The examination of fundamental characteristics of polymer gel detectors in the irradiation of 210MeV protons

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Abstract. This paper is intended as a study of the radiological characteristics of the polymer gel detector in the irradiation to 210MeV protons. The depth dose distributions in the gels were examined with regard of its dose and dose rate dependences. The results indicate the energy dependence of dose-response relations due to LET effect.

1. Introduction
The purpose of our study is to examine the possibility of a polymer gel detector’s utilization for the treatment plans in particle therapy and their 3D dose verifications. Since a polymer gel detectors has been introduced as new domestic tool for 3D dosimetry, their radiological characteristics in the irradiation of photon beam have been well investigated so far (e.g. reviewed in [1]). With regard to the irradiation of high linear energy transfer (LET) particles to polymer gels, a few studies have been reported [2-4]. In these studies, strong suppression of the gel’s response at the Bragg peak has been observed. And it has been indicated that the suppression was related to the increase in LET at the Bragg peak region [5].

In the study of biological effects of ionizing radiation, track simulations for charged particles by Monte Carlo method have been developed including chemical reactions among water radicals, moreover the yield of hydroxyl radical induced by radiation has been estimated by empirical model of deterministic kinetics calculations [6].

The present paper deals with the idea of this model in order to interpret our experimental results on the dose response of the gel in the irradiation of 210MeV protons.

2. Materials and methods
We prepared MAGAT type gel for this study. The gel consists of water, gelatin (10%w/w), methacrylic acid (5%w/w) and tetrakis hydroxymethyl phosphonium chloride (THPC 2mM). The compounded gelatin solution was divided into cylindrical PMMA containers of 3cm diameter and 40cm length for the measurements of spread-out depth dose in the gel. All samples were irradiated in a fixed horizontal 210MeV proton beam at the facility of the Hyogo Ion Beam Medical Center. Precede
the irradiation to the samples, the ionization chamber was irradiated to determine the prescribed irradiation dose at the center of the spread-out Bragg peak (SOBP) in a PE phantom, and also spread-out depth dose was measured in water. In irradiations, cylindrical containers were placed along the beam line including full proton’s ionization range. Firstly various doses from 1 to 20Gy were delivered to eight containers to obtain the response - dose relations, and examine the consistency in the percentage depth dose distribution (PDD) on the irradiated dose independently. The dose rate of 4Gy/min typically applied in treatments was adopted in these irradiations. Secondary the dose rate was varied from 0.4 to 4Gy/min and delivered 4Gy to five containers to examine the dose rate effect on the spread-out depth dose and SOBP in the gel. MR images of samples were recorded by 1.5T PHILIPS Gyroscan Intera scanner with a multiple spin-echo sequence at TE$_1$=20ms, TE$_2$=100ms and TR=10s, and the transverse relaxation rate R$_2$ images were analyzed.

3. Results and discussions

Figure 1 shows the depth R$_2$ distributions in the gels that were irradiated spread-out depth dose of protons with various amount of dose. In the analysis, the image data of pre-irradiation were subtracted from the R$_2$ data in advance to eliminate an effect of no uniform background in the gel.

![Figure 1](image1.png)

**Figure 1.** The depth R$_2$ distributions of 210MeV proton beam in the gel.

Eight cylindrical containers of MAGAT gels from the same production batch were irradiated in various doses as 1, 2, 4, 6, 8, 12, 16, 20Gy.

The horizontal axis presents the depth from the top of container where incident beam in. No constant R$_2$ background in each sample were subtracted from R$_2$ data in advance, but still ambiguity in R$_2$ are left near the entrance of beam due to the effect of the edge of container.

These depth-R$_2$ curves are supposedly correspond to the depth dose distributions, and yet R$_2$-dose relations are required to convert each other. The dose response curve of R$_2$ for MAGAT polymer gel irradiated 210MeV protons is presented in Figure 2. It must be noted that the R$_2$ in this figure are the values at the center of SOBP where the prescribed dose has been calibrated by ionization chamber. The data are fitted with the summational function of exponential as

$$R_2 = R_{2\text{max}}(1 - \exp(-A(dose - d_0))) + B \exp(-C \text{ dose})$$  \hspace{1cm} (1)

where $R_{2\text{max}}$ is the saturation relaxation rate. Second exponential function and $d_0$ parameter represent the “induction” effect, which is generally seen as gently slope of response curve at low dose range [7].

In Figure 3 the PDD are graphed for the gels irradiated 4, 12, 20Gy, which were derived from the depth-R$_2$ relations and R$_2$-dose relations of the expression (1). In the comparison with corresponding PDD measured by ionization chamber, the suppression at the Bragg peak and the excess at the incident side of beam are recognized in the response of gels. This suppression is consistent with previously
reported results by other groups [2], while the excess like our results has not been reported previously. And what has to be noticed is that the excess is more remarkable as much as dose increases, despite PDD should not depend on the irradiated dose, theoretically.

