A comparison of the dose distributions between the brachytherapy 125I source models, STM1251 and Oncoseed 6711, in a geometry lacking radiation equilibrium scatter conditions

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The purpose of this study was to estimate the uncertainty in the dose distribution for the 125I source STM1251, as measured with a radiophotoluminescent glass rod dosimeter and calculated using the Monte Carlo code EGS5 in geometry that included the source structure reported by Kirov et al. This was performed at a range of positions in and on a water phantom 18 cm in diameter and 16 cm in length. Some dosimetry positions were so close to the surface that the backscatter margin was insufficient for photons. Consequently, the combined standard uncertainty (CSU) at the coverage factor $k$ of 1 was 11.0–11.2% for the measurement and 1.8–3.6% for the calculation. The calculation successfully reproduced the measured dose distribution within 13%, with CSU at $k \leq 1.6$ ($P > 0.3$). Dose distributions were then compared with those for the 125I source Oncoseed 6711. Our results supported the American Association of Physicists in Medicine Task Group No. 43 Updated Protocol (TG43U1) formalism, in which STM1251 dose distributions were more penetrating than those of Oncoseed 6711. This trend was also observed in the region near the phantom surface lacking the equilibrium radiation scatter conditions. In this region, the difference between the TG43U1 formalism and the measurement and calculation performed in the present study was not significant ($P > 0.3$) for either of the source models. Selection of the source model based on the treatment plans according to the TG43U1 formalism will be practical.

Keywords: brachytherapy; 125I; TG43U1; EGS5; glass rod dosimeter

INTRODUCTION

At present, dosimetry for brachytherapy is performed [1, 2] using formalism introduced by the American Association of Physicists in Medicine Task Group No. 43: Updated Protocol 1 (AAPM-TG43U1) and its subsequent updates [3, 4]. However, the use of TG43U1 formalism together with the values of the parameters (such as the radial dose function) has limitations. For example, it should not be used for small organs such as the tongue, or in regions close to the air–tissue interface, even for breast cancer or other cancers of the torso. This is because, even in situations in which radiation equilibrium scatter conditions are lacking, the formalism assumes that dosimetry points have a sufficient level of backscatter [3]. Another limitation is that the formalism does not allow for interseed attenuation (ISA) caused by shielding from other implanted seeds. Some groups have estimated ISA to be up to 10% of the tumor dose [5, 6]. As a possible option for improving dose calculations, we previously validated the use of Monte Carlo calculations and measurements with a radiophotoluminescent glass rod dosimeter for the 125I source model Oncoseed 6711 [7, 8]. Those studies were also conducted in order to...
accumulate estimates of the TG43U1 parameters and dosimetry data for geometry lacking the equilibrium radiation scatter conditions. The same procedure was applied to another model, STM1251, and the results were briefly reported [9, 10].

The present paper reports uncertainty estimates for the results for STM1251 and reinvestigates the validity of the dosimetry methods for STM1251 in the light of these estimates. The verified results were compared with those obtained for Oncoseed 6711 and the doses estimated using the TG43U1 formalism.

MATERIALS AND METHODS

Experiment

As the procedure has previously been detailed in [10], it is described briefly here. Dosimeters were irradiated with an $^{125}$I source ‘BARD STM1251’ (Bard Inc., Murray Hill, NJ). The source was calibrated by the manufacturer with a stated air kerma strength of 0.317 U at the beginning of irradiation. The dosimeters used in this work were radiophotoluminescent glass rod dosimeters (GRDs) model GD-302M (Asahi Techno Glass Corporation, Shizuoka). The GRDs were calibrated in advance using a 6-MV X-ray beam from a linear accelerator (Primus KD2/7467, Toshiba Corporation, Tokyo).

