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On correction factors for profile measurements with small solid state detectors and with small ionization chambers

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Abstract

Introduction: Measured profiles, which are crucial to treatment planning system commissioning, are generally affected by averaging effect linked to the size of sensitive volume of detectors used. Such averaging leads to deviation from the true profiles in water even when small field detectors are employed. In order to have access to profile data which are free from the influence of the measuring device, a guidance is required, on when and how much correction is required for a detector in use.

Material and methods: Profile correction factors were determined as the ratio between true profiles in water and associated measured profiles, both as a function of off-axis distance. The identical free air profile is used to simulate measurement and to generate 'measured' profiles at different depths in water. The MC generated profiles in water without the detector were taken as true profiles. Based on such MC generated profile results, detector specific correction factors were determined. Additionally, such factors were approximated by an analytical function using a fit procedure for the function parameters. Optimized parameters were systematically compiled depending on measuring conditions such as beam size, depths in water for detectors-pinpoint, pinpoint 3D, microSilicon and microDiamond.

Results: The method to generate a common dataset of true profiles in water was successful. Also, measured and simulated profiles well agree for all measuring conditions. In addition, correction factors, as well as approximated correction functions were derived. Application of analytical correction functions to measured profiles for given conditions, well reproduced true profiles with the detector being absent.

Conclusions: The MC method to derive correction factors for profile measurements is feasible for all detectors used in this study. Such correction factors can be well approximated by a simple analytical function. It is recommended that ionization chamber measured profiles generally need correction while solid state detectors measured profiles fairly approach the true profiles in water.

Keywords: Monte Carlo simulation; true profiles; averaging effects; profile correction factors; analytical correction function.

Introduction

There has been an escalation in the application of small fields that has been facilitated by the generalized availability of standard and add-on multileaf collimators (MLCs) and a variety of treatment machines of new design allowing new treatment techniques such as conformal radiotherapy, IMRT and SRS/SBRT.[1-4] In any case, measured data are important input data for the commissioning procedure of a treatment planning system.[2,5] However, the use of small field requires the dosimetry in small fields, which is always challenging.[6,7] Measurements with different detector types demonstrate a considerable variation of results,[2-4] that requires answering the question of which type of detector can provide reliable data or, otherwise, which correction of measured profile data is needed before implementing them into a treatment planning system.

In the past, various efforts have been made by different researchers to characterize commercially available detectors for their different dosimetric properties.[8-14] Yuichi Akino et al.[8] characterized microSilicon (model 60023) for small-field photon beam dosimetry by evaluating the photon beams generated by a Truebeam STx and a CyberKnife. In their study, they compared the output factor of microSilicon (model 60023)

Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

detector to the output factors of the other detectors, namely, Diode E, microdiamond and EDGE detectors. The microSilicon showed favorable characteristics, including small temperature and dose rate dependence as well as the small spatial resolution and output factors suitable for small field dosimetry. Similarly, Carolin Weber et al.[9] performed Monte Carlo-based determination of small field output correction factors for unshielded silicon diode detector, microSilicon (model 60023), diode E (model 60017) and diode SRS (model 60018) for a standard linear accelerator as well as CyberKnife System. It was observed that the microSilicon detector required less correction than its predecessors, Diode E and Diode SRS. C. Martens et al.[10] investigated the performance of the PinPoint ion chamber for characterizing small fields used in intensity-modulated radiotherapy (IMRT) and the results were compared with those obtained using the Markus ion chamber and a diamond detector. The study concluded that the PinPoint chamber is an excellent detector for output measurements in small fields down to 2 cm. In profile measurements, the chamber causes a broadening of the measured penumbras, but its spatial resolution is superior to that of Markus chamber.

Isabel Busing et al.[11] performed experimental and Monte Carlo characterization of the novel compact ionization chamber PTW 31023 for reference and relative dosimetry in high energy photon beams. The influence of the diameter of the central electrode and the new guard ring on the beam quality correction factors k_Q was studied by Monte-Carlo simulations. The non-reference condition correction factors k_{NR} have been computed for 6 MV photo beam by varying the field size and measurement depth. Comparisons on these aspects have been made to the previous model.

Kehei Kawata et al.[12] studied the effect of angular dependence for small-field dosimetry using seven different detectors. Out of the seven detectors, namely, CC01, RAZOR, RAZOR Nano, Pinpoint 3D, stereotactic field diode (SFD), microSilicon and microDiamond under study, the Pinpoint 3D chamber had the smallest angular dependence of all detectors for the coplanar and non-coplanar beams. The findings of this study can contribute to the calculation of the angular dependence response correction factor, and it may be possible to adapt detectors with a large angular dependence on coplanar and non-coplanar beams. However, note that the gantry sag and detector-specific uncertainties increase as the field size decreases. Alison J D Scott et al.[13] published a paper titled Characterizing the influence of detector density on dosimeter response in non-equilibrium small photon fields. The impact of density and atomic composition on the dosimetric response of various detectors in small photon radiation fields is characterized using a 'density-correction' factor, $F_{detector}$, defined as the ratio of Monte Carlo calculated doses delivered to water and detector voxels located on-axis, 5 cm deep in a water phantom with a SSD of 100 cm. The variation of $F_{detector}$ with field size has been computed for detector voxels of various materials and densities. For ion chambers and solid-state detectors, the well-known variation of $F_{detector}$ at small field sizes is shown to be due to differences between the densities of detector active volumes and water, rather than differences in atomic number. However, associated changes in the measured shapes of small-field profiles offset these variations in $F_{detector}$, so that integral doses measured using the different detectors are quite similar, at least for slit fields. Since changes in $F_{detector}$ with field size arise primarily from differences between the densities of the detector materials and water, ideal small-field relative dosimeters should have small active volumes and water-like density.

Most of the above mentioned works have been done to determine output correction factors.[8-10] And some studies are focused on characterizing other parameters such as density correction,[13] beam quality correction,[11,14] angular dependence correction[12] and other usual corrections as mentioned in dosimetric protocols like in IAEA TRS 483.

