Rectum Dose Analysis Employing a Multi-purpose Brachytherapy Phantom

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Received October 3, 2006; accepted December 25, 2006; published online May 30, 2007

Purpose: It is difficult to reproduce a brachytherapy measurement because of changes in the rectal shape during inter-fraction. We constructed a multi-purpose brachytherapy phantom (MPBP) and reproduced the same conditions found in actual therapy. We further attempted to apply the measured optimal dose to reduce rectal complications.

Methods: A measured dose was administered at rectal reference point R1 using a diode detector in four patients who used a tandem and ovoid in brachytherapy for carcinoma of the cervix. A total number of 20 rectal dose measurements were performed five times per patient. In addition, discrepancies in the set-up of the diode detector were analyzed with each repetitive measurement. After reproducing the same conditions as found in actual therapy using a multi-function applicator (MFA) in the multi-purpose brachytherapy phantom constructed for this study, the dose was measured at reference points in the rectum using a thermoluminescence dosimeter (TLD).

Results: According to the discrepancies measured in the set-up using a diode detector, Patient 1 showed a maximum value of 11.25 ± 0.95 mm in the Y direction, Patients 2 and 3 exhibited 9.90 ± 2.40 mm and 20.85 ± 4.50 mm in the Z direction, respectively. Patient 4 showed 19.15 ± 3.33 mm in the Z direction. In addition, values of the mean dose according to the position of the diode detector were recorded as 122.82 ± 7.96–323.78 ± 11.16 cGy. In the measured results for TLD in an MPBP, relative error for Patients 1 and 4 at the rectal reference point R2 were a maximum of 8.6 and 7.7%, respectively. For Patients 2 and 3 they were 1.7 and 1.2%, respectively. Furthermore, the dose measured at point R1 and R2 exhibited values approximately 1.7–8.6% higher than the dose calculated in advance, excluding point R1 in Patient 2. The discrepancies in the set-up owing to repetitive measurements and alterations in dosage according to these changes were not analyzed. It was evident that the relative error between the calculated and measured value was within 15%, which was allowable according to the recommendations by the American Association of Physicists in Medicine (AAPM).

Conclusions: The multi-purpose brachytherapy phantom constructed for this study successfully reproduced an optimal dose measured under the same conditions found in actual therapy in which the dose was precisely analyzed at a rectal reference point. In addition, these results were considered reliable and applicable for dose optimization before applying therapy using the measured data from the phantom in order to reduce rectal complications.

Key words: brachytherapy – multi-purpose brachytherapy phantom (MPBP) – MFA – diode detector – TLD

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INTRODUCTION

Radiation therapy for carcinoma of the uterine cervix significantly contributes to an increase in survival rates. Radiation therapy has been conducted using an external radiation therapy (EBRT) and brachytherapy with radioisotopes simultaneously. These therapies deposit radiation in sufficient doses into the uterine cervix where closed critical structures near the cervix, such as the bladder and rectum, become limitation factors. In the case of an overdose affecting these critical organs, there is a decrease in the quality of patient’s life because of secondary complications following therapy. Cook et al. (1) reported that 348 patients who received radiotherapy for uterine cervical cancer showed complications after therapy of which 48% occurred in the rectum. Several studies (2–4) have been performed on absorbed dose and complications in these organs. In addition, efforts to reduce absorbed dose deposited in the rectum and bladder have been performed (5) as well. In recent years, there have been several reports on dose analysis by applying a three-dimensional image of the rectum and bladder using CT, MRI and other equipment (6–9). Furthermore, efforts to reduce absorbed dose deposited in the rectum and bladder have been performed (5) as well. In recent years, there have been several reports on dose analysis by applying a three-dimensional image of the rectum and bladder using CT, MRI and other equipment (6–9). Furthermore, therapy has been applied after determining an optimal dose in advance in order to deposit a minimum dose near these critical organs using a treatment planning system. However, in spite of these efforts, treatment was only performed according to the dose calculated by a treatment planning system without verification of the dose due to the characteristics and difficulty in measuring intracavitary brachytherapy. There has been much effort to estimate optimal doses to sensitive organs subjected to in vivo radiation carried out by Cunningham et al. (10) and other researchers (3,11–13) using a TLD or diode detector. However, these efforts did not successfully reproduce optimal measurements because the type of rectum and bladder varied as a result of inter-fraction. Thus, it was difficult to conduct accurate measurements. In addition, measurements using a commercialized phantom have been employed to complement the in vivo dosimetry. However, among these attempts, there have been no actual applications on the implementation of a phantom under the same conditions found in actual treatment of patients using treatment applicators.

