An EGSnrc Monte Carlo study of the microionization chamber for reference dosimetry of narrow irregular IMRT beamlets

Roberto Capote, Francisco Sánchez-Doblado, Antonio Leal, Juan Ignacio Lagares, and Rafael Arráns
Hospital Universitario Virgen Macarena, Radiofísica, Sevilla, Spain and Departamento de Fisiología Médica y Biofísica, Facultad de Medicina, Universidad de Sevilla, Spain

Günther H. Hartmann
Deutsches Krebsforschungszentrum, Abt. Medizinische Physik, Heidelberg, Germany

(Received 11 December 2003; revised 12 May 2004; accepted for publication 13 May 2004; published 19 August 2004)

Intensity modulated radiation therapy (IMRT) has evolved toward the use of many small radiation fields, or “beamlets,” to increase the resolution of the intensity map. The size of smaller beamlets can be typically about 1‒5 cm². Therefore small ionization chambers (IC) with sensitive volumes ≤0.1 cm³ are generally used for dose verification of IMRT treatment. The dosimetry of these narrow photon beams pertains to the so-called non-reference conditions for beam calibration. The use of ion chambers for such narrow beams remains questionable due to the lack of electron equilibrium in most of the field area. In the present contribution aims to estimate, by the Monte Carlo (MC) method, the total correction needed to convert the IBA-Wellhöfer NAC007 micro IC measured charge in such radiation field to the absolute dose to water. Detailed geometrical simulation of the microionization chamber was performed. The ion chamber was always positioned at a 10 cm depth in water, parallel to the beam axis. The delivered doses to air and water cavity were calculated using the CAVRZ EGSnrc user code. The 6 MV phase-spaces for Primus Clinac (Siemens) used as an input to the CAVRZnc code were derived by BEAM/EGS4 modeling of the treatment head of the machine along with the multileaf collimator [Sánchez-Doblado et al., Phys. Med. Biol. 48, 2081–2099 (2003)] and contrasted with experimental measurements. Dose calculations were carried out for two irradiation geometries, namely, the reference 10×10 cm² field and an irregular (~2×2 cm²) IMRT beamlet. The dose measured by the ion chamber is estimated by MC simulation as a dose averaged over the air cavity inside the ion-chamber (\(D_{\text{air}}\)). The absorbed dose to water is derived as the dose deposited inside the same volume, in the same geometrical position, filled and surrounded by water (\(D_{\text{water}}\)) in the absence of the ionization chamber. Therefore, the \(D_{\text{water}}/D_{\text{air}}\) dose ratio is a MC direct estimation of the total correction factor needed to convert the absorbed dose in air to absorbed dose to water. The dose ratio was calculated for several chamber positions, starting from the penumbra region around the beamlet along the two diagonals crossing the radiation field. For this quantity from 0 up to a 3% difference is observed between the dose ratio values obtained within the small irregular IMRT beamlet in comparison with the dose ratio derived for the reference 10×10 cm² field. Greater differences from the reference value up to 9% were obtained in the penumbra region of the small IMRT beamlet. © 2004 American Association of Physicists in Medicine. [DOI: 10.1118/1.1767691]

Key words: IMRT dosimetry, Monte Carlo, small beam, reference dosimetry, absolute dosimetry

I. INTRODUCTION

Intensity modulated radiation therapy (IMRT) is a highly conformal radiotherapy that is used when conventional methods cannot deliver a prescribed target volume dose without compromising other critical organ’s maximum dose. To achieve a conformal dose distribution, IMRT fields are composed of small subfields, or “beamlets” with a typical characteristic area well below 10 cm². For example the step-and-shoot IMRT employed in the Virgen Macarena hospital uses beams composed of multiple segments of which some of them may be quite small.¹ Similar situations occur at other centers employing dynamic IMRT² as well as tomographic IMRT.³,⁴ Due to the complexity of IMRT treatment plans and delivery, many techniques developed for the verification of two-dimensional (2D) and 3D treatment plans⁵ cannot be used for IMRT. Thus, its plans are usually verified by phantom measurements²,⁶–⁹ including absolute dose measurements at several points using an ionization chamber (IC). Since IMRT uses small fields, there is a tendency to employ small chambers with active volumes of ~0.1 cm³ or less for IMRT verification.³,¹⁰,¹¹ Recently it was experimentally verified that pinpoint ion chamber with an active volume equal to 0.009 cm³ may be used for absolute dose verification,¹² provided the area of uniform target dose has dimensions ≥1 cm and leakage corrections are taken into account. Some studies have been conducted on the dosimetry of small photon beams,¹³–¹⁷ often in connection with dosimetry in radiosurgery.¹⁸–²¹ However, the use of ion chambers for narrow beam absolute dosimetry remains questionable due to the lack of electron equilibrium in most of the field area. In

