Response characteristics of an imaging plate to clinical proton beams

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Abstract

For an application to a dose-distribution measurement, the response of an imaging plate (IP) has been studied with proton beams which are routinely utilized for the radiation therapy. The upper limit of measurable proton dose by an IP system is primarily controlled by the readout range of the scanner that is used. Within this limit, reasonable linear response of an IP to proton dose to water is maintained. Fading curves are neither sensitive to a small change of room temperature (22–26°C) nor to a variation of proton dose (0.0108–0.132 Gy). Reproducibility of the PSL intensity is fairly good if both the fading characteristics and the lot-dependence of the sensitivity of each IP are taken into account carefully. Stopping power dependence of the IP response has been examined at different positions in a Bragg curve.

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1. Introduction

In the charged particle therapy, it is necessary to verify the achievement of expected dose distribution prior to the actual irradiation to patients. This is usually a quite time-consuming task with a small single detector. Therefore, a multi-dimensional dosimeter is much desirable for such routine measurement \cite{1,2}.

An imaging plate (IP) system has been widely used in many fields as a two-dimensional detector for radiations owing to a large sensitive area and a high spatial resolution. The first application of an IP to proton dose-distribution measurement was carried out by Hayakawa et al. \cite{3}. Using clinical proton beams, they showed that the linearity between the intensity of photo-stimulated luminescence (PSL) and “proton dose to water” was
maintained up to 0.013 Gy. As a demonstration of the stopping power dependence, they measured a depth-dose distribution of an ordinary Bragg peak by an IP, which was found to be roughly proportional to that measured by a Si diode. Weissman et al. [4] successfully used an IP to measure the profile of a 600 keV proton beam in vacuum.

In this paper, the application of IPs for proton beams has been extended with the aim of realization of a practical dosimetry system for therapy. Linearity between PSL intensity and proton dose has been measured to search the practical upper limit of measurable dose. Fading characteristics, the lot dependence and the stopping power dependence have been investigated for quantitative dose evaluation.

2. Proton dosimetry with imaging plates

In the clinical dosimetry, ionization chambers are the primary dose measuring devices. In addition to this, other types of detectors have been successfully used to measure the dose deposited by heavy charged particles: such as diodes, thermoluminescent dosimeters (TLDs) and chemical dosimeters [5]. An IP can be a candidate for such application. Actually, in early days, a kind of PSL material, SrS-Eu,Sm, was studied as a dosimeter by Antonov-Romanovsky et al. (1955) [6].

A PSL sheet of the IP tested in the present work (BAS-III 2025, Fuji Film Co., Ltd.) is made of BaFBr:Eu$^{2+}$. The sensitive layer is very thin, 100–150 μm, effectively less due to the attenuation of the stimulating light and its PSL with penetration. Therefore, all the energetic protons of a few MeV or more pass through the sensitive region, while low energy protons stop in it. For this complicated fact, response of IPs to clinical proton beams may not be so simple. On the other hand, however, similar situation is found in the dosimetry with TLDs; very small size of TLD plates whose thickness are a few hundred μm are often used for the precise determination of spatial dose distribution. As TLD dosimetry has been used to characterize the therapeutic heavy charged particles, we expect that proton dosimetry with IPs would be useful for the verification of dose distribution.

3. Apparatus and experimental setup

Proton irradiation was carried out using the horizontal beam line of Proton Medical Research Center (PMRC), University of Tsukuba. In this beam line, approximately monoenergetic 250 MeV protons are delivered from the KEK 500 MeV booster synchrotron with the aid of a carbon energy-degrader and a momentum analyzing system. Delivered proton beams have a sharply-bunched time structure; each pulse consists of about $2\times10^9$ protons with a duration time of 50 ns in fwhm. The pulse frequency was about 1 Hz in the present experiment condition.

