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Dose Linearity and Linear Energy Transfer Dependence of Cr-doped Al_2O_3 Ceramic Thermoluminescence Detector

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A Cr-doped alumina (Al_2O_3:Cr) ceramic thermoluminescent detector (TLD) has the potential to be applied as a two-dimensional (2D) imaging device in radiation therapy. In this work, we investigated the linearity in the dose level of radiotherapy and the linear energy transfer (LET) dependence of Al_2O_3:Cr ceramic TLD using several species of heavy charged particles (HCPs). The Al_2O_3:Cr ceramic TLD had good linearity as a function of irradiation dose. However, the large LET-dependent response made it difficult to apply the detector directly to dose measurement in HCP therapy. The combination of two Al_2O_3 ceramic TLDs, one with Cr doping and one without Cr doping, may be expected to be applied to the measurement of LET distributions because of the different LET dependences.

1. Introduction

Successful radiotherapy requires the correct dose to be delivered; this can be achieved by a routine quality assurance (QA) program and dose verification before treatment. A radiochromic film such as EBT3[(1)] (GAFCHROMIC™, EBT3 dosimetry film, Ashland Co.) is capable of providing a precise two-dimensional (2D) dose distribution and is one of the most widely used dosimeters in conventional photon radiotherapy.[(2–5)] However, the linear energy transfer (LET)-dependent response of EBT3 and the fact that it can be used only once make it unsuitable for heavy charged particle (HCP) radiotherapy.[(6,7)] Consequently, ionization chambers (ICs) have been the most useable dosimeters for QA in HCP therapy. The scanning and multiarray arrangement methods are the most common ways to obtain the dose distribution using ICs, although these two methods have some drawbacks, such as requiring a large amount of time and providing a poor spatial resolution.

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Recently, it has been reported that Al_2O_3-based ceramic plates show good thermoluminescent (TL) characteristics and are available for use in 2D dosimetry.[8] In addition, it has been reported that a nondoped Al_2O_3 ceramic thermoluminescent detector (TLD) has a smaller LET-dependent response than commercially available TLDs such as LiF:Mg,Ti and LiF:Mg,Cu,P.[9] The application of a nondoped Al_2O_3 ceramic TLD to HCP therapy has been suggested. On the other hand, nondoped Al_2O_3 had a low-temperature glow peak that increases the fading effect. Recent research shows that a Cr-doped alumina (Al_2O_3:Cr) ceramic TLD is suitable as a 2D imaging device in conventional photon therapy because it has a linear relationship between dose and response, and a small fading property, while it is easy to handle and reusable.[10]

In this work, with the aim of evaluating the potential of Al_2O_3:Cr ceramic TLDs in HCP therapy, we investigated the dose linearity and LET dependence of an Al_2O_3:Cr ceramic TLD using several HCP beams.

2. Materials and Methods

2.1 Cr-doped alumina-based ceramic TLD

An Al_2O_3:Cr ceramic TLD was provided by Chiba Ceramic Mfg. Co., Ltd. Table 1 shows the composition of this Al_2O_3:Cr ceramic TLD. The bulk density and effective atomic number of the TL slab were 3.7 g/cm^3 and 11.13, respectively. Al_2O_3:Cr ceramic TLDs were fabricated with a size of 11 × 11 × 0.7 mm^3 (Fig. 1).

2.2 Irradiation

Irradiation experiments were performed at the BIO course of the heavy-ion medical accelerator (HIMAC) in Chiba at the National Institute of Radiological Sciences. The beams were laterally broadened by a wobbling and scattering system to produce a uniform field with a 10 cm diameter.[11] Table 2 lists the irradiation beams used in this study. The values of LET in water were calculated using Geant4.[12] For each irradiation, four dose levels were given as 0.5, 1.0, 2.0, and 5.0 Gy in water based on the predicted dose in HCP therapy. In addition, all

Table 1
Nominal composition of Al_2O_3: Cr ceramic TLD (Chiba Ceramic Mfg. Co., Ltd. A10).

Ingredient	Wt.%
Al_2O_3	>99.5
Cr_2O_3	~0.05

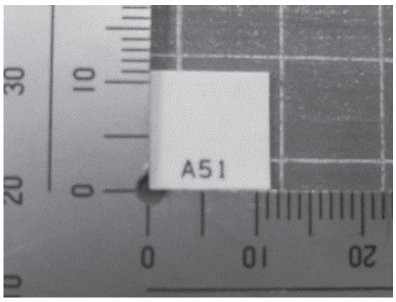

Fig. 1. Sample of Al_2O_3:Cr ceramic TLD used in this study.

Table 2
Irradiation beams used in this study.

Particle	Energy (MeV/u)	LET in water (keV/mm)
H	160	0.5
He	150	2.0
C	290	13
C	135	24
Ne	400	29
Ar	500	86
Fe	500	197

the Al_2O_3:Cr ceramic TLDs were irradiated using a 6 MV photon beam as a reference from a Varian 21Ex linear accelerator at Tokyo Metropolitan University. The irradiations were performed with a 100 cm source-to-axis distance and a field size of 10 × 10 cm^2, and by placing the film packages at a depth of 10 cm in water equivalent phantoms.

