How Does the Chemistry of Polymer Gel Dosimeters Affect their Performance?

A. Jirasek*, K. B. McAuley** and M. Lepage***

*Department of Physics and Astronomy, University of Victoria, Victoria BC Canada V8W 3P6

**Department of Chemical Engineering, Queen’s University, Kingston ON Canada K7L 3N6

***Centre d’imagerie moléculaire de Sherbrooke, Université de Sherbrooke, 3001 12e Avenue Nord, Sherbrooke QC Canada J1H 5N4

jirasek@uvic.ca, kim.mcauley@chee.queensu.ca, martin.lepage@usherbrooke.ca

Abstract. This review article describes the primary chemical processes affecting polymerization in polymer-based radiosensitive gel dosimeters. Furthermore, recently studied environmental factors and gelation processes affecting polymerization and gel dose response are discussed. Finally, the predominant physical factors affecting dose-response sensitivity for each of the three imaging modalities (MRI, Optical CT, x-ray CT) are outlined. Emphasis is concentrated on recent literature in this area, as prior literature was summarized in review articles submitted to DOSGEL 2006 in Sherbrooke (J. Conf. Series, 56, 2006). Discussions from the recent DOSGEL conference (2008) are incorporated into this review.

1. Introduction

This review describes the chemistry of polymer gel dosimeters that use free radical polymerization as the means to capture and store 3-D radiation dose information (e.g., MAG [1], PAG [2], NIPAM [3], and VIPAR [4] dosimeters). Dosimeters that rely on other types of chemical reactions (e.g., Fricke gel [5] and PRESAGE [6] dosimeters) are not included. Review articles from DOSGEL 2006 [7] summarize relevant information prior to 2006, so the focus of the current article is on the most recent literature, including some new results presented at DOSGEL 2008. We begin with some recent insights into the influence of polymerization mechanisms on dose response behavior, followed by a description of new polymer gel dosimeter recipes and additives. The influence of environmental factors on dosimeter response is described, especially the importance of temperature history during gel manufacture. Recent knowledge about the influence of oxygen and other impurities on dosimeter response is also described, along with the influence of THPC (tetrakis hydroxymethylphosphonium chloride) and gelatin. Finally, we discuss the physical phenomena that influence dose-response measurements using three read-out modalities: MRI, optical CT and x-ray CT, and we conclude that different gel recipes are suitable for different modalities.
2. Polymerization Chemistry and Dose-Rate Dependence

Table 1 summarizes the basic chemical reactions that occur in impurity-free polymer gel dosimeters [8-10]. In reaction a), several different types of free radicals are generated by radiolysis of water. These free radicals can react with the vinyl group (carbon-carbon double bond) on monomer molecules. Successive propagation reactions (reaction b) result in the formation of polymer and the release of heat. Many dosimeters (e.g., PAG, NIPAM and VIPAR) contain N,N’-methylene bisacrylamide (Bis), which has two vinyl groups. Reaction c) shows propagation with one of the vinyl groups on a Bis molecule, leaving the remaining vinyl group available for a subsequent reaction. The second vinyl group can be consumed by cyclization (reaction d) or crosslinking (reaction e). Crosslinking is important in PAG, NIPAM and VIPAR dosimeters because crosslinked polymer chains are insoluble in water, and they precipitate to form microgels [11] that influence the NMR, optical and x-ray properties of the gel. PAG dosimeters that have high concentrations of Bis (up to its solubility limit) tend to have higher dose sensitivities than dosimeters with lower crosslinker levels [12, 13]. All current polymer gel dosimeter recipes use Bis [3] as a crosslinker, except for MAG dosimeters [1] and a new fluorescent dosimeter described in Section 3 below [14]. MAG dosimeter recipes are usually crosslinker-free because polymethacrylic acid precipitates to form insoluble particles even when no crosslinker is present. As a result, reactions c), d) and e) are not important in MAG dosimeters. De Deene et al. [15] manufactured and irradiated MAG dosimeters in which a portion of the methacrylic acid monomer was replaced by Bis to determine whether the addition of crosslinker could enhance the dose sensitivity. They determined that the transverse relaxation rate ($R_2$) dose sensitivity decreased with increasing Bis concentration, presumably because crosslinking is not required to induce precipitation and Bis is less reactive than methacrylic acid so that less polymer formed per Gy of absorbed radiation.

