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Thermoluminescent Dosimetry for 14-15 MeV Neutron Beams

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A simple and practical method for monitoring the dose of neutron beams given to patients during radiotherapy using thermoluminescent properties of MgB_4O_7: Tb is presented in this paper.

The neutron beams are inevitably accompanied by gamma rays. Since neutron and gamma rays have different relative biological effectiveness, it is important to measure each component separately in the neutron-gamma ray field.

To obtain the neutron and gamma ray doses separately, two kinds of MgB_4O_7: Tb phosphors were used: one in a polythene cover to enhance the sensitivity to neutrons, the other in a graphite cover to have the reduced sensitivity to neutrons. The neutron and gamma ray doses in air were evaluated separately by this method. Reproducibility within 5 % in estimation of the neutron dose was obtained. On the contrary, the uncertainty contributed to the determination of small gamma ray dose was large. But the uncertainty was smaller than several per cent of the neutron dose. Therefore, it is thought that the uncertainty in determining the gamma ray dose has no problem in neutron therapy.

It is thought that the MgB_4O_7: Tb phosphors can be used as a dosimeter for monitoring the dose of neutron beams given to the patient during radiotherapy.

INTRODUCTION

The 14-15 MeV neutron beams produced by a D-T generator are inevitably accompanied by gamma rays, since neutron and gamma rays have different relative biological effectiveness, it is important to measure each component separately in the mixed field. At present paired ionization chambers are widely recognized as the most convenient do-

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simeter for rapid and precise measurements in the mixed field. But these ionization chambers are not practical for clinical dosimetry, because their handling is troublesome, and they have a large volume which makes for a poor spatial resolution. One of practical dosimeters is a thermoluminescent dosimeter (TLD). It is necessary to use a pair of TLDs to obtain the neutron and gamma ray doses separately. Then the neutron and gamma ray sensitivities of TLD must be calibrated with other dosimeters.

The application of TLD using $CaSO_4$: Tm phosphors for dosimetry during neutron therapy has previously been reported (Blum et al. 1976)[3]. This method includes problems on calibration of the neutron and gamma ray sensitivities. Furthermore, although the TLDs for monitoring the dose of neutron beams given to the patients should respond to neutron doses in a range 10-150 cGy (rad), the response of $CaSO_4$: Tm phosphors was not linear up to 150 cGy.

The aim of this paper is to find out a useful TLD for clinical dosimetry. For this purpose some properties of available thermoluminescent (TL) phosphors were examined. Furthermore, to select a pair of TLDs which have different relative neutron sensitivities, the TL phosphors with covers of different materials were exposed.

MATERIALS AND METHODS

2.1. Thermoluminescenet dosimetry

The TLD phosphors used were LiF (TLD-600, TLD-700) and $CaSO_4$: Tm in powder form; and Mg_2SiO_4: Tb (MSO-D) and MgB_4O_7: Tb (MBO-D) in disc. The size of disc examined was 10 mm in diameter and 0.5 mm thick for MSO-D, and 5 mm in diameter and 0.5 mm thick for MSO-D. The luminescence of TLDs was measured to a temperature of 320 °C with a heating time of 20 sec on a TLD Reader System-1300A: Kasei Optonix Ltd. The measurement was performed at one day after irradiation. After measurements, the LiF phosphors were annealed at 400 °C for 1 hr, followed at 100 °C for 2 hr; the $CaSO_4$: Tm phosphors at 400 °C for 5 min; the Mg_2SiO_4: Tb and the MgB_4O_7: Tb discs at 500°C for 25 min. The discs were exposed in polythene and in graphite covers. The powders were exposed in polythene tube of 3 mm internal diameter and 2 mm wall thickness. The exposures were performed at the depth of electron equilibrium for cobalt-60 gamma rays as well as of secondary charged particle equilibrium for 14-15 MeV neutrons.

The discs were exposed to a known dose of cobalt-60 gamma rays which was measured with a sub-standard ionization chamber. A conversion factor of the reading to the exposure was determined for each disc.