**Figure 2.** $R_2$ versus dose for the gel in the irradiation of 210MeV protons.

$R_2$ in this figure correspond to the value at SOBP of each depth $R_2$ distribution in Figure 1.

The data are fitted with the following summational function of exponential.

$$R_2 = 37.5(1-\exp(-0.0575(dose-0.55))) + 1.625\exp(-1.15dose)$$

**Figure 3.** The percentage depth dose (PDD) of 210MeV proton beam in the gel.

Dose at each depth were converted from $R_2$ based on $R_2$-dose relation in Figure 2, and PDD were calculated as dose/dose_{max}. PDD measured in water by ionization chamber were normalized at the end of our data on the horizontal axis.

These results can be explained by the depth dependence of the $R_2$-dose relation in the gel. The $R_2$-dose relation at the various depths on the PDD representing in Figure 4 are considered. The absorbed dose at each depth was estimated from the PDD measured by ionization chamber, and applied it to the depth-$R_2$ relations in Figure1. The $R_2$-dose relations at each depth appear in Figure 5. The data at each depth are fitted with a summation of exponential function as eq.(1) with same parameters as the expression in Figure 2, except $R_{2_{\text{max}}}$. The value of $R_{2_{\text{max}}}$ decreases with increasing the depth.

The diffusion model for a “spur”[6], which is sought of a cluster of radicals, may interpret the depth dependence, in other words “the energy dependence”, of the $R_2$-dose relation in the gel. Though this empirical model still leaves room for improvements, the concept of this idea is reasonable and acceptable phenomenologically. In this model, a spur is initially produced along the paths of an incident particle and secondary electrons, and propagates into a medium like a diffusion of elementary...
wave. The radicals inside the spur interact with other radicals in the nearby spur at meeting point of both spurs. As the distance between successive initial spurs should depend on a local energy loss of an incident proton, the yields of radical also depend on the energy along its trajectory. With the energy loss advances, the interactions of radicals increase abruptly owing to decrease of distance between the spurs. In consequence the maximum number of radical and $R_{2max}$ must be suppressed gradually as the incident proton energy decreases.

**Figure 4.** On the basis of SOBP measured by ionization chamber, the examinable depths are selected.

Average PDD at each depth is as follows:
- PLATEAU: $68 \pm 1\%$,
- SLOPE: $85 \pm 3\%$,
- SOBP: $99 \pm 1\%$,
- SHOULDER: $96\%$,
- TALE: $40\%$.

**Figure 5.** $R_2$ versus dose in the irradiation with $210\text{MeV}$ protons at various depths of PDD.

Each data are fitted with the following summational function of exponential,

$$R_2 = R_{2max} \left( 1 - \exp(-0.0575(dose - 0.55)) \right) + 1.625\exp(-1.15dose)$$

where $R_{2max}$ represents $45.75\text{[s}^{-1}], 40.0\text{[s}^{-1}], 37.5\text{[s}^{-1}], 31.5\text{[s}^{-1}], 5.5\text{[s}^{-1}]$ for PLATEAU, SLOPE, SOBP, SHOULDER, and TALE respectively.
Another result, which may support this model, is presented next. Figure 6 shows the series of SOBP in the gels with increasing dose rate. From the figure it is clear that absolute values of \( R_2 \) strongly depend on dose rate such that \( R_2 \) increase with decreasing dose rate.

**Figure 6.** The depth \( R_2 \) distribution for the various dose rates of protons irradiating 4Gy.

The absolute value of \( R_2 \) decreases with increasing dose rate due to quenching the spur with other spurs from nearby protons, while the shapes of SOBP and the suppression at SHOULDER are consistent with each other without dose rate dependence.

It is inferred from the fact that the quenching would occur along even single particle trajectory.

This fact of the dose rate dependence of \( R_2 \) can be interpreted as that the decrease of distance between nearby protons with increasing dose rate would increase the spur’s interaction probability, accordingly the polymerization rate decrease.

These results lead us to the remark on the dose estimation from \( R_2 \) in the irradiation of protons. That is, the energy and density of incident proton at each location should be considered in deducing a dose distribution from \( R_2 \) distribution because gel’s sensitivity depends on them.

### 4. Conclusion

In this work, we concerned with the dose response of MAGAT gels in the irradiation of protons. The empirical diffusion model for a spur interprets the depth \( R_2 \) distributions in the gel detector. What the polymer gel detector observes is just a distribution of radicals, and it must be quite complicated process required to deduce a dose distribution, especially in the irradiation of charged particles. It is concluded that the polymer gel detector would not be useful in dose measurements for particle therapy so much, but it can provide us a significant information as the distribution of radical induced by irradiations, which other dosimeter can not offer.

A further direction of this study will be to examine more detail on the characteristics of the dose response to clarify the relation between the radical distributions and dose distributions.

### References

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