Uncertainty evaluation of absorbed dose measurements by means of small-type OSL dosimeter for radiotherapeutic X-ray region

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Abstract: For Quality Assurance of clinical radiation therapy, it is necessary to accurately measure multiple doses, and evaluate and compare the results to the radiation treatment system. Based on the measurements using multiple dosimeters, there is no uncertainty estimation of the delivered dose for accurate analysis. In this study, we focused on small-type optically stimulated luminescence (OSL) dosimeters, and clarified the relationship of uncertainties between the absorbed dose in the radiation therapy region. The experiments were carried out as follows: fifteen dosimeters were placed in a water equivalent phantom, they were irradiated with X-rays having an acceleration voltage of 10-MV with 167.2 cGy (200 MU) and 2,090 cGy (2,500 MU). Each dosimeter was read ten times and the experimental variance and predicted variance were analyzed. As a result, we found that the experimental uncertainties were 3.9 and 6.2 times higher than predicted uncertainty when irradiated at 167.2 cGy and 2,090 cGy, respectively. We discuss the relationship of measurement uncertainties. Then, we concluded that the uncertainty of OSL dosimeters was found to be 3%. We also conclude that the OSL dosimeter can be used to measure the absorbed dose in the radiation therapy region.

Keywords: OSL dosimeter, radiation therapy, uncertainty

1. Introduction

The ability to evaluate the precise dose is required in radiation therapy, especially when using advanced methods such as IMRT (Intensity Modulated Radiotherapy) and SRS (Stereo Tactic Radiosurgery). However, it is still difficult to measure the precise dose experimentally using in vivo dosimetry because of the complexities of the systems [1-2]. In general cases, the patient doses are calculated using a radiation therapy planning system (RTPS) [3], in which the target contour should be determined precisely. Additionally, the absorbed dose outside the target region should be kept as low as possible due to the possible side effects to normal tissues [4-8]. For evaluating low-dose, it is important to measure the actual patient dose in radiation therapy.

In a clinical situation, in vivo dosimetry is rarely performed because most available dosimeters interfere with dose distribution. Also, the precise measurement based on several dosimeters may not be performed because this procedure is considered to be impractical in a clinical setting. In contrast, there are some reports based on phantom studies using thermoluminescent dosimeters (TLDs) and/or photoluminescence glass dosimeters [9-10].

Recently, a small-type optically stimulated luminescence dosimeter (nanoDot™, Landauer, Inc., Glenwood, USA) is commercially available. The dimension of the nanoDot™ OSL dosimeter is 10 mm x 10 mm x 2 mm. Because of its small size and low detection efficiency, this dosimeter has the little influence on actual dose distribution compared with generally used radiation detectors such as a semiconductor detector and an ionization chamber. In addition, nanoDot™ OSL dosimeter is able to give a precise measurement by multiple (repeated) readouts based on convenient handling [11]. We hypothesized that this dosimeter can be applied to measure actual dose distributions [12].

There has been valuable research on the characteristics of the nanoDot™ OSL dosimeter, such as, angular dependence, dose linearity, energy dependence and uncertainty contribution to the accuracy of measurements for the therapeutic, and diagnostic X-ray regions [13-21]. However, the evaluation of uncertainties of the readout is essential to estimate the actual dose within a certain range of irradiated dose. To estimate the uncertainties, two models can be generally applied [22]: one is experimental variance of multiple measurements, another is a theoretically-predicted variance. The experimental variance includes various elements of uncertainties related to the experiment. On the other hand, the predicted variance is assumed by Poisson distribution, and in many cases of radiation measurements the Poisson distribution can be applied. This is determined by the square root of counts in a single measurement. In the early stages of studies using OSL dosimeter, Jursinic et al. estimated the uncertainty with Poisson distribution based on counts which were measured with the nanoDot™ OSL dosimeter [22]. This uncertainty is...
In order to determine if the experimentally derived statistical uncertainty agrees with the predicted one, the experimenter needs more than one nanoDot™ OSL dosimeter, because then the uncertainty can be derived from a theoretical prediction. However, the relationship between them is not clear. In this study, we clearly evaluated the relationship between the experimental variance and the predicted variance in the radio therapeutic region for clinical application, and estimate the measurement accuracy of nanoDot™ OSL dosimeter should be determined experimentally.

