Iranian Journal of Medical Physics
Vol. 10, No. 3, Summer 2013, 147-155
Received: April 22, 2013; Accepted: July 21, 2013

IJMP

Original Article

Effective Point of Measurement in Cylindrical Ion Chamber for Megavoltage Photon Beams

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Abstract

Introduction
For dose measurement in Megavoltage (MV) photon beams with ion chambers, the effect of volume occupied by the air cavity is not negligible. Therefore, the result of measurement should be corrected with a displacement perturbation correction factor (P_{dis}) or using an effective point of measurement (EPOM). The aim of this study is to calculate the EPOM for cylindrical ion chamber and to evaluate the fixed EPOM that was recommended by standard dosimetry protocols.

Materials and Methods
Percent depth doses (PDDs) for 6 MV and 18 MV were measured with two types of chambers for different depths and field sizes. The EPOM was calculated using results obtained from measurement data for two types of chambers, comparison of the readings, and using dosimetry, mathematical, and statistical consideration. For displacement correction factor Δr =0, Δr = 0.6r and different Δr, the minimum standard deviations ratio (SDRs) were calculated at several depths and field sizes.

Results
Maximum level of SDRs was about 0.38% and 0.49% (when assuming variable Δr) for 6 MV and 18 MV, respectively (which was less than 0.5% and acceptable). This quantity was greater than one (for assuming Δr = 0.6r) and greater than 2 when there was no shift (Δr =0)

Conclusion
The results show that the recommended shift for cylindrical ion chamber in dosimetry protocols (upstream of 0.6r) is not correct and using a fixed value for the EPOM at all photon beam energies, depths, and field sizes is not suitable for accurate dosimetry.

Keywords: Cylindrical Chamber; Dosimetry Protocols; Effective Point of Measurement; Plane Parallel Chamber.

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1. Introduction

When an ionization chamber is used for radiation dosimetry in a water phantom, it displaces a certain volume of phantom medium. According to the underlying formulation of the cavity theory, the walls of ionization chambers should be water equivalent. However, even if the chamber wall is medium equivalent, the volume occupied by the air cavity can affect the electron fluence. Clearly, the chamber reading will be affected by this missing medium, so the result of measurement should be corrected with correction factor known as displacement perturbation factor (P_{dis}) which is less than unity. In general, P_{dis} depends on depth of measurement, radiation quality, and the physical dimensions of the air cavity [1-3].

The P_{dis} can be calculated as:

$$P_{dis} = \frac{K_{air,w}}{K'_{air,w}} \qquad (1)$$

Where $K_{air,w}$ is the air Kerma at the reference point in the phantom and $K'_{air,w}$ is the air Kerma in the center of the air-filled cavity at reference depth in the water phantom [1]. Attix has described displacement corrections as chamber-shift correction [2].

In experimental measurements, displacement corrections are performed by selecting an effective point of measurement (EPOM) instead of applying a factor to correct the chamber reading according to its position. For a cylindrical chamber, the electrons enter the wall at various depths, generally in front of its center, and hence the electron fluence in the air cavity is representative of that existing at some point in the uniform medium shifted forward of the chamber center, performing shifts depending on the chamber dimensions is necessary [3].

Dutreix J. and Dutreix A calculated that this shift is about -0.85r (r is the chamber radius) for cylindrical chamber [4]. Zielczynski et al. designed a high-pressure tissue equivalent ionization chamber and determined the EPOM for this chamber. Their method was based on the ionization current at several distances from gamma radiation source in a reference radiation field [5]. Zoetelief determined the EPOM for spherical ionization chamber for ^{60}Co, ^{137}Cs gamma rays, and 300kV X-rays inside a water phantom [6].

Recent dosimetry protocols have expressed effective point values according to chamber radius for different energies. The IAEA TRS-277 protocol recommended a shift of 0.5r for ^{60}Co γ rays and increasing it to 0.75r for all higher energy photon beams for cylindrical chambers [7]. In IAEA TRS-381, a shift equal to 0.6r is recommended for all photon beams with qualities equal to or higher than ^{60}Co γ rays. For practical purposes, a value of 0.55r for both photon and electron beams is acceptable [8].

In IAEA TRS-398, the values of old documents have updated and recommended 0.6r shift for ^{60}Co γ rays and all high energy photon beams and 0.5r for electron beams [9].

