The EPOM shift of cylindrical ionization chambers - a status report

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Introduction

The shift of the effective point of measurement (EPOM) from the reference point (the symmetry axis) of a cylindrical ionization chamber has been experimentally determined for high-energy X-rays by Johansson et al 1978, Huang et al 2010 and Looe et al 2011. For Co-60 gamma radiation, experimental EPOM shift determinations have been carried out by Johansson 1978, Swanpalmer and Johansson 2011 and by Legrand et al 2012. A preliminary review of these results will be given here in order to prepare the consideration of this subject in standards and codes of practice, and to clarify the need for additional measurements. The new issues to be dealt with are (1) that the quotient of - Δz (the upstream EPOM shift) and r (the inner chamber radius), - $\Delta z/r$, is *not constant, but depends on r*, and (b) that in high-energy X-ray fields the EPOM shift - Δz is constant over all depths from the buildup region down to and beyond the "reference depth" (10 cm), whereas in a Co-60 gamma-ray beam the value of - Δz at the reference depth (5 cm) *significantly differs* from that in the region of the depth-dose maximum. This has a bearing upon the calibration of ionization chambers in Co-60 gamma-ray fields.

Methods and Materials

This paper gives a review of published results, so that the experimental methods can be assumed as known to the reader. In our comparison of EPOM shifts between various authors we apply the convention that the EPOM shifts are derived from plots of relative (maximum-normalized) depth dose curves of the same radiation field measured with ionization chambers of different inner radius. In a *first step* the relative depth dose curves are plotted with z = depth coordinate of the *reference point* of the chamber. The assumption of equal amplitudes of the depth-dose maxima corresponds to the assumption that the correct calibration of all compared chambers would yield equal absolute maximum values. In a *second step* the relative depth dose curves are *shifted* to fit a reference depth curve measured with a Roos chamber whose EPOM is known to lie 1.5 mm below its proximal surface. This EPOM shift of the Roos chamber was experimentally determined for high-energy X-rays by Looe et al 2007, Bruggmoser et al 2007, and Looe et al 2011, but still needs experimental confirmation for Co-60 gamma radiation.

Results

A survey of the presently available experimental values of - Δz for high-energy X-rays and for Co-60 gamma radiation is given in Tables 1 to 3. The first two tables show that the r dependence of the quotient - $\Delta z/r$, predicted in Monte Carlo calculations by Tessier 2010a, 2010b, has been experimentally observed for high-energy X-rays by Looe et al 2011, for Co-60 gamma radiation by Swanpalmer and Johansson 2011 and Legrand et al 2012.

Whereas all authors determined - Δz values holding for the build-up branch and the maximum region of the depth dose curve, Legrand et al 2012 also made separate determinations of the - Δz values for the depth 5 cm in a Co-60 gamma-ray beam (Table 3). For the larger chamber radii, these - Δz values were *significantly smaller* than their values for the build-up branch and the region of the depth-dose maximum. Legrand et al 2012 hereby confirmed the existence of an effect already showing up in the paper by Johansson et al 1978 for Co-60 gamma radiation, whereas Johansson et al have not observed it for high-energy X-rays. We have again checked this issue by intercomparing the depth dose curves of 6 and 15 MV photon beams of a Siemens Artiste linac, measured in water with a Roos chamber, with a semiflex chamber of inner radius 2.75 mm (PTW 31013) and with a rigid stem chamber of 3.95 mm inner radius (PTW 23331): we again observed that *for high-energy X-rays* the EPOM shift remains practically the same whatever the depth in water.

Table 1:
Experimentally observed EPOM shift values for cylindrical ionization chambers; high-energy X-rays

Authors	Examined detectors, radius and type	Reference detectors	Photon beam quality	EPOM shift -Δz in mm	Quotient -Δz/r
Johansson et al 1978[1)]	cylindrical chamber 3.5 mm (J-70)	chambers with different radii	5 to 42 MV	 2.3 ± 0.1	 0.65 ± 0.03
Huang et al 2010	cylindrical chambers 2.75 mm (PTW 31002) 2.75 mm (PTW 31003) 3.05 mm (PTW 30006)	Roos chamber	6 and 15 MV	 1.5 ± 0.08 1.5 ± 0.08 1.7 ± 0.09	 0.55 ± 0.03 0.55 ± 0.03 0.55 ± 0.03
Looe et al 2011	cylindrical chambers 1.0 mm (PTW 31006) 2.5 mm (PTW 23332) 2.75 mm (PTW 31013) 3.95 mm (PTW 23331)	Roos chamber	6 and 15 MV	 0.3 ± 0.05 0.9 ± 0.1 1.3 ± 0.1 2.3 ± 0.2	 0.30 ± 0.05 0.36 ± 0.04 0.47 ± 0.04 0.58 ± 0.05

