Response of Alumina-Based Ceramic Thermoluminescence Detector to Charged Particles

Yusuke Koba,* Weishan Chang,[1] Kiyomitsu Shinsho,[1] Shin Yanagisawa,[1]
Genichro Wakabayashi,[2] Kazuki Matsumoto,[3] Hiroaki Ushiba,[3] and Takayuki Ando[4]

Medical Exposure Research Project, National Institute of Radiological Sciences,
4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan
[1]Division of Radiological Sciences, Faculty of Health Sciences, Tokyo Metropolitan University,
7-2-10 Higashi-Ogu, Arakawa-ku, Tokyo 116-8551, Japan
[2]Atomic Energy Research Institute, Kindai University, 3-4-1 Kowakae, Higashiosaka-shi, Osaka 577-8502, Japan
[3]Chiyoda Technol Co., 2-16-2 Sotokanda, Chiyoda-ku, Tokyo 101-0021, Japan
[4]Chiba Ceramic Mfg. Co., Ltd., 2-10-14 Inage-higashi, Inage-ku, Chiba 263-0031, Japan

Ceramic thermoluminescence detectors (TLDs) are low-cost devices with high spatial resolution and very easy to use. The basic characteristics of alumina-based ceramic TLDs (Chiba Ceramic Mfg. Co., Ltd. A8) in response to X-ray and charged particle beams (H, He, C, Ne, Ar) have been reported in an effort to apply TLDs as a QA/QC tool for charged particle therapy. The glow curve has two peaks, and the main peak is located at 148 °C and 694 nm. For each irradiation, four dose levels were given: 0.5, 1.0, 2.0, and 5.0 Gy in water. The main peak showed good linearity and repeatability for X-rays. However, thermoluminescence efficiency decreased slightly with increasing irradiation dose with charged particle irradiation. The thermoluminescence efficiency of the main peak showed a very small dependence on linear energy transfer (LET) compared with common TLDs. This ceramic TLD may be applicable as a verification tool in a limited LET range such as proton therapy.

1. Introduction

Thermoluminescence detectors (TLDs) have been widely used for dosimetry in various fields. In 1972, Broadhead and Newman reported 2D X-ray imaging using $CdSO_4$.[1] Since then, there have been many reports on 2D dosimetry using TLD. Nariyama *et al.*,[2] Shinsho *et al.*,[3] and Marczewska *et al.*[4–6] measured the thermoluminescence (TL) distribution of TL sheets or TL pleats using charge-coupled device (CCD) cameras. These researchers predicted the use of TLDs as quality assurance (QA) / quality control (QC) tools in radiation therapy. In fact, 2D dosimetry using TL sheets in radiation therapy was reported in 1995.[6]

Charged particle therapies, such as proton and carbon therapy, have beome popular internationally as radiation modalities for cancer treatment. Verification of the irradiation field or dose distribution in charged particle therapy requires measurements with high spatial resolution, because these distributions are precipitous and complex. Measurement of dose distributions in

carbon therapy using plate TLD composed of $Li_3B_7O_{12}$ and synthetic resin has been carried out, but it was reported that the TL efficiency decreased crucially in high-LET regions.[7]

Recently, it has been reported that commercial alumina-based ceramic plates show good TL characteristics and are available for use in 2D dosimetry.[8] This ceramic TLD is very easy to use, is low-cost, and has high spatial resolution. To use this ceramic TLD in charged particle therapy as a verification tool, we investigated the TL characteristics of this alumina-based ceramic TLD in response to charged particle beams.

2.   Materials and Methods

2.1   Alumina-based ceramic TLDs

In this study, ceramics from Chiba Ceramic Mfg. Co., Ltd. were used as TLDs. Table 1 shows the composition of this ceramic TLD. Its size was $10 \times 10 \times 1$ mm³. The glow curve of this TLD has a main peak at 694 nm due to the embedded Cr^{3+}, which is paltry amount contained within the ceramic.[8] Figure 1 shows a sample of the wavelength and temperature property of the ceramic TLD recorded with a multichannel spectroscope (HAMAMATSU PMA-12).

Table 1
Nominal composition of the alumina-based ceramic TLD (Chiba Ceramic Mfg. Co., Ltd. A8).