Firstly, the incident protons were scattered by a 3 mm-thick lead plate (referred as “first scatterer”) to obtain laterally uniform spatial distribution. Between the first scatterer and a patient bed, some beam shaping devices and beam monitors were inserted, if necessary: i.e. a binary range shifter, a ridge filter, a field collimator and a secondary-emission chamber (SEC) monitor. Imaging plates sandwiched by Mix-DP plates were put on the patient bed; the sensitive sides were faced toward the beam-coming direction. A thimble ionization chamber (TIC), JARP C110, 0.2 ml, was arranged just near the imaging plates to measure protons; the reading was evaluated as “proton dose to water” with a correction of recombination effect. The sensitivity of the TIC had been calibrated in a $^{60}$Co γ-ray standard field in advance.

Twenty sheets of IPs (BAS-III 2025, Fuji Film Co., Ltd.) were used in the present work. Those IPs were classified into two groups for the sake of lot-dependence consideration: i.e. Group-A (serial No. 17745–17754) and Group-B (serial No. 17537–17546). Before each irradiation, latent images were erased off. During irradiation, each plate was kept inside a black thin vinyl bag. The scanner used was BAS2000-II (Fuji Film Co., Ltd.) with fixed scanning parameters of “Latitude” = 4, “Sensitivity” = 400 and “Resolution” = 200 μm. The upper limit of measurable PSL intensity in this setting is $10^5$ PSL/mm$^2$ [7]. This is maximum one for BAS2000-II operation.
4. Results and discussion

4.1. Linearity of PSL intensity to proton dose

Photo-stimulated luminescence intensity was measured for various proton doses from 0.003 Gy (1 pulse) to 0.240 Gy (75 pulses). The experimental setting is sketched in Fig. 1. A ridge filter was used to form a 70 mm iso-dose region in depth, “spread-out Bragg peak (SOBP)”. An IP was placed in the SOBP. At this position, the maximum residual range of protons was about 50 mm in water, which corresponds to about 80 MeV of proton energy. On the other hand, because the iso-dose region is created by stacking some Bragg peaks of different range beams, the minimum proton energy must be almost 0 MeV at all points inside SOBP. Stored images were readout 90 min after the termination of each irradiation.

As shown in Fig. 2, the PSL intensity is proportional to proton dose up to 0.148 Gy at least. At 0.224 and 0.24 Gy, readout PSL intensity reaches the upper limit of scanner range, $10^5$ PSL/mm$^2$. It seems that the upper limit of measurable dose is controlled by the scanner range in this measurement.

The PSL intensity in Fig. 2 is about twice as large as the one of Fig. 2 in Ref. [3]. The discrepancy is due to the following reasons. First of all, different amounts of “fading” of stored images occurred between both measurements. In Ref. [3], images were readout about 1 day after the irradiation. Secondly, the sort of scanner used in Ref. [3] was not identical with the present one. In addition, the sensitivity of IP used in Ref. [3] is unknown and may be somewhat different from that used here.

4.2. Fading characteristics

It is known that the latent image of radiation stored in an IP fades as time goes by: so-called “fading”. Fading curves have been reported for $\alpha$-rays [8,9], $\beta$-rays [9], $\gamma$-rays [10–12], X-rays [13,14] and electron beams [15]. The fading is essentially important for dosimetry with IPs.

Fading characteristics up to 200 min after irradiation were measured for various proton dose to water, 0.0108–0.132 Gy, under some temperature conditions, 22–26 °C. The experimental arrangement was almost the same as that in Fig. 1. In this measurement, however, 7–10 sheets of IPs were stacked against each other and inserted into the SOBP region; the influence of such stack configuration was carefully examined and found to be negligible for the present purpose. Protons were irradiated to those IPs simultaneously and each IP was readout after a certain duration to obtain the PSL intensity. This procedure was repeated and eight fading curves were evaluated. Those curves were normalized by the PSL intensity per proton.
dose at the termination of irradiation ($t = 0$ min), $I_0$ (PSL/mm$^2$/Gy), and plotted in Fig. 3. Before the normalization by $I_0$, a systematic difference of IP sensitivity was observed between two lot-groups in those fading curves. In Fig. 3, all experimental data can be fitted well by a combination of two exponential curves with different time constants. This means that obtained fading characteristics are neither so sensitive to a small change of room temperature ($22$—$26^\circ$C) nor to a certain variation of irradiated proton dose ($0.0108$—$0.132$ Gy). A result of data fitting with two exponential decay functions gives the following equation:

$$I/I_0 = 0.25 \exp((- \ln 2) t/15.5) + 0.75 \exp((- \ln 2) t/3400).$$

This fading curve ($I/I_0$) consists of two components with half-lives of $15.5$ min (25%) and $3400$ min (75%).

4.3. Proton stopping power dependence

Hayakawa et al. roughly demonstrated that an imaging plate is useful for the measurement of depth-dose distribution of a Bragg curve [3]. However, a direct and precise comparison of IP response with proton dose to water has not been carried out yet by using ionization chambers.

A Bragg curve was measured with IPs by changing a binary range shifter which was arranged at about $3$ m upstream of the patient bed instead of the ridge filter in Fig. 1. The proton dose to water was measured by the TIC which was put just in front of the IP. The SEC was used as a reference monitor in order to compensate the slight beam-intensity fluctuation during irradiation. The dose by $\gamma$-rays was measured with film badges near the IP position and estimated to be less than $0.01\%$ of irradiated proton dose. Therefore, PSL signal due to $\gamma$-rays from the range shifter was negligible.

Fig. 4 shows the obtained data with different detectors, IP and TIC, as a function of the thickness of the range shifter. Each curve is normalized so that their plateaus come to the same level. As indicated in the figure, there is notable disagreement between the two curves beyond the peak position of Bragg curve. It should be kept in mind that the shapes of both Bragg curves are slightly distorted from the real dose distribution at the proximal region. This may be due to a scattering effect by the insertion of range-shifting material and use of thick dosimeters.

In Fig. 4, the ratios of PSL intensity to proton dose measured by TIC are also plotted. That is normalized at the range-shifter thickness of $55$ mm. From $0$ to $190$ mm, the ratio is kept almost constant. On the other hand, more than $190$ mm, it decreases with approaching the distal edge. Similar
Fig. 4. Bragg curves obtained by the TIC and IPs. The ratios of IP signals relative to the dose measured by TIC are also plotted.

Fig. 5. Depth–dose profiles of an SOBP measured in a water phantom with TIC and IPs. The response of IP is calculated from the result in Fig. 4.
phenomenon has been observed in TLD dosimetry of heavy ion beams [16].

By using the result of Fig. 4, response of IPs can be predicted for an SOBP formed by a known ridge filter. As shown in Fig. 5, the distribution of PSL intensity shows a good agreement with calculated one. This means actual depth–dose distribution should agree with the physical dose distribution expected from the ridge filter used. Such procedure is applicable to verify the planning algorithms.

5. Summary

The upper limit of measurable proton dose by an IP system is primarily controlled by the readout range of the scanner used. For the irradiation of clinical dose level (a few Gy), PSL intensity exceeds the scanner limit. When stored images are read out 90 min after irradiation, reasonable linear response of an IP to proton dose to water is ascertained up to about 0.15 Gy. Fading curves are not sensitive to a small change of room temperature (22–26°C) or to a variation of proton dose (0.0108–0.132 Gy). As far as the measurements repeated in the present work are concerned, reproducibility of the PSL intensity seems to be fairly good if both the fading characteristics and the lot-dependence of the sensitivity of each IP are taken into account with caution. Stopping power dependence of the IP response must be considered very carefully for the quantitative evaluation of dose profiles.

For proton dosimetry with IPs, it is necessary to check and control the sensitivity of each IP by the direct comparison with reference dosimeters, such as ionization chambers. By this, small variation of each IP response can be effectively compensated. A change of IP sensitivity due to radiation damage is another important aspect to clarify [17].

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References