Linear-energy-transfer dependence of polymer gel dosimeters under carbon beam irradiation

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Polymer gel dosimeters are widely used for quality assurance in the treatment planning of cancer therapy using low linear-energy-transfer (LET) radiations such as X-rays, and γ-rays. They consist of gel-fixed radiation-sensitive compounds, and the amount of the reaction products after irradiation depends on the dose accumulated at each position in the gel. The proton NMR is sensitive to the reaction products, and its three-dimensional map can be read out by using the magnetic resonance imaging (MRI) technique [1]. With regard to the application of gel dosimeters to heavy-ion beams that have higher biological effectiveness than low-LET radiations, it has been reported that the dose response of all the gel dosimeters except for the nanocomposite Fricke gel developed recently [2] changes with radiation quality, which depends on the charge and velocity of the ion in the case of heavy-ion beams. The dose distribution hence cannot be evaluated directly from the measured MRI signal strength in these gel dosimeters.

In this study, we investigated the dose response of the VIP polymer gel dosimeters [3] for carbon beams having a wide LET range, by comparing the relaxation rate (R_2 [s^{-1}]) obtained by MRI with the dose estimated by the Particle and Heavy Ion Transport code System (PHITS) [4]. The LET is a representative index of radiation quality, and a reliable estimation of the LET and the dose is now available by PHITS. VIP polymer gel dosimeters were prepared following the prescription [3] and sealed into containers, the length of which is sufficient to stop the ions injected into the gel dosimeters. They were irradiated with 135-AMeV and 290-AMeV $^{12}C^{6+}$ ions accelerated by the RIKEN Ring Cyclotron and the Heavy Ion Medical Accelerator in Chiba, respectively. The dose response of irradiated samples was obtained from 1.5-T MRI (Philips).

Results of the dose response [$s^{-1}Gy^{-1}$] are plotted as functions of the dose-weighted average of the LET (hereafter, dose-averaged LET) where the projectile ions and all the secondary particles produced by the nuclear reaction are included. The dose response decreases with increasing LET, as reported in the literature. In addition, the dose response is approximately 10% higher for the 290-AMeV beam than for the 135-AMeV beam at the same dose-averaged LET (Fig 1, symbols). This sizable difference can be explained by the different contributions from secondary particles. Ions with higher injection energy pass the thicker gel before reaching the given dose-averaged LET, and yield mode of secondary particles, mainly light fragments of the projectile. Furthermore, low-LET fragments contribute more effectively to R_2 than high-LET particles. Hence, the 290-AMeV beam has higher dose response than 135-AMeV beam. For the above effects, we are investigating the contribution of minor ions such as target fragments.

To confirm the present explanation quantitatively, we investigated whether the observed 10% difference can be reproduced by assuming that the dose response of the gel dosimeter depends only on the LET value for all the relevant ions. As a result, we found a universal dose response function of the LET (R(LET), blue-dashed line in Fig. 1) that reproduced well the measured dose response for both the 135-AMeV and 290-AMeV carbon beams. The dose-averaged responses R_{ave} defined in Eq. 1 are shown in Fig. 1.

$$R_{ave} = \frac{\int R(LET)Dose(LET)dLET}{\int Dose(LET)dLET} \qquad (1)$$

The dose response obtained here was used for predicting a geometrically more complicated R_2 map measured by the VIP gel under a heterogeneous irradiation condition. The calculated R_2 distributions reproduced the measured ones with the accuracy of ±5% except for the end of the ion range, the position of which was also reproduced within 1-2 mm.

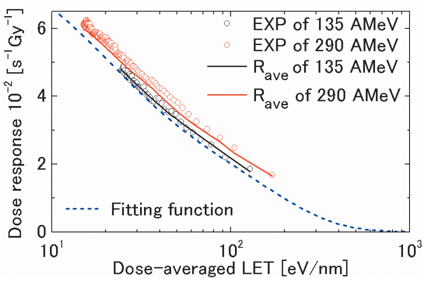

Fig. 1. Comparison of dose response of VIP gel obtained at different incident energies. Symbols represent experimental results, continuous lines represent dose-averaged response calculated by PHITS, and the dashed line represents the assumed fitting function.

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