Comparison of ionization chambers of various volumes for IMRT absolute dose verification

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IMRT plans are usually verified by phantom measurements: dose distributions are measured using film and the absolute dose using an ionization chamber. The measured and calculated doses are compared and planned MUs are modified if necessary. To achieve a conformal dose distribution, IMRT fields are composed of small subfields, or “beamlets.” The size of beamlets is on the order of 1 cm × 1 cm. Therefore, small chambers with sensitive volumes ≤ 0.1 cm³ are generally used for absolute dose verification. A dosimetry system consisting of an electrometer, an ion chamber, and connecting cables may exhibit charge leakage. Since chamber sensitivity is proportional to volume, the effect of leakage on the measured charge is relatively greater for small chambers. Furthermore, the charge contribution from beamlets located at significant distances from the point of measurement may be below the small chambers threshold and hence not detected. On the other hand, large (0.6 cm³) chambers used for the dosimetry of conventional external fields are quite sensitive. Since these chambers are long, the electron fluence through them may not be uniform (“temporal” uniformity may not exist in the chamber volume). However, the cumulative, or “spatial” fluence distribution (as indicated by calculated IMRT dose distribution) may become uniform at the chamber location when the delivery of all IMRT fields is completed. Under the condition of “spatial” fluence uniformity, the charge collected by the large chamber may accurately represent the absolute dose delivered by IMRT to the point of measurement. In this work, 0.6, 0.125, and 0.009 cm³ chambers were used for the absolute dose verification for tomographic and step-and-shoot IMRT plans. With the largest, 0.6 cm³ chamber, the measured dose was equal to calculated within 0.5%, when no leakage corrections were made. Without leakage corrections, the error of measurement with a 0.125 cm³ chamber was 2.6% (tomographic IMRT) and 1.5% (step-and-shoot IMRT). When doses measured by a 0.125 cm³ chamber were corrected for leakage, the difference between the calculated and measured doses reduced to 0.5%. Leakage corrected doses obtained with the 0.009 cm³ chamber were within 1.5%–1.7% of calculated doses. Without leakage corrections, the measurement error was 16% (tomographic IMRT) and 7% (step-and-shoot IMRT). © 2003 American Association of Physicists in Medicine. [DOI: 10.1118/1.1536161]

Key words: IMRT, absolute dose verification, ionization chambers

I. INTRODUCTION

IMRT is a highly conformal treatment modality that is used when conventional methods of radiotherapy cannot deliver a tumoricidal dose without exceeding critical structure tolerance. Due to the complexity of IMRT treatment planning and delivery, many techniques developed for the verification of two-dimensional (2-D) and 3-D treatment plans cannot be used for IMRT. For example, there is no simple formalism for calculating MUs needed to deliver the prescribed dose. Thus, IMRT plans are usually verified by phantom measurements. First, doses in a QA phantom are calculated using fluence distribution developed for the patient treatment plan. Second, dose distributions in selected planes and absolute doses at several points are measured using a film and ionization chamber, respectively. The measured doses are compared against those calculated and changes in planned MUs are made when necessary. For example, Low et al. have reported that, based on phantom verification, they decreased planned MUs by 4% in order to deliver the target dose to within 2% of the calculated values.

To achieve conformal dose distributions, IMRT plans use small fields. For example, the tomographic IMRT uses 0.85 × 1 cm² “beamlets” in the 1 cm MIMiC mode (NOMOS Co., Sewickley, PA) and the step-and-shoot IMRT uses beams composed of multiple segments and some of them may be quite small (1 cm²). Since IMRT uses small fields, there are many junctions between radiation fields within the target. Therefore there is a tendency in the physics community to use small chambers for IMRT absolute dose verification such that the chamber volume is completely covered by all the subfields (including the smallest) that contribute primary radiation to the volume occupied by the chamber. Thus, no field junctions pass through the chamber and dose artifacts caused by them are avoided. Indeed, according to the literature, chambers with volumes of ~0.1 cm³ or less have been used for IMRT verification.