However, more recent reviews of the experimental evidence and Monte Carlo simulations on the magnitude of the shift showed that the 0.6r shift is not always correct.

Kawrakow et al. evaluated the EPOM of cylindrical ionization chamber in megavoltage photon beams using Monte Carlo simulations with the EGSnrc system. Their results showed that the upstream shift of 0.6r recommended in dosimetry protocols is inadequate for accurate relative photon beam dosimetry, especially in the build-up region [10].

McEwen et al. have investigated the results of Kawrakow experimentally for a wide range of ion chambers and found that errors of up to 1.4 mm could occur for certain chamber designs [11]. Wang and Rogers expressed that the values of P_{dis} for cylindrical chambers in photon beams that are reported in AAPM protocol are incorrect [12]. They also used EGSnrc Monte Carlo simulation codes to evaluate why IAEA, P_{dis} values based on Johansson et al. are incorrect [13]. In another study, they defined replacement correction factors for Farmer ion chamber in electron beams and expressed that the values in the TG-51 dosimetry protocol may be wrong by 0.3% for high-energy beams and by more than 1% for low-energy electron beams [14].

In another study, Huang et al. determined the effective point of measurement of cylindrical ionization chambers for high-energy photon and electron beams [15].

Tessier et al. modeled the correct EPOM shift for 12 thimble ion chambers with EGSnrc Monte Carlo calculations and confirmed that an upstream EPOM shift of 0.6r is too large for thimble ion chambers in high energy photon beams [16]. Tessier also suggested a design for a thimble ionization chamber with zero EPOM by adjusting the wall thickness of chamber [17].

In a new research, Legrand et al. investigated the dependence of the displacement effect on the cavity radius of ion chambers using a Roos chamber and cylindrical chambers with different radii in a ^{60}Co beam. Absolute absorbed dose was measured with respect to the IAEA TRS-398 as well as to the German protocol DIN6800-2. Their results have shown that the recommended corrections in both protocols are not fully adequate [18].

In another study, it was shown that beyond the maximum depth, absorbed dose has deviations of up to 0.6% and 0.5% for IAEA TRS-398 and DIN 6800-2, respectively, and deviations of greater than 1% were found for both protocols in the build-up and maximum region. Therefore, they proposed modified formulas for the determination of the EPOM and the displacement correction factor [19].

The main purpose of this research is to investigate the EPOM of cylindrical ionization chamber in high energy photon beams with a new method and to evaluate the dependency of the EPOM with energy, depth, and field size in order to answer this question: Is the use of a fixed shift (according to dosimetry protocols) suitable for accurate dosimetry?

2. Materials and Methods

The absorbed dose can be obtained from electrometer reading ($Q_{reading}$) as:

$$D = K \times Q_{reading} \qquad (2)$$

Where $Q_{reading}$ should be corrected with K factors. In relative dosimetry (such as pdd or profile measurements) with one type of chamber, these factors are not important because their variation with respect to the position is ignored and any constant factors are eliminated in curve normalization. It is notable that all measured data are normalized to the maximum dose.

In dosimetry protocols, using a parallel plate ion chamber is not recommended for absolute dose determination in high energy photon beams, but it can be used for measuring percentage depth dose on the central axis (relative dosimetry) [9].

In this research, two types of chambers, plane parallel (ppc40, Figure 1) and cylindrical (cc13, Figure 2) ionization chambers (scanditronix-wellhöfer, Germany) were used in the same conditions (only k was different).

For parallel-plate chambers, the EPOM is assumed to be situated in the center of the inside face of the front wall of the chamber [9],[11]. so in order to investigate the EPOM for cylindrical chambers, PDD data were measured using a plane parallel chamber and then were compared with the readings from a cylindrical chamber.

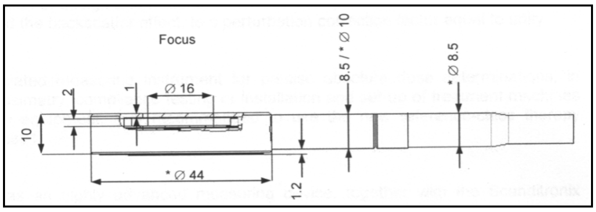

Figure 1. PPC40 ion chamber.