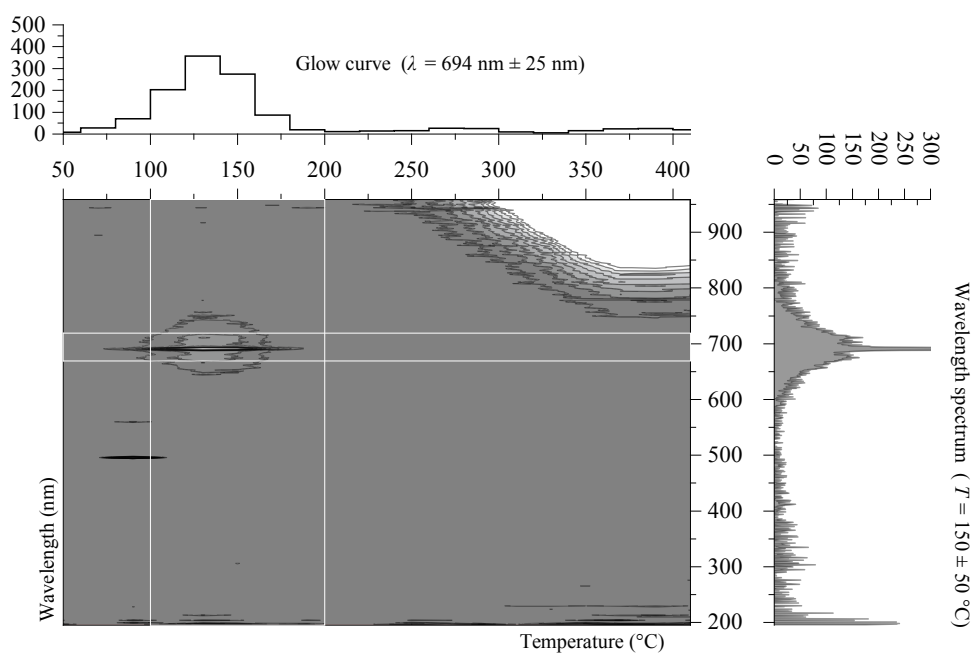| Ingredient	% by weight
Al_2O_3	>99.5
SiO_2	<0.10
Fe_2O_3	<0.05
Na_2O	<0.10

Fig. 1.   Wavelength and temperature property of the ceramic TLD when it is irradiated by X-rays.

2.2   Irradiation beams

Irradiation experiments with several charged particle beams were performed at the BIO course of the Heavy-Ion Medical Accelerator (HIMAC) at the National Institute of Radiological Sciences, Chiba, Japan. The beams were laterally broadened by a wobbling and scattering system to form a uniform field with a 10 cm diameter.[9] Table 2 shows the irradiation beams used in this study. The LET in water was calculated by Geant4.[10] The X-ray irradiation was carried out using a Varian CLINAC-21EX linear accelerator at 6 MV. For each irradiation, four dose levels were given: 0.5, 1.0, 2.0, and 5.0 Gy in water. This range simulates the predicted dose used in the charged particle therapy.

2.3   Glow curve measurement

The precise glow curve of the ceramic TLD was measured using a photon-counting unit (HAMAMATSU H11890-110) and a brass-plate-heater-connected programmable heat controller (Sakaguchi E.H VOC CORP. SCR-SHQ-A). Figure 2 shows the glow curves recorded from room temperature to 400 °C at a heating rate of 0.13 °C/s in air.

Table 2
Irradiation beams in this study.

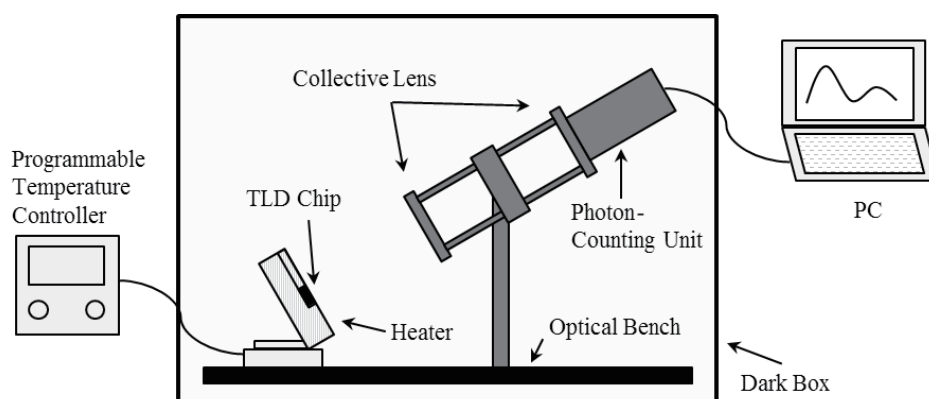| Particle	Energy (MeV/u)	LET in water (keV/μm)
H	160	0.5
He	150	2.0
C	290	13.2
Ne	400	29
Ar	500	86

Fig. 2.   Glow curve measurement system in this study.