2.3 TL glow curve measurement

A readout system(9) developed in house was used to record TL glow curves of the Al_2O_3:Cr ceramic TLDs from room temperature to 400 °C. The TLD was heated by a brass plate connected to a programmable heat controller (Sakaguchi E.H VOC Corp. SCR-SHQ-A) at a heating rate of 0.2 °C/s in air. A thermal cut filter was set in the readout system to decrease the effect of thermal radiation. After passing through the thermal cut filter, the TL signal was collected with a pair of collecting lenses and then counted using a photon-counting unit (Hamamatsu H11890-110). Generally, the TLD demonstrates a fading effect in which the amount of TL decreases as a function of the time elapsed from irradiation to reading. To improve accuracy without correcting the fading effect, the timeline of the readout procedure was made consistent for each experiment. The wavelength spectrum of the TL of the Al_2O_3:Cr ceramic TLD was detected with a multichannel spectroscope (Hamamatsu PMA-12).

3. Results and Discussion

3.1 TL glow curve and dose linearity

Figure 2 shows the TL glow curve of the Al_2O_3:Cr ceramic TLD. The glow peaks were located at 310 °C. Figure 3 shows the wavelength spectrum of the TL; the wavelength of the TL peak is located at 694 nm due to the embedded Cr^{3+}.(13–16) As shown in Fig. 2, the TL intensity was evaluated as an integrated value over a 10 °C range centered on the main peak. The TL intensity was normalized using the following equation,

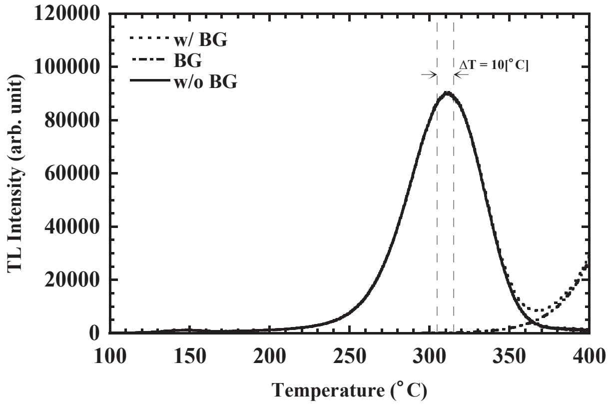

Fig. 2. Glow curve of the Al_2O_3:Cr ceramic TLD.

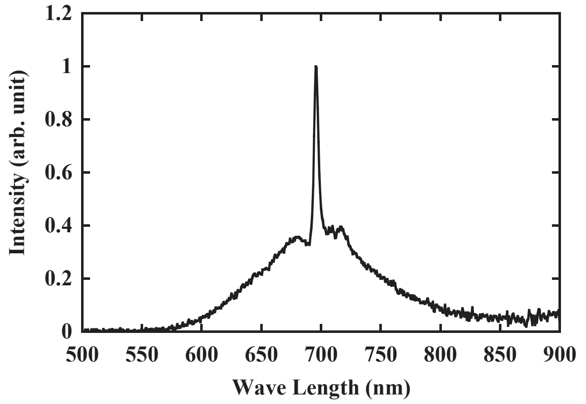

Fig. 3. Wavelength spectrum of Al_2O_3:Cr ceramic TLD.

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

where D is the irradiation dose, $L(D)$ is the TL intensity when the irradiation dose is D Gy, $L_{X\text{-}ray}$(1 Gy) is the TL intensity when an X-ray of 1 Gy is irradiated, and $nL(D)$ is the normalized TL intensity. In addition to $nL(D)$, to evaluate the reproducibility, the TL efficiency nL/D was defined as the TL intensity per irradiation dose. Figure 4 shows the dose response of this ceramic TLD to several species of charged particles. Dose linearity and repeatability were comparatively good. On the other hand, the TL efficiency nL/D changed with the species of HCP.

3.2 LET dependence

Table 3 and Fig. 5 show the relationship between the LET in water of the irradiating particle and the TL efficiency of the Al_2O_3:Cr ceramic TLD for charged particles in this study. The TL efficiency increased from 0.8 and reached a peak value of 1.2 when the LET was 13 keV/mm and decreased to 0.6 when the LET approached 200 keV/mm. The TL efficiency of the nondoped Al_2O_3 ceramic TLD showed a relatively small LET dependence over this LET range,[9] while the Al_2O_3:Cr ceramic TLD had a large LET dependence. Because of its large LET dependence, the Al_2O_3:Cr ceramic TLD is difficult to use directly in QA for HCP therapy. However, the difference in the LET dependence of TL efficiency for these two TLDs with similar physical characteristics may be useful for the estimation of LET. Over a limited LET range, the difference in the LET dependence of the two TLDs may be uniquely determined with respect to the value of LET. In Refs. 17 and 18, a dose estimation method for HCP using two types of optically stimulated luminescence (OSL) elements with different LET dependences has been reported. Using a similar estimation method and 2D imaging of ceramic TLDs,[8] it may be possible to measure the LET distribution in HCP therapy. Recently, research on HCP therapy has focused on not only the physical dose but also the biological dose that makes LET distribution information increasingly important. In HCP therapy with one nuclide beam, the range of the LET of the irradiated beam is limited. Hence, it may be possible for

