ^{60}Co photon beams (similar to results in [10]). The data in this figure were determined at two different positions, in the wedged directions, x (positive x is toward the thick edge, while negative x is toward the thin edge) and in the non-wedged direction y.

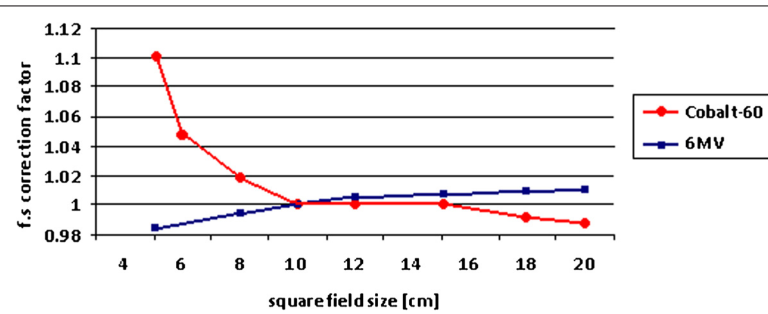

Figure 4 The CF$_{f.s}$ plotted under reference conditions for ^{60}Co and 6-MV photon beams.

Table 1 T_d with possible maximum square field for ^{60}Co and 6-MV photon beams at 15-cm phantom depths

Photon energy	Field size (cm^2)	SSD (cm)	Depth (cm)			
			$d_{m,en}$	5	10	$d_{m,ex}$
^{60}Co	10 × 10	80	1.000	0.788	0.564	0.392
6MV	15 × 15	100	1.000	0.877	0.691	0.566

Also, OAWCF was determined for 15°, 30°, 45°, and 60° wedged fields for 6-MV photon beams with a maximum square field size that can be opened using these wedges (15 × 15-cm^2 field size) and with a reference field size (10 × 10-cm^2 field size). In Figure 2 (similar to results in [10]) and Figure 3, the estimated OAWCF was shown as a function of the off-axis distance in the wedged and in the non-wedged directions using 15 × 15-cm^2 and 10 × 10-cm^2 field sizes for 6-MV photon beams.

Field size correction factor

Figure 4 shows various open field size correction factor ($CF_{f.s}$) using ^{60}Co and 6-MV beams that have been calculated from Equation 2.

Depth transmission

The T_d for ^{60}Co photon beams with 10 × 10-cm^2 fields under reference conditions and for 6-MV photon beams with 15 × 15-cm^2 fields under reference conditions are shown at buildup, $d_{m,en}$ = 5 and 10 cm, and at build down ($d_{m,ex}$) depths in Table 1.

Off-axis wedge correction factor at depth

The $OAWCF_d$ was obtained from Equation 2 in each stage. Table 2 displays the variations of $OAWCF_d$ for ^{60}Co beams in all three wedge angles, using 10 × 10 cm^2-fields in the wedged direction x (positive x is toward the thick edge, while negative x is toward the thin edge) and in the non-wedged direction ±y at depths of 5, 10, $d_{m,en}$ = 0.5, and $d_{m,ex}$ = 14.5 cm. Also, Table 3 displays the variations of $OAWCF_d$ employing a 6-MV beam for all four wedge angles, using 15 × 15-cm^2 fields in the wedged direction x (positive x is toward the thick edge, while negative x is toward the thin edge) and in the non-wedged direction ±y at depths of 5,10, $d_{m,en}$ = 1.6, and $d_{m,ex}$ = 13.4 cm.

Accuracy of method

The results of dose measurements and calculated doses from the proposed method with ^{60}Co photon beams for mentioned wedge angles at three typical positions were presented in Table 4. Also, Comparison of dose measurements and calculated doses from the proposed method with 6-MV photon beams, employing mentioned wedge angles at four typical positions, was presented in Table 5. The results show that the maximum differences between measured and calculated dose values for different ranges of photon energy at all point measurements were less than 1.2%.

