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Monte Carlo correction factors in small field absolute dosimetry

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Abstract.

The calculation by Monte Carlo of correction factors (c) for three air filled PTW chambers (models 31014, 31010 and 30006) in the measurement of output factors (OF) of narrow, MLC-conformed square fields of a 6 MV photon beam is studied in this work. By including detector geometry in the simulations dose to water and dose to chamber air are calculated at 5 cm depth inside a water phantom. Large uncertainties in these OFs are obtained due to the uncertainties in the process of commissioning the accelerator in the simulations. This dependence of the results on the characteristics of the primary electron beam is explained with a simple dual source model.

After correction of measurements by the Monte Carlo calculated c factors a nice agreement with diamond and diode detectors and with a new measurement technique involving relative film dosimetry and a large area plane-parallel chamber is obtained. As the final outcome of this work the accuracy of the Monte Carlo method in correcting chamber measurements in small field dosimetry and the possibility of determining c factors in these conditions that could be included in reference dosimetry protocols are addressed.

1. Introduction

Dose determination in narrow beams is a very difficult task because of the extreme conditions in which it is performed. The lack of lateral CPE and the hardest spectra compared to wider fields makes detectors suitable for larger fields exhibit systematic errors in these conditions. Many works have been devoted to investigate this issue in radiosurgery (see for example Heydarian *et al* 1996, Francescon *et al* 1998, McKerracher and Thwaites 1999, Westermark *et al* 2000 and Paskalev *et al* 2003). In intensity modulated radiation therapy (IMRT) many researchers have been already concerned about the dosimetry of the narrow segments that should be delivered in order to build up the intended final dose distribution (Laub *et al* 2003, Haryanto *et al* 2002 and De Vlamynck *et al* 1999). In most of these works it was clearly pointed out that relative dosimetry of small fields can be accurately conducted employing film (conventional or radiochromic) or diodes (McKerracher and Thwaites 1999, Westermark *et al* 2000). However, the difficulties in absolute dose determination have been addressed in all of them.

Current absolute dosimetry protocols such as IAEA TRS-398 (Andreo *et al* 2000) or AAPM TG-51 (Almond *et al* 1999) only provide methods and correction factors for reference conditions. Extending the absolute reference dose towards small fields relies on accurate output factor determination. For field sizes larger than the reference one (usually 10 cm x 10 cm at SSD = 100 cm) there are several detectors that have been proved reliable measurements. However, when narrow beams are considered, the severe lateral electronic non-equilibrium strongly affects measurements carried out with large air-filled active volume detectors (McKerracher and Thwaites 1999). Diodes and diamond detectors avoid these drawbacks at the cost of having and over-response to low energy photons or a noticeable dose rate dependence, respectively (see for example Fidanzio *et al* 2003 or Westermark *et al* 2000). Thus, currently there are no detectors and well established procedures that fully assure accurate measurements for fields as small as 0.5 cm x 0.5 cm. Nevertheless, the most convenient detectors are, as shown in the above mentioned works, natural diamond detectors or diodes.

Previous studies of measurements in the buildup regions of megavoltage beams (Pena *et al* 2006a) or in IMRT absolute dosimetry (Capote *et al* 2004, Sánchez-Doblado *et al* 2005a,b, Sánchez-Doblado *et al* 2006b) have shown the feasibility of Monte Carlo evaluated factors to correct the inaccuracy of chamber readout. Francescon *et al* (1998) have employed the BEAM code (Rogers *et al* 1995) to calculate correction factors for several detectors when measuring output factors of several circular radiosurgical beams. In this work a very noticeable agreement was obtained between measurements and simulations even employing a very simple model of the radiation source. Their calculated correction factors depended only on the radiation quality of the machine. McNiven *et al* 2006 have employed Monte Carlo for prototype parallel-plane ionization chamber correction factor calculation. De Vlamynck *et al* (1999), Westermark *et al* (2000), Haryanto *et al* (2002) and Heydarian *et al* (1996) determined the suitability of different detectors in radiosurgical or MLC-defined narrow beams aided by Monte Carlo simulations.

However, despite all these works have obtained very nice agreements between simulations and measurements, the Monte Carlo method has fundamental objections to its ability to provide the "true" result when very narrow beams are involved. The very simple primary electron beam modeling in the simulations (generally a gaussian spatial distribution with a gaussian energy spectrum) differs from the actual measured shape of this source (Jaffray *et al* 1993). On the other hand, convolution/superposition algorithms have shown that the size of this primary beam is crucial for an accurate OF prediction (see for example Dunscombe and Nieminen 1992, Jiang *et al* 2001, Liu *et al* 1997). No attention was paid in the previously mentioned Monte Carlo studies on small field dosimetry on the effect of a slight change in the characteristics of the primary electron beam on the final results.

The objective of this paper is to calculate correction factors c associated to the measurement of output factors of MLC-conformed very small square fields (from 3.0

cm x 3.0 cm down to 0.5 cm x 0.5 cm) for three air-filled ionization chambers (IC) of different active volume. The uncertainties of the simulations arising from the Monte Carlo commissioning process are also described and investigated. After the calculation of factors for a single radiation quality and machine, the possibility of providing these factors "protocol-like" is also addressed. By "protocol-like" we mean that these factors should depend only on the model of the ion chamber and the radiation quality (Q) of the beam. For such purpose the sensitivity of the derived c factors to changes on the width of the primary electron beam spatial distribution and on small changes in Q is evaluated.

2. Materials and methods

2.1. Measurements

In this work we have reproduced in the Monte Carlo simulations the conditions of the experiment conducted in Sánchez-Doblado *et al* (2006a), where OFs of 6 MV square fields delivered by the Deutsches Krebsforschungszentrum (DKFZ) Siemens PRIMUS linear accelerator were measured.