However, very few studies have been performed for profile measurements in small fields. Recently, Poudel et al.[15] performed a Monte Carlo calculation of dose profiles with a given profile method. They confirmed that a volume averaging effect indeed occurs in the field edge region for the mid-sized Semiflex chamber. The ratio of these data gives values in the order of 1.1 inside the field edges and values between 0.4 and 0.8 outside.

In this study, we performed a further MC study now with a variety of small-sized detectors. The purpose is to derive correction factors for dose profile measurements with such detectors. Profile correction factors are determined using MC calculations as the ratio between the true profile in water and the associated measured profile, both as a function of the off-axis distance. Characteristics and suitability with respect to profile measurements are discussed.

Material and Methods

Detectors

The detectors selected for this study were all fabricated by PTW Freiburg GmbH. The selection includes three ionization chambers (Semiflex 31010, PinPoint 31023, and PinPoint 3D 31022), and three solid state detectors (microDiamond 60019, microSilicon 60017 and microSilicon 60023.

The Semiflex chamber, which does not represent a micro-detector, was employed because it provides a good compromise between spatial resolution and data fluctuation, which increases with decreasing size of the sensitive volume. Results based on this chamber therefore provide useful test data for the methods of this work. All other detectors are indeed micro-detectors with proven high spatial resolution. This makes them specifically well suited for profile measurements. In addition, according to the manuals offered by PTW, each of these detectors fulfill the condition of stability, dose linearity, dose rate linearity, dose per pulse linearity, the energy dependence of detector response, the small size of detector, orientation, background signal and environmental factors.[16]

Measurement of Dose Profiles

Beam profiles for the 6 MV Photon beam generated by TrueBeam were measured for source to surface distance (SSD) of 100 cm, field size (FS) 4 cm × 4 cm at four different depths (0.5 cm, 5 cm, 10 cm and 20 cm) in water using the given air filled ionization chambers and solid state detectors in PTW MP3 water phantom. The correction method was primarily based on measurements at a field size of 4 cm × 4 cm and the profiles measured for source to surface (SSD) distance of 100 cm and at the depths of 0.5 cm, 5 cm, 10 cm and 20 cm. Air filled ionization chambers were scanned transversally (x-axis) in water phantom while the detectors axes were perpendicular to the beam axis. Solid state detectors were scanned transversally while the detector axes were parallel to the beam axis. Subsequently, Profiles were also measured at other beam sizes. All profile data were symmetrized and converted into percent values by dividing through the dose at the beam center.

Monte Carlo simulations

The details of the MC simulation performed in this study are identical as already described in the paper by Poudel et al.[15], i.e. all simulations were based on the EGSnrc system.[17] Calculations were performed with a modified Fortran version of the DOSXYZnrc code compiled with the Intel Visual Fortran Compiler (IVFC) and running on a Linux cluster. This method enables a straight forward implementation of some modified parts to the code in combination with an extremely helpful debugging tool when testing on the Microsoft Visual Studio platform before. Modifications refer to the implementation of the detectors into DOSXYZnrc and to the new algorithm to compute the spectral fluence of electrons.[18] The relative uncertainty type A was assessed with the event-by-event method using routinely a number of 10^{10} histories and 10^{11} histories in the low dose region.[19] The resulting relative standard uncertainty generally was in the order of 0.5% or less. Main parameters are listed in **Table 1**.

Table 1. Parameter used for the Monte Carlo Simulation

Item	Type	Remarks
Hardware	PC computer cluster	for code testing for long runs
MC Code	DOSXYZnrc	Modified
Operating system	Windows Linux	PC cluster
Compiler	Intel Visual Fortran Compiler	for both operating systems
Geometry	Point source, SSD = 100 cm	
Phantom Material	Water	
Source	'Given profile' source	

This list follows the recommendations given by the AAPM Task Group 268 for records: reporting Monte Carlo simulation.[20]

MC calculation of profiles

The method to obtain detector-free profiles in water using a heuristic free-air input file was already described and proven to be well appropriate in a former paper.[15] In this work, the same method was applied. In order to generate input files also for other beam sizes, the free-air input file initially used for the 4x4 beam must be slightly modified. The modification was again validated by a comparison between really measured and MC simulated profiles.