In this study, we determined that uncertainty of nanoDot™ OSL measurement system and the uncertainty of individual dosimeter. Therefore, we determined that uncertainty of nanoDot™ OSL dosimeter should be determined experimentally.

2. Materials and methods

2.1 Experiment in the radiotherapeutic X-ray region

Fig.1(a) shows the geometry of irradiation for the radiotherapeutic X-ray region. Dosimeters were placed at a depth of 10 cm in a water-equivalent phantom (Solid Water™ (SW phantom), Gammex/RMI, Middleton, WI, USA) of 30 cm × 30 cm × 30 cm. Each dosimeter was fixed in a small dimple on the surface of the SW phantom, and irradiated with a 10 MV X-ray beam generated by a linear accelerator (Siemens Primus High energy KD2 7467, Siemens, Erlangen, Germany). The size of the irradiation field on the phantom was set to be 10 cm × 10 cm with a distance of 100 cm between X-ray target and dosimeter. Fifteen dosimeters were exposed to 167.2 cGy up to 2090 cGy with a dose rate of 418 cGy/min. Before irradiations, the dosimeters were sufficiently annealed with a fluorescent light tube (BB-450, Kowa System Service, Japan) [17].

2.2 Experiment in the diagnostic X-ray region

In addition to the experiments for the therapeutic X-ray region, an experiment in the diagnostic region was performed. Fig.1(b) shows the geometric arrangement of the dosimeters. SW phantom with a thickness of 10 cm was used. Dosimeters were irradiated by an 80-kV X-ray beam with an irradiation field size of 10 cm × 10 cm. The distance between the X-ray target and the dosimeters was 100 cm. Fifteen dosimeters were irradiated under three different conditions; 0.5 mAs, 5 mAs, and 50 mAs.

2.3 Data acquisition of nanoDot™ OSL dosimeters

A reading device (microStar™, Landauer, Glenwood, IL, USA) was used to read the information concerning to the absorbed dose from the dosimeters. The nanoDot™ OSL dosimeter was exposed to a light-emitting diode (LED), which has visible green light, and then optically stimulated luminescence (wave length 420 nm) was emitted in proportion to the absorbed dose [11]. The emitted light was counted with a photomultiplier; in this paper, description of “counts” was used as a measured value. The reader was equipped with two different reading modes that were selected according to irradiated doses; “the high intensity mode” was used for the diagnostic X-ray region and “the low intensity mode” was applied for the radio therapeutic region. In this experiment, each dosimeter was read ten times. The readout counts can be evaluated with the absorbed dose by considering both a calibration curve and detection efficiencies (relative values of 0.8-0.84) determined by Landauer, Inc. [11].

2.4 Data analysis

Initially, the readout counts of each dosimeter were corrected by detection efficiency. Here, the corrected counts are defined as element \(x(i,j) = x(RN, DN)\), where \(RN\) and \(DN\) represent the reading number and dosimeter number, respectively. Matrix \(X\) of the dataset is described as follows:

![Image](https://example.com/image1.png)

**Fig.1** Measurement setup for X-ray source, phantom and nanoDot dosimeter. (a) The exposure conditions for the radio therapeutic X-ray region were as follows: X-ray energy of 10 MV, monitor unit values of 167.2 cGy and 2,090 cGy, and dose rate of 418 cGy/min. (b) The exposure conditions for the diagnostic X-ray region were as follows: tube voltage of 80 kV, current time products of 0.5 mAs, 5 mAs, and 50 mAs.


\[
X = \begin{pmatrix}
  x(1, 1) & \cdots & x(10, 1) \\
  \vdots & \ddots & \vdots \\
  x(i, j) & \cdots & x(i, 10) \\
  \vdots & \ddots & \vdots \\
  x(1, 15) & \cdots & x(10, 15)
\end{pmatrix}
\]

(1)

In this experiment, fifteen dosimeters were used, therefore the data set for each dosimeter is placed in the same row in the equation (1) and the matrix \( X \) has fifteen rows.

