Analysis of the effective point of measurement of a thimble chamber dosimeter set parallel to the X-ray beam axis

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Abstract
To measure the narrow beam used in stereotactic irradiation, installation of the ionization chamber parallel to the X-ray beam axis has been used instead of perpendicular installation. However, the definition of the effective point is a major problem in the parallel installation. In this study, we analyzed the effective point in parallel installation, and considered the prediction and evaluation of measurement point displacement. Relative dosimetry was carried out by installing the thimble ionization chamber in both perpendicular and parallel configurations. We then searched for the measurement point that coincided with the PDD of the perpendicular installation by using the displacement of the measurement point of the parallel installation. We found that the effective point of measurement for relative photon beam dosimetry depends on every detail of the chamber design, including the cavity length and the cavity radius. Moreover, the effective point of measurement also depends on the beam quality and the field size. The amount of effective point displacement for the parallel installation was quantified with the linear expression of TPR 20,10. Our results showed that the amount of effective point displacement can be estimated by the ionization volume of the dosimeter and the energy used.

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1. Introduction

With the development of radiation equipment and radiation therapy planning systems, stereotactic irradiation (STI)\(^{1,2}\) has come to be used widely for clinical applications. Many facilities currently use STI for linear accelerator (LINAC)\(^{3-6}\) radiosurgery. However, methods for dose assessment have not been established for narrow beam irradiation which is used for such STI applications. Usually, a detector is installed perpendicular to the X-ray beam axis in dosimetry. This presents the problem that the relation between the size of the detector and the minimum field size of the field cannot be neglected in dosimetry. Therefore, the detector chamber must be installed parallel to the X-ray beam axis to reduce the effective area of the detector relative to the source. In such an arrangement, the relation between the detector and the field becomes symmetrical with respect to the beam axis, which results in a good geometrical arrangement between the head structure and measurement point.

On the other hand, the definition of the effective point is an important issue in parallel installation. In the case of a thimble ionization chamber, the corrections of the effective point are dependent on the gradient of the dose and diameter of the cavity in the ion chamber: the steeper the gradient, the more correction is needed; the larger the radius, the more correction is needed. For photons, gradient correction factors in various protocols are based on different original reports. The values of TG21\(^{7}\) are based on Cunningham's and Sontag's work\(^8\), which consists of a mixture of experiment and calculations. Many other protocols have utilized the measurement data reported by Johansson et al.\(^9\), but there are significant differences among the original data and those of AAPM TG21\(^{10}\), which is recommended in the IAEA TRS-277\(^{11}\).

It is clear that the gradient correction factor represents a significant error in present dosimetry protocols. The IAEA TRS-277 describes use of another method to correct for the gradient, \textit{i.e.}, the effective point of measurement approach. This approach is recommended when measuring depth-dose or depth-ionization curves in AAPM TG25\(^{12}\) on electron beam dosimetry\(^{13}\). In this method, the point of measurement is treated as being located slightly upstream of the point of the ionizing chamber.

In the new absorbed dose measurement protocol in the AAPM TG51\(^{14}\) protocol and the IAEA TRS-398\(^{15}\) protocol, the effective point of measurement is defined at the geometrical point of the ionization chamber. This is applied only in the case of installation of the ionization chamber perpendicular to the X-ray beam axis, and the definition of the effective point of measurement in the case of parallel installation has not been clarified.

