Title:

Radiation-induced Change of Optical Property of Hydroxypropyl Cellulose Hydrogel Containing
Methacrylate Compounds: As a Basis for Development of a New Type of Radiation Dosimeter

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Abstract:

Hydrogels with matrix of a cellulose derivative, hydrogel of hydroxypropyl cellulose (HPC), containing two of methacrylate compounds (2-hydroxyethyl methacrylate (HEMA) and poly(ethylene glycol) dimethacrylate (9G)) were irradiated with ^{60}Co γ -rays. The gels become white with irradiation, and thus, could be candidates of a new type of radiation dosimeter utilized in radiation therapy because the gels become white with irradiation and can be confirmed directly by human eyes even at low doses of 1-2 Gy. Radiation-induced change of optical properties, haze value and UV-Vis absorption spectrum, of the irradiated gels were measured. Dose response of the white turbidity appearance was different for different compositions of the methacrylate compounds as well as for different dose rates. The degree of the radiation-induced white turbidity was quantified by measuring haze value, showing linear dose response in low dose region (< 2 Gy). We also analyzed the gels with a UV-Vis spectrometer and HEMA- and 9G-rich gels gave different spectral shapes, indicating there are at least two mechanisms leading to the white turbidity. In addition, dose rate dependence was smaller for 9G-rich gels than HEMA-rich gels in the range of 0.015-1.5 Gy/min

Keywords:

hydrogel, hydroxypropyl cellulose (HPC), methacrylate, white turbidity, dosimeter, haze

1. Introduction

Nowadays, cancer is one of the major reasons of human deaths and its therapy with ionizing radiations is spread thanks to high quality of life (Foray and Balosso, 2008). It is required in radiation therapy to control dose, and planned dose should surely be given to cancer, with reducing dose given to normal tissues surrounding the target as much as possible in order to reduce risk of radiation hazards such as secondary carcinogenesis, necrosis, etc. For this purpose, several kinds of irradiation methodologies have been developed, e.g. IMRT (intensity modulated radiation therapy), SRT (stereotactic radiotherapy), BNCT (boron neutron capture therapy), scanning irradiation system, irradiation with rotating gantry system, charged particle irradiations, brachy therapy, and so on. Such a development enables us to plan complicated dose distributions in human bodies (Foray and Balosso, 2008; Noda and Kamada, 2010). It is well studied whether a three-dimensional dose distribution actually given in a phantom is sufficiently accurate compared to that planned in advance to the irradiation. However, there is no useful and convenient tool capable to confirm dose distributions in patients' bodies. Gel dosimeters have been expected to be a promising tool for such a validation because their densities, atomic compositions and mean excitation potentials are almost equivalent to those of human bodies as well as because radiation-induced chemical changes are fixed inside gel matrices (Baldock et al., 2010; McJury et al., 2000).

Gel dosimeters utilizing radiation-induced polymerization of vinyl monomers are called as “polymer gel dosimeters”. Most of them can be categorized into two types; PAG- and MAG-types. The PAG (polyacrylamide gel) type contains acrylamide or similar compounds as the vinyl-type monomers while the MAG (methacrylic acid gel) type does methacrylic acid and similar compounds. In 2001, ascorbic acid was introduced in polymer gel dosimeters as an oxygen scavenger, which realized “normoxic” polymer gel dosimeters (Fong et al., 2001). Another oxygen scavenger, tetrakis(hydroxymethyl)phosphonium chloride (THPC), was proposed in the next year (De Deene et al., 2002). The oxygen scavengers reduced complications in manufacture of polymer gel dosimeters and realized normoxic gel dosimeters such as nPAG and nMAG. It is known that sensitivities of most of proposed gel dosimeters have, more or less, dose rate dependences (Jirasek, 2006). Sensitivities of polymer gel dosimeters are, in most cases, evaluated as increase of R_2 value with unit dose, $R_2/D \text{ s}^{-1}\text{Gy}^{-1}$. Here R_2 is defined as the reciprocal value of the relaxation time T_2 in magnetic resonance measurements. De Deene and co-workers investigated on the sensitivities of PAG, nMAG, and nMAG dosimeters in the dose rate range from 0.25 to 4 Gy/min (De Deene et al., 2006). The sensitivities of the