[1)] Measurements in a PMMA phantom

Table 2:
Experimentally observed EPOM shift values for cylindrical ionization chambers; Co-60 gamma radiation; values for the buildup branch and the dose maximum region

Authors	Examined detectors, radius and type	Reference detectors	Photon beam quality	EPOM shift - Δz in mm	Quotient -Δz/r
Johansson et al 1978[1)]	cylindrical chamber 3.5 mm (J-70)	chambers with different radii	Co-60 gamma rays	 2.3 ± 0.1	 0.65 ± 0.03
Swanpal-mer and Johansson 2011[1), 2)]	cylindrical chambers 1.5 mm (J-30) 2 mm (CC04) 3 mm (CC13) 3.5 mm (J-70)	chambers with different radii	Co-60 gamma rays	 0.62 ± 0.1 1.55 ± 0.1 2.53 ± 0.1 2.73 ± 0.1	 0.41 ± 0.07 0.78 ± 0.05 0.84 ± 0.03 0.78 ± 0.03
Legrand et al 2012	cylindrical chambers 1.0 mm (PTW 30013.1.911) 2.0 mm (PTW 30013.1.921) 2.75 mm (PTW 31010) 3.05 mm (PTW 30013) 4.0 mm (PTW 30013.1.941) 5.0 mm (PTW 30013.1.951) 6.0 mm (PTW 30013.1.961)	Roos chamber	Co-60 gamma rays	 0.2 ± 0.3 1.0 ± 0.2 1.6 ± 0.3 2.0 ± 0.4 2.4 + 0.3 3.6 ± 0.2 4.6 ± 0.4	 0.2 ± 0.3 0.5 ± 0.1 0.6 ± 0.1 0.7 ± 0.1 0.6 ± 0.1 0.72 ± 0.04 0.8 ± 0.1

[1)] Measurements in a PMMA phantom
[2)] The values of - Δz were obtained by assuming the dose maximum to lie at 4 mm depth in PMMA

Table 3:
Experimentally observed EPOM shift values for cylindrical ionization chambers; Co-60 gamma radiation; values for the "reference depth" 5 cm in water

Authors	Examined detectors, radius and type	Reference detectors	Photon beam quality	EPOM shift -Δz in mm	Quotient -Δz/r
Legrand et al 2012	cylindrical chambers 1.0 mm (PTW 30013.1.911) 2.0 mm (PTW 30013.1.921) 2.75 mm (PTW 31010) 3.05 mm (PTW 30013) 4.0 mm (PTW 30013.1.941) 5.0 mm (PTW 30013.1.951) 6.0 mm (PTW 30013.1.961)	Roos chamber	Co-60 gamma rays	 0.9 ± 0.3 1.4 ± 0.2 1.5 ± 0.2 2.0 ± 0.4 2.2 + 0.3 3.0 ± 0.2 3.5 ± 0.4	 0.9 ± 0.3 0.7 ± 0.1 0.6 ± 0.1 0.7 ± 0.1 0.6 ± 0.1 0.60 ± 0.04 0.6 ± 0.07