Seven different detectors and measurement techniques were employed for such purpose, namely the three PTW air-filled ionization chambers considered in the present study: models 31014 ("Pinpoint"), 31010 ("Semiflex") and 30006 ("Farmer"), a natural diamond detector (PTW type 60003), a p type diode (Scanditronix type EDD-5), conventional film dosimetry (Kodak X-OMAT V) and a new technique (called LAC+3film) consisting in the combination of relative film dosimetry with integral dose measurements conducted with a large plane-parallel IC (PTW type 34070, originally designed for hadron beam dosimetry). This new technique allowed the determination of output factors independently of small detector displacements.

All these detectors were placed at a source-to-chamber-distance (SCD) of 100 cm and 5 cm depth inside a water-equivalent phantom.

2.2. Monte Carlo calculation of correction factors

In previous works we have evaluated for different clinical situations a correction factor c (Capote *et al* 2004, Sánchez-Doblado *et al* 2005a,b, Sánchez-Doblado *et al* 2006b and Pena *et al* 2006a), defined as:

$$c = \frac{f_{w,a}^{non-reference}}{f_{w,a}^{reference}} = \frac{\left(\frac{D_w}{D_a}\right)_{Q,\, non-reference}}{\left(\frac{D_w}{D_a}\right)_{Q,\, reference}} \tag{1}$$

This factor, unity in reference conditions by definition, states the deviation of a certain dosimetrical problem from the reference. The actual dose in a certain condition could then be obtained by multiplying the dose determined using protocolized factors derived for reference conditions by this c factor. In our setup, the departure from IAEA TRS-398 protocol reference conditions (a 10 cm x 10 cm field at SSD = 95 cm and a SCD = 100 cm) stands in the small size of the fields studied. Then, equation 1 can be rewritten for the narrow square fields problem as:

$$c = \frac{\left(\frac{D_{water}}{D_{air}}\right)_{Q,\, X\ cm\ x\ X\ cm\ field}}{\left(\frac{D_{water}}{D_{air}}\right)_{Q,\, 10\ cm\ x\ 10\ cm\ field}} \tag{2}$$

The different terms in equation 2 have been evaluated in this work by means of Monte Carlo simulation.

2.3. Accelerator characterization and uncertainty analysis

Accelerator simulations were performed with the EGSnrc-based BEAMnrc code (Rogers *et al* 1995). The methodology employed for characterizing the DKFZ accelerator in the simulations has been described elsewhere (Pena *et al* 2006b, 2006c) and was specifically designed to ensure the best reproducibility of small fields. By performing a simultaneous comparison of measured depth doses and lateral profiles of 2 cm x 2 cm, 10 cm x 10 cm and 20 cm x 20 cm fields (at SSD = 100 cm) and simulations of these same fields for several combinations of primary electron beam mean energy and spatial FWHM the combination of (E,FWHM) that best reproduces the measurements is selected. The inclusion of the 2 cm x 2 cm field in the comparison decreases noticeably the uncertainty of the spatial FWHM.

Besides the nominal parameters of the primary electron beam ($E_{mean} = 6.0$ MeV, spatial FWHM = 1 mm) that lead to the best reproduction of the studied photon beam, their uncertainty was also determined ($\sigma_E = 0.15$ MeV, $\sigma_{FWHM} = 0.2$ mm).

Assuming that this uncertainty may play an important role on the results we have propagated it to the Monte Carlo calculations by considering separately the two components of the output factor uncertainty, namely:

$$\sigma^2_{OF} = \sigma^2_{Simulation} + \sigma^2_{Commissioning} \tag{3}$$

The $\sigma_{Simulation}$ component is the value of uncertainty determined by the Monte Carlo history by history uncertainty estimator (Walters *et al* 2002) and has been estimated as a A type uncertainty. The $\sigma_{Commissioning}$ arises from the commissioning uncertainty and has been estimated as a B type uncertainty:

$$\sigma^2_{Commissioning} = \left(\frac{\partial OF}{\partial E}\right)^2 \cdot \sigma^2_E + \left(\frac{\partial OF}{\partial FWHM}\right)^2 \cdot \sigma^2_{FWHM} + \\ + 2 \cdot COV \cdot \left(\frac{\partial OF}{\partial E}\right) \cdot \left(\frac{\partial OF}{\partial FWHM}\right) \tag{4}$$

In this equation, OF is the output factor of the studied field evaluated by Monte Carlo for a given primary electron beam mean energy E and width of the spatial distribution FWHM. σ_E and σ_{FWHM} are the mean energy and spatial FWHM commissioning uncertainty, respectively. Because the functional form of the partial derivatives is unknown, an estimation can be done by approximating them as:

$$\frac{\partial OF(E, FWHM)}{\partial E} \simeq \left(\frac{OF(E, FWHM) - OF(E + \sigma_E, FWHM)}{\sigma_E}\right) \tag{5}$$

$$\frac{\partial OF(E, FWHM)}{\partial FWHM} \simeq \left(\frac{OF(E, FWHM) - OF(E, FWHM + \sigma_{FWHM})}{\sigma_{FWHM}}\right) \tag{6}$$

Neglecting the covariance term and considering in the approximations of the partial derivatives the effects of both an increase and a decrease in σ_E and σ_{FWHM}, the total uncertainty of the output factors can be evaluated as:

$$\begin{aligned}\sigma_{OF}^2 = &\frac{1}{4}\cdot(|OF(E,FWHM)-OF(E+\sigma_E,FWHM)|+\\&+|OF(E,FWHM)-OF(E-\sigma_E,FWHM)|)^2+\\&+\frac{1}{4}\cdot(|OF(E,FWHM)-OF(E,FWHM+\sigma_{FWHM})|+\\&+|OF(E,FWHM)-OF(E,FWHM-\sigma_{FWHM})|)^2+\\&+\sigma_{Simulation}^2\end{aligned} \tag{7}$$

For the sake of simplicity, the A type uncertainty of the output factor simulations ($\sigma_{Simulation}$) has been considered to be a 1% for all fields.