The purpose of this investigation was to measure the effective point of a thimble ionization chamber in the case of installation parallel to the X-ray beam axis and to evaluate energy dependency and ionization chamber volume dependency.
2. Materials and Methods

2.1. General discussion

In the case of a thimble ionization chamber, calibration factors in the phantom are applied to the central axis of the chamber at the point of measurement. As the insertion of a cavity into a medium causes changes in the electron spectrum, it is necessary to account for these changes with the replacement correction factor, $P_{\text{repl}}$, which has two components, the gradient and fluence correction factors, and can be derived by the following equation:

$$P_{\text{repl}} = P_{\text{gr}} P_{\text{fl}}$$

The effect of the cavity is essentially to move the point of measurement upstream from the point of the chamber. The electron fluence in the cavity is representative of the fluence in the medium at some point near the source, because it is more attenuated or lower in the build-up region compared with the medium. This component of $P_{\text{repl}}$ is called the gradient correction, $P_{\text{gr}}$, because its magnitude is dependent on the dose gradient at the point of measurement. For the thimble ionization chamber, these corrections depend on the gradient of the dose and on the inner diameter of the ion chamber: the steeper the gradient, the larger the correction; and the larger the radius, the larger the correction.

2.2. Dosimetry

We used a linear accelerator (LINAC) (Mevatron KD2/50, Siemens, NY, USA) that generated 4MV ($\text{TPR}_{20,10} = 0.6228$) and 10MV ($\text{TPR}_{20,10} = 0.7390$) beams, and a cyclic electron accelerator (Microtron) (HTM2210 Hitachi, Tokyo, Japan) that generated 4MV ($\text{TPR}_{20,10} = 0.6054$), 6MV ($\text{TPR}_{20,10} = 0.6755$), 10MV ($\text{TPR}_{20,10} = 0.7311$), 14MV ($\text{TPR}_{20,10} = 0.7610$) beams.

We used three thimble ionization chambers: the TN30013 (PTW Co., Freiburg, Germany), the TN31005 (PTW Co.), and the FC65P (Wellhoefer Dosimetry, Schwarzenbruck, Germany). The TN30013 chamber had a cavity diameter of 6.1mm, a cavity length of 23mm, an ionization chamber volume of 0.6ml, and a central aluminum electrode with a diameter of 1.1mm. The reference point was 13 mm from the tip. The chamber wall was coated with polymethylmethacrylate (PMMA) (0.057g/cm$^2$). The TN31005 chamber had a cavity diameter of 5.5mm, a cavity length of 6.5mm, an ionization chamber volume of 0.125ml, and a central aluminum electrode with a diameter of 1.1mm. The reference point was 4.5 mm from the tip. The chamber wall was coated with 0.078g/cm$^2$ of PMMA. The FC65P chamber had a cavity diameter of 6.1mm, a cavity length of 23.1mm, an ionization chamber volume of 0.65ml, and a central aluminum electrode with a diameter of 1mm. The reference point was 13 mm from the tip. The chamber wall was coated with 0.057g/cm$^2$ of Derlin.

The DynaScan (Computerized Medical Systems Co., St. Louis, MO, USA) was used as the water phantom system.
2.3. Determination of the effective point of measurement

Relative dosimetry was carried out by installing the chamber both perpendicular and parallel. First, the long axis of the ionization chamber was set perpendicular to the central axis of the X-ray beam. We obtained percent depth dose (PDD) curves every 1mm according to AAPM TG51 protocol. The effective point measurement for the chamber is taken to be 0.6r (where r is the radius of the chamber cavity) upstream of the point of the chamber and a 10 cm × 10 cm field at 100cm SSD. Second, the long axis of the ionization chamber was set parallel to the central axis of the X-ray beam, and PDD curves were measured. Each PDD curve was normalized to a depth of 10 cm, and was compared with the curves of the perpendicular installation. We then searched for the measurement point for which the PDD of the perpendicular installation coincided with the displacement of the measurement point of the parallel installation. The effective point of the parallel installation was decided with the point where both PDD coincided. Measurement of the PDD curve was performed with a sampling number of 24 and an interval of 0.25 mm. The effective point shows the distance from the tip of the ionization chamber.

2.3.1. Measurement of the effective point in the 10 × 10cm² field

Measurement of the effective points in the parallel installation of the linear accelerator Mevatron and Microtron was done in a standard radiation field of 10 cm × 10 cm for three chambers TN30013, TN31005, and FC65P.