Discussion

Comparing the results of OAWCF for field sizes of 15 × 15 and 10 × 10 cm^2 (Figures 2 and 3) with $CF_{f.s}$ for a 15 × 15-cm^2 field size (Figure 4) under 6-MV photon irradiation, it can be deduced that an OAWCF at a non-reference field size is approximated by multiplying the given correction factor at a reference field size by the corresponding correction factor at a non-reference field size. In other words, $CF_{f.s}$ is necessary to account for the diode response difference between the 10 × 10-cm^2 field

Table 2 $OAWCF_d$ in wedged and non-wedged directions employing a ^{60}Co beam between entrance and exit depths

Wedge angle	Depth (cm)	Off-axis distance in wedged direction x (cm)							Off-axis distance in non-wedged direction y (cm)			
		−4	−3	−2	0	2	3	4	0	±2	±3	±4
30°	0.5	0.999	0.989	0.971	0.925	0.940	0.993	1.010	0.925	0.932	0.946	0.971
	5	0.787	0.779	0.765	0.729	0.740	0.782	0.796	0.729	0.734	0.745	0.765
	10	0.563	0.558	0.548	0.522	0.530	0.560	0.570	0.522	0.526	0.534	0.548
	14.5	0.392	0.388	0.381	0.363	0.368	0.389	0.396	0.363	0.365	0.371	0.381
40°	0.5	0.991	0.983	0.956	0.911	0.952	0.994	1.022	0.911	0.924	0.937	0.968
	5	0.781	0.774	0.753	0.718	0.750	0.783	0.805	0.718	0.728	0.738	0.763
	10	0.559	0.554	0.539	0.514	0.537	0.561	0.576	0.514	0.521	0.528	0.546
	14.5	0.388	0.385	0.375	0.357	0.373	0.390	0.401	0.357	0.362	0.367	0.379
60°	0.5	0.977	0.963	0.919	0.891	0.933	0.985	1.054	0.891	0.908	0.924	0.932
	5	0.770	0.759	0.724	0.702	0.735	0.776	0.831	0.702	0.716	0.728	0.734
	10	0.562	0.543	0.518	0.503	0.526	0.556	0.594	0.503	0.512	0.521	0.526
	14.5	0.383	0.377	0.360	0.349	0.366	0.386	0.413	0.349	0.356	0.362	0.365

Table 3 OAWCF$_d$ in wedged and non-wedged directions employing a 6-MV beam between entrance and exit depths

Wedge angle	Depth (cm)	Off-axis distance in wedged direction x (cm)							Off-axis distance in non-wedged direction y (cm)			
		−6	−4	−2	0	2	4	6	0	±2	±4	±6
15°	1.6	0.990	0.992	0.995	1.001	1.000	0.991	0. 988	1.001	1.000	1.000	0.999
	5	0.868	0.870	0.873	0.878	0.877	0.869	0.866	0.878	0.877	0.877	0.876
	10	0684	0.685	0.688	0.692	0.691	0.685	0.683	0.692	0.691	0.691	0.690
	13.4	0.560	0.561	0.563	0.567	0.566	0.561	0.559	0.567	0.566	0.566	0.565
30°	1.6	0.979	0.984	0.995	1.000	0.995	0.989	0.984	1.000	0.997	0.995	0.994
	5	0.859	0.863	0.873	0.877	0.873	0.867	0.863	0.877	0.874	0.873	0.872
	10	0.676	0.680	0.688	0.691	0.688	0.683	0.680	0.691	0.689	0.688	0.687
	13.4	0.554	0.557	0.563	0.566	0.563	0.560	0.557	0.566	0.564	0.563	0.563
45°	1.6	0.966	0.976	0.978	1.000	0.996	0.990	0.985	1.000	0.995	0.994	0.992
	5	0.847	0.856	0.858	0.877	0.873	0.868	0.864	0.877	0.873	0.872	0.870
	10	0.668	0.674	0.676	0.691	0.688	0.684	0.681	0.691	0.688	0.687	0.685
	13.4	0.547	0.552	0.554	0.566	0.564	0.560	0.558	0.566	0.563	0.563	0.561
60°	1.6	0.956	0.969	0.974	1.004	0.999	0.996	0.972	1.004	0.999	0.998	0.995
	5	0.838	0.850	0.854	0.881	0.876	0.873	0.852	0.881	0.876	0.875	0.873
	10	0.661	0.670	0.673	0.694	0.690	0.688	0.672	0.694	0.690	0.690	0.688
	13.4	0.541	0.548	0.551	0.568	0.565	0.563	0.550	0.568	0.565	0.565	0.563

size and any other field sizes. This conclusion confirms other published studies [13,14].