2.4. Ionization chamber simulation

The dose to the air of the three PTW ion chambers: type 31014 (0.015 cm^3 active volume), type 31010 (0.125 cm^3 active volume) and type 30006 (0.6 cm^3 active volume) was simulated by Monte Carlo in reference and also in non-reference conditions. For such purpose we have employed the CAVRZnrc code (Rogers *et al* 2003), modeling the IC geometry and the water phantom in the simulations. A special attention was paid to reproduce accurately the conical (Farmer) and semi-spherical (Pinpoint and Semiflex) chamber endings, adjusting the air volume in the simulations to be the same as the nominal IC volume. The geometry implemented in the simulations is plotted in figure 1. Only mechanical drawings provided by the manufacturer were employed for constructing the geometry. No chamber specific measurements or radiographs were performed, according to the aim of this work to provide correction factors based only on IC model and not on its specific details. In all the simulations the chamber axis was placed perpendicular to the radiation axis with its reference point coincident with isocenter machine.

The dose to water at the reference point of the chambers (which was positioned in coincidence with isocenter machine) was determined inside a tiny (0.78 mm^3) cylindrical water volume (1 mm radius, 1 mm height) employing the same code.

In order to obtain accurate results the phase spaces employed for IC simulation

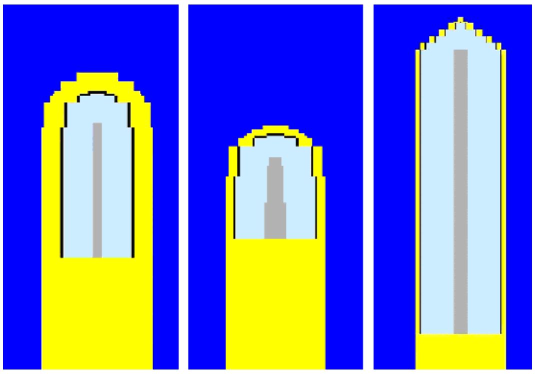


Figure 1. Geometry of the PTW chambers as implemented in the simulations (not to scale): 31014 "Pinpoint" IC (*left*), 31010 "Semiflex" IC (*middle*) and 30006 "Farmer" IC (*right*).

had, on average, 300.000 statistically independent particles per cm^2. This was achieved by simulating the whole accelerator geometry down to a SSD = 90 cm in a single step for each field size. The employment of the DBS splitting technique decreased dramatically simulation times.

Both in accelerator and phantom simulations the most accurate physics was implemented by enabling spin effects, bound Compton scattering, photoelectron angular sampling, Rayleigh scattering, atomic relaxations, triplet production and radiative Compton corrections. Cross sections employed were Koch and Motz for bremsstrahlung and pair angular sampling and NIST for bremsstrahlung interaction.

Kinetic energy cutoffs in IC simulation were set to be 1 KeV for both photons and electrons in the active volume and a 0.5 cm thick surrounding region and 10 KeV for photons and 200 KeV for electrons in the rest of the phantom. Variance reduction techniques employed were range rejection with a threshold of 1 MeV and photon splitting with a splitting factor of 60.

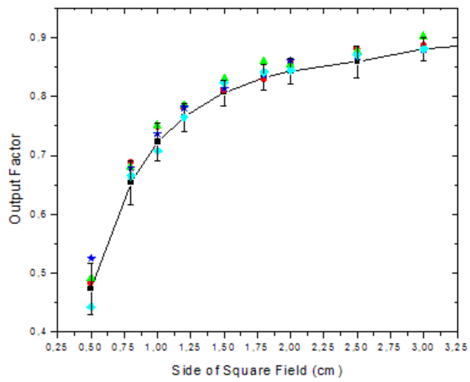
3. Results and discussion

3.1. Measured and simulated in-water output factors

The in-water output factors determined by Monte Carlo are plotted in figure 2, including the partial contributions from E $\pm$ σ_E and FWHM $\pm$ σ_{FWHM} that were used to build the complete simulation uncertainty as given by equation 7. The in-phantom measurements carried out in the work of Sánchez-Doblado *et al* (2006a) are also shown in the lower plot of this same figure.

The effect of changing the spatial FWHM is more relevant for smaller field sizes, where the amount of primary source that sees a point on-axis at the isocenter changes rapidly as the size of the source increases (see section 3.3 for a complete discussion). A slight change in energy, however, had almost no effect on the simulated OFs. The $\sigma_{Simulation}$ uncertainty plays a minor role in small fields, being the major contribution to the total OF uncertainty the $\sigma_{Commissioning}$, especially σ_{FWHM}. This source of uncertainty has not been addressed in any other works related to narrow beam Monte Carlo simulation and may explain some slight discrepancies in the OF simulation found, for example, in De Vlamynck *et al* (1999). The percentage local uncertainty of the simulated OFs ranges from a 2% for a 3.0 cm x 3.0 cm field up to a 9% for the smallest one, which is a large amount if Monte Carlo simulations want to be employed to select or correct the chamber measurements (as in Haryanto *et al* 2002).

