MONTE CARLO CALCULATION OF CORRECTION FACTORS FOR DOSIMETRY IN RADIOTHERAPY USING THE CORRELATED SAMPLING METHOD*

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Abstract. In the present work, the correlated sampling technique in Monte Carlo calculations related to diamond dosimetry and graphite calorimetry will be described. The eg_chamber and DOSRZnrc user-codes included in the EGSnrc package are used. Eg_chamber is already provided with routines enabling the use of correlated sampling while an in-house implementation of this technique was made in the original version of DOSRZnrc. Both codes have been used for calculating perturbation factors needed for absorbed dose measurements in radiotherapy dosimetry. Correlated sampling turned out to be a reliable method, allowing to determine, in reasonable times, accurate correction factors, even in unfavourable conditions as when absorbed dose is scored in very small volumes.

Key words: correlated sampling, diamond detector, graphite calorimeter, small fields.

1. INTRODUCTION

In radiotherapy dosimetry, a number of correction factors, whose nature and amount is largely dependent on the type of dosimetric technique, are required in the expression of the absorbed dose. In principle, at least in some cases, they could be calculated by theoretical formulas or, directly obtained by experimental measurements, but, unfortunately, this is not always the case. Monte Carlo method has been largely applied in this field even if in its early stage the main drawback was the very long computational time necessary to reach satisfactory uncertainties [1]. Due to the improvements of computer performances and to the implementation of Monte Carlo codes, the method has gained more and more popularity and it is nowadays the method of choice in most cases.

A common situation, in high-energy beam dosimetry (1 MeV–25 MeV), is given by in-phantom studies of perturbation effects introduced by dosimeter materials different from the reference material, where the absorbed dose must be determined. Correction factors accounting for these perturbations can be expressed as ratios of absorbed doses, evaluated in simulations, where computational geometries differ from one another only for the composing media of the dosimeter and its accessory parts (i.e. electrode, housing etc.). In the Monte Carlo simulations a huge number of particles (histories) has to be followed not only within the dosimeter volume, 1 cm³ or less, but also throughout the whole phantom volume which is much larger, typically several thousands of cm³. With ordinary Monte Carlo simulations, the radiation transport is to be repeated all over the phantom volume for each different material involved in the simulation of the detector assembly, thus leading to a huge amount of unnecessary and time-consuming calculations. CPU times often as long as hundreds of hours are needed to get correction factors with low statistical uncertainty (0.1%–0.3%), therefore variance reduction techniques (VRTs) must be introduced to improve computational efficiency.

Correlated sampling (CS) is a useful VRT that allows calculating absorbed dose ratios related to different media within the same simulation [2,4]. The improvement of calculation efficiency related to the CS technique is particularly evident when the dose scoring region is extremely small (e.g. diode, diamond dosimeter, pin point ionization chambers) or made of low-density material (e.g. air). Many examples of the use of CS technique can be mentioned, like to evaluate the central electrode or wall composition effects in ionization chambers [5, 6, 7, 8], to take into account the wall effect in vessels used for chemical dosimeters [9, 10], and so on. In general, CS technique makes possible to treat more detailed dosimeter models, and, therefore, to perform more realistic simulations.

In this work, the CS-implemented Monte Carlo method is applied to the evaluation of some correction factors in high-energy photon beams in two main fields, diamond dosimetry and graphite calorimetry.

2. CORRELATED SAMPLING TECHNIQUE

Correlated sampling technique is applicable when radiation transport has to be simulated using geometries with different composing media for regions having identical shape and size. When applying the CS technique, a single simulation geometry is considered. The geometry consists of ordinary regions, where the composing medium is fixed, and correlated sampling (CS) regions, where the composing medium is variable. A flow chart of particle transport using CS is reported in Fig. 1. For ordinary regions, particle transport is done normally and only once. For CS regions, particle transport is repeated for all composing media.
Each time the particle enters a CS region the values of its parameters (charge, energy, position, etc.) are memorized. When the transport is concluded for the current material, the initial parameters are restored and the particle is transported in the subsequent medium, within the same CS region, using the same random number sequence thus increasing the correlation among results. Only after completing all media for the CS region, a new particle history is initiated.