dosimeters commonly decreased with increasing dose rate. The decreasing percentage in the dose rate range was 6% for PAG, 4% for nPAG, and 34% for nMAG. Thus, generally speaking, dose rate dependences of MAG-type dosimeters are rather significant compared to those of PAG-type dosimeters. Recently, Vandecasteele and co-workers examined dose rate dependences of radiochromic leucodye micelle hydrogel dosimeters, LMD1-3 and LCS (Vandecasteele et al., 2011). Although their gel dosimeters are different from polymer gel dosimeters of PAG- and MAG-types in terms of reaction mechanisms as well as of the way of dose determination, all of their dosimeters also showed dose rate dependences. Their sensitivities, which were evaluated based on the absorbances measured at around 587-636 nm, decreased with increasing dose rate from 0.5 to 4 Gy/min. The decreasing percentages of the sensitivities were 42% for LMD1, 24% for LMD2, 36% for LMD3 and 35% for LCS.

There are still a few points to be improved as follows. First, hydrogels of gelatin need appropriate temperature management because they can soften with increasing temperature and could release water during storage. Chemical gels, which have covalent bonding between matrix polymers, are more stable in terms of shape or conservation of solvent than physical gels, such as gelatin and agarose gels, which have only weak hydrogen bonding. It has already been shown that a cellulose derivative prepared with a radiation crosslinking technique (Tamada and Maekawa, 2010) can be utilized for polymer gel dosimeters (Hiroki et al., 2013). Second, spatial dose distributions are read out from irradiated gel dosimeters normally by using magnetic resonance apparatuses such as MRI or NMR. These apparatuses are huge and expensive. If chemical changes induced by ionizing radiations in gel dosimeters are visible and easily quantified, such dosimeters are more convenient. Some gels of cellulose derivatives prepared with a radiation crosslinking technique are much more transparent than gelatin or agarose gels, and it is quite easy to see radiation induced polymerizations inside the gel matrix (Hiroki et al., 2013). Third, vinyl-type monomers used in the polymer gel dosimeters are rather toxic. There are some attempts to use less toxic monomers (Hiroki et al., 2013; Senden et al., 2006), however, there is still a room to hope for much less toxic monomers.

In this study, it was aimed to observe radiation-induced change of optical properties of hydroxypropyl cellulose (HPC) hydrogels containing methacrylate compounds because such a chemical system is proposed as a new type of polymer gel dosimeter (Hiroki et al., 2013), which has a potential to reduce the abovementioned weaknesses. From the viewpoint of toxicity as well as of sensitivity toward irradiations, two methacrylate

compounds, 2-hydroxyethyl methacrylate (HEMA) and poly(ethylene glycol) dimethacrylate (9G), were selected as polymerizing monomers with irradiation. The present article will show dose response of white turbidity evolution by using optical measurements such as haze measurement and UV-Vis spectroscopy, and discuss composition dependence, dose rate effect, and mechanism leading to visual change.

2. Experimental

2.1. Chemicals

Hydroxypropyl cellulose (HPC), viscosity of which in 2 wt% aqueous solution at 20°C is in the range of 1000-5000 cP, and 2-hydroxyethyl methacrylate (HEMA) of Wako 1st Grade were purchased from Wako Pure Chemical Industries Ltd. Poly(ethylene glycol) dimethacrylate (9G) of 536 g/mol in averaged molecular weight and 80 wt% aqueous solution of tetrakis(hydroxymethyl)phosphonium chloride (THPC) were purchased from Shin-Nakamura Chemical Co., Ltd. and Tokyo Chemical Industry Co., Ltd., respectively. Chemical structures of HPC, HEMA and 9G are shown in **figure 1**. All chemicals were used without further purification, and polymerization inhibitor, hydroquinone monomethyl ether (MEHQ) in HEMA (250 ppm) and 9G (100 ppm), was not removed. Ultrapure water (> 18.3 MΩ cm) from a Milli-Q system was used throughout all the processes of both radiation crosslinking of HPC and manufacture of gel samples.

Figure 1 Chemical Structures of HPC, HEMA and 9G.

2.2. Manufacture of Gel Samples

In the present study, gels samples went through three steps: (i) manufacture, (ii) irradiation, and (iii) analysis. Note that ionizing radiations were used not only in the step (ii) but also in the step (i) in order to prepare chemically bonded gel matrices of HPC. An electron beam of 2.0 MeV was used in the step (i) while ^{60}Co γ -rays were used in the step (ii).