As it has been already discussed in the introduction of this paper and also in the works of McKerracher and Thwaites (1999) and Sánchez-Doblado *et al* (2006a) there is not a detector among those employed to measure the output factors that fully assures its accuracy. However, it is clear the tendency in the measurements shown in figure 2: as the size of the detector diminishes, the output factor curve rises. The agreement of the simulations in most of the points with three detection techniques: diamond, diode and LAC+3film is consistent with the works of McKerracher and Thwaites (1999) and Westermark *et al* (2000), where the OFs for the smallest collimator sizes were well



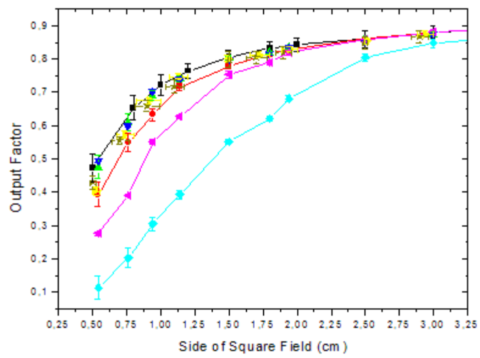


Figure 2. *Upper plot*: Monte Carlo calculated output factors of the DKFZ Siemens PRIMUS linac (squares) including simulation and commissioning uncertainty. Also plotted are the different simulations employed for $\sigma_{Commissioning}$ estimation: E = 5.85 MeV, FWHM = 1 mm (circles); E = 6.15 MeV, FWHM = 1 mm (triangle); E = 6.0 MeV, FWHM = 0.8 mm (star) and E = 6.0 MeV, FWHM = 1.2 mm (diamond). *Lower plot*: comparison of Monte Carlo calculated output factors (square) and measurements (taken from Sánchez-Doblado *et al* 2006b) employing several measurement procedures and detectors: p-type diode ($\bigtriangledown$), diamond chamber ($\triangle$), PTW 31014 IC (circle), 31010 IC ($\triangleleft$), 30006 IC (diamond), film ($\triangleright$) and LAC+3film (star).

predicted with unshielded diodes and a diamond detector. Heydarian *et al* (1996) also found very good agreement between diode and diamond detectors in the dosimetry of stereotactic radiosurgery output factors.

None of the referenced studies that employed Monte Carlo to obtain an estimation of the best OFs experienced discrepancies between simulations and measurements, even employing rather simple methods for primary electron beam characterization as in Fidanzio *et al* (2003). Accelerator commissioning in these works was mainly done by comparison of simulated and measured depth doses of the 10 cm x 10 cm field, which has been shown to be a method rather insensitive to both electron's mean energy and spatial distribution (Lovelock *et al* 1995). However, in De Vlamynck *et al* 1999, despite a very rigorous characterization method was conducted, differences in the output factors for a 10 cm x 1 cm field are pointed out. Their guess of the rather simple description of the electron source as a circular distribution as the origin of this discrepancy is further confirmed by the uncertainty analysis carried out in this work. Upper plot in figure 2 confirms that, despite an accurate commissioning method that focused in predicting small fields was conducted in the present work, the remaining uncertainty of the process predicts output factors with a relatively large amount of uncertainty.

3.2. Measured and simulated dose to chamber air

The comparison between the measured ionization and the calculated dose to IC air can be seen in figure 3 for the three ICs. Simulation uncertainties were calculated employing a procedure analogous to that employed for the in water output factors. For efficiency purposes they have only been calculated for several field sizes. Curves corresponding to σ_E and σ_{FWHM} variations are not shown for clarity.

The agreement between simulations and measurements is fairly good, especially for the pinpoint and farmer chambers. The percentage deviations are plotted in figure 4, being most points reproduced within a 4%.

The observed differences between simulations and measurements arise from a combination of commissioning uncertainty and discrepancies between the modelled and actual IC geometry and composition. All these differences contribute also in dose-to-water simulation but the highest geometrical complexity of ionization chambers and the largest active volume where dose is integrated lead to higher deviations in IC simulation. The detector positioning in the measurement setup also plays an important role in this

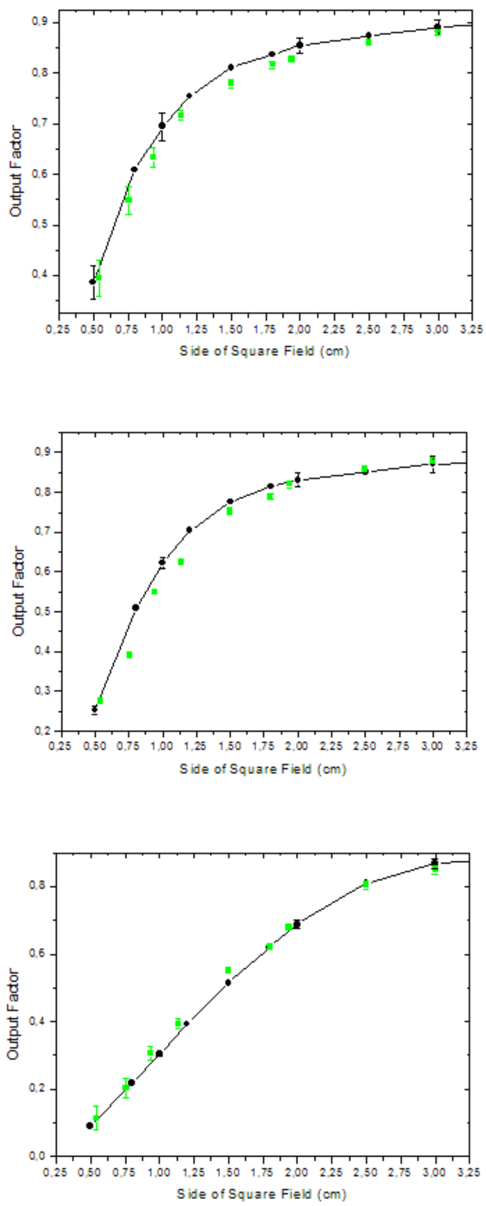


Figure 3. Measured ionization (□) and simulated dose to chamber air (◯) for the three chambers: PTW 31014 (*upper plot*), PTW 31010 (*middle plot*) and PTW 30006 (*lower plot*). The full uncertainty of simulated data was determined only for some square field sizes.