Table 1. Cartoon showing free radical polymerization mechanism in polymer gel dosimeters.

| a) Generation of primary radicals by radiolysis | $H_2O + \text{Radiation} \rightarrow H_2, H_2O_2, e_{aq}^-, H^+, OH^+$ |
| b) Propagation with monomer | $\bullet \quad + \quad \rightarrow \quad \bullet$ |
| c) Propagation with crosslinker | $\bullet \quad + \quad \rightarrow \quad \bullet$ |
| d) Primary cyclization | $\bullet \quad \rightarrow \quad \bullet$ |
| e) Crosslinking | $\bullet \quad + \quad \rightarrow \quad \bullet$ |
| f) Chain transfer to monomer | $\bullet \quad + \quad \rightarrow \quad \bullet$ |
| g) Termination | $\bullet + \bullet \rightarrow \bullet + \bullet$ |
| h) Chain transfer to gelatin | $\bullet + G \rightarrow \bullet + G$ |
| i) Propagation of gelatin-centred radicals | $G\bullet + \rightarrow G\bullet$ |
| j) Termination with primary radicals | $\bullet + OH\bullet \rightarrow \bullet$ |
2.1. Dominant Chain-Stopping Mechanisms and their Influence on Dose Integration

De Deene et al. [16] and Karlsson et al. [19] observed that the dose response of MAG dosimeters depends on the dose rate. MAG dosimeters have significantly lower dose sensitivities when the radiation dose is delivered over a short period of time than when the same total dose is delivered over a longer period of time. In PAG and NIPAM dosimeters, however, the dose response is much less dose-rate dependent [3,15,18]. The reaction mechanism in Table 1 can explain this difference in dose-rate behaviour, and also the influence of gelatin on the dose sensitivity of PAG dosimeters [8].

In all polymer gel dosimeters, each polymer chain continues to grow via propagation and crosslinking reactions b), c) and e) until the radical is consumed via a chain-transfer reaction (e.g., reaction f) or by a bimolecular termination reaction (e.g. reaction f). Note that the radicals on crosslinked polymer molecules can react with pendant vinyl groups on other polymer molecules to form very large crosslinked molecules within the precipitated microgel particles. Chain-transfer reactions consume one radical and generate another; termination reactions consume two radicals. Reaction g) shows a termination reaction between two growing polymeric radicals, but any two radicals that encounter each other can readily terminate. For example, termination between polymeric radicals and primary radicals generated by reaction a) also occurs (j). Reaction h) shows a chain-transfer reaction in which a growing polymeric radical abstracts a proton from a strand of gelatin, creating a dead polymer chain and a free radical on the gelatin. This gelatin radical can either terminate with another radical, or it can react with monomer (reaction i) or crosslinker to initiate further propagation. If reaction i) is slow because the gelatin radicals are relatively stable compared to polymeric radicals then many gelatin radicals terminate rather than propagate, thereby reducing the polymerization rate. Fuxman et al. [8,9] successfully used reactions h) and i) to explain the decrease in dose sensitivity with increasing gelatin levels that has been observed experimentally in PAG dosimeters (Figure 1) [15,16]. This mechanism can also explain [10] the high sensitivity to dose rate of MAG dosimeters and the low sensitivity to dose-rate observed in PAG [15,18] and NIPAM [3].

Figure 1: Dependence of the transverse relaxation rate ($R_2$) on the absorbed dose for anoxic polymer gel dosimeters with a fixed content of acrylamide (AA) and N,N'-methylenebisacrylamide (BIS) and a varying gelatin content. The initial slope is large and, the initial value of $R_2$ is lower for lower gelatin concentration. Data from [39].
dosimeters. Since polymeric radicals may react with gelatin, then it is also plausible that water free radicals may also react with gelatin, leaving fewer radicals to initiate polymerization.

In dosimeters like MAG and the new fluorescent dosimeter [14] where the dominant chain-stopping mechanism is termination between two radicals (e.g., reaction g), the concentration of the radicals in the solution has a large influence on average amount of polymer that forms. When radicals are generated quickly, the overall radical concentration is high and the termination rate is very high because the rate of termination is proportional to the square of the radical concentration. When the same number of radicals is generated over a longer time period, the radical concentration remains low and the termination rate is low, so that more polymer is generated per radical.

In PAG and NIPAM dosimeters, where gelatin radicals react very slowly with the monomer, the dominant chain-stopping mechanism is reaction h) rather than reaction g). Since reaction h) involves only a single radical, the rate of chain death is proportional to the radical concentration. Since the rates of propagation and chain-stopping reactions are both first-order in the radical concentration, the average amount of polymer generated by each radical is nearly independent of the radical concentration. As a result, there is little influence of dose rate on the total amount of polymer formed, making PAG and NIPAM dosimeters better integrating dosimeters than MAG.