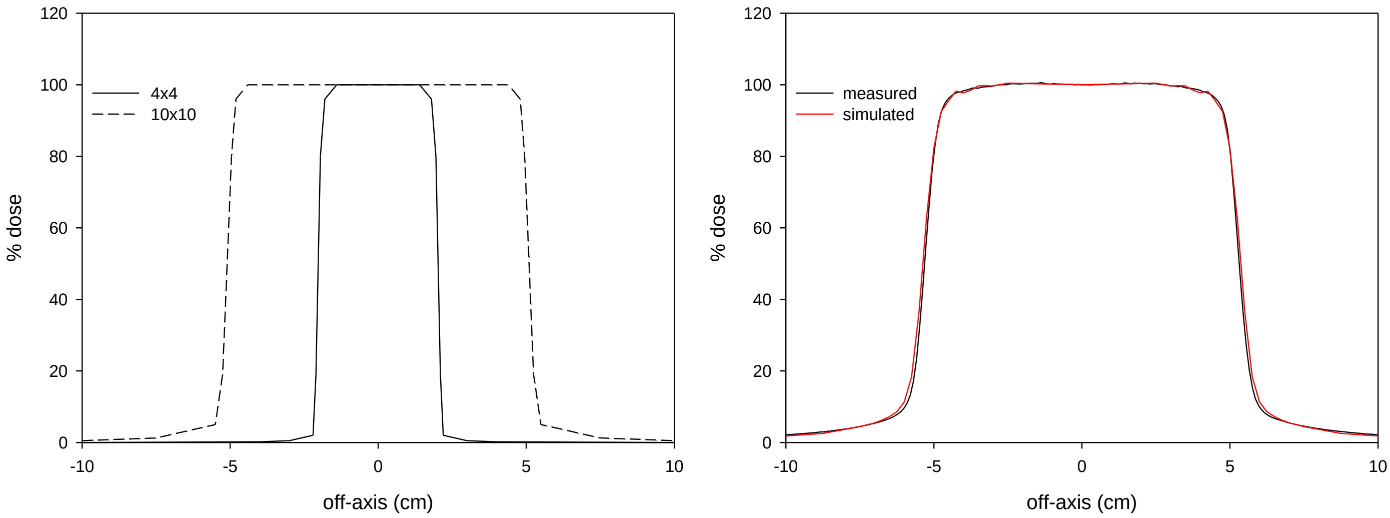

Figure 1. Left: 'Given free air input files' (a) for the initially used 4 × 4 beam and for the 10 × 10 beam. Right: Resulting agreement between measured and simulated profiles for the 10 × 10 beam using the Semiflex chamber and the input file as shown left.

The following modification of the free-air input file for the 4 × 4 beam turned out to be suited: (1) multiplication of the distance of the x-values from the nominal field edge by the ratio f/4 where f denotes the wanted beam size, and (2) multiplication of the y-values outside the field edges by the same ratio f/4. The input files for the 4x4 field and the derived input file for a 10x10 field are shown in **Figure 1**, left. With this method, a good agreement between measured and simulated profiles was indeed obtained for all measurement conditions. An example is shown in **Figure 2**, right. Conditions refer to a profile measurement with the Semiflex chamber at a depth of 5 cm in a 10 × 10 beam.

Determination of correction factors

Profile correction factors are determined by the ratio between true profiles in water and measured profiles where these profiles either refer to real measurements or to MC simulations. Such ratios may considerably deviate from 1.0 at the small dose values outside the beam edges. This disagreement was attributed to two reasons: (1) there is a larger fluctuation of data in that region, and (2) the "given input file" method still remains an approximation. Common simulation of both, profiles with and without detector is less affected by the fact that the "given free air" profile" method is not a perfect approximation. Therefore, the determination of correction factors was based exclusively on profiles obtained by MC simulations.

Determination of an analytical function for the correction factors

In a second step, the dependence of these correction factors on off-axis values was approximated by a heuristic function. The aim of this step was to find out whether one can establish correction factors without depending on MC simulations before. Generally, a function simulating a deviation from 1.0 around a fixed point appears to be appropriate. A test function like that of the following form meets this condition:

$$f_{cf} = 1 - b\left(\frac{z}{a}\right) \cdot \exp\left[-\left(\frac{z}{a}\right)^2\right] \qquad \text{Eq. 1}$$

where a and b are function parameters and z is related to the off-axis distance x through the expression:

$$z = \frac{x}{x_0} - 1 \qquad \text{Eq. 2}$$

where x_0 is that off-axis distance where the profile in water takes on the value of 50%. In this expression the parameter a is a measure of the width of the deviation, whereas the parameter b is a measure of the degree of the deviation.

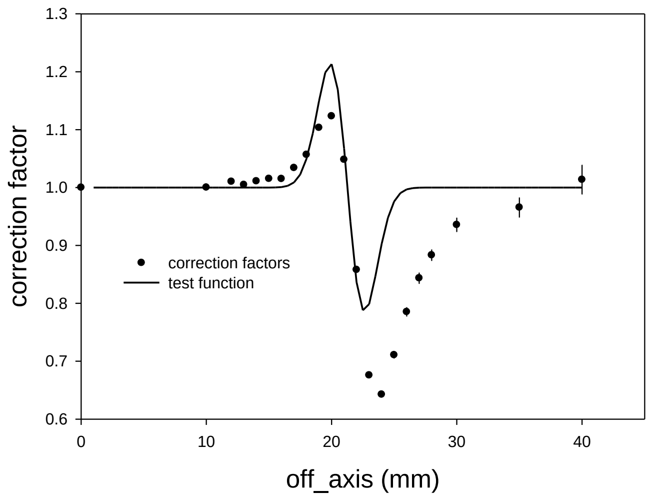

Figure 2. Correction factor for the Semiflex chamber obtained at the 4 × 4 beam in 5 cm depth (dots) and test function using Equation 2 (solid curve).

However, such functions are always symmetrical around x_0 whereas the obtained correction data are not symmetrical (see **Figure 2**). Therefore, different function parameters must be used depending on whether the off-axis distance is lower or larger than x_0 (inside or outside the beam). These four parameters are denoted as a_{inside} and b_{inside}, or $a_{outside}$ and $b_{outside}$, respectively.

The parameters were determined for all detector types, for different depths in the water phantom as well as for different beam sizes, using the nonlinear curve fitting option of SigmaPlot. As a result, a variety of parameter combinations was obtained.

The feasibility of this two-step procedure was initially tested using the data obtained with the Semiflex chamber. Subsequently, the method was applied at all micro-detectors of this study.

Results

Comparison between measured and simulated profiles

A series of comparisons between measured profiles and MC calculated profiles were obtained. As examples, results obtained with the Semiflex chamber, the microdiamond detector and with the 3D chamber are shown in **Figure 3**. Measurement conditions refer to four different depths (0.5 cm, 5 cm, 10 cm and 20 cm in water) at a field size of 4 cm × 4 cm. In all cases, the visual assessment showed a close agreement between a specific measured profile and the associated profile obtained by simulating a measurement with MC. This finding confirms that the chosen MC method is adequate to provide correct true profiles.