2.3.2. Measurement of the effective point with changes in the radiation field size

Measurements of the effective points in the parallel installation of the linear accelerator Mevatron and Microtron were obtained while changing the radiation field size from 2.0 cm × 2.0 cm to 40 cm × 40 cm for three chambers TN30013, TN31005, and FC65P.

3. Results

3.1. Measurement of the effective point in the 10 × 10cm² field

3.1.1. Measurement at each beam energy for the LINAC

The results of LINAC experiments using the TN31005 (chamber volume, 0.125ml) for and 4 MV X-ray beam are shown in Fig. 1. The curve measured for the 2.0 mm displacement coincided with that in the perpendicular installation. The effective point of TN31005 for the parallel installation was decided as 2mm from the tip of the ionization chamber.

Table 1 summarizes the effective point for each

![Fig. 1 PDD curves for the LINAC with TN31005 (0.125 ml) ionization chamber for 10 × 10cm² field and 4 MV X-ray beam.](image)
Table 1: Comparison of the displacement of the effective point with TN31005, TN30013 and FC65P for 10 × 10cm² field. The chamber axis is parallel to the beam axis.

<table>
<thead>
<tr>
<th>Nominal Energy (MV)</th>
<th>Microtron</th>
<th>LINAC</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>4MV</td>
<td>6MV</td>
</tr>
<tr>
<td>TN31005</td>
<td>2.25</td>
<td>1.50</td>
</tr>
<tr>
<td>TN30013</td>
<td>8.25</td>
<td>7.25</td>
</tr>
<tr>
<td>FC65P</td>
<td>8.00</td>
<td>7.00</td>
</tr>
</tbody>
</table>

Beam energy of the LINAC experiments for parallel installation (10 × 10cm² field). The differences in the effective point for the two energy beams were 1mm for TN31005, 1.75 mm for TN30013, and 1.75 mm for FC65P. These results indicated that the effective point depends on the cavity radius and length in addition to the beam energy.

3.1.2. Measurement at each beam energy for the Microtron

Table 1 also shows the effective point for each energy of the Microtron experiments (10 × 10cm² field). The displacement of the effective point for the energy were 1.5mm for TN31005, 2.5mm for TN30013, and 2.25mm for FC65P. These observations regarding the point displacement confirmed the dependence on energy and ionization chamber volume. The results indicated that the effective point depends on the cavity radius and length, in addition to the beam energy. The effective point of measurement used for the Microtron corresponds to the Siemens LINAC.

3.1.3. Correlation between displacement and TPR₂₀,₁₀

The comparison results of displacement of the effective point in the TN30013, TN31005, and FC65P chambers are shown in Fig. 2 for the LINAC or Microtron. A correlation between displacement from the effective point and TPR₂₀,₁₀ was observed. The collinear approximation was: y = −15.359x + 17.585 (p < 0.01) for the TN30013; y = −9.3203x + 7.8399 (p < 0.01) for the TN31005; and y = −14.2x + 16.703 (p < 0.01) for the FC65P.

3.2. The effective points of measurement for different square field size

Figs. 3, 4, and 5 show the results for displacement of the effective point for Microtron using TN30013, TN31005, and FC65P chambers, when the side of the square field was changed from 2.0cm × 2.0cm to 40cm × 40cm. The displacement of the effective point coincided from 4.0cm × 4.0cm to 40cm × 40cm. In addition, the data presented in Figs. 3, 4, and 5 show shifts in the measured displacement of the effective point at field sizes smaller than 4.0cm. For the TN30013, 2.0cm
Fig. 3 Changes in the displacement of the effective point measured using Microtron with the TN31005 (0.125 ml) chamber when the side of the square field was changed from 2.0 to 40 cm.

Fig. 4 Changes in the displacement of the effective point measured using Microtron with the TN30013 (0.6 ml) chamber when the side of the square field was changed from 2.0 to 40 cm.