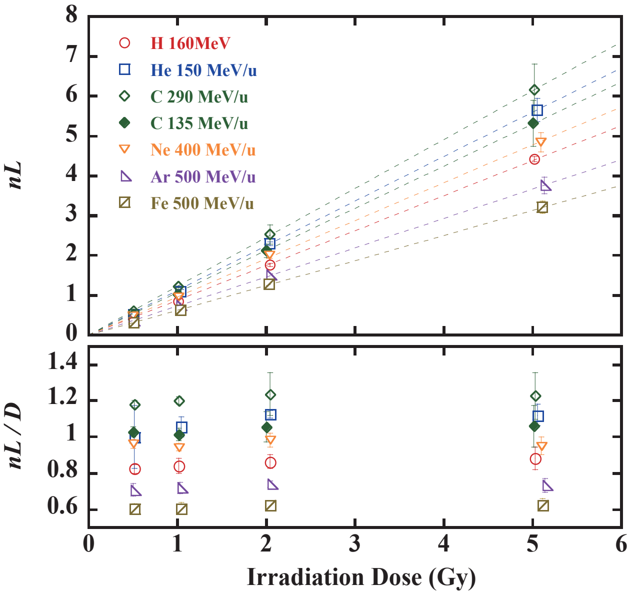

Fig. 4. (Color online) Dose responses to X-ray and charged particles. The TL intensity was normalized at 1 Gy.

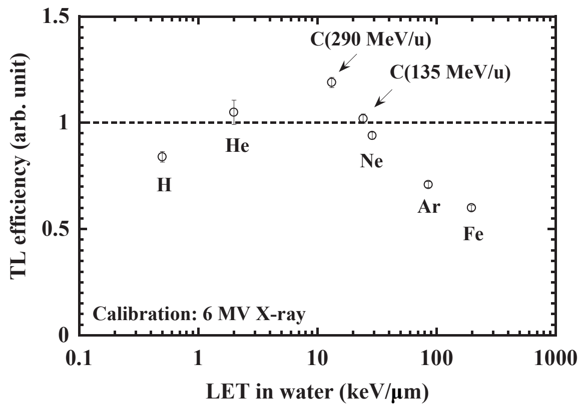

Fig. 5. LET dependence of TL efficiency *nL*/*D*.

Table 3
Relative TL efficiency of alumina-based ceramic TLD.

Irradiation particle	LET in water (keV/mm)	*nL*/*D*				
		0.5 Gy	1 Gy	2 Gy	5 Gy	Average
H	0.5	0.81	0.83	0.86	0.86	0.84
He	2	0.98	1.03	1.10	1.09	1.05
C	13	1.16	1.18	1.21	1.20	1.19
C	24	1.01	0.99	1.03	1.04	1.02
Ne	29	0.94	0.93	0.96	0.93	0.94
Ar	86	0.69	0.70	0.72	0.72	0.71
Fe	197	0.59	0.59	0.60	0.61	0.60

the combination of one Al_2O_3 ceramic TLD with Cr doping and one without Cr doping to be applied to the measurement of the LET distribution in HCP therapy.

In previous reports, the LET dependence of several TLDs based on Al_2O_3 has been reported. Spurny and coworkers reported the LET dependence of Al_2O_3:Na TLD and Al_2O_3:C TLD.[19–21] In this work, Al_2O_3:Cr ceramic TLDs showed characteristics similar to the TL efficiency of the Al_2O_3:Na TLD that increased up to a range of tens of keV/mm and then decreased in the higher LET region. On the other hand, the TL efficiency of Al_2O_3:C TLD decreased monotonically in the range of several keV/mm to several hundred keV/mm. In Berger and Hajek's review[22] of the LET dependence of many TLDs other than Al_2O_3, most TLDs showed a TL efficiency peak in the LET region of tens of keV/mm or showed a monotonically decreasing TL efficiency with increasing LET. In addition, they reported that the TL response to different HCPs with the same LET is not a unique function of ionization density, but rather depends on the microscopic pattern of energy deposition. Therefore, further study of the LET dependence of the Al_2O_3:Cr ceramic TLD for each HCP is necessary to assess possible applications to HCP therapy.

4. Conclusions

In this study, we investigated the dose response in radiotherapy and the LET dependence of Al_2O_3:Cr ceramic TLDs using several HCP beams. The main peak of the glow curve located at 300 °C showed good linearity with the irradiation dose. Even though it seems that a large LET dependence may make the direct application of Al_2O_3:Cr ceramic TLDs in HCP therapy difficult, the combination of two Al_2O_3 ceramic TLDs, one with Cr doping and one without Cr doping, may possibly be applied to the measurement of LET distribution because of their different LET dependences. In order to apply Al_2O_3:Cr ceramic TLDs to QA in HCP therapy, further investigation of the LET dependence of Al_2O_3:Cr ceramic TLDs for each HCP is necessary.

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