The source and GRDs were set in or on an H$_2$O phantom, as shown in Fig. 1. The phantom was a cylinder made of 2-mm thick polymethyl-methacrylate (PMMA) with a diameter of 18 cm and a length of 16 cm. These materials and dimensions were chosen in order to simulate a human head receiving treatment such as for a tongue tumor. The source and GRDs were located on the ‘supporting plate’ (made of 2-mm thick PMMA) set along the phantom centerline, as shown in Fig. 1b. The source was set at $r = 0$ cm. Although the dosimeters were set at various $r$, $\theta$ and $\phi$, in order that the dose distributions near the phantom surface could be compared between the two sources and the TG43U1 formalism, we particularly focused on the dose distribution at $\theta = 90^\circ$ in this study. The irradiation period was 73 860 s. The absorbed dose to water was estimated after correcting the photon-energy dependence of the GRD using the ratio of the mass energy-absorption coefficient [11].

Calculation

Calculations were carried out using the Monte Carlo (MC) code EGS5 [12]. The absorbed dose to the GRDs was calculated for the same geometry as the GRD measurement. The EGS5 output was then converted to an absorbed dose to water using the mass energy-absorption coefficient [11]. The calculation geometry included the $^{125}$I source, GRDs and the phantom placed on a Styrofoam block (25 × 25 × 20 cm

![Fig. 1. Geometry for the dosimetry using a cylindrical phantom. (a) Overview; (b) cross-sectional view; (c) photograph.](https://example.com)
thickness) and Pb (90 × 90 × 6 cm thickness). The geometry input for the $^{125}$I source (STM1251) was the same as that used by Kirov et al. [13].

**Uncertainty estimation**

The dose uncertainty for STM1251 was estimated in a manner similar to that of the Oncoseed 6711 investigation [7]. The dose uncertainties for each of the uncertainty components were combined in quadrature to obtain the Combined Standard Uncertainty (CSU) for the coverage factor $k_s$ et al. 1.

The uncertainty in the MC calculation due to the geometric uncertainties was evaluated using EGS5 calculations. This was performed using the formalism of Dolan and Williamson [14]. The included geometric uncertainties consisted of (i) the position of the copper rod in the Ti shell (±0.24 mm in the longitudinal direction and ± 0.065 mm in the transversal direction with respect to the source centerline); (ii) the angle (0–1.96°) between the rod and the Ti shell axes; and (iii) GRD position variations (±0.15 mm in the transversal direction with respect to the GRD centerline).

In estimating the uncertainty in the GRD measurement, the geometric uncertainties were similarly estimated with EGS5. In addition, the type B uncertainty in the energy response of the GRD caused by using a constant value independent of the distance $r$ was estimated with EGS5, setting the range of energies at 3.77–35.4922 keV [11, 14]. Miscellaneous uncertainties in the uniformity of the dose at GRD calibration, GRD sensitivity, and source strength were taken from the references [7, 15, 16].

In the statistical tests for the significance of the difference between the evaluated doses, the significance level was set at 5%. The type of test was chosen according to the quantities being compared and will be indicated later, together with the evaluated results.

**RESULTS**

An example of the dose distributions at $\theta = 90^\circ$ is displayed in Fig. 2. The absolute values of the dose obtained from the GRD measurement and MC calculation were normalized to the TG43U1 formalism at its reference point, defined as 1 cm from the longitudinal axis of the source ($r = 1$ cm, $\theta = 90^\circ$). The dose was 0.0642 Gy. The estimated uncertainties are listed in Table 1 for the GRD measurement and in Table 2 for the MC calculation for some locations. All the type A and type B uncertainty estimates refer to 1-sigma standard deviations of the mean. They are also exhibited as error bars in Fig. 2. The GRD measurement uncertainty ranged from 11.0% at $r = 1$ cm to 11.2% at $r = 9$ cm. The uncertainty for the MC calculation was from 1.8% at $r = 1$ cm to 3.6% at $r = 9$ cm. The maximum discrepancy between the measured and the calculated data was 13% at $r = 3$ cm, which corresponds to the CSU at $k = 1.6$. Although the results in other directions ($\theta$, $\phi$) are not illustrated (because the graphs look very similar), the measured dose was also successfully reproduced by the calculation (within 13%) [10]. This supports the validity of the GRD measurement and the MC calculation in this situation. The discrepancy between these and the TG43U1 formalism will be discussed later.