The Monte Carlo (MC) simulations are, in principle, free from the problems due to detector resolution and lateral electron nonequilibrium, as is the case for the IC measurements in small photon beams. The MC method has been widely used in the calculation of correction factors in radiation dosimetry. Using the MC technique, Nath and Schulz calculated ion chamber response and correction factors associated with photon attenuation and scatter, and with electron drift. Rogers and Bielajew showed that the MC calculated wall correction factors differed by up to 1% from the factors derived by extrapolation from the experimental values for most of the primary standards for air kerma. As a consequence some standard laboratories have recently announced the change of their $^{60}$Co and $^{137}$Cs air kerma standards to up to 1% as a result of the reevaluation of the wall correction factors. Mainegra-Hing, Kawrakow, and Rogers recently published a detailed study of the correction factors involved in the absolute dosimetry using plane-parallel chambers. A latest revision of MC calculated correction factors for primary standards of air kerma with the sensitivity analysis of the derived corrections to the employed cross section and ionization data was carried out by Rogers and Kawrakow.

Monte Carlo calculations have also been used extensively in the derivation of dosimetry protocol related data. The depth dependence of the water/air stopping-power ratios with the photon field size was first studied by Andreo and Brahme. Similar studies for electron beams were conducted by Ding, Rogers, and Mackie and for the stereotactic radiosurgery field by Heydarian, Hoban, and Beddoe and Verhaegen, Das, and Palmans. The latest study included a detailed simulation of a Varian Clinac-600SR accelerator with the BEAM/EGS4 Monte Carlo code. In a recent study by Sánchez-Doblado et al., Spencer-Attix $\Delta$=10 keV water/air ($s_{w,air}$) and PMMA/air ($s_{PMMA,air}$) stopping power ratios have been calculated and compared to those used in the IAEA TRS-398 Code of Practice.

For radiosurgery applicators and narrow IMRT beamlets, it was shown that the calculated stopping-power values agree with the reference within ±0.3%, well within the estimated uncertainty of the reference stopping-power ratios (0.5%). However, the additional IC correction factors for the reference dosimetry were not studied in that work.

The recently released EGSnrc MC code is the first code thought to be able to simulate ion chamber response at the 0.1% level of accuracy, at least with respect to its own cross sections. This MC code system features, as far as we know, the most advanced electron transport algorithm of all MC codes frequently used in medical physics. Recently Buckley, Kawrakow, and Rogers showed that the EGSnrc calculated values of the thick-walled chamber response differ from the Spencer-Attix cavity theory by 0.15 and 0.01% for the graphite and aluminum walled thimble chambers, respectively. Very detailed studies by Verhaegen confirmed the accuracy of the EGSnrc system for the near-to-interface dosimetry. He also demonstrated that including models for the ion chamber geometry in Monte Carlo simulations it is a requisite to guarantee an excellent agreement with experimental results.

The present work aims to estimate, by using the EGSnrc Monte Carlo system, the total correction $f_{water,air}$ needed to convert the ion chamber measured dose to the absolute dose to water for two geometries: reference $10\times10\,cm^2$ field and irregular ($\sim2\times2\,cm^2$) IMRT beamlet. The dependence of the total correction factor $f_{water,air}$ on the ion chamber position in respect to the radiation beam will also be studied. To fulfill our goal a detailed simulation of the ionization chamber combined with a full phase space description of the radiation fields will be carried out.