2.2. Dosimetry used for calibration of TLD phosphors

In order to calibrate TLD phosphor, the paired ionization chambers were used; a tissue-equivalent ionization chamber filled with TE gas (the TE chamber) and a graphite ionization chamber filled with carbon dioxide (the graphite chamber).

According to ICRU notation, the quotients of the responses of the dosimeters by their sensitivities to the gamma rays used for calibration, R_t and R_u, respectively, are given by

$$\begin{aligned} R_t &= k_t\, D_n + h_t\, D_g \text{ (the TE chamber)} \\ R_u &= k_u\, D_n + h_u\, D_g \text{ (the graphite chamber)} \end{aligned} \qquad \text{(A)}$$

where D_n and D_g are the absorbed doses in tissue of neutron and of photons in the mixed field, k_t and k_u are the ratios of the sensitivities of each dosimeter to neutrons to its sensitivity to the gamma rays used for calibration, and h_t and h_u are the ratios of the sensitivities of each dosimeter to the photons in the mixed field to its sensitivity to gamma rays used for calibration, respectively.

Explicit expressions for D_n and D_g are obtained by simultaneous solution to give

$$Dn = \frac{h_u R_t - h_t R_u}{h_u k_t - h_t k_u}$$

$$Dg = \frac{k_t R_u - k_u R_t}{h_u k_t - h_t k_u}$$

In these equations h_t and h_u are usually taken to be unity; they would be exactly one, if the gamma rays in the neutron beam had the same energy as the gamma rays from cobalt-60, or if the photon responses for the two dosimeters were independent of energy.

The sensitivities k_t and k_u for the 14-15 MeV neutrons were evaluated using the data of ICRU report 27 (1978)[8] and Waterman[5] (1979) as follows;

$$\begin{aligned} k_t &= 0.97 \pm 0.08 \\ k_u &= 0.25 \end{aligned}$$

With the use of the following equations, the neutron and gamma ray doses can be estimated separately.

$$\begin{aligned} D_n &= 1.389\ (R_t - R_u) \\ D_g &= 1.347\ R_u - 0.347\ R_t \end{aligned}$$

The TLD phosphors were calibrated with the paired ionization chamber technique described above.

In a similar way, to obtain the neutron and gamma ray doses separately, the TLD phosphors were used in pairs: one in polythene cover to enhance the sensitivity to neutrons, the other in graphite cover to have the reduced sensitivity to neutrons. To derive the doses of neutron and gamma rays from reading of the TLD phosphors, it is necessary to assume that the response to these radiations are purely additive. The responses of the paired TLD phosphors can be expressed as follows;

$$\begin{aligned} R_p \text{ (in polythene cover)} &= k_p\, D_n + h_p\, D_g \\ R_g \text{ (in graphite cover)} &= k_g\, D_n + h_g\, D_g \end{aligned} \qquad \text{(B)}$$

where R_p and R_g are the values of the measurement in terms of cGy in tissue from cobalt-60 gamma rays for the paired phosphors in polythene and in graphite cover, respectively. The coefficients k_p and k_g correspond to k_t and k_u in equations (A), respectively and are the same definition as k_t and k_u' respectively. In a similar way, the coefficients h_p and h_g are correspond to h_t and h_u' respectively and are the same definition as h_t and h_u' respectively. In these equations h_p and h_g are usually to be unity. The coefficients k_p and k_g can be calculated from a known exposure of the neutron beams which was measured by the paired ionization chambers.

RESULTS

3.1. Choice of a pair of TLDs

The relative neutron sensitivities of the TL phosphors for 14–15 MeV neutrons are determined with the paired ionization chamber technique and are shown in Table 1.

MgB_4O_7: Tb phosphor was used in further experiments for following reason; 1) the glow curve was simple (Fig.1.). 2) careful annealing was less important. 3) the response was strictly linear up to a neutron dose of 240 cGy (Fig.4.). 4) the standard deviation of the read-outs was 5.2 % from four measurements at 25 cGy of neutron doses. 5) the difference between the relative neutron sensitivity of the MgB_4O_7: Tb phosphor in polythene and in graphite covers was greatest as shown in Table 1.