Powders of HPC were dispersed into ultrapure water at the concentration of 20% in weight and kneaded for at least 30 minutes, giving paste like state of HPC-water mixture. After 1-week storage at (4±1)°C in a refrigerator, the paste like mixture was pressed, with the pressure of approximately 18 MPa for 30 minutes, into a sheet of 1-mm thickness (150×150 mm²). The sheet was packed in a PE/nylon package after purging air,

and immediately irradiated with the electron beam at room temperature. The sheet was put on a conveyer system and irradiated with the current of 2.0 mA. The speed of the conveyer was set at 4.16 m/min, corresponding to the dose rate of 5 kGy per one-time passage through an irradiation field. All the sheets were repeatedly passed through the irradiation field 4 times, giving total dose of 20 kGy.

The irradiated sheet was stored in the refrigerator for 1 week to wait stabilization of radiation-induced crosslinking reactions. Subsequently, it was taken out from the package and cut into small pieces (20×30 mm²), and washed by dipping them into ultrapure water for 1 week or longer with refreshing water every day. The washed small pieces were dried in vacuum at 40°C for at least 1 day. The swelling ratio of radiation-crosslinked HPC was measured gravimetrically to be 16.6±0.3. In other words, the concentration of radiation-crosslinked HPC in a sufficiently swollen state is (5.7±0.1)% in weight. Such gel properties can be varied by controlling the HPC concentration at the paste like state as well as the dose of the electron beam irradiation. It is worth noting that the gel properties could be also one of the important factors affecting characteristics of gel dosimeters (Hiroki et al., 2013).

The dried pieces of radiation-crosslinked HPC were permeated into aqueous solutions of HEMA and 9G of three different compositions shown in **table 1**. After sufficient swelling of the dried pieces within a few days, an oxygen scavenger, THPC, was added into the solutions. The swollen pieces were taken out from the solutions for 12 hours following the addition of THPC, and immediately packed in PE/nylon packages with purging air. All the procedures were done in ambient conditions, however, any exposure to light or heat was avoided as much as possible.

Table 1 Compositions of the Aqueous Solutions into which the Dried Pieces of Radiation-Crosslinked HPC were Permeated.

Index	HEMA	9G	THPC
9G-rich	1.0	4.0	0.16
Even	2.5	2.5	0.16
HEMA-rich	4.0	1.0	0.16

Note that unit for all the values in the table is wt%.

As oxygen is an important factor affecting dose response of radiation polymerization, the following three provisions were applied. First, enough amount of oxygen scavenger, THPC, was added. Second, the gel samples packed in nylon/PE films were preserved in an Eval® (Kuraray Co., Ltd.) package, of which oxygen permeability is known to be very low. Third, free-oxygen-absorbing agent, Ageless® (Mitsubishi Gas Chemical Company, Inc.), was put in the Eval ® package together with the gel samples. These manufactured gel samples were stored in the refrigerator except during γ -irradiations and optical analyses.

2.3. Irradiation and Analysis of Irradiated Gel Samples

The gel samples manufactured with the abovementioned procedure were irradiated with ^{60}Co γ -rays at Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency (JAEA). Dose rate, which was measured with the Fricke dosimeter in advance, was varied from 0.015 to 1.5 Gy/min by controlling the distance between γ -source and the samples. Temperature deviations can also affect dose response of radiation polymerization, so temperature of the irradiation room was kept at $(18\pm1)^\circ\text{C}$.

The irradiated gel samples were kept in a refrigerator for 1 week. After that, the gels were taken out from the package and washed softly with ultrapure water before analyzed with a haze meter and a UV-Vis spectrometer. Haze is one of indicators for cloudiness and standardized by International Standard Organization (ISO 14782:1999), which is used as a standard for evaluation of transparency of plastic sheets. The haze value, H , is defined as follows:

$$H = I_d / I_t = I_d / (I_d + I_p) \quad (1)$$

where I_p , I_d , and I_t are the light intensities of parallel, diffractive, and total transmissions. The gels were put between two pieces of transparent PET film in order to stabilize shapes of the gels. The haze values of the gels were measured with a haze meter, NDH 5000 (Nippon Denshoku Industries Co., Ltd.). Consequently, the gels were cut into a smaller size ($10\times 30\text{ mm}^2$) to fit them to a standard rectangular quartz cell and their UV-Vis spectra were scanned with a SEC-2000 spectrometer system (ALS Co., Ltd.). These optical analyses were conducted at $(25\pm 3)^\circ\text{C}$.