3.   Results and Discussion

3.1   Glow curve and dose linearity

   Figure 3 shows the precise glow curve of this alumina-based ceramic TLD. The peaks were located at 148 °C (main peak) and 285 °C (subpeak). The subpeak was affected by the thermal radiation of the heater. In this study, the main peak, which was not affected by the thermal radiation, was evaluated. The TL intensity was evaluated over a range of 10 °C centered on the main peak. Figure 4 shows the dose response of this ceramic TLD to several irradiations. The TL intensity was normalized using the following equation:
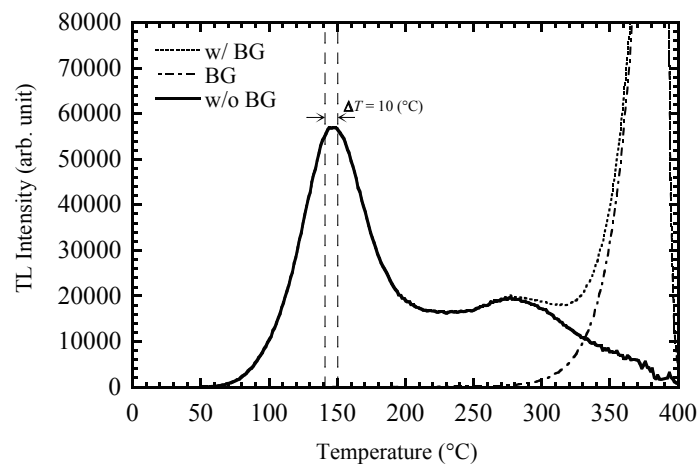
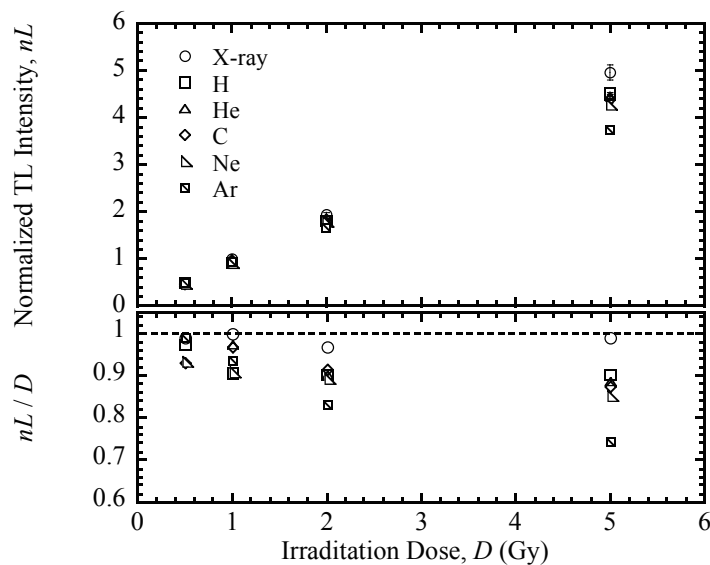Fig. 3.   Glow curve of the alumina-based ceramic TLD.

Fig. 4.   Dose responses to X-ray and charged particles. TL intensity was normalized at 1 Gy for X-rays.

$$nL(D) = \frac{L(D)}{L_{\text{X-ray}}(1\text{Gy})}, \tag{1}$$

where D is the irradiation dose, $L(D)$ is the TL intensity for an irradiation of D Gy, and $nL(D)$ is the normalized TL intensity. For X-rays, dose linearity and repeatability were comparatively good. However, for charged particles, the TL efficiency nL/D decreased slightly with increasing irradiation dose. This dose response showed a greater tendency with particles of higher atomic number.

3.2   LET dependence

Table 3 and Fig. 5 show the LET dependence of the TL efficiency $nL(D)$ of the main peak. When the irradiation was lower than 1 Gy, the LET dependence was very small (less than 10%). In the range from 0.1 to 30 keV/mm, the LET dependence was less than 15% with 15 Gy irradiation. The TL efficiency of the peak located at 148 °C showed a small LET dependence as compared

Table 3
TL efficiency *nL/D* of alumina-based ceramic TLD.