The dose distributions were compared with those similarly evaluated for the $^{125}$I source Oncoseed 6711 (GE Healthcare, Arlington Heights, IL) [7]. The results are shown in Fig. 3a and b. All data were normalized to the unity at $r = 1$ cm. The uncertainty for Oncoseed 6711 was 10.1–10.2% for the GRD measurement and 2.9–5.4% for the MC calculation. The dose distributions based on the TG43U1 formalism are plotted in Fig. 3c. The dose distribution using the TG43U1 formalism at $\theta = 90^\circ$ reflects the radial dose function $g(r)$ among its parameters. The uncertainty is not clearly specified for STM1251, and it is not shown in Fig. 3c as the error.

| Component                        | Type A | Type B |
|----------------------------------|--------|--------|
| Repeated GRD measurements        | 2.0%   |        |
| Uniformity of dose at GRD calibration $^a$ | 2.0%   |        |
| GRD sensitivity $^b$              | 2.4%   | 3.0%   |
| Source and GRD geometry          | 1.8–3.0% |        |
| Energy response                  | 8.4%   |        |
| Source strength $^c$              | 5.0%   |        |
| Quadrature sum                   | 3.1%   | 10.6–10.8% |
| Combined standard uncertainty ($k = 1$) | 11.0–11.2% |   |

$^a$As reported in Tanaka et al. [7]. $^b$As reported in Rah et al. [15]. $^c$As reported in Ito et al. [16].
bar; it is stated to be ~7% for Oncoseed 6711 [3]. In the present paper, a total of six datasets (displayed in Fig. 3a, 3b, and 3c) were compared. The present study focuses on a discussion of what can be concluded, even if the uncertainty of $g(r)$ for STM1251 is underestimated. The dose decrease was more rapid for Oncoseed 6711 in the GRD measurement (Fig. 3a), MC calculation (Fig. 3b) and TG43U1 formalism (Fig. 3c).

The TG43U1 formalism predicts the dose on the assumption that the radiation equilibrium scatter condition is realized at all distances for $r$. Namely, there is assumed to be a sufficient backscatter margin (5 cm or more of water) for all dosimetry positions. Thus, the TG43U1 formalism is not for use within 5 cm of the body surface. In the present study, the GRD measurement and the MC calculation at the distances $r > 4$ cm were performed with insufficient backscatter margin. The dose ratios GRD measurement:TG43U1 and MC calculation:TG43U1 are plotted in Fig. 4a and 4b so that the discrepancy between the results of the present study and the TG43U1 formalism can be easily observed. The difference in the dose ratio from unity corresponds to the discrepancy between the TG43U1 formalism and the GRD measurement (Fig. 4a) or the MC calculation (Fig. 4b).

**DISCUSSION**

In current brachytherapy, $^{125}$I sources are applied to tumors in the torso such as prostate, thymoma, lung, etc. In the present study, the phantom utilized (18 cm in diameter and 16 cm in length) simulated a human head receiving treatment for e.g. a tongue tumor. The results for this phantom will be utilized for future applications of $^{125}$I sources for head-and-neck tumors. Also, the TG43U1 report suggests that a backscatter margin of 5 cm is enough for $^{125}$I photons. Consequently, the phantom setup in the present study also simulated treatment for a tumor in a torso with larger dimensions, where the $^{125}$I source is placed

| Geometry parameter       | Uncertainty at (r) |
|--------------------------|--------------------|
|                          | (1 cm)            | (9 cm)            |
| Type A                   |                    |
| MC statistic             | 0.1%              | 2.0%              |
| Type B                   |                    |
| Rod shift (transversal)  | 0.6%              | 2.6%              |
| Rod shift (longitudinal) | <0.1%             | 1.5%              |
| Rod tilt angle           | 0.3%              | 0.4%              |
| GRD position             | 1.6%              | 0.2%              |
| Quadrature sum           | 1.8%              | 3.0%              |
| CSU ($k = 1$)            | 1.8%              | 3.6%              |

![Fig. 3. Relative dose distribution at $\theta = 90^\circ$ dependent on source model normalized to unity at $r = 1$ cm. (a) GRD measurement; (b) MC calculation; (c) TG43U1 formalism. To show the difference clearly, the dose is exhibited after being multiplied by the square of the distance. The error bar is not shown for the TG43U1 dose of STM1251 because it was not reported clearly [3].](https://academic.oup.com/jrr/article-abstract/56/2/366/2755466)
9 cm from the body surface. In this sense, the present paper offers discussions that can also be applied to part of the tumors in torso for which the brachytherapy is conducted with $^{125}$I.