4. Discussion

When the PDD curves are measured in the perpendicular installation, the effective point is displaced in the radiation source direction by 0.75r in the IAEA TRS-277 11), 2/3r in Japanese Standard Dosimetry 8616), 0.6r in Japanese Standard Dosimetry 0117), 0.6r in the AAPM TG51 14), and 0.6r in the IAEA TRS398 15). Regardless of energy, the effective points of measurement were constant through all other displacements. However, Japanese Standard Dosimetry 86 states that the measurement point depends on the radiation source and energy. Thus, for IAEA TRS-277 11), the displacement of the measurement point with respect to each energy was described. That is, the measurement point is displaced from the reference point in the radiation source direction by 0.75r in the high energy photon beam. With cobalt 60 gamma rays, it is displaced in the radiation source direction by 0.5r, and with cesium 137 gamma rays, it is displaced in the radiation source direction by 0.35r, and with mid-energy X-rays, there is no displacement.

In consideration of the displacement of the measurement point in dosimetry for the parallel installation, the displacement was dependent on energy and ionization chamber volume. Moreover, we showed that the distance from the reference point to the effective point was represented by a linear equation of TPR₂₀,₁₀ regardless of differences in the photon beam of the LINAC and the Microtron. High-accuracy dosimetry can be facilitated by predicting the effective point using the linear equation of TPR₂₀,₁₀. In addition, it is necessary to
check for similarities in dependence in effective point analysis for the perpendicular installation.

The effective point coincided with that of the standard radiation field in dosimetry using TN31005 (0.125 ml), TN30013 (0.6 ml), and FC65P (0.65 ml) ionization chambers even when the field size was changed from 4.0 cm × 4.0 cm to 40 cm × 40 cm. In broad photon beams and electron equilibrium condition, we showed the displacement of the effective point depended markedly on the energy and ionization volume of the chamber rather than the field size. Moreover, the position of the effective point was related to the ionization chamber cavity length in the depth direction.

It was clearly seen that the smaller fields required an additional upstream shift, when the field size was changed from 2.0 cm × 2.0 cm to 4.0 cm × 4.0 cm.

The difference in the field contributes the photon fluence spectrum\(^{18}\). In the small field, the photon fluence spectrum shifts to the high energy side in comparison with the 10 × 10 cm\(^2\) field. The present results demonstrated that the effective point of the shift was dependent on specifications of the ionization chamber (cavity length and radius) in addition to the beam energy and field size. In the small field, it seemed that the upstream shift of 0.6 times the cavity radius, recommended in current dosimetry protocols, may be inadequate for accurate relative photon beam dosimetry, under the electron equilibrium condition.

With regard to different wall materials, the effective point of the dosimeter with walls made from materials such as PMMA and Delrin coincided well. The reason was due to that the correction for wall material was related to the mean restricted mass collision stopping power ratio\(^{19}\) and the mean mass energy-absorption coefficient ratio\(^{11}\). We observed no differences between the two of them.

Additional investigations are needed to determine whether it is possible to derive a general effective point of measurement dependence on the various parameters that have an influence. High-accuracy dosimetry would require calculating effective point of measurement shift tables for individual chambers as a function of the beam quality, just like the \(k_Q\) factors needed for reference dosimetry based on absorbed dose to water standards.

5. Conclusion

The results presented in this paper demonstrated that the effective point of measurement was dependent on details of the ionization chamber (cavity length and radius) in addition to the beam energy and field size. Using a thimble chamber dosimeter with parallel installation to the X-ray beam axis, we found a statistically significant correlation between the effective point of measure-
ment displacement and the energy and we showed it as the linear-expression of TPR20.10.

The displacement of the effective point could be predicted by the ionization volume of the dosimeter and the energy. The parallel installation to the X-ray beam axis was useful in measurements of a narrow beam such as for stereotactic irradiation.

The High-accuracy dosimetry measurements would be to create effective point of measurement shift tables for individual chambers as a function of the beam quality, just like the k0 factors needed for reference dosimetry based on absorbed dose to water standards.

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