In this study, the rectal dose for a patient was measured using a diode detector and discrepancies in the set-up after repeated measurements were analyzed. In addition, we attempted to reduce rectal complications by applying a dose measured from the same conditions found in actual treatment using a multi-purpose brachytherapy phantom constructed for this study.

MATERIALS AND METHODS

DESIGN AND FABRICATION OF A MULTI-PURPOSE BRACHYTHERAPY PHANTOM

The multi-purpose brachytherapy phantom used in this study was constructed in our department and functioned three-dimensionally as illustrated in Figs 1 and 2. In addition, it was designed to set up applicators required for intracavitary radiotherapy. The internal dimensions of the phantom were $34 \times 30 \times 30$ cm$^3$. Precision rulers were attached in three directions in order to control precision within 0.05 mm. Materials used in the phantom were acryl and aluminum.

An ion chamber, film and TLD were installed at the center of the X-axis to apply dose dosimetry in a three-dimensional space. Furthermore, a multi-function applicator was constructed to set up applicators under the same conditions found in actual treatment. Moreover, it was possible to apply an applicator set-up for source calibration when the source changed. Finally, an adjustment level was
installed at the bottom of the phantom to maintain stability, accuracy in dosimetry and precision (Fig. 3).

**DOSE CALCULATION AND TREATMENTS**

As illustrated in Fig. 4, dose dosimetry was calculated by means of a conventional method (15) using an anterior to posterior and lateral radiograph produced in a simulation treatment in four patients who were subjected to a tandem and ovoid in intracavitary brachytherapy for carcinoma of the uterine cervix. Point A was configured 2 cm away from both the anterior and lateral side of the cervical os and point B was configured 3 cm away from the lateral side of point A. A treatment planning system (Plato, BPS v13.2, Nucletron, Holland) was used for dose calculation. Delivery was executed by inter-fraction divided into six fractions for a total of 3000 cGy by determining irradiation time in order to apply a delivery dose of 500 cGy to point A. Three reference points were configured to determine the rectal reference point in a simulation treatment. R1 constituted the junction at a parallel line which was drawn from the cervical os by injecting 40 cm³ of barium sulfate and 20 cm³ of air into the rectum to the rectal anterior wall. R constituted a line that connected R1 to the lumbar spine of S1 and S2 and was located 2 cm away from anterior side and 2 cm away from the anus, which constituted R2 (1). In addition, dose optimization was applied to prevent an overdose exceeding 500 cGy at these reference points. To configure coordinate directions, the direction from foot to head was configured as +Y, lateral direction was +X, and anterior to posterior direction was +Z.

**IN VIVO DOSIMETRY**

*In vivo* dosimetry in the rectum was applied to reference point R1 using a diode detector on four patients using a tandem and ovoid who received brachytherapy for carcinoma of the cervix. Twenty measurements were recorded five times per patient. In order to determine the precise position for reference point R1, the detector was inserted into the rectum by increasing the flexibility of a connection line connected to a diode detector, using a vinyl tube. Accurate positioning of the detector at a measured point was attempted using the radiograph produced in the simulation and fluoroscopy in order to determine precisely the point of R1. Measurements continued throughout treatment.

To calibrate a diode detector, a 150 cm catheter was inserted through a hole drilled to a diameter of 0.4 cm and a length of 10 cm on a 1 cm thick phantom plate using a commercial white polystyrene phantom (30 × 30 × 30 cm³, RW3, PTW, Germany). The diode detector was installed 2 cm away from the catheter. By positioning the source at four different positions at a distance of 0.5 cm using a computer planning system (BPS v13.2, Nucletron, Holland), irradiation time was calculated to irradiate 500 cGy to a point 2 cm away from these four points. The calibration factor applied to the irradiator was obtained using high dose rate brachytherapy (microSelectron, Nucletron, Holland) equipped with an Ir-192 source.

**PHANTOM DOSIMETRY**

Measurements were made five times per patient and applied under the same conditions found in actual *in vivo*...
measurements for phantom dosimetry. A TLD was used as a measuring instrument. An LIF TLD-100 chip (3 × 3 × 1 mm³) was used in the TLD and a Harshaw 5500 TLD system (PTW, Germany) was used as a reader. The calibration factor applied to TLD calibration was obtained by exposing 100 cGy to a 6 MV X-ray (Linac, KD-2, Seimens, USA) and field size of 10 × 10 cm² in a 5 cm deep hole using a commercial white polystyrene phantom (30 × 30 × 30 cm³, RW3, PTW, Germany). The calibrated TLD was used to select the element included to an uncertainty within ±5%. In addition, the TLD was waterproof treated in order to prevent water soaking using a wrap and located at the water phantom.