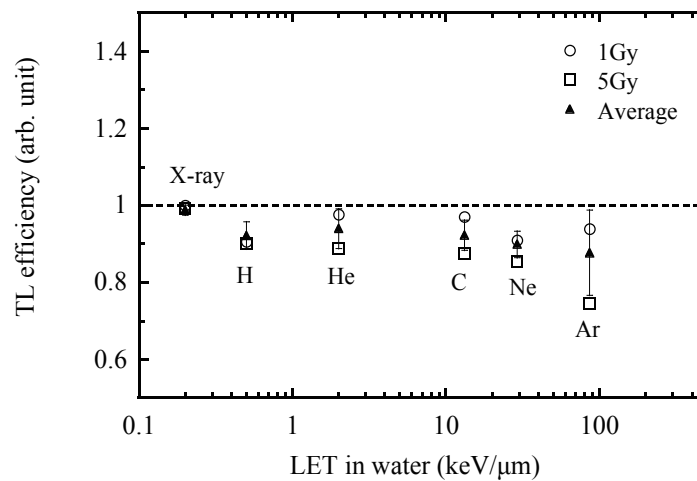|	LET (keV/μm)	*nL/D*				
		0.5 Gy	1 Gy	2 Gy	5 Gy	Average
X-ray	0.2	0.99	1.00	0.97	0.99	0.99
H	0.5	0.98	0.91	0.90	0.90	0.92
He	2.0	0.99	0.98	0.90	0.89	0.94
C	13.2	0.93	0.97	0.92	0.87	0.92
Ne	29	0.94	0.91	0.89	0.85	0.90
Ar	86	0.99	0.94	0.83	0.74	0.88

Fig. 5.   LET dependence of TL efficiency *nL/D*.

with common TLDs.[11] In Ar irradiation, the TL efficiency was >74% at 86 keV/mm. Berger and Hajek reported an overview of the TL efficiency of several common TLDs.[11] According to their report, the TL efficiency of most TLDs in the range of 10–100 keV/mm was less than 50%. For dosimetry in charged particle therapy, the use of solid-state detectors such as TLDs has been generally avoided, owing to the large dependence on LET. The ceramic TLD may be applicable as a verification tool in a limited LET range, such as that of proton therapy, because the measurement system using this ceramic TLD provides 2D dose distribution in a very simple manner.[8]

4.   Conclusions

In this study, the basic characteristics of an alumina-based ceramic TLD (Chiba Ceramic Mfg. Co., Ltd. A8) in response to X-rays and charged particle beams were determined. The glow curve had two peaks, and the main peak located at 148 °C showed good linearity and repeatability in response to X-ray. However, the TL efficiency decreased slightly with increasing irradiation dose with charged particle irradiation. The TL efficiency of the main peak showed a very small dependence on LET compared with common TLDs. This ceramic TLD may be applicable as a verification tool in a limited LET range, such as that of proton therapy.

References

1   P. Broadhead and G.A. Newman: J. Phys., E. **5** (1972) 024.
2   N. Nariyama, A. Konnai, S. Ohnishi, N. Odano, A. Yamaji, N. Ozasa, and Y. Ishikawa: Radiat. Prot. Dosimetry **120** (2006) 136.
3   K. Shinsho, Y. Tomizawa, H. Horikawa, S. Miyajima, H. Saitoh, and A. Urushiyama: Radiat. Meas. **46** (2011) 1912.
4   B. Marczewska, P. Bilski, M. Nesladek, P. Olko, M. Rębisz, and M. P. R. Waligórski: Phys. Status Solidi Appl. Res. **193** (2002) 470.
5   B. Marczewska, P. Bilski, L. Czopyk, P. Olko, M. P. R. Waligórski, and S. Zapotoczny: Radiat. Prot. Dosimetry **120** (2006) 129.
6   K. Iwata, H. Yoshimura, T. Tamada, H. Ohishi, H. Uchida, M. Nakagawa, K. Utsunomiya, I. Yamamoto, and T. Wada: Cancer Detect Prev. **19** (1995) 367.
7   Y. Koba, S. Fukuda, K. Shinsho, G. Wakabayashi, and S. Tamatsu: J. Korean Phys. Soc. **63** (2013) 1432.
8   K. Shinsho, Y. Kawaji, S. Yanagisawa, K. Otsubo, Y. Koba, G. Wakabayashi, K. Matsumoto, and H. Ushiba: Appl. Radiat. Isot. **111** (2016) 117.
9   M. Torikoshi, S. Minohara, N. Kanematsu, M. Komori, M. Kanazawa, K. Noda, N. Miyahara, H. Itoh, M. Endo, and T. Kanai: J. Radiat. Res. **48**, Suppl. A (2007) A15.
10   S. Agostinelli, J. Allison, and K. Amako: Nucl. Instrum. Methods Phys. Res., Sect. A. **506** (2003) 250.
11   T. Berger and M. Hajek: Radiat. Meas. **43** (2008) 146.