From Fig. 2, the combination of EGS5 and Kirov’s source structure produced a GRD measurement within 13%, with CSU at $k \leq 1.6$, even for geometry lacking the equilibrium radiation scatter conditions. The $P$ value for the significance of the difference between the GRD measurement and the MC calculation in the normal test was over 0.3. The MC calculation was not concluded to be significantly different from the GRD measurement, setting a significance level at 5%. On the other hand, the GRD measurement in this study for STM1251 had an uncertainty of ~11%. From the 95% confidence interval, assuming normal distribution, the measured dose could differ by ~20%. The MC calculated dose was higher than the GRD measured dose by a maximum of 13%. From the 95% confidence interval, the MC calculation appears to have reproduced the GRD measurement, while it also appears that the calculated dose ranged from 7% lower to 33% higher than the measured dose. In utilizing the MC calculation for the dose from the STM1251 source, it is advisable to consider a possible discrepancy of up to ~33%. Future developments making the GRD measurement more precise and accurate will decrease this possible discrepancy.

With respect to the dose decrease with increasing distance from the source, the difference between the source models was investigated with a $t$-test. The degree of freedom was set at 5 because the data in Fig. 3 consisted of seven points, and the difference for the decreasing slope, $a$, was evaluated from the regression with two parameters, $a$ and $b$, in the equation:

$$D = b \exp(-ar).$$

Here, $D$ denotes the dose and $r$ denotes the distance from the source to the dosimetry position. The $P$ value was 0.0035 for the GRD measurement in Fig. 3a, and 0.044 for the MC calculation in Fig. 3b. This suggested a difference using a significance level of 5%, which was in consistent with that the TG43U1 formalism also indicated a significant difference (with $P$ at 0.00035) between the source models used (see Fig. 3c). This supports previous reports that the STM1251 had a more penetrating dose distribution [3, 13]. The present study also suggests this trend, even in the geometry with insufficient backscatter margin. The difference in doses between the source models was, for example, 9% for TG43U1, and 16% for the GRD measurement and MC calculation at $r = 4$ cm. Furthermore, at $r = 9$ cm, it was 21% for TG43U1, 42% for GRD, and 13% for MC.

The discrepancy between the TG43U1 formalism and the GRD measurement or MC calculation was, at the start of this investigation, expected to have a different trend, depending on whether the backscatter margin was sufficient or not, i.e. whether $r$ was within 4 cm or over 4 cm. The GRD measurement in Fig. 4a appeared to indicate a lower dose ratio at $r > 4$ cm than that at $r \leq 4$ cm. The measured dose for both sources was 0–20% higher than the TG43U1 formalism at $r \leq 4$ cm, and lower by 16–20% for Oncoseed 6711, and by 2–6% for STM1251 at $r > 4$ cm. Considering the lack of backscatter radiation at $r > 4$ cm, this trend looks reasonable. In contrast, a similar trend was not obvious from the MC calculation in Fig. 4b. However, the normal test resulted in a $P$ value of over 0.3 throughout the phantom, except for the MC calculation for STM1251. The $P$ value for this exception was below 0.05, setting the uncertainty of the TG43U1 for STM1251 at zero. Although the uncertainty was not reported clearly, setting it at zero would not be reasonable. A more reasonable assumption would be ~7%, i.e. similar to that for Oncoseed 6711. The $P$ value for this assumption would also
be over 0.3. Thus, the difference (using the TG43U1 formalism) from the GRD measurement or MC calculation cannot be concluded as significant. From this study, it cannot be concluded that TG43U1 agreed with the measurement or calculation at the positions with insufficient backscatter margin.