3.2. MgB_4O_7:Tb phosphor

a) Effect of thickness of polythene cover

Fig.2 shows the effect of increase in the thickness of polythene when the phosphor was exposed to the neutron beams in air. The polythene cover used was 2 mm thick. The polythene cover of this thickness produced the secondary charged particle equilibrium for 14–15 MeV neutrons. The graphite cover cover used was 2 mm thick. The graphite cover of the thickness produced the electron equilibrium for cobalt-60 gamma ray beam.

Table 1. Response of TL phosphors to 14–15 MeV neutrons

Phosphor	Relative neutron sensitivity		
	Polythene k_p	Graphite k_g	(Polythene + Alcohol)*
^6LiF	0.31	0.19	0.35
^7LiF	0.20	0.12	0.23
$CaSO_4$: Tm	0.22	0.09	0.24
Mg_2SiO_4 : Tb	0.17	0.08	—
MgB_4O_7 : Tb	0.46	0.04	—

*The powder phosphors in polythene tube were mixed with alcohol.

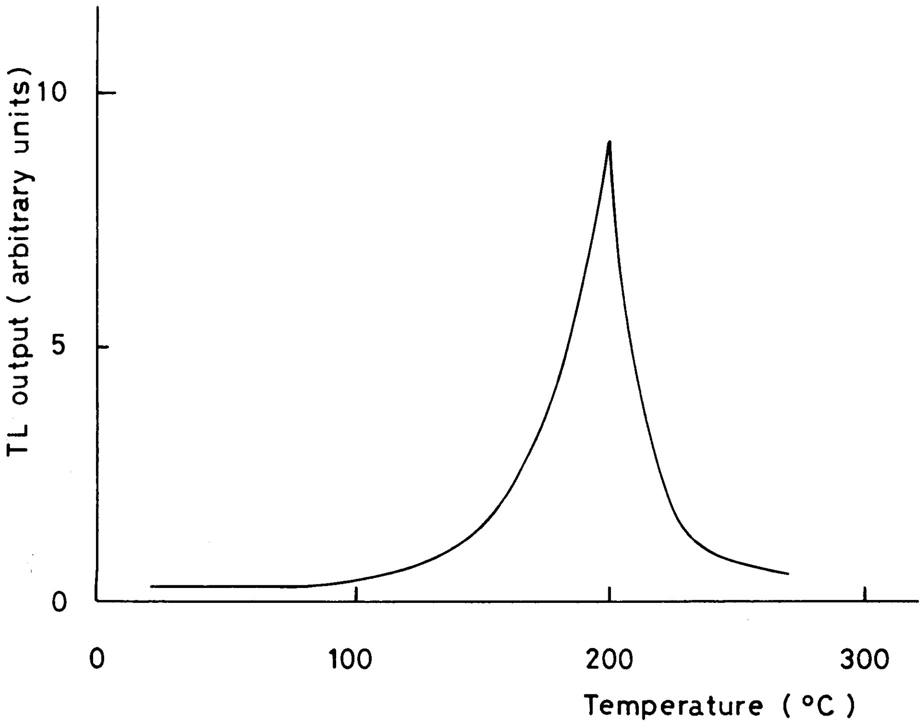

Fig. 1. Glow curve of MgB_4O_7: Tb phosphor measured at one day after irradiation.