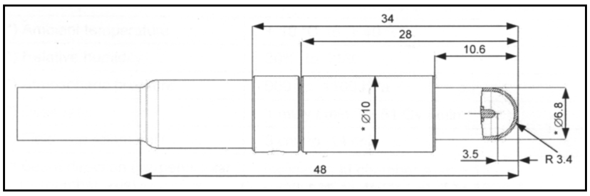

Figure 2. CC13 ion chamber.

As shown in Figure 3, when the center of a cylindrical chamber is placed in a water phantom at R_1 position and exposed to high energy photon beams, the quantity of produced charge in the chamber volume is related to the deposited dose at point R_2 in the water phantom without the chamber. Therefore,

$$D_{med}(R_2) = K_{cylinder} \times Q_{Cylinder}(R_1) \quad (3)$$

$$R_2 = R_1 + \Delta r \quad (4)$$

Where R_1 is the distance between the center of cylindrical chamber and water surface on central axis and Δr is a displacement correction on the central axis.

The same equation for plane parallel is acceptable with a different displacement correction.

$$D_{med}(R_2) = K_{Planeparallel} \times Q_{plane}(R_2) \quad (5)$$

In the above equation, R_2 is the distance between the water surface and the inner surface of the plane parallel chamber.

Therefore, in general we can write:

$$R_{2i} = R_{1i} + \Delta r_i \quad (6)$$

$$D_{Planeparallel}(R_{2i}) = D_{Cylinderical}(R_{1i} + \Delta r_i) \quad (7)$$

Where, Δr_i is the shift correction for the cylindrical chamber. Assume χ_i as the ratio of doses in cylindrical and plane parallel chambers

$$\chi_i = \frac{D_{Cylinder}(R_{1i}+\Delta r_i)}{D_{Planeparallel}(R_{1i})} \quad (8)$$

Therefore, if the shift has a correct value, the χ_i has minimum dependency to the chamber depth and therefore χ_i has the closest value to unity.

The quality of analyzes is presented as a square deviation of the residuals (SDR), i.e.,

$$SDR = \sqrt{\frac{1}{N}\sum_{i=1}^{i=N}\left(\frac{\chi_i - \bar{\chi}}{\bar{\chi}}\right)^2} \quad (9)$$

On the SDR equation, $\bar{\chi}$ is the average of χ_i and is very close to unit so it is assumed as unit in calculations.

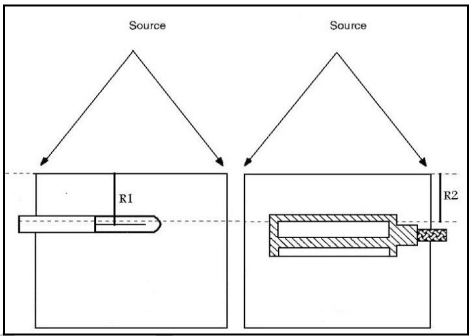

Figure 3. cc13 and ppc40 for measuring cylindrical EPOM in this research.

Data were obtained for two photon energies (6 MV and 18 MV) produced by Varian 2100C/D Linac accelerator. (Field sizes 5×5 cm^2 to 35×35 cm^2) for depths measurement in the range of 0.1 to 300 mm. Three-dimensional water phantom and scanditronix-wellhöfer CUE500E electrometer were used for the dosimetry process.

PPC40 and cc13 chambers were used to determine central-axis depth dose curves for high and low X-ray beams. The center of the geometrical volume of the cylindrical chamber on the water surface was set as the zero point and for thin plane-parallel chambers, it was accepted that the inner front surface of the collecting volume would be set as zero depth. No corrections were applied on the depths of the measurements [9].

As mentioned before, the doses (the charges collected by the chambers) were obtained by the plane parallel chamber in the water phantom at depths from 0 to 30 cm with 0.3 mm steps on the central axis. The readings were normalized to the maximum dose. The same process was done for the other chamber. All dosimetry experiments were done at +300V voltage. Then, both dose measurements

($D_{cylindrical}$ and $D_{planeparalell}$) were compared by SDR minimization.

To provide statistical analysis properties, any point at range of 0.5 cm length with 30 data measurements was investigated.

To achieve the best shift, Δr values were changed to get the minimum SDR. The Δr values were calculated for various depths and field sizes.

3. Results

In order to derive the EPOM, the SDR parameter was calculated at various depths and field sizes for two photon energies.

The variation of SDRs as a function of Δr for the 6 MV and 18 MV photon beams for a 10×10 cm^2 field size are shown in Figures 4 and 5, respectively. The minima of the "V" shape curves indicate the minimal SDRs corresponding to a specific shift value on the Δr axis.