Next, the mean counts \( \bar{y}(RN) \) of fifteen dosimeters located in each column are calculated:

\[
\bar{y}(RN) = \frac{\sum_{i=1}^{15} x(RN, DN)}{15}.
\]

(2)

Then, the mean vector \( \bar{X} \) is defined as follows:

\[
\bar{X} = (\bar{y}(1), \bar{y}(2), \ldots, \bar{y}(10)).
\]

(3)

Finally, by dividing the equation (1) by the equation (2), we calculate a new matrix \( Y \):

\[
Y = \begin{pmatrix}
  y(1, 1) = \frac{x(1, 1)}{\bar{y}(1)} & \cdots & y(10, 1) \\
  \vdots & \ddots & \vdots \\
  y(i, j) = \frac{x(i, j)}{\bar{y}(i)} & \cdots & y(i, 10) \\
  \vdots & \ddots & \vdots \\
  y(1, 15) = \frac{x(1, 15)}{\bar{y}(15)} & \cdots & y(10, 15)
\end{pmatrix}
\]

(4)

The nanoDot™ OSL dosimeter has small optical discharge effect caused by the irradiation light emitted for the reading. Therefore all data in equation (3) is affected by different rates of discharge [13-16]. To remove the effect of optical discharge, the mean value for each reading times for all dosimeters was determined using equation (2) and the each component in equation (1) was normalized by the mean counts \( \bar{y}(i) \). The matrix \( Y \) does not include discharge effect. The experimental uncertainty of reading and dosimeter number can be calculated using the dataset \( Y \). In this dataset \( Y \), the mean values of each column and row were described by \( \bar{y}(RN) \) and \( \bar{y}(DN) \), respectively, as follows:

\[
\bar{y}(DN) = \frac{\sum_{i=1}^{15} y(RN, DN)}{10},
\]

(5)

\[
\bar{y}(RN) = \frac{\sum_{i=1}^{15} x(RN, DN)}{15}.
\]

(6)

Then, the relative uncertainty caused by the statistical deviation of readings and individual characteristics of dosimeters can be calculated with the following equations:

\[
s_{DN} = \sqrt{\frac{\sum_{i=1}^{15} (y(RN, DN) - \bar{y}(DN))^2}{9 \bar{y}(DN)}},
\]

(7)

\[
s_{RN} = \sqrt{\frac{\sum_{i=1}^{15} (x(RN, DN) - \bar{y}(RN))^2}{14 \bar{y}(DN)}}.
\]

(8)

In this experiment, the \( s_{DN} \) was calculated based on the counts of the first reading \( (RN = 1) \). Then, \( s_{RN} \) is calculated using the following equation:

\[
s_{RN} = \frac{\sqrt{x(1, DN)}}{x(1, DN)}.
\]

(9)

In this paper, we defined that experimental uncertainty as \( s_{RN} \), experimentally derived statistical uncertainty is \( s_{DN} \), and predicted statistical uncertainty is \( s_{RN} \).

3. Results

3.1 Irradiations with 10-MV photons

Fig.2(a) and (b) show the experimental results of the radio therapeutic region using 167.2 cGy. Fig.2(a) represents \( s_{DN} \) and \( s_{RN} \) for each dosimeter. The \( s_{DN} \) value for most dosimeters is less than 0.015 (1.5%). The \( s_{DN} \) is approximately 0.003 (0.3%) and is lower than \( s_{RN} \). Fig.2(b) represents the \( s_{DN} \) for each reading number. The \( s_{DN} \) for most reading values is approximately 0.03 (3%) and is lower than the \( s_{RN} \).

Fig.2(c) and (d) show the experimental results using 2,090 cGy. Fig.2(c) represents \( s_{DN} \) and \( s_{RN} \) for each dosimeter. The \( s_{DN} \) values for most dosimeters is approximately 0.003 (0.3%). The \( s_{DN} \) is approximately 0.0008 (0.08%) that is lower than the \( s_{RN} \). Fig.2(d) represents \( s_{DN} \) for each reading number. The \( s_{DN} \) for most reading values is approximately 0.02 (2%) and is lower than the \( s_{RN} \). These uncertainties at the 2,090 cGy setting are smaller than the uncertainties at the 167.2 cGy setting.

