Modelling ionization chamber response to nonstandard beam configurations

Laurent Tantot and Jan Seuntjens
Medical Physics Unit, McGill University Health Centre, 1650 Cedar ave, L5-113, Montreal, Quebec H3G1A4, Canada
E-mail: laurent.tantot@mail.mcgill.ca

Abstract. Novel technologies aiming at improving target dose coverage while minimising dose to organs at risk use delivery of radiation fields that significantly deviate from reference conditions defined in protocols such as TG-51 and TRS-398. The use of ionization chambers for patient-specific quality assurance of these new delivery procedures calibrated in reference conditions increases the uncertainties on dose delivery. The conversion of the dose to the chamber cavity to the dose to water becomes uncertain; and the geometrical details of the chamber, as well as the details of the delivery, are expected to be significant. In this study, a realistic model of the Exradin® A12 Farmer chamber is simulated. A framework is applied for the calculation of ionization chamber response to arbitrarily modulated fields as a summation of responses to pencil beams. This approach is used with the chamber model and tested against measurements in static open fields and dynamic MLC IMRT fields. As a benchmark test of the model, quality conversion factors values calculated by Monte-Carlo simulation with the chamber model are in agreement within 0.1 % and 0.4 % with those in the AAPM TG-51, for 6 MV and 18 MV photon beams, respectively. Pencil-beam kernels show a strong dependence on the geometrical details of the chamber. Kernel summations with open fields show a relative agreement within 4.0 % with experimental data; the agreement is within 2.0 % for dynamic MLC IMRT beams. Simulations show a strong sensitivity of chamber response on positioning uncertainties, sometimes leading to dose uncertainties of 15 %.

1. Introduction
Although the use of ionization chambers for reference dosimetry is the preferred method for the patient-specific quality assurance of Intensity-Modulated Radiation Therapy (IMRT), it has inherent problems that have yet to be solved. The irregular conditions under which the IMRT beams are delivered differ dramatically from the reference conditions defined in the dosimetry protocols [1]. The calibration coefficient $N_{D,w}$ specified for each chamber under reference conditions can no longer be trusted to convert the signal of the ionization inside the chamber cavity to the dose to water. This difficulty is allegedly circumvented by placing the ionization chamber in a low dose gradient and high dose region of the phantom [2]. However, the chamber size may make it hard to find a low-dose-gradient region that envelopes its entire sensitive part. Furthermore, each beam of the treatment plan may create high dose gradients where the chamber is placed, and inaccuracies in the movement of the MLC leaves and physical properties of the MLC unaccounted for by the treatment planning system may prevent the high dose gradients from evening out, or may lead to a poor reproducibility of the measurements [3].

As a result of dose gradients, point dose measurements often disagree with the treatment planning system, sometimes by up to 10 %. Discrepancies are usually attributed to tongue-and-groove effect and to positioning uncertainties of the chamber in high dose gradient regions [4].
These discrepancies are a sign that transient charged particle equilibrium can be locally violated in the chamber volume, and that the value of $N_{D,w}$ under the IMRT conditions is not the same as that under reference conditions. The effect of chamber size has been studied [1; 5–9] but not completely eliminated by the use of small chambers because of significant polarity effects and potential effects of leakage. The other characteristics of the chamber, such as shape or wall material, seem to play a role in measurement perturbation [10].

Our goal in this article is to test if geometrical characteristics of an ion chamber can be accurately modelled in a Monte-Carlo simulation in nonstandard beam configurations. Subsequently, we test the accuracy of a proposed kernel summation model to calculate chamber response in arbitrary beams. This work also shows how the results from the simulation compare to experimental measurements. We present a realistic model of the Exradin® A12 Farmer chamber, which is used for point dose verifications of IMRT plans at the Montreal General Hospital. The Monte-Carlo EGSnrc user code CAVITY that can model this complex geometry is tested against the well-known user code CAVRZnrc; the chamber model is tested in TG-51 reference conditions, and the results are compared to those in TG-51 [11]. Finally, the kernel summation method is used with open fields and IMRT fields to quantify the chamber response. The results are compared to experimental data performed on a Varian® Clinac 6EX.