II. MATERIALS AND METHODS

A. Accelerator and collimator

A 6 MV photon beam produced by a Siemens Primus accelerator has been employed in this study. This accelerator is a dual photon linac equipped with a multileaf collimator (MLC) used for IMRT treatments. The MLC has 29 opposed leaf pairs, the outer leaves of each bank project a shadow width of 6.5 cm at the isocenter plane, while the inner 27 leaf pairs project a width of 1 cm. Both leaf end and leaf side match the beam divergence, making the configuration double-focused.

B. Ionization chamber

An ion chamber (IC) introduced in water could cause significant chamber-dependent fluence perturbations and volume-averaging effects, especially when used for the dosimetry of the narrow photon beams. It is therefore important to include a model as complete as possible of the IC into the Monte Carlo simulations to fully reproduce the experimental set-up. Polarity and recombination effects are implicitly ignored in this study. The collection efficiency of the chamber was assumed 100%.

The IBA-Wellhofer NAC 007 microionization chamber with an active volume equal to 0.007 cm$^3$ was fully simulated as a typical example of the pinpoint chamber used in the field dosimetry of small photon fields. High-resolution radiography, taken by a mammography machine, allowed us to measure the true dimensions of the regions around the active volume of the chamber as represented in Fig. 1(left). These dimensions slightly differ from the ones given by the manufacturer (Dr. Igor Gomola can be contacted for information at igor.gomola@wellhofer.com). We used a cylindrical model of the microionization chamber as depicted in Fig. 1(right). The chamber wall was simulated as a VESPEL $\left(N_2O_4C_{22}H_{18}\right)$ hollow cylinder 0.305 cm radius by 0.9 cm height. The outer electrode was taken as a Shonka tissue-equivalent plastic A150 ($\rho=1.12\,g/cm^3$) hollow cylinder 0.145 cm radius by 0.78 cm height. The contact cable was assumed to be a copper cylinder 0.06 cm radius by...
where water is the irradiated medium and air is the material contained in the detector cavity. Recently Paskalev et al.31 employed a similar approach for the calculations of the correction factor to the measured relative dose profiles in water, however in that work the ion chamber was modeled as an air cavity alone, therefore the fluence perturbation effects were not fully accounted for.

The dose \( D_{\text{air}} \) measured by the ion chamber is estimated as energy deposited inside the chamber’s air cavity and averaged over its volume (calculated by MC simulation using the full ion-chamber model). The absorbed dose in water \( D_{\text{water}} \), is derived as the dose deposited inside the same volume, in the same geometrical position, filled and surrounded by water in the absence of the ionization chamber. Therefore, in a good approximation it can be taken as the absorbed dose in water in the beam center at 10 cm depth. The \( D_{\text{water}}/D_{\text{air}} \) dose ratio is the MC direct estimation of the total correction factor \( f_{\text{water,air}} \) needed to convert the IC measured dose to the absorbed dose to water. We would like to remark that it is difficult to define, in a physically transparent way, the effective point of measurement for a cylindrical chamber in our simulation set-up. Therefore, we decided to calculate the dose to water as the dose averaged over the active IC volume filled with water.

Using the total correction factor \( f_{\text{water,air}} \), we can introduce a new correction factor \( c \), particularly useful to characterize a potential change in the stopping power ratio and/or in the perturbation factors between reference conditions and the small beamlet situation. This correction factor is defined as

\[
f_{\text{water,air}} = \frac{D_{\text{water},6 \text{ MV}}}{D_{\text{air},6 \text{ MV}}},
\]

This factor is equal to 1 (by definition) for a 6 MV reference beam, so it describes how big the difference is between the dosimetry for nonreference and reference conditions.

We can relate this newly introduced factor to the dosimetric quantities recommended by IAEA TRS398 protocol.33 Let us assume the following situation: a dose measurement (i.e., the absolute dose in units of Gy per detector reading) is to be made for a small IMRT beamlet of 6 MV photons with a microionization chamber. This is a typical dosimetry task under nonreference conditions. A simplified approach would consist of determining the dose \( D_{\text{water}} \) with a specific micro-chamber which has the calibration factor \( N_{D,w,Q_0} \) and for which the beam quality correction factor for the 6 MV photon beam, \( k_{6 \text{ MV}(\text{ref}),Q_0} \) is known in the same way as it is performed under reference conditions. According to TRS 398 protocol, the beam quality correction factor \( k_{6 \text{ MV}(\text{ref}),Q_0} \) can be calculated by