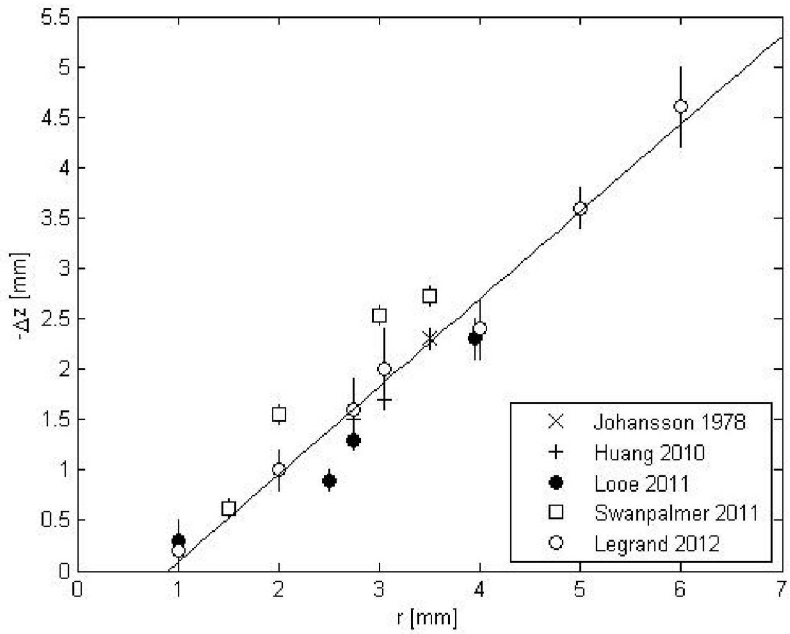

Fig. 1 Measured values of the EPOM shift, - Δz, as a function of the inner radius r of the examined ionization chamber (Tables 1 and 2). Data for high-energy X-rays (Johansson, Huang, Looe) are valid for the entire depth dose curves; data for Co-60 gamma radiation (Johansson, Swanpalmer, Legrand) are valid for the buildup and maximum regions of the depth-dose curves. Interpol. line see eq. (1).

Fig. 1 shows an approximately uniform dependence of the EPOM shift of all examined chambers on their inner radius - a linear increase above a threshold value of the radius at about 0.9 mm. The threshold can be explained by the role of the secondary electrons emitted by the central electrode: with increasing relative contribution of these electrons to the total chamber signal the EPOM will tend to approach the symmetry line of the chamber. This interpretation is underpinned by Monte Carlo results obtained with chambers equipped with thick central electrodes (Tessier 2010 a,b).

The straight interpolation line drawn in Fig. 1 corresponds to the equation

$$- \Delta z = 0.87\ (r - 0.9) \quad \text{with } \Delta z \text{ and r in mm} \qquad (1)$$

and may be used for all inner radii of cylindrical ionization chambers from 1 to 6 mm with an uncertainty of - Δz by not more than 0.5 mm for high-energy X-rays as well as Co-60 gamma rays. This empirical rule replaces the previous rule - Δz = 0.6 r (IAEA TRS 398) or - Δz = 0.5 r (DIN 6800-2). It is valid for the EPOM shift of *the entire depth dose curve (high energy X-rays) and of the buildup and maximum region in the case of Co-60 gamma rays*.

For the special case of the *depth region around 5 cm in a Co-60 gamma-ray beam*, Legrand et al 2012 approximated their data (Table 3) by a linear relationship which can be rewritten as

$$- \Delta z = 0.53\ (r + 0.45) \quad \text{with } \Delta z \text{ and r in mm} \qquad (2)$$

This relationship is close to the hitherto used relationship - Δz = 0.5 r; but anyway it would be appropriate to accordingly change the correction factor k_r (DIN 6800-2). This factor is regularly applied to compensate for the displacement effect when cylindrical ionization chambers, with their axes positioned at a depth of measurement of 5 cm in water, are calibrated in a Co-60 gamma-ray field. The corrected k_r value would then amount to

$$k_r = 1 + 0.006 \times 0.53\ (r + 0.45)\ \text{(with r in mm)} \qquad (3)$$

For the chambers with r between 2 and 3 mm, this value exceeds the previous k_r value by 0.2 %.

Discussion

For high-energy X-rays, experiments have confirmed that the EPOM shift is constant throughout all depths, from the buildup region up to and beyond the region of the reference depth (10 cm). This holds with high precision at 6 MV and still in a very good approximation at 15 MV. The associated value of the EPOM shift is represented by eq. (1). For Co-60 gamma radiation, the EPOM shift in the buildup branch and in the maximum region of the depth dose curve also corresponds to eq. (1), whereas in the region of the reference depth (5 cm) the EPOM shift corresponds to eq. (2). After a qualitative indication of this effect in Johanssons paper 1978, it was quantified by Legrand et al 2012 and is also described by Legrand et al in this conference.

In order to understand this phenomenon it is useful to remember that the displacement effect, underlying the EPOM shift of a cylindrical ionization chamber, is due to the *preferred entry of secondary electrons into the upstream surface* of the chamber, a geometrical effect which in turn is caused by the preferred forward flight direction of the secondary electrons in the surrounding medium. This preferred orientation of the electron tracks is well-known from bubble chamber pictures and is known to cause the buildup effect. Therefore the chamber signal corresponds to a mean value of the secondary electron fluence weighted by their entry points on the surface of the chamber, which preferently lie on the upstream side.