2. Materials and methods

2.1. Theory

Bouchard and Seuntjens [12] and Capote et al [13] independently proposed to introduce a correction factor $C_{\text{IMRT}}$ to correct $N_{D,w}$ for IMRT conditions. It is defined as follows:

$$N_{D,w}^{\text{IMRT},Q} = C_{\text{IMRT},Q} \cdot N_{D,w}^Q \quad \text{or} \quad C_{\text{IMRT},Q} = \frac{[D_a^w]_{\text{IMRT},Q}}{[D_a^w]^Q},$$

where $[D_a^w]^Q$ is the ratio of the dose to water to the dose to the air cavity in reference conditions for the beam quality $Q$, and $[D_a^w]_{\text{IMRT},Q}$ is the same ratio in IMRT conditions.

Taking a pencil-beam approach, Bouchard and Seuntjens [12] developed a summation method that uses precalculated Monte-Carlo chamber and water kernels to determine the ratio of the dose to water to the dose to air for any IMRT field. The chamber kernel depends on the chamber geometry and depth, and it can be used to calculate dose to air at that depth for an arbitrary field modulation. The chamber kernel $d_a(x, y; z)$ is the dose to the chamber air cavity divided by the fluence through the kernel cell area at $(x, y)$ when the chamber is placed at depth $z$, the cavity centroid on axis, and a pencil beam hits the isocentre plane at $(x, y)$. The water kernel $d_w(x, y; z)$ is the dose to water divided by the fluence through the kernel cell area at $(x, y)$, in a 1 mm$^3$ water voxel centred at the isocentre in the absence of the chamber. Using both chamber and air kernels, defined in the isocentre plane, the dose ratios are calculated as follows:

$$[D_a^w]^Q = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d_w(x, y; z) f(x, y) dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d_a(x, y; z) f(x, y) dx dy}$$

and

$$[D_a^{w,\text{IMRT},Q}] = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d_w(x, y; z) T_{\text{IMRT}}(x, y) f(x, y) dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d_a(x, y; z) T_{\text{IMRT}}(x, y) f(x, y) dx dy},$$

where $T_{\text{IMRT}}(x, y)$ is the transmission function representing the transmission of the photon beam through the MLC at the point $(x, y)$ other a complete MLC sequence, and $f(x, y)$ is the (relative) radial photon fluence at $(x, y)$ in the isocentre plane.
2.2. Chamber model and kernels

2.2.1. The chamber model Using the EGSpp geometry package of EGSnrc [14; 15], a detailed model of the Exradin A12 Farmer chamber was constructed (Figure 1). The dimensions and components of the chamber follow the prescriptions of the manufacturer’s blueprint. The wires, the central electrode, the inside joints, and especially the cavity volume were carefully designed.

2.2.2. Calculations We used the CAVITY/EGSnrc Monte-Carlo code to calculate the dose kernels in water and the air cavity of the chamber. CAVITY is a similar code to DOSXYZnrc or DOSRZnrc, but it can use any geometry that can be modelled within the EGSpp geometry package. A comparison of CAVITY with the well-benchmarked CAVRZnrc in a simple set-up was performed. A $^{60}$Co source at an SSD of 100 cm, collimated in a disc with a radius of 1.3 cm, was incident on a pancake air cavity with graphite walls. The air cavity dimensions were $1 \text{ cm OD} \times 0.2 \text{ cm}$, and the wall thickness was 0.3 cm. The results show an agreement within 0.1 % between both user codes, with a relative uncertainty of 0.2 %.

Figure 1: Detailed Exradin A12 Farmer chamber model. The nonsensitive region is the air region between the wall and the guard; although the air is polarised, the ions created in this region are not collected and do not contribute to the chamber reading.

Figure 2: This diagram illustrates how the chamber kernel is acquired. The chamber model is placed at 10 cm in a water phantom, and a pencil beam is swept at the surface of the phantom.