\[
k_{6 \text{ MV}(\text{ref}),Q_0} = \frac{(s_{\text{w,air}})_6 \text{ MV}(\text{ref})}{(s_{\text{w,air}})Q_0} \frac{P_{6 \text{ MV}(\text{ref})}}{P_{Q_0}}.
\]
This approach can only be applied in nonreference conditions if the stopping power ratio and perturbation effects involved in $k_{\text{MV(ref)}}Q_{\text{0}}$ can be assumed to have a reasonable accuracy independent of the field size, i.e., identical to that under reference conditions. Otherwise we must apply an additional correction factor $c$:

$$k_{\text{MV(nonref)}}Q_{\text{0}} = k_{\text{MV(ref)}}Q_{\text{0}} \times c.$$  (5)

Using the expression given in the Appendix to the IAEA TRS398 protocol, it can be easily demonstrated that correction factors $c$, defined by Eqs. (3) and (5), are the same.

### D. Monte Carlo calculations

#### 1. Phase space calculations

The BEAM/EGS4 Monte Carlo code has been used to simulate the radiation transport through the configurations of the Siemens Primus accelerator. The phase spaces characterizing the beams were obtained first just above the jaws of the accelerator. These were used as input for the subsequent simulations throughout the whole collimator system (including the MLC collimator), yielding the phase space in air at the position of the water phantom surface. The data were scored in a plane perpendicular to the beam axis, at 90 cm from the accelerator target. The phase space data corresponding to a standard 10×10 cm² reference field and to the irregular IMRT beamlet were stored. The resulting phase space files contained approximately 51 and 28 million particles, respectively. They were already contrasted with experimental measurements in previous work, showing excellent agreement. Therefore we can be confident that the accelerator-collimator system was simulated with a high level of accuracy.

#### 2. Ionization chamber dose calculations

The ionization chamber was modeled with a CAVRZnc user code which is an offspring with cylindrical geometry of the CAVITY user code. Electron range rejection was used for electrons with energy less than 2 MeV. A photon splitting technique (by 50) was employed as a variance reduction technique. This variance reduction technique showed an increase in the efficiency of typical ion chamber calculations by a factor of five compared to using photon interaction forcing. Electron and photon cut-off for these calculations were 521 keV (total electron energy) and 1 keV, respectively. The number of histories simulated was chosen so that the type A uncertainty of the dose in the active volume of the chamber within the beam was below 0.4% in all cases and below 1% in the penumbra region and outside the beam as well as for the reference 10×10 field.

The phase space files at the water phantom surface were used as input to calculate the dose measured by the ion chamber positioned at 10 cm depth. We were recycling phase spaces by a 10–15 factor on average. Therefore we were concerned about the statistics in the calculations. Dose calculation inside the chamber located at 10 cm depth in water should minimize the correlation effects, arising from phase space recycling. As an additional test, we carry out dose calculations for 60Co parallel beams (0.35 and 5 cm radii). The factor $c$ obtained for our chamber in 60Co beam quality was 0.948 (0.7%). The uncertainty in this test case was simi-

---

**Table I.** Calculated doses averaged over the active volume of the water or IC air cavities for the reference position irradiation (the IC axis is along the beam axis, IC is positioned at 10 cm depth) for both beam geometries studied: reference 10×10 cm² field and irregular (2×2 cm²) IMRT beamlet. The type A uncertainty of the calculated dose values is listed in parentheses as a relative value in percent of the dose value.

<table>
<thead>
<tr>
<th>Beam Configuration</th>
<th>Reference Field (10×10 cm²)</th>
<th>IMRT On-axis Beamlet (2×2 cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{water,6 MV(ref)}}$</td>
<td>7.70 (0.6%)</td>
<td>5.495 (0.2%)</td>
</tr>
<tr>
<td>$D_{\text{air,6 MV(ref)}}$</td>
<td>7.02 (0.4%)</td>
<td>5.070 (0.3%)</td>
</tr>
</tbody>
</table>