The improvement of Monte Carlo efficiency when using CS is expressed by the efficiency gain parameter \( G \) and is given by [3]

\[
G = \frac{K}{1 + \alpha (K - 1)} \sigma_{uncorr}^2, \quad (1)
\]

where \( K \) is the number of composing media for the CS regions, \( \alpha \) the fractional increase of calculation time for each additional medium or CS region, \( \sigma_{uncorr}^2 \) the variance obtained without CS and \( \sigma_{corr}^2 \) the variance obtained with CS.

In this work the \textit{egs\_chamber} [4] and DOSRZnrc [11] user codes, within the EGSnrc Monte Carlo system[12], are utilized. The \textit{egs\_chamber} code, written in C++ language, is distributed already provided with the CS technique. The user code written in Fortran is not available in a CS-implemented version. An in-house implementation of CS in the DOSRZnrc user code has been developed and utilized for simulations concerning the graphite calorimeter that can be modeled using cylindrical symmetry.
3. CORRECTION FACTORS FOR DIAMOND DOSIMETERS

3.1. MATERIALS AND METHODS

Diamond dosimeters are currently considered as adequate detectors for dosimetry in small photon beams, owing to a number of characteristics, including high spatial resolution and atomic number \( Z \) close to that of water, thus ensuring a weak energy dependence of dosimeter response. However, diamond density (3.51 g cm\(^{-3}\)) is very different from that of water. Moreover the detectors do not consist simply of diamond but they also include accessories made of non-water equivalent materials (i.e. electrodes and housing). As a consequence, possible correction factors must be evaluated before proposing diamond detectors for radiotherapy dosimetry.

At present, one type of detector, based on natural diamond, is commercially available (PTW, Freiburg, Germany) and a lot of prototypes based on chemical vapor deposition (CVD) diamond have been described in literature [13, 14, 15, 16]. Most of the detectors can be schematized as shown in Fig. 2, where the detector model used for the Monte Carlo simulations is also shown. It includes a diamond plate, a couple of electrodes and a plastic housing.

Starting from the cavity theory and following the formalism introduced for ionization chamber dosimetry by Bouchard et al. [17], the absorbed dose to water by a diamond dosimeter may be written as:

\[
D_w = D_{det} \left( \frac{S}{\rho} \right)_d \Gamma \prod_i p_i, \tag{2}
\]

![Figure 2](image-url)
where $D_w$ is the absorbed dose to water, $D_{det}$ the absorbed dose in the sensitive volume of diamond detector, $(S/p)_{w,d}$ the water-to-diamond stopping-power ratio and $p_i$ indicates correction factors accounting for deviations from the cavity theory. For the purpose of Monte Carlo calculations, the correction factors $p_i$ may be defined as the following dose ratios:

$$p_h = \left( \frac{D_{d+el}}{D_{det}} \right), \quad p_{el} = \left( \frac{D_d}{D_{d+el}} \right), \quad \left( \frac{S}{\rho} \right)_d, \quad p_{cav} = \left( \frac{D_w}{D_d} \right),$$

(3)

where $D_d$ is the absorbed dose to the sensitive diamond (bare diamond) in water, $D_{d+el}$ the absorbed dose to bare diamond with electrodes, $D_{det}$ the absorbed dose to bare diamond with electrodes and housing.

In this work, the correction factors in Eqns. (3) were studied with the help of the CS technique as a function of radiation beam quality, beam field size, dosimeter and electrode thickness and materials. These parameters were varied as reported in Table 1. For the calculation of the $p_i$ factors, the irradiation of the diamond dosimeter in a cubic water phantom (30 cm side) was simulated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>6 MV to 24 MV</td>
</tr>
<tr>
<td>beam field size</td>
<td>0.5 × 0.5 cm² to 10 × 10 cm²</td>
</tr>
<tr>
<td>diamond thickness</td>
<td>50 µm to 500 µm</td>
</tr>
<tr>
<td>electrode material</td>
<td>gold, silver, aluminium, titanium</td>
</tr>
<tr>
<td>electrode thickness</td>
<td>20 nm to 200 nm</td>
</tr>
</tbody>
</table>

3.2. RESULTS AND DISCUSSION

The efficiency gain with the CS technique in the performed simulations was evaluated according to the Eq. (1). The main improvement in the efficiency is related to the much lower statistical uncertainties of dose ratios obtained when using CS technique, which takes into account the covariance between the quantities scored in the correspondent CS regions. The increase in CPU time for each additional geometry is small when compared to the CPU time needed by an ordinary simulation. The $\alpha$ value is around 0.02 on average. In simulations with a high number of small-size computational CS regions and different media, as with the couple of electrodes, the gain is higher. Data with the use of CS technique and without CS are compared using the same geometry and the efficiency reaches values up to about 400 in case of particularly high degree of correlation.