3.2 Irradiations with 80-kV photons

Fig.3 shows the experimental results for \( s_{DN} \) and \( s_{RN} \) under the tube current-time products of 0.5 mAs, 5 mAs, and 50 mAs. The \( s_{DN} \) varies around 0.1 (10%), 0.03 (3%) and 0.01 (0.1%), at the 0.5 mAs, 5 mAs, and 50 mAs, respectively. The \( s_{DN} \) is approximately 0.1 (10%), 0.03 (3%) and 0.009 (0.09%), respectively. The values of \( s_{RN} \) are similar to those of \( s_{DN} \). Also, it was observed that both the \( s_{DN} \) and \( s_{RN} \) increase as the tube current-time product decreases. The \( s_{DN} \) varies at around 0.15 (15%), 0.05 (5%), 0.04 (4%), respectively.

3.3 Relationship between the experimental variance and the predicted variance

Fig.4 shows the relationship between the \( s_{DN} \) and \( s_{RN} \) for each dosimeter at the X-ray beam energies of 10 MV and 80 kV. For data at 80 kV, a proportional relationship between \( s_{DN} \) and \( s_{RN} \) is observed. On the other hand, for data at 10 MV, a similar relationship is not clearly observed : each \( s_{DN} \) is much higher than \( s_{RN} \). Here, we evaluate the difference using the mean value of the \( s_{DN} \). For the 10 MV X-ray beam, the mean \( s_{DN} \) is 3.9 times larger than mean \( s_{RN} \) at the 167.2 cGy and 6.2 times larger at the 2,090 cGy.

4. Discussion

In this study, we evaluated the uncertainty associated with nanoDot™ OSL dosimeters in the therapeutic and diagnostic X-ray regions. Then, we determined the uncertainties using three different methodologies ; one is the predicted statistical uncertainty \( s_{DN} \), the others are experimentally derived uncertainties \( s_{DN} \, s_{RN} \). In the following description, the differences between
Fig. 2 The experimental results of the radiotherapeutic X-ray region at energy of 10 MV. Relationship between dosimeter number and relative uncertainty of (a) 167.2 cGy (c) 2,090 cGy. Relationship between reading number and relative uncertainty of (b) 167.2 cGy (d) 2,090 cGy.

Fig. 3 The experimental results of the diagnostic X-ray region at energy of 80 kV. Relationship between dosimeter number and relative uncertainty of (a) 0.5 mAs (c) 5 mAs (e) 50 mAs. Relationship between reading number and relative uncertainty of (b) 0.5 mAs (d) 5 mAs and (f) 50 mAs.
they are discussed.

In general, the relationship among $\sigma_{\text{DN}}, s_{\text{RN}}$ and $s_{\text{RN}}$ can be determined using the equation as following:

$$s_{\text{RN}} = \sigma_{\text{DN}},$$  \(11\)

where $s_{\text{RN}}$ is systematic uncertainty which consists of differences between the dosimeters and accuracy of the reading device. The $s_{\text{RN}}$ value includes all variation factors contained in experiments. The larger factors seem to be statistical fluctuations and individualities of the dosimeters.

4.1 Irradiations with 80-kV photons

For the diagnostic region as shown in Fig.3, the $s_{\text{RN}}$ is in good agreement with the $\sigma_{\text{DN}}$. The results from the diagnostic region are the same as those reported by Hayashi et al. [19] in which individualities of the dosimeters were estimated to be 5%. The uncertainty of 5% indicates limitations; when high dose is accumulated in the diagnostic region so as to reduce statistical fluctuations, the uncertainty of 5% caused by individuality of the dosimeters may remain. Assuming that the systematic uncertainties $s_{\text{RN}}$ is 5%, the relationship among $s_{\text{RN}}, s_{\text{DN}}$ and $\sigma_{\text{DN}}$ can be represented by the equation as follows; the diagnostic region is

$$s_{\text{DN}} = \sqrt{(s_{\text{DN}})^2 + (5\%)^2},$$  \(12\)

$$s_{\text{RN}} = \sigma_{\text{DN}},$$  \(13\)

The $s_{\text{DN}}$ and $s_{\text{RN}}$ are calculated to be approximately 11.0%, 5.8%, and 5.0% under the condition of 0.5 mAs, 5 mAs and 50 mAs, respectively. Calculated $s_{\text{DN}}$ is consistent with the experimental uncertainty for $s_{\text{RN}}$, which is represented in Fig.3.