The same process was done for other field sizes (15×15, 20×20, 25×25, 30×30 and 35×35 cm^2) but the related curves are not shown.

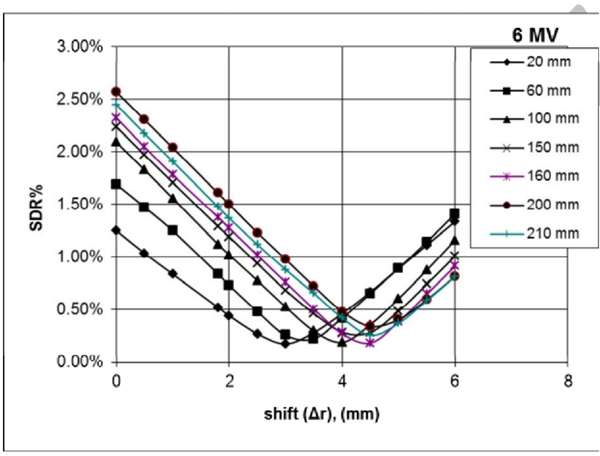

Figure 4. SDRs vs Δr for 6MV photon beams at different depths.

The variation of Δr with field sizes for different energies (6 MV & 18 MV) was investigated too. Results are shown on Figures 6 and 7 and showed that for accurate dosimetry considering fixed value for Δr is not correct.

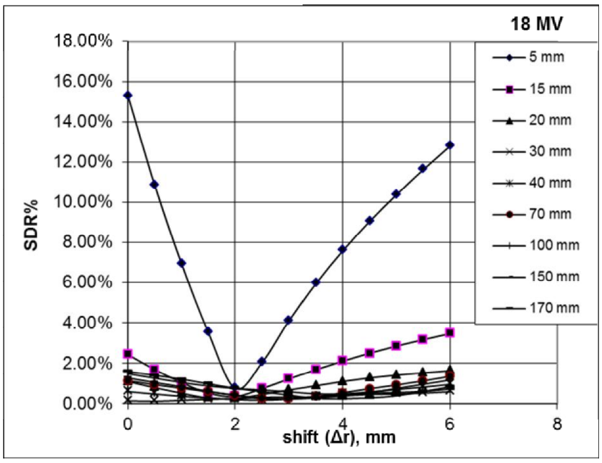

Figure 5. SDRs vs. Δr for 18 MV photon beams at different depths.

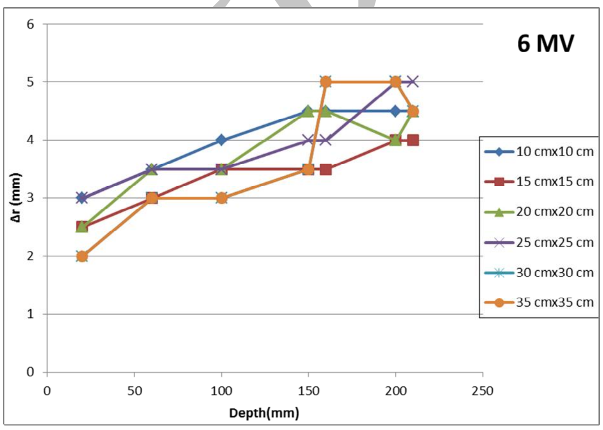

Figure 6. Δr vs. Depth for 6 MV photon beams at different field sizes.

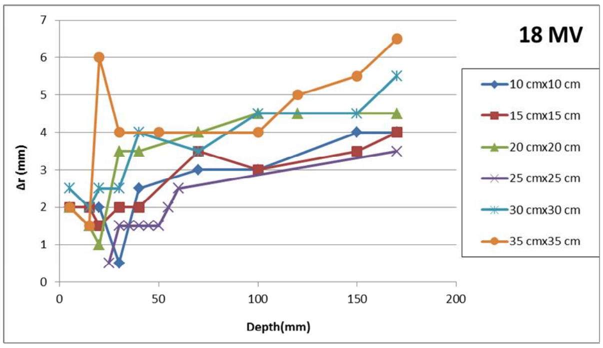

Figure 7. Δr vs. Depth for 18 MV photon beams at different field sizes.

SDRs was calculated for different field sizes and depths considering no shift for effective point of measurement (Δr=0) and are shown in Tables 1 and 2.