Figure 3 shows the calculated $D_w/D_d$ ratio as a function of photon beam energy for different diamond thicknesses in a 10 cm × 10 cm field size. The water-to-diamond stopping power ratios, calculated by SPRZnrc-EGSnrc user code [11], are also represented. The $D_w/D_d$ values do not differ from the water-to-
diamond stopping power ratio by more than 0.2%. Therefore, according to Eqns. (3), a $p_{cav}$ factor equal to unity can be taken for values of diamond thickness up to 500 µm.

In Fig. 4 the water-to-diamond dose ratio is reported for a 500 µm dosimeter as a function of field size for different photon energies. The data show that the diamond response in terms of absorbed dose to water can be considered independent of field size down to 2 cm × 2 cm while it tends to increase for smaller field sizes. Therefore, if diamond detectors are used in such small fields appropriate correction factors should be applied.

![Fig. 3 – Energy dependence of the $D_w/D_d$ ratio for different diamond thicknesses in a 10 cm × 10 cm field size.](image)

![Fig. 4 – Field size dependence of $D_w/D_d$ ratio for different beam energies. Data are for a sensitive diamond thickness of 500 µm.](image)
Figure 5 reports the $p_{el}$ correction factor as a function of beam energy for several electrode materials in $10 \text{ cm} \times 10 \text{ cm}$ beam size. The electrode thickness is 200 nm and two diamond thicknesses are considered: 500 µm and 50 µm. The results show that the electrode material can significantly affect the detector response especially when high Z material and very thin diamond plates are used.

Fig. 5 – Energy dependence of the $p_{el}$ factor for several electrode materials in a $10 \text{ cm} \times 10 \text{ cm}$ beam size. Data refer to simulations performed with an electrode thickness of 200 nm and a sensitive diamond thickness of 500 µm, on the left figure, and 50 µm, on the right one.

Figure 6 reports the correction factors accounting for PMMA housing effects, $p_h$, as a function of beam quality index, for various dosimeter thicknesses in a $10 \text{ cm} \times 10 \text{ cm}$ field size. Values of $p_h$ range between 0.997 and 1.013 and increases when increasing energy or when decreasing dosimeter thickness.

Fig. 6 – Energy dependence of the $p_h$ correction factor for several sensitive diamond thicknesses in a $10 \text{ cm} \times 10 \text{ cm}$ beam size and PMMA housing material.
All the above results show that if not applying any correction factors to the diamond detector response, errors up to a few percent can be introduced in absorbed dose determination especially when measurements are made in small field sizes. On the other hand, correction factors appropriate for the actual detector to be used can be calculated, with high accuracy, using Monte Carlo simulations and the CS technique.

4. CORRECTION FACTOR FOR GRAPHITE CALORIMETER

4.1. MATERIALS AND METHODS

Graphite calorimeters are used for realizing the unit of the quantity absorbed dose to graphite [18]. The calorimeter working principle is the measurement of the temperature rise in its sensitive part, the core, due to the ionizing radiation absorption.

The most important parts of a graphite calorimeter consist of bodies arranged in a nested design, e.g. the core (innermost), the surrounding jacket and the next surrounding medium. Heat flow throughout the calorimeter bodies has to be minimized and, therefore, vacuum gaps, about 1 mm thick, are situated around the core, the jacket and the medium, to ensure their thermal insulation.

The perturbation effects introduced by these gaps must be evaluated and taken into account in the absorbed dose determination. In this work Monte Carlo calculation with the CS technique was applied to this aim for the graphite calorimeter built at ENEA-INMRI to measure absorbed dose due to high-dose-rate $^{192}$Ir brachytherapy sources [19].