**Table II.** The dose ratio $D_{\text{water}}/D_{\text{air}}$ calculated by IC simulation for the reference position irradiation for both studied beam geometries. The ratio of the dose ratio for nonreference beam to the dose ratio for the reference beam is given in the last column. The type A uncertainty of the calculated dose ratios is listed in parentheses as a relative value in percent of the dose value.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ratio</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 10×10 cm² field</td>
<td>$D_{\text{water}}/D_{\text{air}}$</td>
<td>1.10 (1%)</td>
</tr>
<tr>
<td>Nonreference condition (2×2 cm²)</td>
<td>$D_{\text{water}}/D_{\text{air}}$</td>
<td>1.083 (0.5%)</td>
</tr>
<tr>
<td>Correction factor</td>
<td>$c$</td>
<td>1.083/1.10 (1.5%) = 0.98 (1)</td>
</tr>
</tbody>
</table>
Fig. 3. Deposited dose and corresponding dose ratios for the IMRT beamlet irradiation. The ellipses encircle the points considered to be within the studied beamlet. Upper row: Calculated doses in air (filled squares) and water (empty circles) averaged over the ion chamber volume. The left figure corresponds to the ion chamber movement from the bottom right corner of the beamlet along the diagonal up to the upper left corner, as shown by the white arrow in Fig. 2. The right figure corresponds to the ion chamber movement indicated by the white arrow in the bottom left corner of Fig. 2. Lower row: Calculated dose ratio $D_{water}/D_{air}$ (i.e., the total correction factor $f_{water,air}$) averaged over the ion chamber active volume. The left figure corresponds to the ion chamber movement from the bottom right corner of the beamlet along the diagonal up to the upper left corner, as shown by the white arrow in Fig. 2. The right figure corresponds to the ion chamber movement indicated by the white arrow in the bottom left corner of Fig. 2. In this figure the horizontal bold black line situated at the value 1.10 indicates the dose ratio, i.e., the total correction factor $f_{water,air}$ for the reference 10×10 cm$^2$ open field.

3. Ionization chamber movement

A modification of the solid.morx EGSnrc source file was done by including two new macro-variables $XSHIFT$ and $YSHIFT$ immediately after the $READ_PHSP$ call (for source 21). The macro-variables were added to (XIN) and (YIN) particle coordinates, so effectively we were introducing a shift of our phase space data from the point (XIN, YIN,ZIN) to the new point (XIN+$XSHIFT$,YIN+$YSHIFT$,ZIN). The phase space shift is equivalent to the ion chamber movement in the opposite direction at the constant depth. Then we could assign a value to these macrovariables within our user code, so we were able to study the

eral to the one obtained for the incident linac beams, so we are confident in the statistical accuracy of our results.

The dose calculations were carried out for two irradiation geometries, namely the reference 10×10 cm$^2$ field and an irregular (≈2×2 cm$^2$) IMRT beamlet. In the former case we are able to derive the total correction factor for the reference field that is compared to the later correction factor derived at each ion chamber position (see Fig. 2) in the IMRT beamlet.

The CPU time required for the calculations was drastically reduced with the use of a Linux cluster with 87 personal computers (47 Pentium III 1.1 GHz and 40 Pentium IV 2.4 GHz), capable of running processes simultaneously using an in-house specific model for the distribution of the simulation tasks.52

### TABLE III. Dose ratio $D_{water}/D_{air}$ calculated by full ion chamber simulation for all IC positions is shown in Fig. 2 for the irregular (≈2×2 cm$^2$) IMRT beamlet. Bold cells correspond to IC measurement points located within the beamlet. The type A uncertainty of the calculated dose values (correction factors $f_{water,air}$ and $c$) is listed in parentheses as a relative (absolute) value in percent of the dose value. The corresponding dose ratio value for the reference field is equal 1.10(1).