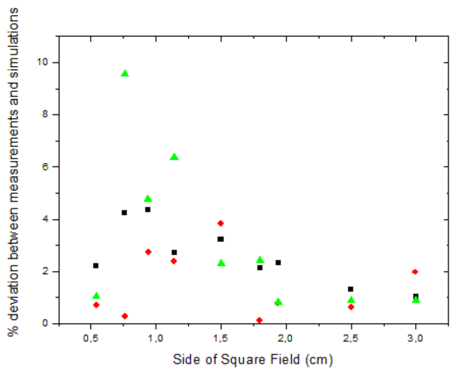


Figure 4. Percentage deviation of simulations with respect to measurements for the PTW 31014 (□), PTW 31010 (△) and PTW 30006 (◯) chambers.

issue, as will be shown in section 3.5.

3.3. Origin of uncertainty influence on output factors

The origin of the dependence of the Monte Carlo simulations on the commissioning uncertainty, specially on σ_{FWHM}, can be easily explained employing an analytical dual source model (as in Jiang *et al* 2001) to describe the radiation generated in the accelerator head. Many conventional dose algorithms as well as some Monte Carlo codes (Fippel *et al* 2001) employ two photon sources to describe the radiation generated in the accelerator head. For the purpose of explaining the dependence of Monte Carlo results on characterization uncertainties we will assume that a primary source with a gaussian spatial distribution generates those photons that come directly from the bremsstrahlung target and have not interacted in the primary collimator or flattening filter. The distribution of the scattered photons coming from these components will be modelled by a superposition of two gaussians with different relative intensities and standard deviations located at a distance D_{Ef} from the primary source. With this model, the fluence in a point on-axis at a distance D of the primary source is approximately given by (neglecting normalization factors) as:

$$\Psi(D) = \frac{P}{D^2} \cdot \Psi_{focal} + \frac{(1-P)}{(D-D_{Ef})^2} \cdot \Psi_{extrafocal} = \\ = \frac{P}{D^2} \cdot e^{-\frac{x^2_{focal}}{2\sigma^2_{focal}}} + \frac{(1-P)}{(D-D_{Ef})^2} \cdot (A \cdot e^{-\frac{x^2_{Ef}}{2\sigma^2_{Ef_1}}} + B \cdot e^{-\frac{x^2_{Ef}}{2\sigma^2_{Ef_2}}}) \tag{8}$$

Being P is the primary source strength. In our model, the relative intensities of the two contributions to the extrafocal source and their standard deviations have been taken from Jiang *et al* (2001): A = $0.332 \cdot 10^{-1}$, B = $0.517 \cdot 10^{-1}$, σ_1 = 0.650 cm and σ_1 = 13.3 cm. Also following this work, we have considered D_{Ef} = 13 cm.

In figure 5 the fraction of focal source that a point on-axis at a distance of 100 cm "sees" as a function of the position of the upper collimator edge has been plotted. Different field sizes (assumed square) were analyzed for different σ_{focal}. The collimator that defines the field is considered to be straight (as in radiosurgery applicators) with a height of 8 cm.

It can be seen that when the collimator is placed at a distance from the source between 20 cm and 40 cm (where jaws and MLC are placed in most linacs) the amount of primary source integrated by the point changes sharply with a small change in primary FWHM. Considering that the strength of this source amounts for about a 90% of the total fluence, this clearly explains the sharp change in the output factors of the smallest fields seen in the upper plot of figure 2 as the spatial FWHM was slightly changed. This effect, only relevant for field sizes below 1 cm, has no influence at all for radiosurgery studies, where the collimator is placed at distances higher than 50 cm.

In this same figure 5, the percentage of the extrafocal source that this point on-axis "sees" for different square field sizes is also plotted. The change in extrafocal fluence as the field size changes from 1 cm to 4 cm is about a 20%-30%, which considering the small contribution of this source (usually below 10%) has a negligible effect on the on-axis fluence. In figure 6 half-profiles of a 2 cm x 2 cm field simulated by Monte Carlo for a fixed energy and different spatial FWHMs have been plotted. It can be seen that as the FWHM is increased the dose off-axis noticeably decreases. This effect leads to a

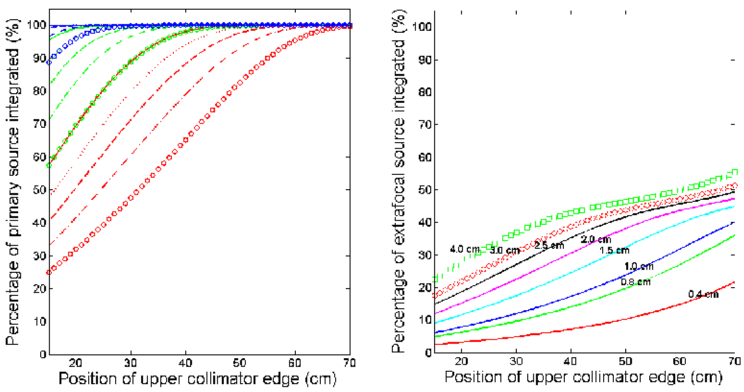


Figure 5. *Left:* percentage of focal source (placed at the origin of coordinates) that a point located in the radiation axis at a distance of 100 cm sees as a function of the distance from the collimator upper edge to the origin. Three field sizes (at SSD = 100 cm) were considered: 0.2 cm x 0.2 cm (red lines), 0.5 cm x 0.5 cm (green lines) and 1.0 cm x 1.0 cm (blue lines). FWHMs for the spatial distribution of the primary source were: 0.8 mm (solid line), 1.0 mm (dotted line), 1.2 mm (dashed line), 1.5 mm (dash-dotted line) and 2.0 mm (circles). *Right:* percentage of extrafocal source (located at Z = 13 cm) that a point placed in the radiation axis at a distance of 100 cm sees as a function of the distance from the collimator upper edge to the origin. Square field sizes considered are quoted in the plots. NOTE: in both plots the height of the collimator was assumed to be 8 cm.