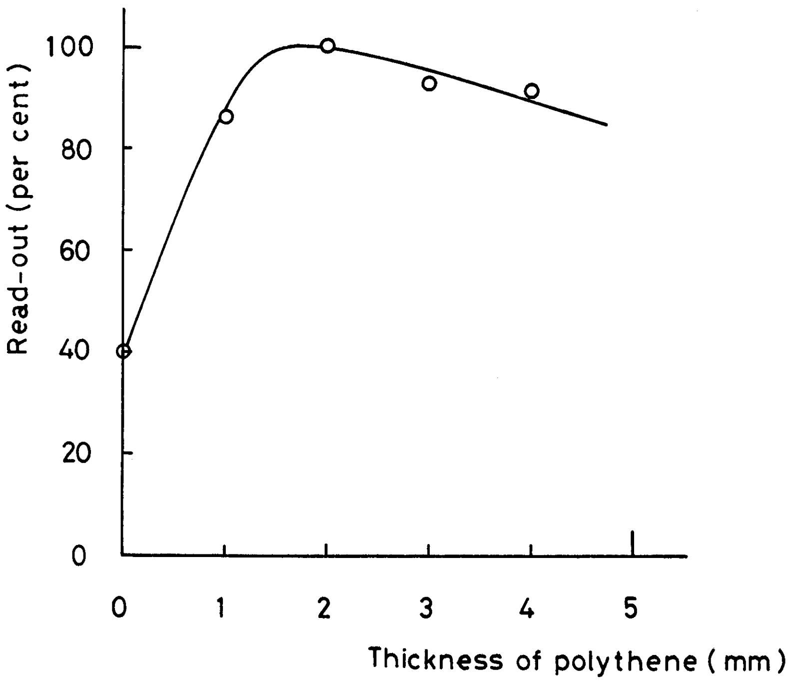

Fig. 2. Build up curve in 14-15 MeV neutron beam.

b) Fading property

Fig. 3 shows the fading of the phosphor after irradiation for a period of three days. After one day of irradiation, the response became stable and good reproducibility was obtained. Therefore, the measurement was performed at one day after irradiation.

c) Linearity

Fig. 4 shows the linearity of response of the phosphor. The response was normalized to unity at a neutron does of 12 cGy. The response was linear up to a neutron dose of 240 cGy.

d) Sensitivity

As shown in Table 1, the relative neutron sensitivity of the MgB_4O_7: Tb phosphor was about two times as high as that of the $CaSO_4$: Tm phosphor when those phosphors were exposed in polythene. The relative neutron sensitivity of the MgB_4O_7: Tb phosphor in polythene cover was about 12 times as high as that in graphite. This pair of MgB_4O_7: Tb phosphors can enable to measure the neutron and gamma ray doses.

3.3. Calculation of dose from measured values with MgB_4O_7: Tb

The coefficients k_p and k_g as shown in Table 1 were evaluated as follows.