<table>
<thead>
<tr>
<th>Distance to beam axis [cm]</th>
<th>$D_{water}\times 10^{17}$ [Gy/hist]</th>
<th>$D_{air}\times 10^{17}$ [Gy/hist]</th>
<th>$f_{water,air}=D_{water}/D_{air}$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagonal from the left bottom to the right upper corner</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.707</td>
<td>0.808 (0.2%)</td>
<td>0.775 (0.6%)</td>
<td>1.042(9)</td>
<td>0.95(1)</td>
</tr>
<tr>
<td>0.495</td>
<td>1.964 (0.2%)</td>
<td>1.844 (0.4%)</td>
<td>1.065(7)</td>
<td>0.97(1)</td>
</tr>
<tr>
<td>0.212</td>
<td>4.580 (0.2%)</td>
<td>4.120 (0.2%)</td>
<td>1.112(5)</td>
<td>1.01(1)</td>
</tr>
<tr>
<td>0</td>
<td>5.495 (0.2%)</td>
<td>5.070 (0.3%)</td>
<td>1.083(5)</td>
<td>0.98(1)</td>
</tr>
<tr>
<td>0.495</td>
<td>6.220 (0.2%)</td>
<td>5.650 (0.3%)</td>
<td>1.101(6)</td>
<td>1.00(1)</td>
</tr>
<tr>
<td>0.849</td>
<td>6.070 (0.2%)</td>
<td>5.440 (0.4%)</td>
<td>1.116(6)</td>
<td>1.01(1)</td>
</tr>
<tr>
<td>1.131</td>
<td>5.173 (0.2%)</td>
<td>4.750 (0.4%)</td>
<td>1.089(6)</td>
<td>0.99(1)</td>
</tr>
<tr>
<td>1.414</td>
<td>3.093 (0.2%)</td>
<td>2.840 (0.3%)</td>
<td>1.089(6)</td>
<td>0.99(1)</td>
</tr>
<tr>
<td>1.697</td>
<td>0.870 (0.3%)</td>
<td>0.866 (0.3%)</td>
<td>1.005(7)</td>
<td>0.91(1)</td>
</tr>
<tr>
<td><strong>Diagonal from the right bottom to the left upper corner</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.414</td>
<td>0.911 (0.3%)</td>
<td>0.895 (0.3%)</td>
<td>1.018(7)</td>
<td>0.93(1)</td>
</tr>
<tr>
<td>1.273</td>
<td>1.760 (0.3%)</td>
<td>1.649 (0.4%)</td>
<td>1.067(7)</td>
<td>0.97(1)</td>
</tr>
<tr>
<td>1.061</td>
<td>3.421 (0.2%)</td>
<td>3.135 (0.3%)</td>
<td>1.091(5)</td>
<td>0.99(1)</td>
</tr>
<tr>
<td>0.848</td>
<td>3.878 (0.2%)</td>
<td>3.430 (0.3%)</td>
<td>1.131(6)</td>
<td>1.03(1)</td>
</tr>
<tr>
<td>0.707</td>
<td>3.544 (0.2%)</td>
<td>3.125 (0.3%)</td>
<td>1.134(6)</td>
<td>1.03(1)</td>
</tr>
<tr>
<td>0.495</td>
<td>2.888 (0.2%)</td>
<td>2.766 (0.3%)</td>
<td>1.044(6)</td>
<td>0.95(1)</td>
</tr>
<tr>
<td>0</td>
<td>5.495 (0.2%)</td>
<td>5.070 (0.3%)</td>
<td>1.083(5)</td>
<td>0.98(1)</td>
</tr>
<tr>
<td>0.495</td>
<td>4.954 (0.2%)</td>
<td>4.618 (0.3%)</td>
<td>1.072(6)</td>
<td>0.97(1)</td>
</tr>
<tr>
<td>0.707</td>
<td>2.820 (0.2%)</td>
<td>2.693 (0.3%)</td>
<td>1.047(6)</td>
<td>0.95(1)</td>
</tr>
<tr>
<td>0.849</td>
<td>1.682 (0.2%)</td>
<td>1.580 (0.3%)</td>
<td>1.065(6)</td>
<td>0.97(1)</td>
</tr>
<tr>
<td>1.061</td>
<td>0.734 (0.3%)</td>
<td>0.667 (0.4%)</td>
<td>1.101(8)</td>
<td>1.00(1)</td>
</tr>
</tbody>
</table>
total correction factor $f_{water,air}$ dependence on the ion chamber position both at any point within the field as well as in the penumbra and outside the beam regions. The selected dose ratios were calculated starting from the penumbra region around the beamlet along the two diagonals crossing the radiation field at the positions indicated by small circles in Fig. 2. The small circle corresponds to the IC active volume cross section. The IC cross section is also shown for comparison with the dimensions of the IMRT beamlet at one point within the beamlet in Fig. 2 (as a bigger circle enclosing the smaller active volume circular region).