3. Results and Discussion

3.1. Evolution of White Turbidity

Figure 2 Visual Change and Haze Increase of the γ -irradiated Gel Samples.

(a) a photograph of dose response at a fixed dose rate of 0.24 Gy/min, (b) haze increase with γ -irradiation, (■, ●): “9G-rich” and “HEMA-rich” gels irradiated with the γ -rays at a fixed dose rate of 0.24 Gy/min, respectively.

Figure 2 (a) shows a photograph of non- and γ -irradiated gel samples at a constant dose rate of 0.24 Gy/min. It is clearly seen that the gel samples of any composition lose their transparencies with the increase of dose. In other words, white turbidity appears with irradiation, which is due to radiation-induced polymerization of HEMA and 9G molecules. In the low dose region of 0-4 Gy, the white turbidity of the 9G-rich composition looks denser than that of the HEMA-rich one. However, as opposed to the low dose region, the white turbidity of the 9G-rich composition looks less dense than that of the HEMA-rich one in the high dose region of 4-32 Gy. Haze measurements were employed to quantify such subjective information, “white turbidity”, and its results are

shown in **figure 2 (b)**. There are three findings from the figure. First, the haze value of both of the 9G- and the HEMA-rich gels increases with increasing dose. Second, in the high dose region (> 4 Gy), the haze value of the HEMA-rich composition is higher than that of the 9G-rich one. Third, the haze value of the 9G-rich composition is higher than that of the HEMA-rich one in the low dose region (< 4 Gy).

Figure 3 Dose Rate Effect in terms of Visual Change and Haze

(a) a photograph of non- and γ -irradiated gels samples with a fixed dose of 4.0 Gy with different dose rate, (b) haze decrease with increasing dose rate, (■, ●): “9G-rich” and “HEMA-rich” gels, respectively.

Dose rate effect was also examined. **Figure 3 (a)** shows a photograph of non- and γ -irradiated gel samples after irradiated with a constant dose of 4.0 Gy but with different dose rates. White turbidity of the irradiated gels with a lower dose rate looks denser than that with a higher dose rate. However, such dose rate dependence becomes less significant in the 9G-rich composition than in the HEMA-rich one. The haze value of each gel was measured and shown in **figure 3 (b)**. As expected from the photograph, the haze value decreases with increasing dose rate, and haze increase with dose was less significant for the 9G-rich gel than the HEMA-rich one. These findings agree very well with what are seen from the photograph, suggesting that haze

can be a good index of white turbidity.

Thus, chemical dosimeters including gel dosimeters inherently show dose rate dependences in their dose response behaviors. In our case, upper limitation of dose rate to irradiate the gels with 4 Gy was 1.5 Gy/min because we need approximately a few minutes to move the ^{60}Co γ -source out from and back into its storage pool. So, the dose rate range in this study is slightly lower than those of earlier reports, typically 1-6 Gy/min. Focusing on the data of **figure 3 (b)** at dose rates of 0.24 and 1.5 Gy/min, the haze values of the 9G- and the HEMA-rich gels irradiated with dose rate of 1.5 Gy/min are 80% and 50% of those with dose rate of 0.24 Gy/min, respectively. Such a change is comparable to the change of sensitivity of nMAG, which decreases to 80% with increasing dose rate from 0.25 to 1 Gy/min (De Deene et al., 2006).

3.2. Mechanisms Leading to White Turbidity

Figure 4 UV-Vis Absorption Spectra of Non- and γ -irradiated Gel Samples.

The upper panel (a) shows UV-Vis spectra of the 9G-rich gels and the bottom panel (b) shows those of the HEMA-rich gels. (Solid, dashed, dotted, short-dashed, short dotted, and dash-dotted lines): non-irradiated, 1, 2, 4, 8, and 16 Gy. All of the γ -irradiations were conducted at a fixed dose rate of 0.24 Gy/min. Note that thickness of the gel samples were commonly 1.7 mm.