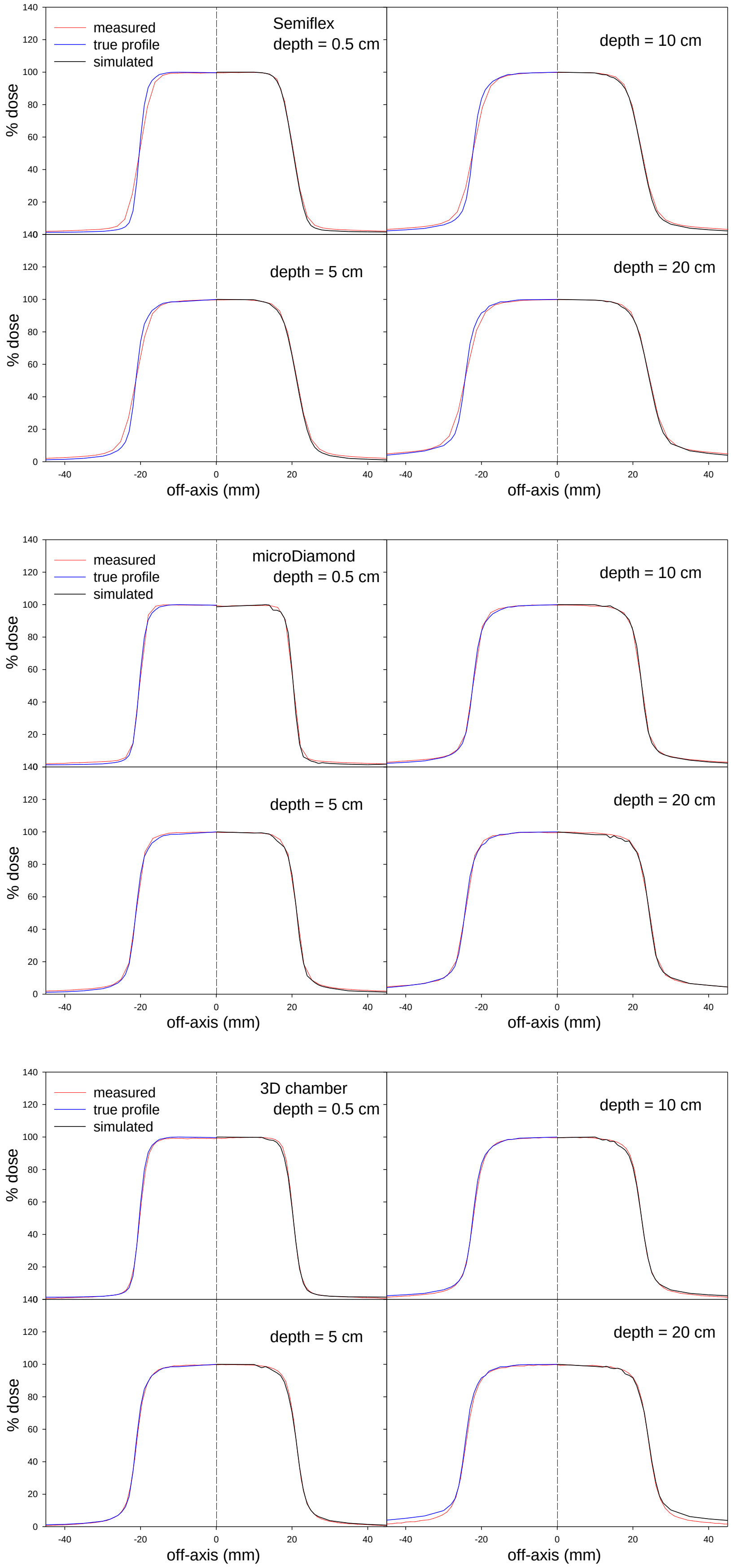

Figure 3. Comparison between measured and calculated profiles

Profiles with and without the presence of the detector (true profiles) are also included in **Figure 3**. For solid state detectors (microdiamond and microsilicon), measured profiles generally well match the true profiles. For ionization chambers (Pinpoint, Pinpoint 3D and Semiflex), there is always a disagreement of varying degree between the measured and the true profiles. The degree of disagreement varies with depth in water and also with field size.

Initial results obtained with the Semiflex chamber

The profile correction factors as determined by the ratio between true profiles in water and measured profiles and associated analytical functions using **Equation 1** are shown in **Figure 4**.

The function parameters obtained by parameter fitting are only slightly different at different depth with the exception of $b_{outside}$ which shows a decreasing slope with depth. The depth dependence for a_{inside} and $a_{outside}$, as well as for b_{inside} and $b_{outside}$ in the 4 × 4 beam is shown in **Figure 5**.

Figure 6 demonstrates that the analytical correction function can indeed well be used to convert the measured profiles into the true profiles in water.

Results at a depth of 5 cm obtained in water at different beam sizes, specifically at 1 × 1, 2 × 2, 4 × 4, 5 × 5, and 10 × 10 are shown in **Figure 7**. In this case the dependence of the function parameters can be well approximated by a simple mathematical expression.

Correction factors obtained for the micro-ionization chambers

The depth dependence for a_{inside} and $a_{outside}$, as well as for b_{inside} and $b_{outside}$ in the 4 × 4 beam is shown in **Figure 8**. For comparison, the function parameter b_{inside} and $b_{outside}$ (which are a measure of the deviation from 1.0) obtained for the Semiflex Chamber are also included. The comparison confirms the expectation that the correction factors for the two micro-chambers are smaller than those of the Semiflex chamber.

Correction factors for the solid state detectors

Results obtained with the solid state micro-detectors show a different behavior when compared with ionization chambers. First of all, in contrast to ionization chambers, the uncorrected profiles measured with the solid state detectors (really measured as well as simulated) obviously matched very well to the true profiles in water. This is demonstrated in **Figure 9**, left, in which the profiles measured in 5 cm depth in the 4 × 4 beam with the 3D Chamber (top) and with the microdiamond detector (bottom) are compared. Whereas a small but still clear deviation is visible for the 3D Chamber, the deviation appears to be almost negligible for the microDiamond detector.

For any of the four function parameters the following expression is valid:

$$a_{inside}, a_{outside}, b_{inside,}\ or\ b_{outside} = a_0 + a_1 \cdot \exp[-a_2\, fs] \quad \text{Eq. 3}$$

where fs is the beam size in cm. Values for the fit parameter a_0, a_1, and a_2 are given in **Table 2**.