**III. RESULTS AND DISCUSSION**

The calculated doses averaged over the IC cavity (active volume) for the water filled cavity ($D_{water}$) and the full ion chamber ($D_{air}$) cases for the IC located at the beamlet or $10 \times 10 \text{ cm}^2$ field axis are listed in Table I.

From these results the $D_{water}/D_{air}$ dose ratios as shown in Table II were obtained. The calculated $c$ correction factor according to the Eq. (3) for the ion chamber at the reference position (aligned with the beam axis at 10 cm depth) in the two irradiation beams studied is also shown in Table II.

As stated before, the dose ratio $D_{water}/D_{air}$ of the dose absorbed inside the water cavity to the dose deposited inside the ion-chamber active volume filled with air is the direct estimation of the total correction factor $f_{water,air}$ needed to consider the ion chamber presence during the measurement. For correction factor $c$ a value of 0.98(1) is obtained. It should be noted (as shown in Fig. 2) that the beamlet axis ($X=0, Y=0$ point, i.e., the cross point of the diagonals) is not centered but it is located near the beamlet border. Therefore, being the point of measurement near to the nonequilibrium penumbra region, a bigger correction factor could be expected for this point.

Finally, in Table III we listed the doses deposited inside the IC active volume filled with water and air ($D_{water}$ and $D_{air}$, respectively) as well as the corresponding dose ratio $D_{water}/D_{air}$, or $f_{water,air}$, that represents the total correction factor obtained for the non-reference irradiation conditions. These values are presented for all IC positions shown in Fig. 2 for the irregular ($\sim 2 \times 2 \text{ cm}^2$) IMRT beamlet. In the last column the correction factor $c$ is listed, giving us the estimation of how big the difference between the IMRT beamlet and the corresponding 6 MV reference field is.

The graphical representation of the calculated dose and dose ratio values along the two diagonals crossing the IMRT beamlet, contained in Table III, are shown in Fig. 3. The dashed ellipses encircle the calculated points, which are located within the beamlet. As can be seen the maximum deviation of the dose ratio for all these points in respect to the reference dose ratio for the open field (marked with a bold black line) are less than 3%. On the other hand, deviations from the reference dose ratio value reach up to 9% for points of measurements located outside the beamlet.

**IV. CONCLUSIONS**

Absolute dosimetry with microion chamber of a narrow irregular IMRT beamlet has been addressed using Monte Carlo methods. We observed sizeable differences of the correction factor $c$ from 1.0 (i.e., between the total correction factor $f_{water,air}$ to convert from dose in air to absorbed dose in water calculated for the typical 6 MV IMRT beamlet with the same factor calculated for the open reference field). If the ion chamber is within the beam, the observed differences range from almost 0 up to 3%, however differences could reach 9% if the ion chamber is located outside the beamlet. The impact of the present study in IMRT clinical cases will be presented elsewhere. Further work on the ion chamber perturbation correction calculation for IMRT beamlets and narrow radiosurgery beams is warranted.

**ACKNOWLEDGMENTS**

The authors are indebted to the Spanish “Fondo de Investigaciones Sanitarias” (FIS) as well as to the University Law (LOU) contract between the University of Seville and the Andalusian Health Service (SAS) for financial support. One of the authors (RC) acknowledges discussion on the effective point of measure with Professor P. Andreo. Special thanks go to Michelle Sigrid Kremser for her help in improving the text.

---

*Presented in part at the “World Congress in Medical Physics and Biomedical Engineering” at Sydney, Australia, August 24–29, 2003 and at the “7th Biennial ESTRO meeting on physics and radiation technology for clinical radiotherapy” at Geneva, Switzerland, September 13–18, 2003.

Author to whom correspondence should be addressed. Dr. Roberto Capote, International Atomic Energy Agency, NDS, Wagramerstrasse 5, P.O. Box 100, Vienna A-1400, Austria; electronic mail: R.CapoteNoy@iaea.org

2422 Capote et al.: EGSnrc study of ion chamber IMRT reference dosimetry

31 F. M. Khan


\textbf{Medical Physics, Vol. 31, No. 9, September 2004}