$$k_p = 0.46 \pm 0.03$$
$$k_g = 0.04 \pm 0.02$$

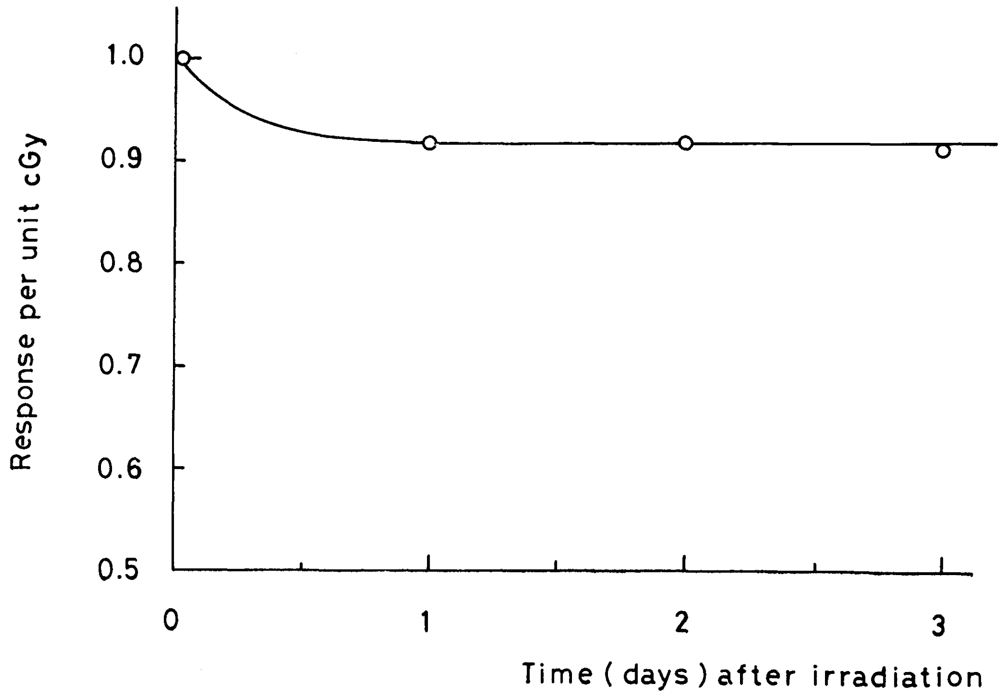

Fig. 3. The fading property. The response was normalized to unity at one hour after irradiation.

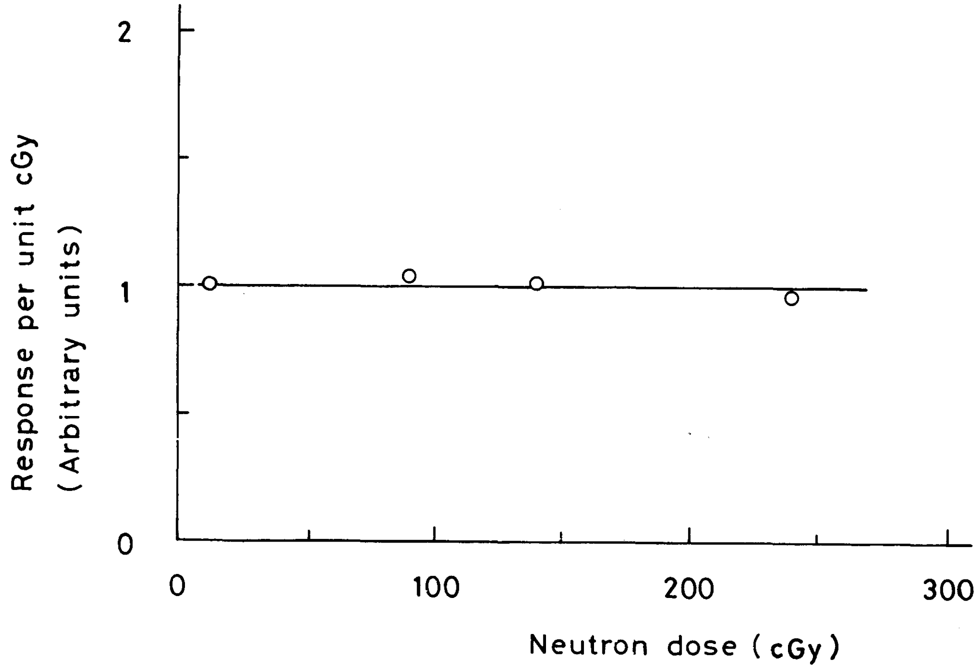

Fig. 4. Linearity of response of MgB_4O_7: Tb phosphor. The response was normalized to unity at a neutron dose of 12 cGy.

The neutron and gamma ray doses in air may be evaluated from the measurements of R_p and R_g as follows from equations (B),

$$D_n = \frac{R_p - R_g}{0.42}$$
$$D_g = 1.1R_g - 0.095R_p$$

Neutron and gamma ray doses in a neutron field were measured by this TLD method and the paired chamber technique. A comparison between the doses measured by the two methods is presented in Table 2.

The mean neutron dose measured by TLD was good agreement with the dose given by the paired chambers technique with a standard error of 3 % from measurements of four pairs of TLDs. The gamma ray dose was not agreement between TLD and the paired chambers technique. This aspect is detailed in next section.