However, there may be some disadvantages of using small chambers. First, the chamber sensitivity drops with decreasing volume. According to our measurements, sensitivity of a 0.009 cm³ chamber is ~60 times less than that of...
a 0.6 cm$^3$ chamber. Therefore, a small chamber may not detect contributions from remote fields because of low sensitivity. Second, since the delivery of IMRT takes a relatively long time,$^{10}$ the dosimetry system leakage may significantly reduce the charge collected during radiation when a low sensitivity chamber is used.

In this work we have evaluated the use of three chambers with 0.6, 0.125, and 0.009 cm$^3$ volumes for the verification of tomographic and step-and-shoot IMRT plans. As expected, the 0.6 cm$^3$ chamber could not satisfy the requirement that no field junction passes through it. Nevertheless, all chambers measured the same absolute dose (within 2%) for both IMRT techniques. However, small (0.125 and 0.009 cm$^3$) chamber measurements had to be corrected for charge leakage.

II. MATERIALS AND METHODS

Two IMRT plans were verified in this study. The first plan was developed for a H&N tumor using a NOMOS–CORVUS (NOMOS Co., Sewickley, PA) treatment planning system (TPS). Tomographic IMRT was selected for this patient. The target length was ~7 cm. The 6 MV photons, 1 cm MIMiC mode, five 290° arcs, and no couch angulation were used in this plan. The second plan was developed for a prostate tumor using the CMS FOCUS TPS (CMS Inc., St. Louis, MO). The target length was 7 cm (the same as the length of the H&N target). Step-and-shoot IMRT was chosen for this case. The 10 MV photons and five coplanar fields were utilized. For pretreatment QA, the first plan was transferred to the NOMOS 16×16×16 cm$^3$ verification phantom (NOMOS Co., Sewickley, PA). The phantom was filled with polystyrene. The second plan used a 25×25×25 cm$^3$ polystyrene phantom for absolute dose verification. Both phantoms could accept 0.6, 0.125, and 0.009 cm$^3$ ionization chambers. Tomographic IMRT was delivered using a Varian 6/100 linear accelerator (Varian Medical Systems, Palo Alto, CA). Absolute dose measurements were done using a Keithley 35614 electrometer (Inovision, Cleveland, OH) and either NE 2581 0.6 cm$^3$ (NE Technology, Essex, UK), PTW 0.125 cm$^3$ (PTW-New York, Hicksville, NY), or Exradin A1 0.009 cm$^3$ (Standard Imaging Inc., Middleton, WI) chambers. Step-and-shoot IMRT was delivered using Varian 21EX linear accelerator. For absolute dose measurements, a Capintec 192A electrometer (Capintec, Inc., Ramsey, NJ) was used. A Capintec PR-06 0.6 cm$^3$ chamber replaced a NE 0.6 cm$^3$ chamber for the prostate plan verification. The length of sensitive volumes of both 0.6 cm$^3$ chambers was 24 mm. The lengths of 0.125 and 0.009 cm$^3$ chambers were 6 and 2 mm, respectively. Two dosimetry systems were used because in our department tomographic and step-and-shoot IMRT are done at separate facilities, each equipped with its own primary dosimetry system. Both electrometers with their respective 0.6 cm$^3$ chambers were calibrated by an ADCL (Accredited Dose Calibration Laboratory). The 0.125 and 0.009 cm$^3$ chambers were calibrated against 0.6 cm$^3$ chambers at both facilities using a 25×25×25 cm$^3$ polystyrene phantom. Chambers were positioned at the center of a 10×10 cm$^2$ field at the depth of maximum dose in the phantom located at 100 cm SSD. Photon beams with 6 and 10 MV energies were used for chamber calibration. Doses of 2, 3, and 6 Gy were delivered to 0.6, 0.125, and 0.009 cm$^3$ chambers, respectively. For IMRT plan verification, chambers were positioned along the coronal plane passing through the target center. The center of a 0.6 cm$^3$ chamber-sensitive volume coincided with the target center. Since the same hole in a QA phantom was used for the placement of all chambers with respective inserts, the centers of the 0.125 and 0.009 cm$^3$ chamber sensitive volumes were shifted superiorly (toward the gantry) by (24−6)/2=9 mm (0.9 cm) and (24−2)/2=11 mm (1.1 cm), respectively, (Fig. 1). Although Fig. 1 shows chamber positions for tomographic IMRT only, the relative chamber positions were the same for step-and-shoot IMRT measurements. Effectively, absolute doses were measured at three points for each plan. The calculated dose variation at these chamber locations did not exceed 2%−3% in both IMRT plans. For each chamber, the leakage rate (nC/min) was determined by recording the electrometer reading for a 5 min interval with the beam turned off. The chambers were positioned in the phantom and connected to the electrometer according to the experimental setup. For absolute dose verification, readings were taken separately for each arc (tomographic IMRT) or each field (step-and-shoot IMRT). The delivery time for each arc (field) was recorded for the subsequent correction of the electrometer readings for leakage. Corrections were made by adding the product of the chamber-specific leakage rate and the exposure time to the electrometer reading. The dose delivered to the phantom varied with the chamber volume: prescription dose (PD), 1.5PD, and 3PD Gy for 0.6, 0.125, and 0.009 cm$^3$ chambers, respectively. After the delivery of all
arcs (fields), the sum of all electrometer readings was obtained and used to determine the absolute dose per fraction. Readings obtained with 0.125 and 0.009 cm$^3$ chambers were scaled down by a factor of 1.5 and 3, respectively. The measured doses were compared with the calculated values at the chamber location. In addition, the dose determined with leakage corrected measurements was compared with the uncorrected results.