The dose kernels in water and air were calculated for different set-ups. The tests of the chamber model were made with dose kernels calculated using an SSD of 100 cm and a reference depth of 10 cm. However, the kernels used in IMRT conditions were calculated in Solid Water®, with a SAD of 100 cm and a reference depth of 8.5 cm to reproduce the conditions in which IMRT QA is performed at the Montreal General Hospital. A $1 \text{ mm}^3$ water voxel and the chamber model were embedded in a rectangular parallelepipedic water phantom whose dimensions were $30 \times 30 \times 17 \text{ cm}^3$, and the dose was recorded in the water voxel or the chamber air cavity centred on the beam axis at the reference depth. The chamber axis was positioned perpendicularly to the main beam axis. The kernels were acquired by sweeping a pencil photon beam on the surface of the water phantom (Figure 2).

A total of 1702 beam positions were simulated for half of the chamber because of its symmetry. For the water voxel that has three axes of symmetry, 190 beam positions were simulated for one eighth of the voxel. The beam positions were defined at critical points on an irregular rectangle grid, the spacing of points being smaller near the chamber to capture geometrical details and increasing near the field edges.
2.2.3. Interpolation

The kernels acquired by Monte-Carlo were interpolated and mapped onto a fine and regular grid of 1001 \times 1001 points in a 10 \times 10 \text{cm}^2 field. However, the contribution of a photon to the fluence through a cell of the kernel depends on the distance from the source at (0, 0, −SAD) to the point (x, y, 0), as well as on the angle of the photon when it hits the isocentre plane. Therefore, for each cell of the kernels, corrections were made in order to translate dose per history into dose divided by the fluence through the cell (see 2.1), as is shown below:

\[
D(x, y; z) \text{ [Gy cm}^2\text{]} = (\text{cell area}) \times (\text{angle corr.}) \times (\text{inv. square law}) \times D(x, y; z) \text{ [Gy/history]}
\]

\[
= (10^{-4} \text{ cm}^2) \times \left(\frac{\text{SAD}^2}{\text{SAD}^2 + x^2 + y^2}\right)^{\frac{3}{2}} \times D(x, y; z) \text{ [Gy/history]}.
\]

Finally, the kernels were stored in tables with the position (x, y) in the isocentre plane, the dose per fluence, and the standard deviation.

2.3. Code algorithm

We used the code algorithm developed by Bouchard and Seuntjens [12]. It reads the kernel tables and the MLC sequence. It then calculates the effective transmission function over a complete dynamic delivery, and it computes the integrations of the dose kernels weighted by the radial fluence and the transmission function. The integrations are performed for both reference conditions and the MLC sequence. The transmission function takes into account most of the geometrical properties of the Varian® Millenium 120 MLC including the rounded leaf ends, the divergence and the tongue-and-groove details.

The code yields the dose to water and the dose to air for the reference conditions and for the MLC sequence. From these four quantities, we can calculate the relative dose factor (RDF), the relative cavity dose (RCD) and C^{IMRT}. The code also has a feature allowing the calculation of the uncertainty on the dose due to the positioning of the chamber. The dose is calculated for the main chamber position and for the eight chamber positions obtained by shifting the chamber by 1 mm in any direction in the (x, y) plane.

2.4. Experiments

We compared Monte-Carlo calculations to measurements for ten static open fields and one dynamic wedge. The measurements were performed on a Varian 6EX, with an Exradin A12 Farmer chamber at 10 cm in a water phantom. For each measurement, 100 MU were delivered at a rate of 400 MU/min.

Twelve IMRT fields from actual IMRT treatment plans were also selected. They were submitted to the code algorithm and RCD values were obtained for each one of them with the kernel summation method. They were also delivered with a Varian Clinac 6EX equipped with a 120 Millenium MLC. The plans were delivered in the conditions of patient-specific quality assurance, i.e., on a Solid Water phantom whose dimensions were 30 \times 30 \times 17 \text{ cm}^3. An Exradin A12 Farmer chamber was placed with the cavity centroid at the centre of the phantom. In order to compare Monte-Carlo and experimental measurements, the kernels used in the summation had been specifically simulated in a Solid Water phantom with the chamber model embedded at the same depth as in the experiment.