smaller dose contribution of off-axis radiation on the central axis. Then a decrease of output factors in field sizes between 1 cm and 5 cm as the primary FWHM is increased is expected.

3.4. Calculation of c factors

From the calculated dose to water and dose to chamber air shown in figures 2 and 3, c factors have been evaluated following equation 2 and are plotted in figure 7. The correction factor required for a 0.5 cm x 0.5 cm field ranges from about 1.22 for the smallest IC up to a 5.25 for the Farmer chamber. Evidently none of these factors could be employed for a clinical use because the amount of correction is comparable (and for some chambers much larger) than the measurement itself. However, in order to test

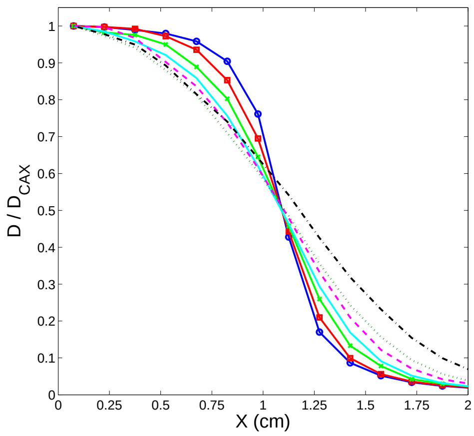


Figure 6. Dependence of the simulated lateral profiles of a 2 cm x 2 cm field (SSD = 100 cm) from a 6 MV Siemens PRIMUS on the primary electron beam spatial FWHM: 0.5 mm (solid line with circles), 1 mm (solid line with squares), 1.5 mm (solid line with crosses), 2.0 mm (solid line), 2.5 mm (dashed line), 3.0 mm (dotted line) and 4.0 mm (dash-dotted line). Primary electron beam mean energy was 6.0 MeV in all cases.

Table 1. Range of applicability of c factors considering $c \in [1.02, 1.1]$.

Ionization chamber	Field size interval (cm)
PTW 31014	[1.16, 0.75]
PTW 31010	[1.80, 1.2]
PTW 30006	[3.0, 2.4]

the viability of the determined factors they will be applied in section 3.5 to correct the measurements in the whole range from 0.5 cm x 0.5 cm to 3.0 cm x 3.0 cm.

Assuming that correction factors are valuable when the measurements deviate from the "true" value by more than a 2% (c = 1.02) and could be used up to a reasonable value of a 10% (c = 1.1), the field size ranges for which the calculated c factors are valuable was determined and are shown in table 1.

Because of the sharp increase of the c curve shape as the field size decreases the range of applicability of the factors is very narrow (0.6 cm at most). However, there is

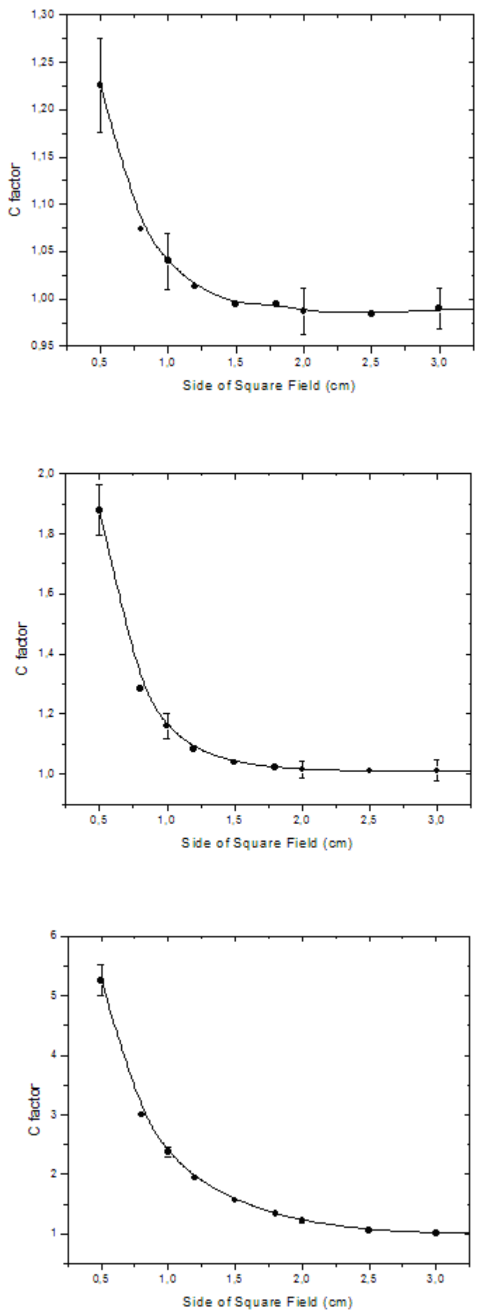


Figure 7. Correction factors for the three ionization chambers: PTW 31014 (*upper plot*), PTW 31010 (*middle plot*) and PTW 30006 (*lower plot*) calculated from the Monte Carlo dose to water and dose to IC air.

a clear relationship between the size of the IC and the minimum field size that can be accurately measured. From these considerations, the *c* factors may be of more interest for chambers with active volume smaller than 0.015 cm^3, which are not considered in the present work. However, this type of ICs suffer from a smaller signal to noise ratio and a higher instability in the measurements.