### III. RESULTS

The leakage rates for two dosimetry systems are shown in Table I. The Keithley electrometer exhibited a smaller level of leakage. This table also gives estimates of errors caused by leakage when a dose of 2 Gy was delivered using a 10 × 10 cm$^2$ static field. Whereas large (0.6 cm$^3$) chambers used with both dosimetry systems showed negligible error caused by leakage (less than 0.1%), the PTW 0.125 cm$^3$ chamber demonstrated a noticeable (1.1%) leakage effect with a Capintec electrometer. The Exradin 0.009 cm$^3$ chamber demonstrated 0.7% and 1.5% error with Keithley and Capintec electrometers, respectively.

Figures 2 and 3 show uncorrected and corrected for leakage doses measured for tomographic and step-and-shoot IMRT, respectively. For the 0.6 cm$^3$ chamber, uncorrected and corrected doses were practically the same for all arcs or fields. With decreasing chamber volume, the difference between corrected and uncorrected doses became larger. Table II summarizes the results of the absolute dose verification for two IMRT techniques using chambers of different volumes. When the 0.6 cm$^3$ chamber was used, the difference between corrected, uncorrected, and calculated target doses was quite small (<0.3%). With the 0.125 cm$^3$ chamber, the difference between uncorrected measured and calculated target doses still was not great, but was noticeable: 2.6% for tomographic and 1.5% for step-and-shoot IMRT. After applying leakage corrections, the difference between the measured and calculated target doses reduced to <0.5%. For the 0.009 cm$^3$ chamber, uncorrected for leakage measurements produced large deviations from the calculated doses: 16% for tomographic and 7% for step-and-shoot IMRT. After leakage corrections, the difference became acceptable: ~1.5% for both techniques.

### IV. DISCUSSION

With IMRT techniques, the target dose is delivered using multiple small subfields. The size of the smallest field, or a

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**Table I.** A comparison of leakage of two dosimetry systems using chambers of various volumes. Here 2 Gy was delivered using a 10×10 cm$^2$ field, 100 cm SSD.

<table>
<thead>
<tr>
<th>Electrometer Chamber</th>
<th>Leakage, (nC/min)</th>
<th>Reading-per 2 Gy (nC)</th>
<th>Error caused by leakage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keithley 35614 NE 2581 0.6 cm$^3$</td>
<td>0.0036</td>
<td>33.2</td>
<td>0.01</td>
</tr>
<tr>
<td>PTW 0.125 cm$^3$</td>
<td>0.0036</td>
<td>5.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Extrin 1A, 0.009 cm$^3$</td>
<td>0.0042</td>
<td>0.58</td>
<td>0.72</td>
</tr>
<tr>
<td>Capintec 192A PR-06, 0.6 cm$^3$</td>
<td>0.141</td>
<td>199.8</td>
<td>0.07</td>
</tr>
<tr>
<td>PTW 0.125 cm$^3$</td>
<td>0.09</td>
<td>26.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Extrin 1A, 0.009 cm$^3$</td>
<td>0.3</td>
<td>6.14</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Dose/arc as detected by different chambers during measurements of absolute dose delivered by tomographic IMRT: (a) 0.6 cm$^3$ chamber; (b) 0.125 cm$^3$ chamber; (c) 0.009 cm$^3$ chamber. Solid and empty bars represent uncorrected and corrected for leakage results, respectively.