Table 2. Values of the fit parameter in Equation 3.

	a_{inside}	$a_{outside}$	b_{inside}	$b_{outside}$
a_0	0.067	0.140	0.117	0.264
a_1	0.956	1.310	0.831	1.573
a_2	1.074	0.831	0.308	0.300

When assessing correction factors (**Figure 9**, right) two further observations become apparent:
(1) although small, a correction factor can still be derived also for the microdiamond, and
(2) its dependence on the off-axis distance close to the beam edge is opposite to that with ionization chambers. Both observations were found for any of the solid state detectors of this study.
The function parameter of the correction functions obtained for the solid state detectors is not shown. In all cases, the b parameter which is a measure of the degree of deviation from 1.0, was negative (according to observation 2) and only in the order of a tenth of the values found for the micro-ionization chambers.
In summary, the uncorrected profiles measured with any of the three solid states micro-detectors agree very good with the corresponding true profiles in water. At large off-axis distances, the correction factors can considerably differ from 1.0. This fact, however, is not of importance since it occurs in the very low dose region only.

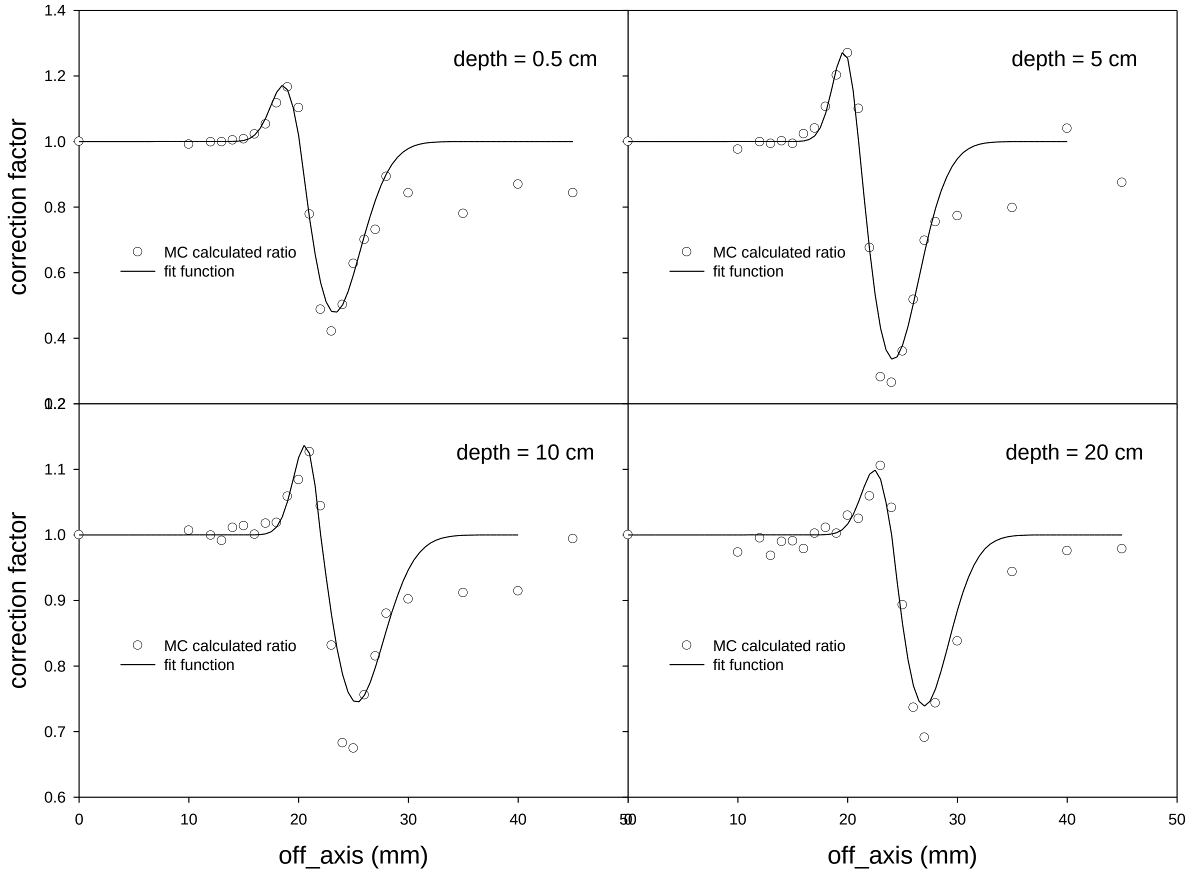

Figure 4. Comparison between MC derived correction factors and the analytical function values given by Equation 1. Parameter values for a_{inner} and a_{outer}, and b_{inner} and b_{outer} were obtained by parameter fitting.