White turbidity is apparently originated from radiation-induced polymerization of methacrylate compounds at the C=C double bond, however, there is no conclusive explanation on what kind of phenomenon leads to white turbidity. As mentioned above, the haze measurement can provide a good index of white turbidity, however, white light is used to determine the haze value and no detailed information on reaction mechanisms can be extracted from the measurements. Then, UV-Vis spectroscopy was conducted to investigate origins of white turbidity. Generally, small particles scatter lights of short wavelengths, and larger scattering particles scatter lights of longer wavelengths. Maryanski and co-workers (Maryanski et al., 1996) investigated on size of precipitations in BANG gel by UV-Vis spectroscopy although gel type is different from that used in the present study. **Figure 4** shows spectral changes of the gel samples with (a) 9G-rich and (b) HEMA-rich compositions. Spectra of non-irradiated gels in the figure commonly have a peak in UV domain (at about 240 nm). Absorption of non-irradiated 9G-rich gel is slightly higher than non-irradiated HEMA-rich gel in the range between 200-240 nm, indicating slightly different absorptions of 9G and HEMA in this region. The spectral shapes of the irradiated the 9G-rich gels are almost constant while those of the HEMA-rich ones are apparently different at different doses. In the latter spectra, an absorption peak appears at the wavelength between 250 and 300 nm after irradiation of 4 Gy, which gradually shifts to longer wavelength and broadens with increasing dose.

The difference seen in the spectral changes with increasing dose indicates that there are at least two mechanisms leading to white turbidity although radiation-induced polymerization of the methacrylate compounds would commonly be the initial step of the mechanisms. Thus, it is deduced that small precipitations of comparable sizes composed mainly of 9G molecules would be produced with irradiation in the 9G-rich condition while the size of aggregation of polymerized HEMA molecules would exponentially grow with irradiation in the HEMA-rich condition.

3.3. Radiation-Induced Chemical Reactions

Radiation-induced chemical reactions of acrylate/methacrylate compounds have been well investigated but only in aqueous solutions not in hydrogels (Kozicki et al., 2002; Safrany et al., 1993; Safrany and Wojnarovits, 2003; Wojnarovits and Takacs, 1999). As to the earlier investigations, radiation-induced chemical reactions and their rate constants for acrylate/methacrylate compounds are similar because the major

reaction site is common. Briefly speaking, water is decomposed initially into an oxidative radical, the hydroxyl radical ($\cdot\text{OH}$), and a reductive radical, the hydrated electron (e_{aq}^-) (see for example, Buxton, 1987; Spinks and Woods, 1990). Both of the radicals react with acrylate compounds at near diffusion-controlled rates, leading to initiations of radiation-induced polymerization.

The reaction of $\cdot\text{OH}$ with acrylate/methacrylate compounds is an adduct onto the C=C double bond in the acrylate/methacrylate group, leading to production of α -carboxyalkyl type radicals (Kozicki et al., 2002; Safrany et al., 1993; Safrany and Wojnarovits, 2003; Wojnarovits and Takacs, 1999).

Here, X is hydrogen atom (acrylate) or methyl group (methacrylate), and Y is hydrogen atom or substituted group, which is 2-hydroxyethyl group for HEMA.

On the other hand, e_{aq}^- attaches on oxygen atom in the carbonyl group, and consequently hydrolysis or protonation follows, leading to neutral radicals.

The rate constant for the reductive reaction (Eq. 3) is in the magnitude of $10^{10} \text{ M}^{-1} \text{ s}^{-1}$ while that for the oxidative one (Eq. 2) is in the magnitude of $10^9 \text{ M}^{-1} \text{ s}^{-1}$. The concentrations of methacrylate group in HEMA and 9G used in this study are in the ranges of 77-307 and 37-149 mM, respectively, while those of $\cdot\text{OH}$ and e_{aq}^- can be estimated as **at highest 15 μM** with assuming their initial G values of 0.4-0.5 $\mu\text{mol/J}$ and dose of 30 Gy. Then, the initial reactions (Eqs. 2 and 3) can be regarded as pseudo-first-order reactions with the reaction rates given as the products of the reaction rate constants and concentrations of the methacrylate group. Time scales of the initiation reactions are estimated to be 10 ns or shorter based on the reaction rate of the pseudo-first-order reactions.