Table 1. Minimum SDRs at different depths and field sizes with fixed shift $(\Delta r = 0)$ for 6 MV.

FieldSizes (cm^2) / Depth (mm)	10×10	15×15	20×20	25×25	30×30	35×35
20	1.25	1.11	1.02	1.02	0.79	1.08
60	1.69	1.41	1.47	1.48	1.16	1.31
100	2.09	1.67	1.68	1.78	1.45	1.81
150	2.24	2	2.12	1.87	1.70	1.83
160	2.32	1.86	2.29	1.96	2.20	2.07
200	2.57	2.04	2.42	2.48	2.53	2.35
210	2.45	2.13	2.16	2.40	2.18	2.26

Table 2. Minimum SDRs at different depths and field sizes with fixed shift $(\Delta r = 0)$ for 18 MV.

FieldSizes (cm^2) / Depth (mm)	10×10	15×15	20×20	25×25	30×30	35×35
30	0.15	0.48	0.70	0.31	0.75	1.05
35	0.36	0.86	0.88	0.49	0.98	1.18
40	0.60	0.65	1.18	0.50	1.33	1.27
50	0.85	0.89	1.35	0.71	1.35	1.34
60	0.96	1.16	1.33	0.86	1.28	1.45
70	1.15	1.33	1.57	0.88	1.22	1.49
100	1.28	1.11	1.64	0.98	1.46	1.63
150	1.50	1.57	2.02	1.43	1.83	2.02
170	1.61	1.90	1.65	1.34	1.90	2.07

As mentioned before, standard dosimetry protocols recommend a fixed shift value (0.6 r_{cyl}) for all depths and field sizes. It equals 1.8 mm for the ion chamber that was used in this study. The minimum SDRs values for this situation $(\Delta r = 1.8mm)$ for 6 MV and 18 MV were calculated and are shown in Tables 3 and 4.

Table 3. Minimum SDRs at different depths and field sizes with fixed shift $(\Delta r = 1.8mm)$ for 6 MV.

FieldSizes (cm^2) / Depth (mm)	10×10	15×15	20×20	25×25	30×30	35×35
20	0.64	0.36	0.36	0.41	0.23	0.45
60	1	0.62	0.67	0.76	0.50	0.58
100	1.28	0.81	0.84	0.94	0.66	1.06
150	1.44	1.06	1.27	1.06	0.92	1.09
160	1.53	0.88	1.40	1.10	1.45	1.27
200	1.77	1.11	1.42	1.64	1.67	1.57
210	1.64	1.08	1.28	1.53	1.30	1.41

Table 4. Minimum SDRs at different depths and field sizes with fixed shift $(\Delta r = 1.8mm)$ for 18 MV.

FieldSizes (cm²) / Depth (mm)	10×10	15×15	20×20	25×25	30×30	35×35
30	0.24	0.23	0.42	0.18	0.35	0.64
35	0.23	0.47	0.36	0.17	0.51	0.70
40	0.23	0.16	0.65	0.18	0.69	0.62
50	0.20	0.24	0.73	0.27	0.76	0.76
60	0.28	0.45	0.71	0.34	0.69	0.85
70	0.44	0.60	0.94	0.35	0.60	0.90
100	0.50	0.51	0.98	0.37	1.01	0.94
150	0.81	0.84	1.35	0.78	1.14	1.35
170	0.85	1.10	1.11	0.69	1.26	1.44

Table 5. Δr(mm) and minimum SDRs at different depths and field sizes for 6 MV.

Field Sizes (cm²)	10×10		15×15		20×20		25×25		30×30		35×35	
Depth (mm)	Δr(	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)
20	3	0.18	2.5	0.16	2.5	0.15	3	0.16	2	0.19	3	0.15
60	3.5	0.23	3	0.23	3.5	0.20	3.5	0.17	3	0.16	3	0.16
100	4	0.19	3.5	0.20	3.5	0.20	3.5	0.22	3	0.26	4	0.18
150	4.5	0.28	3.5	0.30	4.5	0.25	4	0.25	3.5	0.26	4.5	0.25
160	4.5	0.19	3.5	0.23	4.5	0.22	4	0.24	5	0.21	4.5	0.16
200	4.5	0.34	4	0.32	4	0.38	5	0.19	5	0.28	5	0.30
210	4.5	0.26	4	0.36	4.5	0.25	5	0.27	4.5	0.19	4.5	0.25

Table 6. Δr(mm) and minimum SDRs at different depths and field sizes for 18 MV.