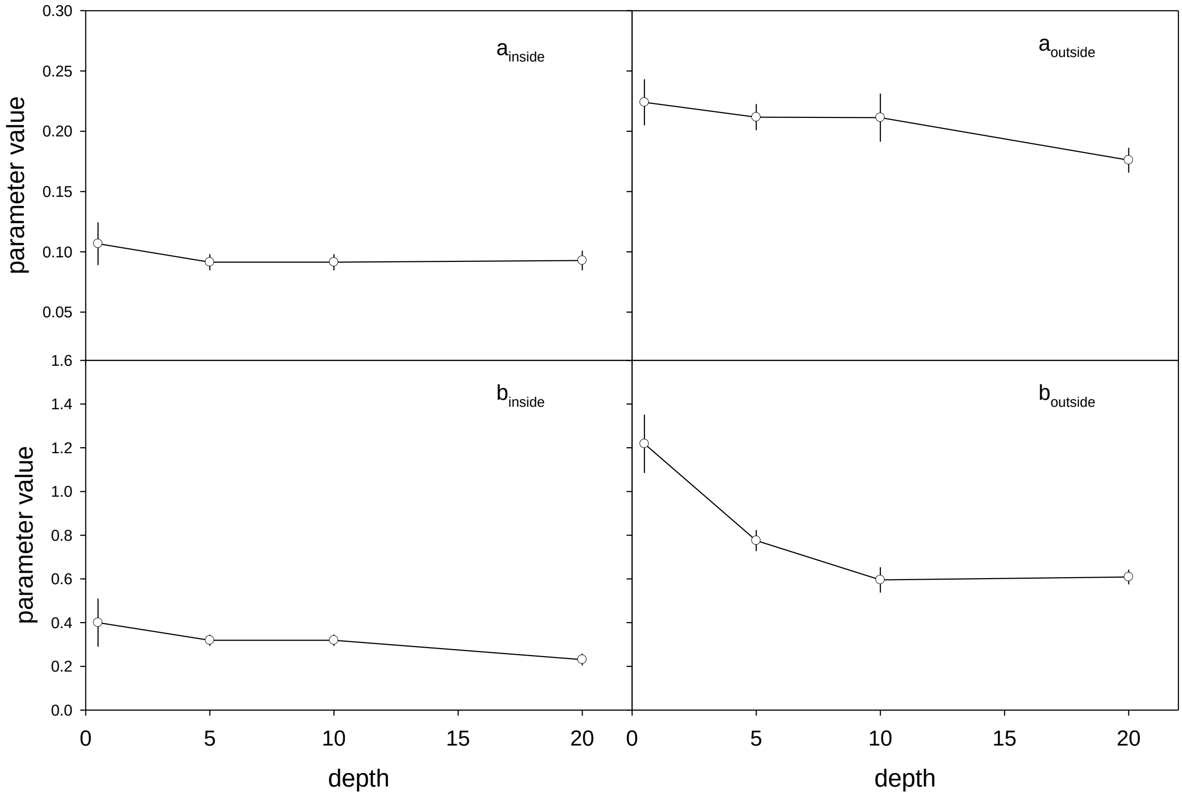

Figure 5. Depth dependence of the function parameters used in Equation 2.

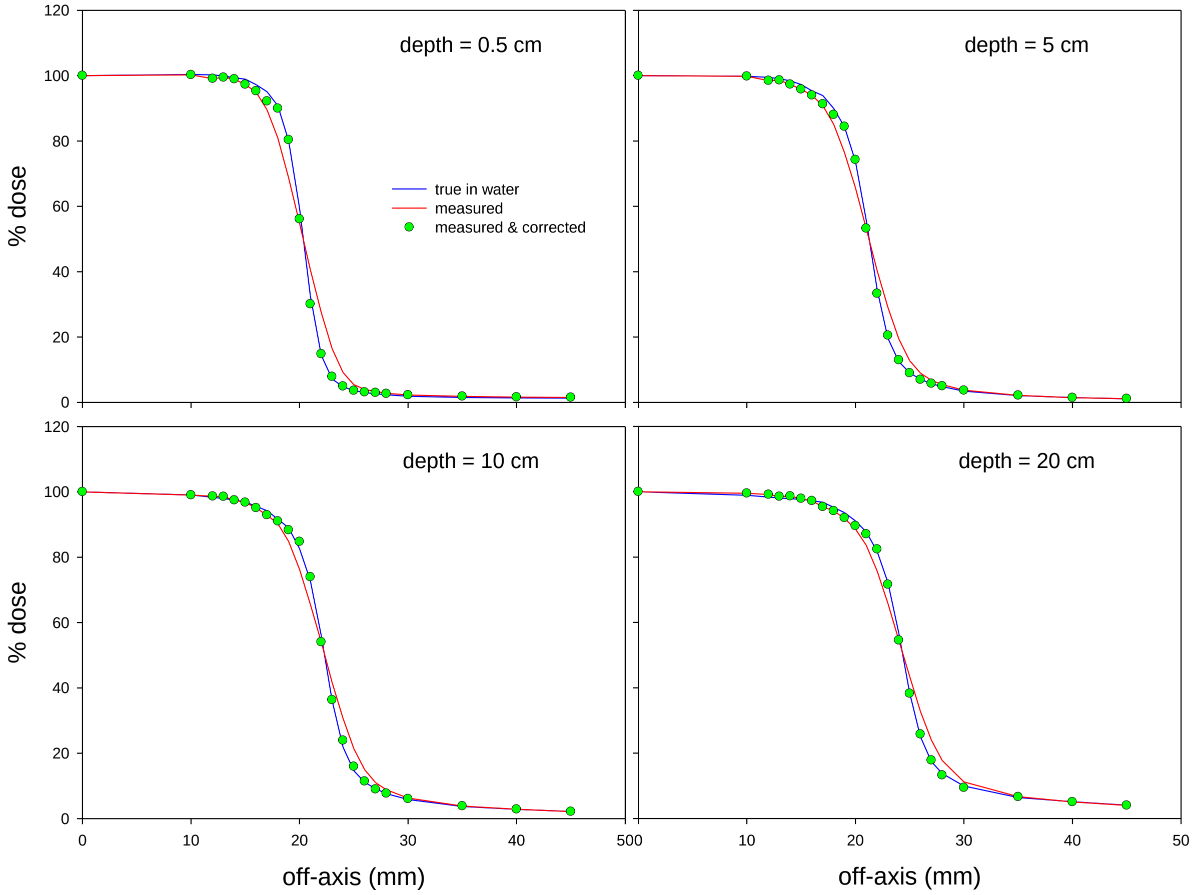

Figure 6. Measured and corrected profiles using the correction function of Equation 2.