Table 2. Comparison of D_n and D_g by TLD and paired chambers

Method	Neutron dose (cGy)	Gamma ray dose (cGy)
Paired chambers	24.4 ± 0.5	0.2 ± 0.9
TLD	25.1 ± 0.7	1.3 ± 1.8

DISCUSSION

This method described above was proved to measure the neutron and gamma ray components separately as shown in Table 2. In this case the neutron dose was measured accurately with reproducibility of about 5 %. The gamma ray dose measured by the paired chambers technique had a large uncertainty. As the TLD was calibrated by the neutron and gamma ray doses determined by the paired chambers technique, the gamma ray dose by the TLD had the uncertainty larger than that by the paired chambers technique. This may be explained by the uncertainty contributed to the determination of the fairly small gamma ray dose. The paired chambers technique used for calibration of the TLD includes a problem. As the neutron sensitivity k_u in the equation (A) for the graphite chamber is not known accurately at present, the uncertainly of k_u leads to the large uncertainty of the absolute absorbed dose of gamma rays. If it is assumed that the relative neutron sensitivities k_p and k_g of the TLD are determined accurately by the paired chambers technique, accuracy of the TLD on the measurement can be evaluated as follows. Now consider the uncertainties $\triangle D_n$ and $\triangle D_g$ in two components of absorbed dose by the uncertainties $\triangle R_p$ and $\triangle R_g$ of measured values R_p and R_g. Assuming the values of $\triangle R_p/R_p=\pm3\%$, $\triangle R_g/R_g=\pm22\%$, for example, for $D_g/D_n=0.01$, $\triangle D_n/D_n=\pm2.5\%$ and $\triangle D_g/D_g=\pm135\%$ are evaluated. In similar way, for $D_g/D_n=0.1$, $\triangle D_n/D_n=\pm4.3\%$ and $\triangle D_g/D_g=\pm22\%$ are evaluated. From above analysis, when the partial dose of gamma rays in the 14–15 MeV neutron beam is increased, it is concluded that the uncertainty contributed to the determination of the absorbed dose of neutrons is almost unchanged, but the uncertainty contributed to the determination of absorbed dose of gamma rays is decreased. These examples clearly illustrate the difficulty in accurately determining small absorbed dose of gamma rays accompanying neutron irradiation. However, the gamma ray dose was the fairly small proportion in the 14–15 MeV neutron field, and as the relative biological effectiveness (RBE) of the neutrons is usually greater than one, the gamma ray dose is relatively unimportant biologically. Therefore, the uncertainty in determining small absorbed dose of gamma rays includes no problem in radiotherapy with neutron beams from the D–T generator.

As the TLD has the advantage of good spatial resolution, it was thought that it was useful to evaluate the dose-distributions of neutron and gamma rays. But, in order to be applied to depth-dose measurements, it will further be necessary to know the changes in neutron energy spectrum in the transmission of neutrons through the phantom and the neutron energy response of the TLD system.

The MgB_4O_7:Tb TLD is activated by $^{24}Mg(n,p)\ ^{24}Na$, $^{25}Mg(n,p)\ ^{25}Mg$ and $^{16}O\ (n,p)\ ^{16}N$ reactions for the 14–15 MeV neutrons. Half life of the reaction products is 15 hr, 60 sec and 7.1 sec, respectively. In this case it was thought influence of those reaction products to the measurements at one day after neutron irradiations was negligible small from calculations.

Since the graphite covers often stained the TLD and the stains affected the measurements, careful handling would be necessary.

CONCLUSION

It is thought that the TLD using MgB_4O_7:Tb phosphor can be used as a dosimeter for evaluating the dose of neutron beams given to the patient during radiotherapy. In this case, to obtain the neutron and gamma ray doses separately, the MgB_4O_7: Tb TLDs were used in pairs: one in polythene cover, the other in graphite cover. This TLD has the advantage of a good spatial resolution due to small size, no interference from an attached cable and the ability to measure the partial doses of both neutron and gamma rays. Reproducibility within 5 % in the estimation of the neutron dose was obtained. On the contrary, the uncertainty contributed to the determination of small gamma ray dose was large. But the uncertainty was smaller than several per cents of the neutron dose. Therefore, it is thought that the uncertainty in determining the gamma ray dose has no problem in radiotherapy with neutron beam from the D-T generator. A principal disadvantage is that the measurements must be performed after one day of irradiations to give good reproducibility. Since many TLDs can be placed at different points, it is thought that this TLD method is very useful to determine dose-distributions of neutron and gamma rays at one irradiation.

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