**Fig. 3.** Dose/field as detected by different chambers during measurements of absolute dose delivered by step-and-shoot IMRT: (a) 0.6 cm$^3$ chamber; (b) 0.125 cm$^3$ chamber; (c) 0.009 cm$^3$ chamber. Solid and empty bars represent uncorrected and corrected for leakage results, respectively.
"beamlet" may be on the order of 0.8×1 cm² (tomographic IMRT). Thus, an ionization chamber’s collecting volume (cavity) may be partially irradiated at a given moment. Even when the entire chamber volume is irradiated, the fluence distribution along the cavity may not be uniform due to a nonuniform beam profile. However, when the entire IMRT field sequence is delivered, the dose distribution in the target volume becomes reasonably uniform (as indicated by the calculated IMRT dose distribution). Thus, “spatial” fluence uniformity may be achieved at the chamber location when the delivery of all IMRT fields is completed. Our goal in this study was to demonstrate that as long as an ionization chamber is positioned in the area with a reasonably (within few percent) uniform dose distribution, a “spatial” fluence uniformity would exist in the chamber’s collecting volume and the dose measured by a chamber would not be affected by its dimensions.

As seen from Fig. 2, the 0.6 cm³ chamber was directly irradiated by two arcs (#2 and #3). However, at any given moment, the chamber volume was only partially irradiated by these arcs during IMRT delivery. For arc #3, the collected charge was a 20% higher dose than for arc #2, although each arc delivers the same dose to the respective patient’s slice. Therefore, it means that arc #3 covered a larger portion of the chamber volume than arc #2. The delivery of arcs #1 and #4 resulted in about 15 and 12 times smaller charges, respectively. The charge collected for arc #5 was only 3% of that for arc #3. These charges correspond to scatter radiation from the aforementioned arcs, and their magnitudes drop with increasing distance from the respective arcs. When all the charges were summed, the measured dose was within 0.3% of the calculated target dose. These observations support the hypothesis that when the calculated (and delivered) dose is uniform at the chamber location, “spatial” fluence uniformity will exist in the chamber volume and the measurements will be accurate.

When the 0.125 cm³ chamber was used, the maximum collected charge corresponded to arc #2 radiation because the center of chamber’s sensitive volume was shifted by 1.1 cm superiorly as compared to the position of the 0.6 cm³ chamber (see Fig. 1). Arc #3 resulted in a collection of the charge that was ~60% of the charge corresponding to arc #2. Charges accumulated with the rest of the arcs were much smaller than that corresponding to arcs #2 and #3.

With the 0.009 cm³ chamber, only arc #2 resulted in a large collected charge. This implies that the entire chamber volume was directly irradiated with only arc #2. It is interesting to note that arcs #4 and #5 resulted in “negative” collected charges. This means that the charge lost due to leakage was larger than the charge collected due to scatter radiation from these remote arcs.

Whereas practically all of the primary radiation may be delivered to the chamber location by one or two arcs, a collection of the charge contributed by remote fields is important in the establishment of “spatial” fluence uniformity and hence accurate dose measurements. For example, the exclusion of very small charges collected by a 0.009 cm³ chamber when arcs #4 and #5 were delivered (see Fig. 2), would have increased the error of the dose measurement by ~4%.

However, in the step-and-shoot IMRT, each field (although not all segments) delivered primary radiation to the chamber location. Therefore, all chambers showed a similar collected charge distribution between the fields, especially 0.6 and 0.125 cm³ chambers (Fig. 3).