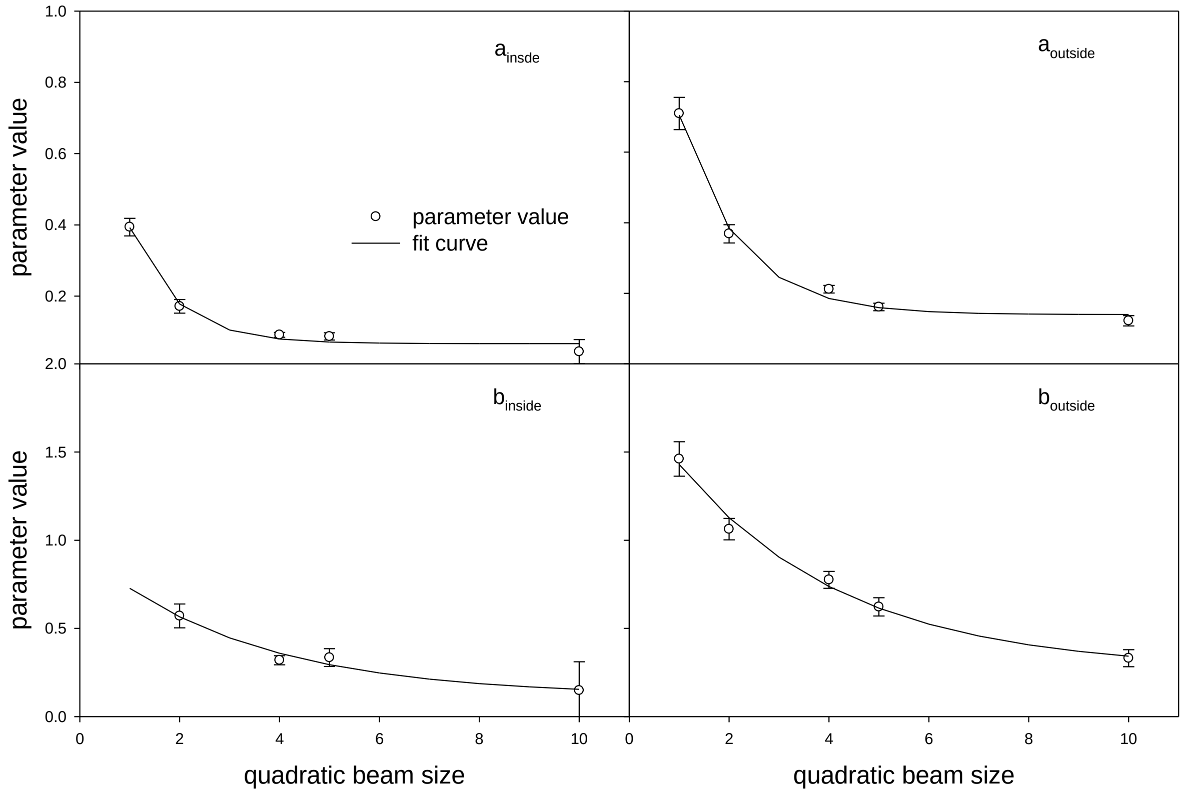

Figure 7. Beam size dependence of the function parameters used in Eq. 2 and fit curve for function parameters using the values of Table 2.

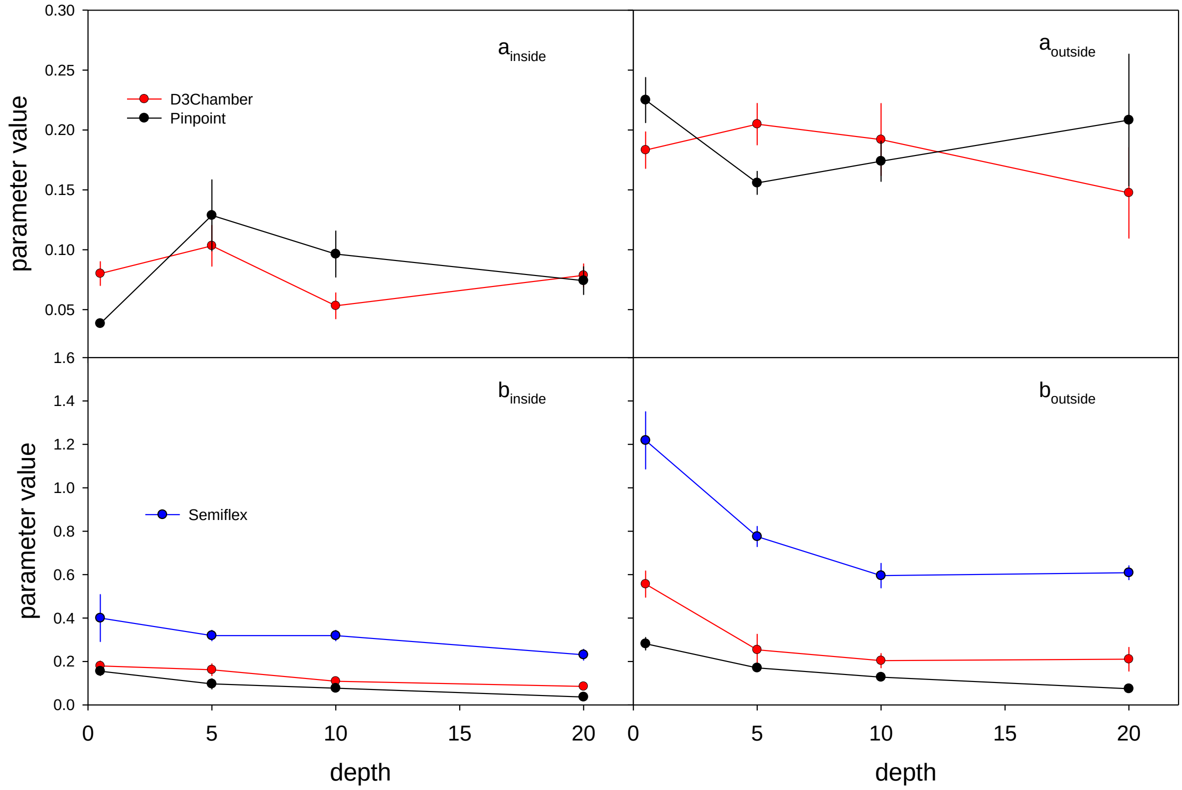

Figure 8. Values for a_{inside}, $a_{outside}$, b_{inside} and $b_{outside}$ for the two micro chambers