This picture will however change with changing directional distribution of the secondary electrons in the surrounding medium. This distribution is coined by their initial directions due to the Compton effect in the relativistic energy region and by their further transport under the influence of their ranges and multiple scattering. While the mean initial energy of the Compton electrons produced by 6 or 15 MV X-rays is near or beyond 1 MeV, it amounts to less than 0.5 MeV in case of the Co-60 gamma radiation. Furthermore there is a change of the spectrum and directional distribution of the *photons* with increasing depth, to be characterized by their mean energies in the reference depths of 10 cm for the high-energy X-rays and 5 cm for the Co-60 gamma rays (see Fig. 2). These mean energies are 1.2 MeV and 2.9 MeV for the 6 and 15 MV X-rays, with an *increasing* tendency at the larger depths due to a dominating filter effect, whereas the mean energy is only 0.9 MeV for the Co-60 gamma radiation, with a *decreasing* tendency at the larger depths due to the dominating effect of the buildup of Compton-scattered photons (Chofor et al 2012). We are in the process of more precisely modeling these spectral influences upon the directional distribution of the secondary electrons.

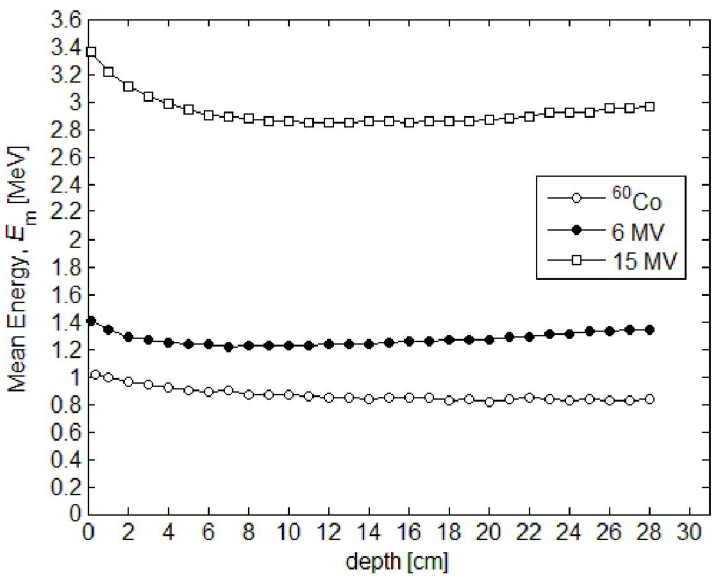

Fig. 2 The depth dependence of the mean photon energy $E_m = \int E\ \Phi_E(E)\ dE \ / \int \Phi_E(E)\ dE$ with $\Phi_E(E)$ = spectral fluence, Monte-Carlo calculated for on-axis points in 15 MV, 6 MV and Co-60 photon beams of SSD 100 cm and surface field size 10 cm × 10 cm, as a function of the depth in water (Chofor 2012).

In this paper, Monte Carlo calculations have been considered to give essential qualitative information such as on the r dependence of the quotient - $\Delta z/r$ and on the role of the central electrode (Tessier et al 2010a,b), as well as on the depth dependence of the mean photon energy E_m (Chofor 2012). The highest possible accuracy of the EPOM data, however, can presently be achieved experimentally, because the experimental data are subject to all possible influences and effects whereas the Monte Carlo calculations can only reflect the effects that have been implemented in their algorithms.

Conclusions

In conclusion, experiments have shown that the dependence of the EPOM shift of cylindrical ionization chambers upon the chamber radius follows equations (1) and (2) and differs from the previously assumed proportional relationship. The different EPOM-radius relationship for Co-60 gamma rays observed by Legrand et al 2012 near the reference depth of 5 cm has been qualitatively explained by the different directional distribution of the secondary electrons entering the chambers. We recommend to use eq. (1) to allow for the EPOM shift in the measurement of the depth-dose data of high-energy X-rays, but to use eq. (3) to determine factor k_r in the context of chamber calibrations in Co-60 gamma-ray beams. The position of the EPOM of the Roos chamber at 1.5 mm below its proximal surface still needs experimental confirmation for Co-60 gamma radiation.

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