4.2 Irradiations with 10-MV photons

The therapeutic region shows poor agreement; the $s_{\text{RN}}$ is larger than the $\sigma_{\text{DN}}$, which is shown in Fig.2. Additionally, the ratio of $s_{\text{DN}}$ and $\sigma_{\text{DN}}$ changed depending on the irradiated dose. We consider this a strange phenomenon. When compared to the diagnostic X-ray region, the X-rays used for radiation therapy have higher energy and higher dose. Thus, these differences may affect the results. As described previously, it is impractical to estimate the $s_{\text{DN}}$ of the dose measurement of patients in a clinical setting. It is a critical problem, because the uncertainty based on Poisson theory may be underestimated.

As shown in Fig.2 the $s_{\text{RN}}$ varies depending on irradiated dose. The $s_{\text{RN}}$ in the diagnostic X-ray region is larger than that of the therapeutic region. Compared with the $s_{\text{RN}}$, the $s_{\text{DN}}$ became a higher value, because the $s_{\text{DN}}$ consists both the $s_{\text{RN}}$ and $\sigma_{\text{DN}}$. Assuming that the systematic uncertainties $s_{\text{RN}}$ is 3.0%, the relationship among the $s_{\text{DN}}, s_{\text{DN}}$, the $\sigma_{\text{DN}}$ and the $s_{\text{DN}}$ can be determined by the equation as following:

$$s_{\text{DN}} = \sqrt{(s_{\text{DN}})^2 + (3.0\%)^2},$$  \(14\)

$$s_{\text{DN}} = \sigma_{\text{DN}},$$  \(15\)

The $s_{\text{DN}}$ are calculated to be approximately 3.2%, and 3.0% under the condition of 167.2 cGy and 2,090 cGy, respectively. The calculated value of the $s_{\text{DN}}$ is consistent with the experimental uncertainty $s_{\text{RN}}$, which was represent by Fig.2. In the case when individual dosimeters are used, the $s_{\text{DN}}$ should be added to the $s_{\text{RN}}$. However, as shown in Fig.2 and Fig.4, the ratios of $s_{\text{DN}}$ and $\sigma_{\text{DN}}$ are varied depending on the irradiated dose; in the range of doses 167.2-2,090 cGy, the $s_{\text{DN}}$ was found to be in the range of 0.3-1.5%. Therefore, it is necessary to determine the appropriate value of $s_{\text{DN}}$ according to the dose.

In radiation therapy, a prescription dose of 2 Gy is iteratively irradiated. In this case, the $s_{\text{DN}}$ may be approximately 3% as shown in Fig.2. The ICRU Report 24 recommends that the uncertainty be minimized in the patient dose to within 5% of the radiation therapy [23]. The present result indicates that the nanoDot™ OSL dosimeter can properly measure the patient dose. When the nanoDot™ OSL dosimeter can be attached to a patient during radiotherapy, quality assurance of dose and exposure dose can be evaluated on the basis of actual measurement.

5. Conclusions

In the present study, we evaluated the uncertainties of nanoDot™ OSL dosimeters based on experimentally and predicted procedures for both the radiation therapeutic and diagnostic X-ray regions. Then, the relationship between experimentally derived uncertainty and measured uncertainty was clarified. In the diagnostic region, these two uncertainties were consistent, but in the radio therapeutic region they were not. The uncertainty of the nanoDot™ OSL dosimeter in the radiotherapy region was found to be 3%. Therefore, we consider that nanoDot™ OSL dosimeter can be used to measure the patient dose in the radio therapeutic region when multiple readings were performed so as to reduce the statistical uncertainty. Furthermore, we evaluated the feasibility to measure patient doses by means of nanoDot™ OSL dosimeter in the radio therapeutic region. The assumed inaccuracy was at most 3%, so the nanoDot™ OSL dosimeter is thought to be valuable to directly measure the patient dose.

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7. References