One possible concern is the selection of the source model. The GRD measurement and the MC calculation agreed with the TG43U1 formalism with respect to the dose difference between the models. It would be practical to select the model based on the TG43U1 formalism, which indicates that the Oncoseed 6711 has a dose distribution that decreases more rapidly as distance increases, and that the STM1251 has a more penetrating dose distribution. At positions within 5 cm of the body surface, the actual dose may differ from the prediction using the TG43U1 formalism. If the critical organ and tumor is >5 cm from the body surface, it is important to consider the possible dose difference, to monitor the dose at and near the skin, and to correct the dose distribution in the plan, e.g. using the MC calculation in this study. Although it would be difficult to measure the dose inside the tissues, it would be somehow easier to measure at the body surface using the GRD, etc.

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REFERENCES

1. Yoshida K, Takenaka T, Akiyama H et al. Three-dimensional image-based high-dose-rate interstitial brachytherapy for mobile tongue cancer. J Rad Res 2014;55:154–61.

2. Yayier A, Hayashi K, Yoshimura R. Low-dose-rate interstitial brachytherapy preserves good quality of life in buccal mucosa cancer patients. J Rad Res 2012;53:655–9.

3. Rivard M-J, Coursey B-M, DeWerd L-A et al. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. Med Phys 2004;31:633–74.

4. Nath R, Anderson L-L, Luxton G et al. Dosimetry of interstitial brachytherapy sources: recommendation of the AAPM Radiation Therapy Committee Task Group No. 43. Med Phys 1995;22:209–34.

5. Meigooni A-S, Melt J-A, Nath R. Intersed effects on dose for 125I brachytherapy implants. Med Phys 1992;19:385–90.

6. Carrier J-F, Beaulieu L, Therriault-Proulx F et al. Impact of intersed attenuation and tissue composition of permanent prostate implants. Med Phys 2006;33:595–604.

7. Tanaka K, Tateoka K, Asanuma O et al. A dosimetry study of the Oncoseed 6711 using glass rod dosimeters and EGS5 Monte Carlo code in a geometry lacking radiation equilibrium scatter conditions. Med Phys 2011;38:3069–76.

8. Tanaka K, Tateoka K, Asanuma O et al. A dosimetry method for low dose rate brachytherapy by EGS5 combined with regression to reflect source strength shortage. J Rad Res 2014;55:608–12.

9. Tanaka K, Tateoka K, Asanuma O et al. Benchmark of EGS5 for 125I brachytherapy. Prog Nucl Sci Tech 2014;4:888–90.

10. Tanaka K, Tateoka K, Asanuma O et al. Verification of dose calculation for brachytherapy using EGS5. KEK Proceedings 2012–7. Tsukuba: High Energy Accelerator Research Organization, 2012. Pp. 94–7.

11. Hubbell J-H, Seltzer S-M. Tables of X-ray mass attenuation coefficients and mass-energy-absorption coefficients from 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest: NISTIR 5632 (Version 1.4). http://www.nist.gov/pml/data/xraycoef/ (5 June 2013, date last accessed).

12. Hiramaya H, Namito Y, Bielajew A-F et al. The EGS5 code system, SLAC-R-730 and KEK report 2005–08. Stanford: Stanford Linear Accelerator Center and Tsukuba: High Energy Accelerator Research Organization, 2005.

13. Kirov A-S, Williamson J-F. Monte Carlo-aided dosimetry of the 125I brachytherapy seed. Med Phys 2006;33:4675–84.

14. Dolan J, Li Z, Williamson J-F. Monte Carlo and experimental dosimetry of an 125I brachytherapy seed. Med Phys 2006;33:1976–84.

15. Rah J, Kim S, Cheong K et al. Feasibility study of radiophotoluminescent glass rod dosimeter postal dose intercomparison for high energy photon beam. Appl Rad Isot 2009;67:324–8.

16. Ito A, Takahashi Y, Sumida I et al. Standard dosimetry of 125I seeds against prostate cancer. In: Kim S-I, Suh T-S (eds). World Congress of Medical Physics and Biomedical Engineering 2006 (IFMBE Proceedings, Vol. 14). Weinheim: Springer, 2006, 2076–8.