The minimum square field sizes which can be measured with the studied chambers arise to be somehow in contradiction with previous results from McKerracher and Thwaites (1999). In this work, by requiring that IC active volume maximum dimension (including chamber walls) fall at least within the 99% isodose of circular radiosurgical beams, it was determined that the minimum collimator diameter for which output factors could be measured with a pinpoint and semiflex chambers were 2.25 cm and 2.5 cm, respectively. Despite these results were obtained for circular radiosurgical collimators the 99% presciption should be independent on the delivery technique and, at least for square fields delivered by a MLC, limits the applicability of a certain IC much above the field size determined by Monte Carlo.

3.5. Application of c factors to measurement correction

Despite it has been shown in the previous section that the range of applicability of the correction factors in a clinical environment would be rather small, from a methodological point of view it is still desirable to know whether they can correct the measurements within reasonable uncertainties. For such purpose the calculated *c* factors have been applied to correct the measurements of the three PTW chambers, interpolating them linearly to the equivalent square fields to whom measurements are associated.

The original and corrected output factors are presented in figure 8. Diamond and LAC+3film measurements are also presented for comparison. It can be seen that for the Pinpoint chamber the agreement between corrected OFs and diamond and LAC+3film measurements is good within uncertainties. For the Semiflex IC, the agreement is slightly worse (except for the 0.5 cm x 0.5 cm field). The 0.75 cm x 0.75 cm output factor,

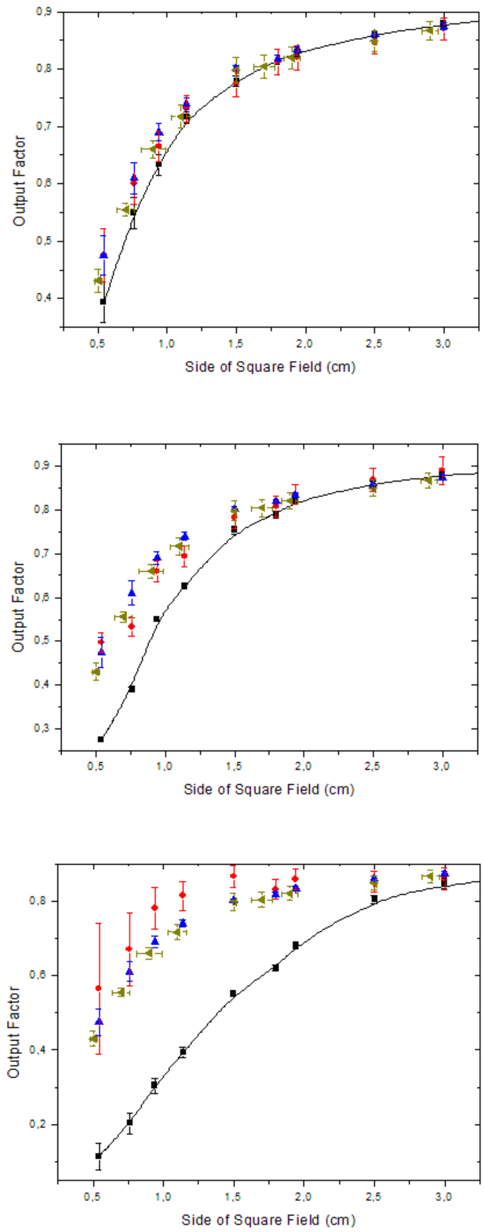


Figure 8. Output factors measured by the PTW 31014 (*upper plot*), PTW 31010 (*middle plot*) and PTW 30006 (*lower plot*) ionization chambers (□) and corrected by the c factors presented in figure 5 (◯). Diamond (△) and LAC+3film (◁) measurements are shown for comparison.

however, deviates from measurements more than its neighbors. This is a clear evidence of the strong influence of the experimental positioning uncertainty on the final measured output factors. This effect is more evident in the Farmer chamber for field sizes between 1.0 cm x 1.0 cm and 1.5 cm x 1.5 cm. The agreement in this region is worst than for the smallest field, despite being associated to a smaller value of the c factors.

3.6. Extension of c factors to other radiation qualities and primary radiation source spatial FWHM

Up to this point, the above presented results were computed for the mean energy and spatial FWHM that best reproduced the DKFZ linac in the simulations. For the ionization chambers studied the calculation of correction factors for small field dosimetry, despite valid from a methodological point of view, has a severe limitation on the range of field sizes for which the derived c factors are applicable. However, there is another limitation on the correction factors if they want to be provided "protocol-like": their dependence on the primary electron beam's spatial width. This is a critical parameter because of the difficulty to determine it experimentally.

In order to study the importance of this dependence on the c factors and also their variation with the beam quality we have re-evaluated the c factors for the three ICs changing noticeably the primary electron beam mean energy and spatial FWHM. The results are shown in figure 9, where it can be seen that a 1 mm change in the FWHM leads to an unacceptably large change in the c factors for field sizes below 1 cm x 1 cm.

On the other hand, the effect of changing the radiation quality (evaluated by an increase in the primary beam mean energy) is much smaller than changing the FWHM and for the Farmer chamber completely negligible.