Field Sizes (cm²)	10×10		15×15		20×20		25×25		30×30		35×35	
Depth (mm)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)	Δr	SDR(%)
30	0.5	0.12	2	0.24	3.5	0.24	1.5	0.14	2.5	0.27	4	0.12
35	1.5	0.20	3	0.17	3	0.17	1.5	0.15	3	0.16	3.5	0.23
40	2.5	0.18	2	0.12	3.5	0.34	1.5	0.12	4	0.12	3.5	0.16
50	2	0.18	2.5	0.19	3.5	0.19	1.5	0.27	3.5	0.16	4	0.16
60	2.5	0.23	3	0.25	4	0.19	2.5	0.17	3.5	0.23	4.5	0.12
70	3	0.24	3.5	0.26	4	0.34	2	0.34	3.5	0.21	4.5	0.11
100	3	0.24	3	0.21	4.5	0.10	2.5	0.22	4.5	0.18	4	0.19
150	4	0.49	3.5	0.24	5.5	0.20	4	0.19	4.5	0.15	5.5	0.20
170	4	0.25	4	0.14	4.5	0.26	3.5	0.24	5.5	0.11	6.5	0.27

The values for Δr corresponding to the minimum SDR are presented in Table 5 (6 MV) and Table 6 (18 MV) for different depths and field sizes.
As demonstrated in Tables 5 and 6, field sizes and depths can affect Δr values for 6 MV and 18 MV photon beams.
Δr can cause SDR reduction if it is assumed as a function of depth . From Tables 5 and 6 one can see that the maximum of SDR values to be equal to 0.38% and 0.49% for 6 MV and 18 MV photon beams, respectively.

4. Discussion

Results of this research showed that, if the EPOM shift is not considered at all, SDRs will be big and cannot be accepted. From Tables 1 and 2, the maximum of SDRs in this case (Δr=0) is about 1. 69 for depths up to 6 cm and 2.57 for depths beyond 6 cm in 6 MV and about 1.45 for depths up to 6 cm and 2.07 for depths beyond 10 cm in 18 MV photon beams (the errors are greater than 0.5%).
Some researchers evaluated the EPOM of cylindrical ionization chambers in megavoltage photon beams and showed that -0.6r shift that is recommended in dosimetry protocols is not always correct. These researches showed that the EPOM depends on the chamber design including the cavity height and radius, the mass density of the wall material, the size of central electrode, and some other parameters [11, 16, 18,20].
The results of this study are in agreement with their results, because using fixed value (-0.6r) for the cc13 ionization chamber that was used in this work, (equal to Δr=1.8 mm) can cause a maximum error of about 0.76% (maximum of SDRs from Tables 3 and 4) for depths up to 5 cm and 1.77% for depths beyond 6 cm for 6 MV and 1.01% for depths up to 10 cm and 1.44% for depths beyond 10 cm for 18MV photon beams. The errors are greater than one and not acceptable.
In general, the value of p_{dis} depends on both the radiation quality and the physical qualities of the air cavity in the direction of the beam, and also on the depth of measurement. In some applications such as photon beams, the displacement is assumed to be practically constant beyond the depth of maximum dose [3, 9,21] but our results suggest to use different effective points for various depths and energies.
Results of this research also showed that using a Δr that varies with depth, field size, and energy can reduce SDRs. From Tables 5 and 6, maximum of SDRs for this situation is only about 0.38% in 6 MV and 0.49% in 18 MV that are less than 0.5% and are acceptable.

5. Conclusions

It is recommended to use variable EPOM values when beam qualities, depths, and field sizes have major variation in dose measurement.
Data analyses indicate that SDR values increase in deeper depths. It seems that this effect is due to the variation of radiation quality with depth but in dosimetry process, quality of radiation is considered as a constant value and the increase of SDRs in 6 MV is more significant than 18 MV. It might be because of more scattering that occurs in 6 MV than 18 MV.
Similar study with Monte Carlo methods for different energy spectra and radiation quality factor in order to obtain EPOM variation with depths and field sizes is recommended.

Acknowledgment

This work was supported by the Student Research Committee of Ahvaz Jundishapur University of Medical Sciences [Grant number: 90s.111].

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