As shown in Figure 4, variations of CF$_{f.s}$ in ^{60}Co and 6-MV energies have different trends. The results indicate that variations of this correction factor for ^{60}Co energy significantly are less than those for 6-MV energy. It can be attributed to the fact that beam scattering for ^{60}Co photons is more than that for 6-MV photons.

In some previous studies, measurements of absorbed doses with diode dosimeters were done to calculate target dose using arithmetic mean and geometric methods [3,14,18]. In these cases, the arithmetic mean method and geometric method errors were reported within 4% and 1.5%, respectively. In comparison, the error of our method is within 1.2%.

This can be attributed to the fact that in our proposed method, the estimation of delivered dose at exact depth is considered with a single diode dosimeter, and using approximated depth for the target is avoided. On the other hand, in past investigations wherein a single diode *in vivo* dosimetry was implemented, only wedge correction factors on central beam axis have been used [3,5,11,12], whereas the results in Tables 2 and 3 illustrate that measurements of dose value without applying the related OAWCF$_d$, which may be lead to a major inaccuracy of about 6%.

Table 4 Comparison of calculated and measured dose values at three positions for ^{60}Co photon energy

Positions		Target dose value (cGy)		
Wedge angle = 30°,	1	x = −3 cm	x = +3 cm	y = ±3 cm
d = 5 cm,	Measured	40.95	29.52	32.69
off-axis distance = 3 cm	Calculated	41.51	29.87	32.09
Wedge angle=45°,	2	x = −2 cm	x = +2 cm	y = ±2 cm
d = 10 cm,	Measured	23.68	17.30	18.16
off-axis distance = 2 cm	Calculated	23.82	17.32	18.03
Wedge angle = 60°,	3	x = −4 cm	x = +4 cm	y = ±4 cm
d = 0.5 cm,	Measured	46.96	13.62	20.89
off-axis distance = 4 cm	Calculated	47.53	13.50	21.10

Comparison of calculated and measured dose values out of central beam axis in the wedged direction (toward the thick edge (+x) and toward the thin edge (−x) of wedge) and in the non-wedged direction (±y) at three positions for 10 × 10-cm^2 field sizes of a ^{60}Co photon energy with 30°, 45°, and 60° wedges.

Table 5 Comparison of calculated and measured dose values at four positions for a 6-MV photon energy

Positions		Target dose value (cGy)		
Wedge angle = 15°,	1	*x* = −2 cm	*x* = +2 cm	*y* = ±2 cm
d = 13.4 cm,	Measured	48.09	45.85	46.99
off-axis distance = 2 cm	Calculated	47.52	45.67	46.41
Wedge angle=30°,	2	*x* = −4 cm	*x* = +4 cm	*y* = ±4 cm
d = 5 cm,	Measured	65.04	51.66	58.34
off-axis distance = 4 cm	Calculated	65.07	51.58	58.52
Wedge angle = 45°,	3	*x* = −6 cm	*x* = +6 cm	*y* = ±6 cm
d = 10 cm,	Measured	46.65	26.53	34.79
off-axis distance = 6 cm	Calculated	46.61	25.90	34.81
Wedge angle = 60°,	4	*x* = −4 cm	*x* = +4 cm	*y* = ±4 cm
d = 10 cm,	Measured	41.01	22.27	30.12
off-axis distance = 4 cm	Calculated	40.98	22.23	29.93

Comparison of calculated and measured dose values out of central beam axis in the wedged direction (toward the thick edge (+*x*) and toward the thin edge (−*x*) of wedge) and in the non-wedged direction (±*y*) at four positions for 15 × 15-cm^2 field sizes of a 6-MV photon energy with 15°, 30°, 45°, and 60° wedges.

All in all, it is clear that in a diode *in vivo* dosimetry process, varying physical parameters of beam radiation may cause non-negligible variations on accuracy of diode dosimeter readings.

Conclusions

The *in vivo* dosimetry system using p-type diode dosimeters on the entrance surface for wedged beams was characterized for clinical use. In summary, it can be concluded from the results of this work that the magnitude of wedge correction factor depends on the specific wedge, off-axis distance, and depth in the phantom; it is within 6%. The estimated absorbed doses from the proposed method are actual values for comparison with the prescribed dose values at each depth of tissue homogeneities.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
AM carried out the experiments, analyzed the data, and drafted the manuscript. MA and HN provided guidance at various stages of the study. Other authors - ME, AS, GG - contributed equally in all steps of the present paper. All authors read and approved the final manuscript.

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