For measurement, a treatment applicator was reproduced in the phantom and configured to the same conditions found in a simulation radiograph produced in the design of a simulation treatment for patients (Fig. 5A–D). A TLD was installed at measurement points in the multi-purpose brachytherapy phantom using the coordinates produced by the computer planning system (Fig. 5E).

The measured dose in the rectum was verified by measuring the dose before the application of the first brachytherapy. The measured dose was compared to the calculated value. If the measured dose showed levels higher than the calculated value, the measured dose in the rectum was reduced using gauze packing.
Figure 4. Set of orthogonal radiographs indicating how to mark rectal points. Barium is injected into a rectal sound, which is verified with orthogonal radiographs, and based on these radiographs, three rectal points, R, R1 and R2, were obtained. Lat, lateral. (Please note that a color version of this figure is available as supplementary data at http://www.jjco.oxfordjournals.org.)

Figure 5. TLD measurement procedure. (A) and (B) show AP radiographs for patient and phantoms, respectively and (C) and (D) the corresponding RL radiographs. (E) shows the sheet from a RTP system used to calculate the coordinates of points of interest. TLD were positioned at these points. (Please note that a color version of this figure is available as supplementary data at http://www.jjco.oxfordjournals.org.)
RESULTS

**In Vivo Measurements**

After inserting a diode detector, an anterior–posterior and lateral radiograph was produced similar to the film produced in a simulation treatment. Based on the produced radiograph, discrepancies in the set-up of a diode detector were measured using a Vernier caliper, 1/20 mm. The reference point for the discrepancy in the set-up of the diode detector was configured as rectal reference point R1 that was marked in the simulation treatment. The direction of movement was configured to be the same as the direction used in the dose calculation. Table 1 shows the results of the discrepancy in the set-up of the diode detector in the rectum. The discrepancy in the set-up for Patient 1 was $11.25 \pm 0.95$ mm in the Y direction. Patients 2 and 3 were $9.90 \pm 2.40$ mm and $20.85 \pm 4.50$ mm in the Z direction, respectively, and Patient 4 was $19.15 \pm 3.33$ mm in the Z direction. Analyzing the discrepancies, the Z direction was larger in scale than the X and Y directions, excluding Patient 1. Factors attributing to changes in the diode detector varied largely according to the amount of content in the rectum. In particular, more factors attributing to change were exhibited in the Z direction than in the X and Y directions. In addition, a patient who suffered from pain from the insertion of the detector showed a significant discrepancy in the Y direction. In particular, Patient 1 showed difficulty with the insertion of the detector up to the measured point owing to the flexibility of the detector and pain. The average values of the measured dose according to the position of the diode detector were recorded as $323.78 \pm 11.16$ cGy, $249.2 \pm 16.43$ cGy, $122.82 \pm 7.96$ cGy and $168.28 \pm 9.23$ cGy. It was difficult to compare these results to the dose calculated at reference point R1 and the application of an optimal dose at reference point R1 resulted in errors.

**Phantom Dosimetry**

Table 2 illustrates the results of the measurement using a TLD in the multi-purpose brachytherapy phantom designed and constructed for this study. The calculated dose and relative error for Patients 1 and 4 were 8.6 and 7.7%, respectively and patients 2 and 3 were 1.7 and 1.2%, respectively. Table 2 illustrates the measured dose between points R1 and R2 positioned at the rectal point of interest, excluding point R1. The dose measured at points R1 and R2 showed values $1.7–8.6\%$ higher than the value calculated in advance, excluding reference point R1 in Patient 2. Although this result confirms a correction for the air and water in the algorithm used in a dose calculation program, it was evident that a correction for the scattering was not considered (14). However, the measured value registering to within 15% of the recommended value in the report (15) from the AAPM matched with the value calculated in advance. In addition, no change in dose was observed owing to discrepancies in the set-up according to repetitive measurements differing from an *in vivo* dosimetry in the overall measured value.

**Discussion and Conclusion**

Efforts to minimize complications have been largely made by decreasing the dose irradiated to the rectum, which is one of many radiation-sensitive organs near the cervix, in intracavitary brachytherapy (1–5,16). Efforts to decrease complications in the rectum have also been made by determining the maximum dose reference point in the rectum in ICRU 38 (17). In spite of these efforts, there has been are no specific method to accurately measure and analyze the dose. Although various measurement instruments have been developed for treatment modality according to the development of measurement systems (18,19) in recent radiation therapy, difficulties remain in the instant application of intracavitary brachytherapy.