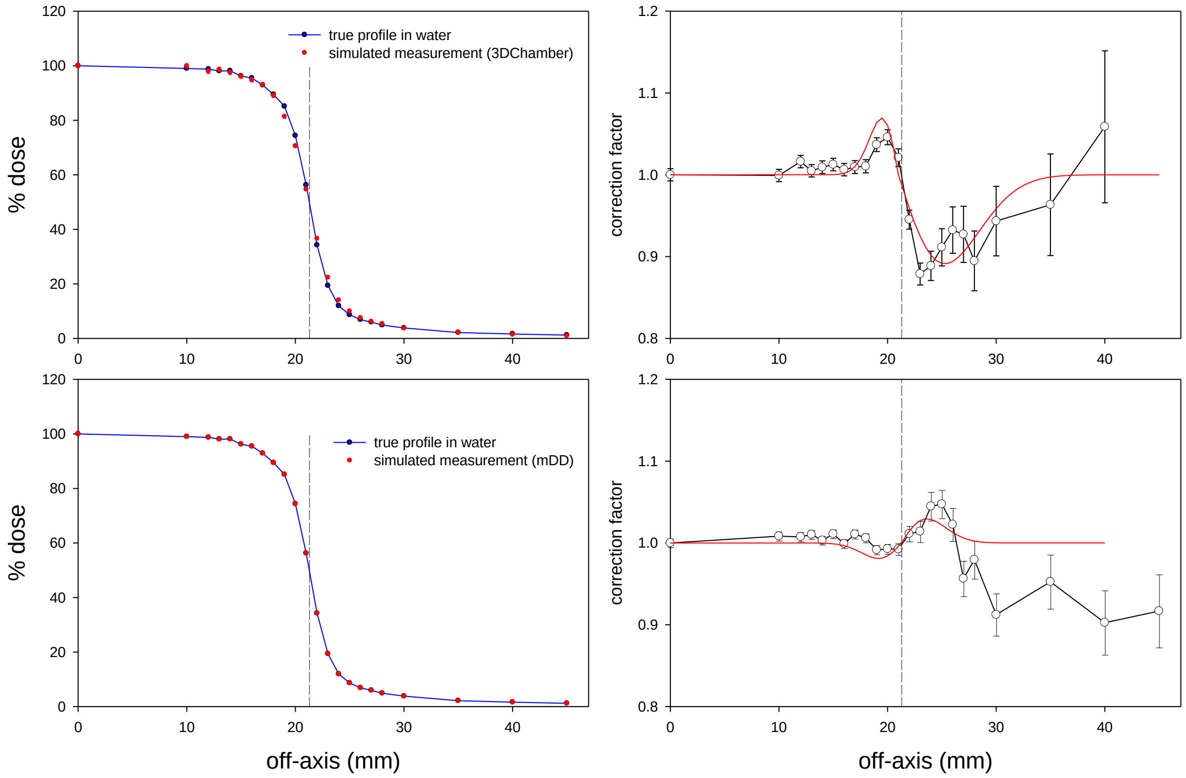

Figure 9. Left: Profiles measured (red dots) with the 3D Chamber (upper plot) and with the microDiamond (lower plot) and the true profiles in water (blue solid curve). Right: Corresponding correction factors.

Discussion

Nowadays MC calculation of absorbed dose is considered to be an accurate and reliable method. Thus it is an ideal tool to investigate many problems in dosimetry, which still exist particularly at non-reference measuring conditions. One of the problems is the existence of the volume averaging effect which always occurs at high dose gradients, for instance at the field edge. In order to minimize volume averaging, small sized detectors are usually employed. However, the volume averaging effect may occur even with small field detectors. The combination of high precision measurements and MC based dose calculation with high statistical accuracy turned out to be a very useful approach to investigate this problem and to answer the question which type of detector is best suited, i.e. can directly provide profile data without a correction or, otherwise, which correction must be applied.

The method based on MC simulations used in this paper is a novel technique which was recently described in a paper by Poudel et al.[15] It was found that the approach to use a heuristic "given free-air-input" profile is a well doable method for MC simulations of detector-free dose distributions. Although the method is an approximation only, it represents a reasonable tool for obtaining a-priori unknown (detector free) dose distributions in water. Based on this method, so-called true dose profiles and hence profile correction factors can be well obtained.

However, this MC based approach can certainly not be performed in a radiotherapy department without having access to research resources. Therefore, alternative ways were additionally sought in this work. It turned out that it is indeed possible to substitute the MC based correction factors by an approximate correction function which requires only few adjustable parameters. Thus this two-step procedure is a good example of the role that can be resumed by the MC technique for dosimetry in radiotherapy departments.

A further important result was confirmed in this work: the differently shaped curve of the correction factor, for ionization chambers on one hand, and for solid state detectors on the other hand. This fact which was already described in a former MC study[18] was attributed to the difference in density of the detector material. Thus, it appears that for solid state detectors used in inhomogeneous dose distributions the inevitable volume averaging effect is at least partly compensated by a density effect.

Conclusion

The MC method of this work to derive correction factors for profile measurements is well feasible for all detectors used in this study. Both types of detectors, ionization chambers and solid state detectors can be used for measurement of beam profiles in small field regions. Profile measurements with solid state detectors are generally recommended against small volume ionization chambers. This recommendation is based on the fact that uncorrected profiles measured with the solid state detectors generally better approaches the true profiles in water. Nevertheless, the use of ionization chambers is also acceptable but should be done in combination with a correction. Furthermore, MC based correction factors can be approximated by simple analytical functions with adjustable function parameters. Values for the ionization chambers of this work were provided. Thus corrections can be performed without the need to perform MC calculations before.

Conflict of Interest

There is no conflict of interest in relation to this article.

Acknowledgements

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