The total charge (corrected for leakage) collected by smaller chambers resulted in the measured dose equal to that calculated to within 1.4%–1.7%. The magnitude of correction was larger for tomographic IMRT, because it takes a longer time to deliver than step-and-shoot IMRT.

It seems that the selection of a very small chamber for IMRT absolute dose verification is not imperative because all chambers produced practically the same result. However, as a chamber’s collecting volume decreases, its sensitivity proportionally drops. Since electrometer leakage does not appreciably change with a chamber, the leakage plays a significantly increasing role as the chamber sensitivity is reduced. Therefore, the leakage correction of results obtained with very small (0.009 cm³) chambers is very important for IMRT measurements. Indeed, if leakage corrections had not been done, the dose measured by a 0.009 cm³ chamber would be lower by 7% (step-and-shoot IMRT) and 16% (tomographic IMRT) lower than the “true” value.

The inclusion of leakage corrections is not necessarily a trivial matter. First, the leakage rate for the same chamber changes from one electrometer to the other (Table I). Second, the leakage rate depends on the conditions of cables and

<table>
<thead>
<tr>
<th>Electrometer</th>
<th>Chamber</th>
<th>Leakage uncorrected target dose (Gy)</th>
<th>% difference between measured and calculated doses</th>
<th>Leakage corrected target dose (Gy)</th>
<th>% difference between measured and calculated doses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomographic IMRT</td>
<td>NE 2581 0.6 cm³</td>
<td>2.131</td>
<td>0.05</td>
<td>2.136</td>
<td>0.3</td>
</tr>
<tr>
<td>Calculated target dose</td>
<td>PTW 0.125 cm³</td>
<td>2.075</td>
<td>2.6</td>
<td>2.124</td>
<td>0.3</td>
</tr>
<tr>
<td>2.13 Gy</td>
<td>Exradin 1A, 0.009 cm³</td>
<td>1.78</td>
<td>16.4</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Step-and-shoot IMRT</td>
<td>Capintec PR-06, 0.6 cm³</td>
<td>2.03</td>
<td>0.5</td>
<td>2.05</td>
<td>0.25</td>
</tr>
<tr>
<td>Calculated target dose</td>
<td>PTW 0.125 cm³</td>
<td>2.01</td>
<td>1.5</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2.04 Gy</td>
<td>Exradin 1A, 0.009 cm³</td>
<td>1.90</td>
<td>7</td>
<td>2.005</td>
<td>1.7</td>
</tr>
</tbody>
</table>
connectors and also may change with humidity, temperature, and electrometer aging. And, finally, accurate leakage correction requires separate measurements for each arc (field) and the recording of “beam on” times.

Overall, the 0.6 cm$^3$ chamber produced accurate measurements with or without leakage corrections. The 0.125 cm$^3$ chamber needed leakage corrections for tomographic IMRT and the 0.009 cm$^3$ chamber required leakage corrections for both IMRT techniques.

The leakage corrected doses measured with the 0.009 cm$^3$ chamber were consistently (by ~1.5%) lower than calculated doses for both IMRT techniques. This may be attributed to a very low sensitivity of this chamber (~60 times less than that of a 0.6 cm$^3$ chamber). Thus, some scatter radiation from remote arcs (fields) could have been below the chamber threshold and not detected.

V. CONCLUSIONS

1. If the volume of the uniform target dose has a length of more than 2.5–3 cm, any size chamber (considered in this study) can be used for IMRT absolute dose verification. The 0.6 cm$^3$ chamber may be used for both tomographic and step-and-shoot IMRT dose verification without leakage corrections.

2. When the area of uniform target dose has dimensions 1 cm, 0.125 and 0.009 cm$^3$ chambers may be used for absolute dose verification. The 0.125 cm$^3$ chamber does not require leakage correction for step-and-shoot IMRT, although leakage correction improves the accuracy of measurements. Tomographic IMRT dose verification with this chamber may require leakage correction. The 0.009 cm$^3$ chamber should be checked for leakage effects prior to measurements. Due to its reduced sensitivity, the results obtained with a 0.009 cm$^3$ chamber may not be as accurate as those obtained with 0.6 and 0.125 cm$^3$ chambers.

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