3. Results

3.1. Chamber profiles

The chamber profiles in Figures 3 and 4 show a high dependence on the chamber geometry. The effect of the central electrode, for example, is significant. The material details in the chamber
stem, however, do not create significant dose response differences compared to the effect of the nonsensitive air region where there is no charge collection. We found that the chamber model could be further simplified by replacing different materials in the stem by C552, leading to a sixfold reduction in CPU time.

Figure 3: Transverse profile of the chamber model obtained at 3 cm in water with a pencil beam.

3.2. Chamber model test
The chamber model was tested in reference conditions, with photon beams of energies 1.25 MeV, 6 MV and 18 MV, for which spectra were adapted from Mohan et al [16] and Sheikh-Bagheri and Rogers [17], respectively. The quality conversion factors $k_Q$ for 6 MV and 18 MV were simulated and compared with those in the report TG-51 [11]. The values of $k_Q$ obtained with the chamber model (Table 1) agree with the values from the TG-51 within one standard deviation.

| $\%dd_X$ | Dose/(10^{-16} Gy cm^2) | $[D_a^w]^Q$ | Monte-Carlo | TG-51 |
|---------|--------------------------|------------|-------------|--------|
| 1.25 MeV | 57.7 | 2.954 ± 0.009 | 2.632 ± 0.004 | 1.123 ± 0.004 |
| 6 MV     | 66.5 | 4.872 ± 0.005 | 4.352 ± 0.013 | 1.119 ± 0.004 | 0.996 ± 0.005 | 0.995 |
| 18 MV    | 80.3 | 9.905 ± 0.010 | 9.105 ± 0.009 | 1.088 ± 0.002 | 0.969 ± 0.004 | 0.973 |

3.3. Kernel summation test
The kernel summation method was tested in reference conditions. The calculations of $[D_a^w]^Q$ and $k_Q$ were compared to those acquired in the direct calculation shown in Table 1. The results in Table 2 show a good agreement between both methods, within one standard deviation.

| $[D_a^w]^Q$ | $k_Q$ |
|------------|-------|
| $^{60}$Co | 6 MV | 6 MV | $k_Q$ |
| Direct MC calculation | 1.123 ± 0.004 | 1.119 ± 0.004 | 0.996 ± 0.005 |
| Kernel summation | 1.125 ± 0.008 | 1.120 ± 0.004 | 0.995 ± 0.008 |
3.4. Kernel summation in static and IMRT fields
Comparison of relative cavity dose (RCD) between kernel summation and experimental measurements in static open fields and IMRT fields are shown in Table 3. The uncertainty on Monte-Carlo calculations includes the statistical uncertainty as well as the uncertainty due to a chamber positioning error of 1 mm in any direction in the isocentre plane. The positioning error is predominant for fields with the chamber in high gradients, leading to a high uncertainty on the relative difference between the Monte-Carlo and experimental measurements. The results for the open fields named “5 × 10” and “10 × 5” illustrate the positioning issue. On the other hand, for fields with the chamber in low dose gradients, the statistical uncertainty is predominant, as can be seen for all the fields where the uncertainty on the relative difference is typically below 5.2 %.

Table 3: Comparison of dose-to-air kernel summation to measurements in static open fields and IMRT fields. Measurement reproducibility was 0.2 %, excluding set-up reproducibility.