4. Conclusions

In this work we have studied the capability of the Monte Carlo method to provide correction factors for three PTW ionization chambers in the absolute dosimetry of

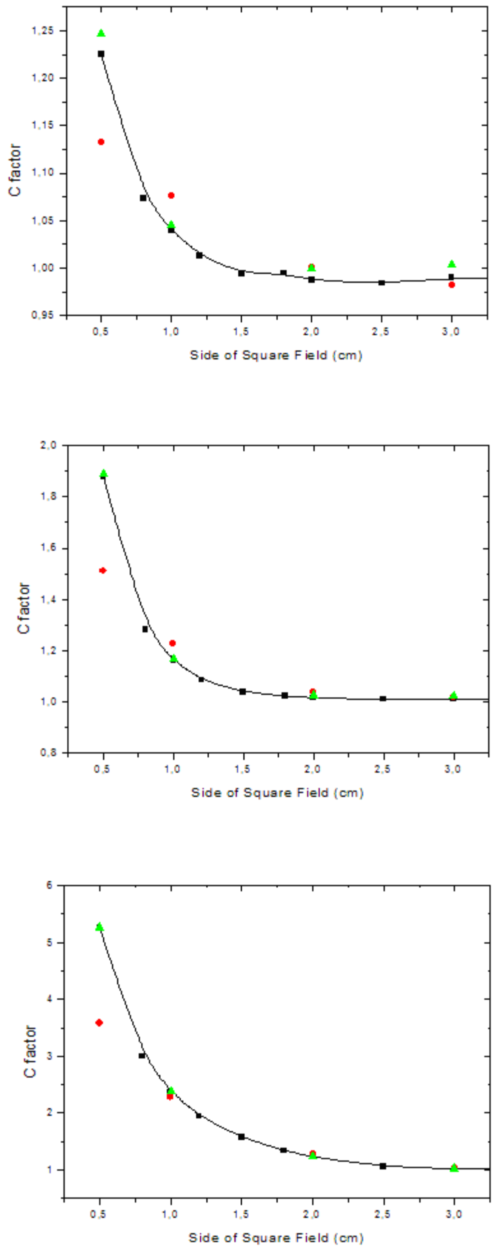


Figure 9. Extension of c factor calculation to other radiation qualities and primary electron beam spatial widths for the three ICs studied: PTW 31014 (upper plot), PTW 31010 (middle plot) and PTW 30006 (lower plot). Configurations studied were E = 6.0 MeV, FWHM = 2 mm (◯) and E = 6.5 MeV, FWHM = 1 mm (△). Also plotted is the nominal configuration E = 6.0 MeV, FWHM = 1 mm (□).

very small square fields conformed by a MLC. The dependence of these factors on the uncertainty of the commissioning process and the possibility of providing them "protocol-like" (i.e. depending only on the IC model and the radiation quality of the beam) have also been addressed.

In section 3.1 we have seen that the main contribution to the uncertainty of the in-water Monte Carlo calculated output factors comes from the commissioning uncertainty in the FWHM rather than from the simulation uncertainty itself. Porcentually, it ranges from a 2% for a 3.0 cm x 3.0 cm field up to a 9% for the smallest one. However, the in-water simulated output factors coincide with diamond, diode and LAC+3film measurements within uncertainty. This result is in agreement with the works of McKerracher and Thwaites (1999) and Westermark *et al* (2000), where unshielded diodes and diamond detectors were pointed out as the best detectors to perform output factor measurement in narrow beams.

A slight worst agreement respect to diode or diamond detectors (generally below 4%) is obtained when dose to chamber air is simulated. This discrepancy would then represent the effects on the final result of the differences between the simulated and actual IC and accelerator geometry and composition.

The source of the severe dependence of output factor simulations on the spatial FWHM of the primary electron source has been addressed in section 3.3. By employing a dual source model equivalent to those employed in many convolution/superposition algorithms we have demonstrated that this dependence can be explained by a combination of two effects. For square fields smaller than 1 cm x 1 cm a slight change in the primary electron beam FWHM leads to a noticeable change on the amount of radiation that reaches the detector (equivalent to the size of radiation source that the detector "sees"). This effect is only relevant when the collimator is positioned at distances from the source ranging from 20 cm to about 40 cm, being then negligible for radiosurgical studies. However, in narrow beams defined only by jaws and MLC (such as in IMRT) this severe dependence has to be taken into account.

For field sizes between 1 cm x 1 cm and 5 cm x 5 cm the integration of the primary source is complete and the slight changes in the amount of extrafocal source integrated are of small relevance. The decrease in the amount of scatter that reaches the active volume from points situated off-axis with increasing spatial FWHM explains the increase of output factors in this field size region.

The use of the Monte Carlo method provides a critical tool for the evaluation of the convenience of a chamber for such measurements. However, it may not distinguish between two measurement methods whose results differ in less than a few percent.

From the dose to water and dose to chamber air simulations we have constructed the c factors for the three PTW chambers in section 3.4. These factors have been proven (see section 3.5) to correct accurately the Pinpoint measurements but their applicability to higher active volume chambers is restricted by the magnitude of the factors themselves and the positional uncertainties. For the Semiflex chamber these effects lead to a worst agreement than for the Pinpoint, especially for field sizes between 0.75 cm and 2.0 cm. The correction of the Farmer IC measurements leaded to non-satisfactory results because of the very large value of the c factors. Considering that correction factors are valuable only within the reasonable boundaries of 1.02 and 1.1, the range of field sizes to whom they are applicable was determined to be about 0.6 cm for the three chambers (see table 1).

Finally, in section 3.6 the possibility of providing a c factor value independently of the spatial FWHM was evaluated. The results show that the dependence of the c factors on this parameter is critical, preventing the possibility of providing them associated only to the radiation quality as in standard dosimetry protocols.

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