Several attempts to analysis dosage at the reference point and other points of interest recommended by the ICRU 38 have used a TLD, film, and diode (3,10–13,20). However,

<p>| Table 1. Variation of set-up for diode detector in the rectum |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Patient</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.60 ± 2.30</td>
<td>11.25 ± 0.95</td>
<td>4.35 ± 1.23</td>
</tr>
<tr>
<td>2</td>
<td>4.90 ± 2.85</td>
<td>4.65 ± 1.73</td>
<td>9.90 ± 2.40</td>
</tr>
<tr>
<td>3</td>
<td>3.50 ± 3.40</td>
<td>3.85 ± 1.63</td>
<td>20.85 ± 4.50</td>
</tr>
<tr>
<td>4</td>
<td>6.75 ± 2.65</td>
<td>3.50 ± 2.40</td>
<td>19.15 ± 3.33</td>
</tr>
</tbody>
</table>

X, the lateral direction; Y, the feet to head direction; Z, the anterior to posterior direction.

| Table 2. A comparison of calculated dose and measured dose at rectal points (R1, R2) in phantom |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Patient | 1 | 2 | 3 | 4 |
| Rectum | Cal (cGy) | Mea (cGy) | D (%) | Cal (cGy) | Mea (cGy) | D (%) | Cal (cGy) | Mea (cGy) | D (%) | Cal (cGy) | Mea (cGy) | D (%) |
| R1 | 334.4 | 381.4 ± 0.45 | 8.08 | 331.2 | 325.2 ± 1.27 | −1.80 | 400.8 | 399.9 ± 0.72 | 0.20 | 435.3 | 463.4 ± 0.17 | 6.50 |
| R2 | 320.3 | 348.3 ± 0.28 | 8.60 | 315.5 | 320.8 ± 1.21 | 1.70 | 357.1 | 361.4 ± 0.2 | 1.20 | 416.5 | 446.5 ± 0.34 | 7.70 |

Cal, calculation; Mea, measurement; D, difference.
there were no particular values in the measured dose that could be compared to the point of interest.

Chung et al. (13) measured dosage in the rectum using a 9112 type diode detector provided by PTW from a patient who used a tandem and ovoid in intracavitary brachytherapy. To configure the measured point, the detector was positioned at the nearest point to the reference point recommended by the ICRU 38. By determining this position as a reference point (Rs), discrepancies were reported in the repetitive measurements showing significant levels of relative error ranging from +6.7 to +60.8% according to the patient’s rectal type. In addition, they proposed quality assurance to obtain the highest performance by recognizing the differences in the rectal type in advance during treatment using a rectal indicator in order to prevent the irradiation of high doses to the rectum. Waldhaußl et al. (21) showed variation ranging from −31 to +90% in in vivo dosimetry using a diode detector. In addition, they reported that more than 10% of relative errors occurred even though the position of the diode was moved more than 2.5 mm. Based on these results, an accurate measurement was difficult to obtain from the reference point recommended by the ICRU 38 and other points of interest. As shown in the report performed by Chung and Waldhaußl et al., repetitive dosimetry could not present unique values due to various factors in the in vivo dosimetry in the rectum. In addition, it was evident that the measurement at the reference point recommended by the ICRU 38 and closed rectal anterior wall to the source was not feasible.

In this study, it was impossible to obtain results more advanced than those obtained by Chung and Waldhaußl although in vivo dosimetry was applied to the rectum using a diode detector.

Alecu et al. (12) performed a measurement using a diode detector under in vivo dosimetry conditions in a phantom by applying a Fletcher Suit Delclos applicator equipped with a pelvic phantom and compared the measured results to that of the calculated dose. They reported that the comparison agreed to within 5%. However, because the commercial pelvic phantom had no system for precise control in a three-dimensional space, it was impossible to perform an accurate dose analysis at the reference point.

The multi-purpose brachytherapy phantom constructed in this study has overcome certain problems related to in vivo dosimetry and was designed to precisely move within a three-dimensional space. In addition, it was constructed to implement treatment by inserting applicators into the uterine under conditions similar to the development of a multipurpose applicator (MFA) used in actual treatment rather than a commercial phantom. Consequently, it was possible to obtain results that agreed to a maximum dose calculated to a value of 0.2–8.6% from the measurement applied at point of interest R1, R2 using a TLD in a phantom. Because it was in agreement with the results obtained by Alecu and Pai (18), we believe that it could assure quality applicable for intracavitary therapy. However, further verification of dose is required in the future using an ion chamber, diode detector, radiochromic film and analysis of isodose curves using CT scanning in order to achieve various analyses.

The multi-purpose brachytherapy phantom (MPBP) constructed for this study successfully reproduced measurements at a rectal reference point under the same conditions found in actual treatment and was able to precisely analyze the absorbed dosage at the rectal reference point. In addition, data measured in the phantom was satisfactorily applied to perform dose optimization in pretreatment in order to reduce rectal complications.

Acknowledgment
This work was carried out under the Nuclear R&D program by MOST.

Conflict of interest statement
None declared.

References