Figure 7 shows a schematic drawing of the ENEA-INMRI calorimeter and a detail of the geometrical model for the DOSRZnrc simulations. The $^{192}$Ir source is put at the center of the calorimeter core having cylindrical symmetry around the $^{192}$Ir source axis. The calorimeter core consists of a 50 mm diameter annular ring of graphite, 5 mm high and 2 mm thick. The core is completely surrounded by a second graphite body the jacket, matching the core mass and the core heat capacity and acting as a thermal buffer for controlling the core temperature. Core and jacket are thermally insulated by two vacuum gaps, about 0.75 mm thick and are surrounded by a third graphite body, 90 mm diameter medium, insulated by a third vacuum gap 1 mm thick that surrounds the medium. Two graphite discs, on top and bottom, and a lateral 130 mm diameter PMMA housing encompass the medium.
The correction for the gap effects is determined as

\[ k_G = \frac{D_0}{D_G}, \]  

(4)

where \( D_0 \) and \( D_G \) are the absorbed dose to graphite values calculated simulating irradiation of the calorimeter without gaps and with all gaps, respectively. The effect of each single gap is also evaluated as

\[ k_{Gi} = \frac{D_0}{D_{Gi}}, \]  

(5)

where \( D_{Gi} \) is the absorbed dose to graphite as calculated by allowing only for the i-th gap. In order to apply the CS technique, the ‘removal’ of a gap was obtained by ‘filling’ the corresponding volume with graphite.

4.2. RESULTS AND DISCUSSION

The efficiency gain with the CS technique was again evaluated according to the Eq. (1). An efficiency gain around 10 has been obtained using the in-house implementation of CS. The lower \( G \) value may be attributed to differences in the source energy, the dimensions and number of the CS regions compared to the diamond simulations. Moreover the in-house code has not been optimized but it is worth to point out that the CS in-house implementation is more attractive when FORTRAN user-code options, like calculation of dose from primary photons, scattered radiation and secondary electrons are of interest.

Gap effect correction factors are reported in Table 2. The overall correction factor was determined in two ways, respectively by direct Monte Carlo calculations and by the product of the three Monte Carlo calculated partial correction factors.
The overall correction factor directly calculated by Monte Carlo agrees with that obtained as a product of partial factors, showing that the overall gap effect is factorizable in terms of the partial effects given by each single gap. However, none of the factors differ significantly from unity, thus proving that gaps do not significantly affect the dose absorbed by the core for the $^{192}$Ir source.

<table>
<thead>
<tr>
<th>Gap type</th>
<th>Correction factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap 1 (0.75 mm)</td>
<td>$k_{G1}$</td>
<td>1.000±0.001</td>
</tr>
<tr>
<td>Gap 2 (0.75 mm)</td>
<td>$k_{G2}$</td>
<td>0.999±0.001</td>
</tr>
<tr>
<td>Gap 3 (1.0 mm)</td>
<td>$k_{G3}$</td>
<td>0.999±0.001</td>
</tr>
<tr>
<td>All the 3 gaps</td>
<td>$k_G$</td>
<td>0.998±0.002</td>
</tr>
<tr>
<td>All the 3 gaps</td>
<td>$k_{G1}k_{G2}k_{G3}$</td>
<td>0.998±0.002</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Monte Carlo calculation with correlated sampling technique has been applied for calculating correction factors needed for absorbed dose determination in radiotherapy dosimetry. Accurate determination of correction factors is achieved, by using CS, with reasonable CPU times, even in unfavourable conditions (i.e. very small scoring volumes). The CS technique allows to improve the calculation efficiency by a factor up to about 400. The remarkable lowering of CPU time required to achieve a given statistical uncertainty is due to both the possibility to treat in the same simulation several geometries differing only in the composing media and to the decrease of uncertainty values given by the correlation existing among results.

Results obtained for diamond dosimeters show that energy and field size depending correction factors should be evaluated for this type of detectors when performing accurate dosimetry in small photon beams. The Monte Carlo calculation with CS technique results to be a reliable and efficient method for this aim. The reduced CPU times also allows to apply this method to optimize the choice of materials to be used in designing new detectors.

Results obtained for the ENEA-INMRI graphite calorimeter for high-dose-rate $^{192}$Ir sources show that the vacuum gaps surrounding the core, the jacket and the medium do not significantly affect the value of the absorbed dose measured in graphite. These results allow the use of the adopted nested design with 0.75 mm – 1 mm vacuum gaps around the graphite bodies as a convenient method to minimize the heat exchange among the bodies and to better insulate the calorimeter innermost sensitive body, the core.
REFERENCES