| 6 MV , z = 10 cm | Relative Cavity Dose (RCD) | Relative difference (%) |
|-----------------|-----------------------------|--------------------------|
| 100 cm SSD      | Experiment                  | MC kernel summation      |                           |
| Closed          | 0.0933 ± 0.007              | 0.091 ± 0.007            | 2.9 ± 7.0                |
| 5 × 10 cm² right| 0.5418 ± 0.041              | 0.550 ± 0.041            | 1.5 ± 7.3                |
| 5 × 10 cm² left | 0.5506 ± 0.041              | 0.541 ± 0.041            | 1.8 ± 7.6                |
| 10 × 5 cm² down | 0.5488 ± 0.087              | 0.550 ± 0.087            | 0.3 ± 15.6               |
| 10 × 5 cm² up   | 0.5009 ± 0.087              | 0.541 ± 0.087            | 7.3 ± 14.8               |
| 10 × 1 cm²      | 0.7596 ± 0.032              | 0.791 ± 0.032            | 4.0 ± 3.8                |
| 1 × 10 cm²      | 0.4715 ± 0.021              | 0.459 ± 0.021            | 2.9 ± 4.7                |
| 8 × 8 cm²       | 0.9760 ± 0.037              | 0.978 ± 0.037            | 0.2 ± 3.7                |
| 6 × 6 cm²       | 0.9434 ± 0.036              | 0.949 ± 0.036            | 0.6 ± 3.7                |
| 4 × 4 cm²       | 0.8927 ± 0.035              | 0.907 ± 0.035            | 1.6 ± 3.7                |
| dyn. wedge      | 0.5079 ± 0.022              | 0.515 ± 0.022            | 1.4 ± 4.1                |
| Dynamic #1      | 0.451 ± 0.017               | 0.459 ± 0.017            | 1.7 ± 3.7                |
| Dynamic #2      | 0.342 ± 0.020               | 0.349 ± 0.020            | 2.0 ± 5.7                |
| Dynamic #3      | 0.283 ± 0.025               | 0.288 ± 0.025            | 1.7 ± 8.6                |
| Dynamic #4      | 0.348 ± 0.013               | 0.350 ± 0.013            | 0.5 ± 3.8                |
| Dynamic #5      | 0.338 ± 0.013               | 0.344 ± 0.013            | 1.8 ± 3.7                |
| Dynamic #6      | 0.505 ± 0.019               | 0.510 ± 0.019            | 0.9 ± 3.7                |
| Dynamic #7      | 0.477 ± 0.018               | 0.483 ± 0.018            | 1.3 ± 3.8                |
| Dynamic #8      | 0.403 ± 0.016               | 0.407 ± 0.016            | 1.1 ± 4.0                |
| Dynamic #9      | 0.543 ± 0.021               | 0.550 ± 0.021            | 1.3 ± 3.7                |
| Dynamic #10     | 0.354 ± 0.013               | 0.355 ± 0.013            | 0.3 ± 3.8                |
| Dynamic #11     | 0.455 ± 0.017               | 0.460 ± 0.017            | 1.1 ± 3.8                |
| Dynamic #12     | 0.366 ± 0.015               | 0.515 ± 0.015            | 1.5 ± 3.9                |

4. Discussion and conclusion
With the benchmarked EGSnrc/CAVITY Monte-Carlo code, we showed the accuracy of the detailed chamber model, as well as the validity of the kernel summation method using the model. It was also shown that the chamber kernel highly depends on the chamber geometrical details, especially the dimensions, the thickness of air crossed by the pencil beams in the cavity nonsensitive region, and the central electrode. Details in the stem were found to be of less importance.

The kernel summation method was further used to simulate RCDs in static and IMRT fields. The results appear to agree with the experimental measurements within one standard error,
which includes the positioning error of the chamber. However, the interpolation of 1001 × 1001 points from 1702 simulated points yields to covariance terms in the kernel summation statistical error that currently limit the overall uncertainty to 3.7 %. This is due to the fact that the calculated points near the edges of the 10 × 10 cm$^2$ field, with an uncertainty of 5 % to 10 %, are used for interpolation much more often than the points in the centre of the field, which have a typical uncertainty of 0.1 %. When the kernels are summed up, the consequence is an artificial high uncertainty, which could be termed “latent kernel uncertainty”, similarly to that for phase-space source representations. Therefore, to circumvent this problem, there is a need to adjust the density of points simulated and the number of interpolated points without losing any chamber detail.

Nevertheless, the summation method can be used for any chamber potentially in any type of field delivery, in particular fields that do not comply with reference protocols.

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