The produced acrylate/methacrylate radicals react with another monomer, and radiation-induced polymerization propagates. Except the protonated electron-attached acrylate radical, propagation reactions of the initially oxidized and reduced radicals are expected as follows:

Rate constants of such propagation reactions are reported to be in the range of 10^3 - $10^5 \text{ M}^{-1}\text{s}^{-1}$ (Wojnarovits and Takacs, 1999). These propagation reactions occur approximately in the time scale of 0.1-100 ms at the condition of the present study although the reactions become gradually slower with consumption of methacrylate monomers and perhaps with increasing number of polymerized methacrylate monomers. After certain duration of the propagation, oligomer or polymer radicals go through termination reactions such as dimerization or disproportionation. An overall reaction rate constant of these second-order reactions was reported from the viewpoint of a decay of the acrylate/methacrylate radicals by a pulse radiolysis experiment (Wojnarovits and Takacs, 1999). The apparent rate constants for monomer and oligomer radicals were reported in the ranges of 10^8 - 10^9 and 10^7 - $10^8 \text{ M}^{-1}\text{s}^{-1}$, respectively. Thus, the propagation and the termination compete with each other, leading probably to dose rate effects seen in the present work.

3.4. Effects of Polymerization Inhibitors

If dissolved oxygen exists, peroxidation followed by elimination of $\text{HO}_2^\cdot/\text{O}_2^{\cdot-}$ can also be one of termination reactions instead of the dimerization or disproportionation reactions. A typical value of the rate constant of peroxidation ranges in 10^9 - $10^{10} \text{ M}^{-1}\text{s}^{-1}$, so significance of this pathway depends on how much oxygen remains in the chemical system. For example, a time scale of peroxidation reaction at an aerated condition is expected to be 0.4-4 μs because the concentration of dissolved oxygen at the condition is 0.25 mM. It was attempted to see difference between the gels irradiated immediately and 1 week after their manufactures, showing that obviously white turbidity appearing in the latter gels was much less dense than the former. It is

1 known that oxygen gas can gradually passes through PE/nylon, of which film was used to pack the gels in this
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7 It is worth to note that the concentration of the polymerization inhibitor MEHQ in the gels used in the
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9 present study is in a range of 5-12.5 ppm, i.e. 40-101 nM, and such low concentration of MEHQ can be effective
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11 in the time scale of 1 μ s at earliest. Of course, the inhibitor might reduce sensitivity of radiation-induced
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13 polymerization to irradiation. However, assuming that MEHQ is consumed with G value of 0.5 μ mol/J, it would
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15 diminish within dose of 0.2 Gy. In addition, removal of MEHQ leads to very low stability of the
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17 acrylate/methacrylate compounds during manufacture and storage of the gel samples.
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4. Conclusion

Radiation-induced visual changes of HPC hydrogels containing methacrylate compounds were observed. The gels become white with ^{60}Co γ -irradiation and the white turbidity was easily observable directly by our eyes even with 1 or 2 Gy thanks to the high transparency of the gel matrix. Thus, the gels used in the present study could be a candidate of a new type of radiation dosimeter utilized in radiation therapy because the gels become white with irradiation and can be confirmed directly by human eyes even at low doses of 1-2 Gy. It was attempted to quantify the visual change by haze measurement. The measured haze value agreed very well with the degree of white turbidity, showing that haze can be an index of white turbidity.

The dose response of the haze value was dependent on composition of methacrylate compounds as well as on dose rate. Sensitivity in terms of the haze increase with irradiation was higher for the 9G-rich composition than HEMA-rich one in the low dose region ($< 4\text{Gy}$) while the opposite tendency was shown in the high dose region ($> 4\text{Gy}$). Dose rate effect was seen in both of the HEMA- and 9G-rich gels although it was less significant in the 9G-rich gels, suggesting that the former composition is more suitable for practical use.

UV-Vis spectroscopy showed that spectral shape of the HEMA-rich gel changes with increasing dose and showed a red shift together with broadening, indicating the increase of the sized of aggregates composed of polymerized HEMA molecules. On the other hand, there was no obvious spectral change in the 9G-rich gels. Thus, the increase of haze or absorbance of the 9G-rich gels with irradiation are thought to be due to accumulation of small precipitations of comparable size composed of polymerized 9G molecules.

It is also important to know how gel properties such as swelling ratio and HPC/water composition affect the dose response of the gel samples used in the present study. Such properties can be varied by controlling the condition of the preliminary radiation-crosslinking treatment. In addition, radiation chemistry inside gel matrix is not well known yet, and to scrutinize on fundamental reactions is necessary in development of any type of gel dosimeters.

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