2.2. The Influence of Gelatin on Dose Sensitivity

One peculiarity of MAG dosimeters that is not explained by the mechanism in Table 1 is that the dose sensitivity of these dosimeters increases rather than decreases with the amount of gelatin used in the recipe [15]. If reactions h) and i) are not important in MAG dosimeters, because either h) does not occur appreciably or because reaction i) is fast, then it is straightforward to predict that gelatin should have little or no effect on the rate of polymerization. However, it is not possible to predict an increase in the amount of polymer formed with increasing gelatin concentration from the reaction mechanism in Table 1. At DOSGEL 2006, McAuley [10] suggested that the gelatin might be causing changes in the properties of the aqueous solution, thereby helping more polymethacrylic acid to precipitate from solution when more gelatin is present. Her suggestion was based on previous studies [19-21], which showed that uncrosslinked polymethacrylic acid is sometimes soluble and sometimes insoluble in aqueous solutions, depending on the pH, ionic strength and temperature of the solution, and that solution properties also influence the molecular weight of the polymer. Gelatin could be influencing the size and number of polymethacrylic acid particles that precipitate, thereby influencing the dose sensitivity. Since DOSGEL 2006, it has become clear that this explanation is not sufficient to explain the influence of gelatin on dose sensitivity in MAG dosimeters. Recently, Hayashi et al. [22] used temperature probes in MAG dosimeters to monitor the rise in temperature associated with the heat released by the propagation reactions [23]. They showed that when no gelatin is present, there is no temperature rise and hence no appreciable polymerization. They also showed that there is an increase in the temperature rise per unit radiation dose when the amount of gelatin in the recipe increases. These experiments show definitively that gelatin influences the rate of polymerization rather than just the relative amounts of polymer that stay in solution and that precipitate.

Thorough examination of the free-radical polymerization literature shows that similar “trigger” phenomena have been observed previously in the polymerization of methacrylic acid and also acrylic acid in aqueous solutions. In 1968, Bamford and Shiiki [24] studied the free-radical polymerization of acrylic acid in the presence (and absence) of polyethyleneimine at 25 °C. When no polyethyleneimine was dissolved in the solution, the rate of polymerization was effectively zero. However, substantial polyacrylic acid formation was observed when polyethyleneimine was present in solution. The polymerization rate increased with increasing concentrations of polyethyleneimine until the molar concentration of base groups from the polyethyleneimine was approximately equal to the acrylic acid concentration in the solution. Bamford and Shiiki suggested that the polyethyleneimine acts as a “template” that complexes with the acrylic acid molecules, enabling their polymerization at a temperature where polymerization would not occur without the template. A review [25] of more-recent literature reveals that acrylic acid and methacrylic acid undergo template polymerization in the
presence of several different water-soluble polymers containing basic groups, including poly(vinyl pyrrolidone) and poly(4-vinyl pyridine). The template polymerization of methacrylic acid using gelatin has not been previously reported in the literature, but the observations of DeDeene et al. [15] and Hayashi et al. [22] are consistent with this type of mechanism.

We already mentioned that OH• radicals can interact with the growing polymer chain and can cause termination of the polymerization reaction. The polymer formed by methacrylic acid monomers in MAG is more water-soluble than polymer containing Bis in PAG. Experiments also reveal more polymer is formed per unit dose from methacrylic acid, which suggests the methacryllic acid polymer radical is more reactive than its acrylamide polymer radical counterpart. This is consistent with the observation of a higher temperature increase in MAG dosimeters than in PAG dosimeters for an equivalent initial concentration of monomers and for the same irradiation dose. As a consequence, the methacrylic acid polymer radicals are more likely to react with additional OH• radicals. When adding gelatin, the number of OH• radicals becomes smaller, thus decreasing the termination of polymerization of methacrylic acid polymer radicals. This mechanism could also explain the dose-rate dependence of MAG and the observation that little or no MAG polymer is formed in the absence of gelatin. Clearly, more work is required to determine the mechanism by which gelatin affects the dose dependence in PAG and MAG dosimeters.

3. New Dosimeter Recipes
One new type of polymer gel dosimeter [14] was reported at DOSGEL 2008, and several new dosimeter additives, such as formaldehyde, have been studied since DOSGEL 2008 [27]. The new dosimeter [14] uses methylmethacrylate as the main monomer and small quantities of a fluorogenic probe species as a comonomer. When the comonomer molecule is incorporated into a polymer change, it changes from being very weakly fluorescent to highly fluorescent, so that the dose distribution can be determined using fluorometric dose imaging. This dosimeter, which does not include water, is not tissue-equivalent. A more serious issue is that this dosimeter is highly dose-rate dependent because the free radicals terminate solely via biomolecular termination.

A new dosimeter additive that has been reported is formaldehyde, which is used to increase the melting temperature and gel strength of MAG gels [26]. This additive also increases the dose sensitivity, but the mechanism for this sensitivity increase is not known.

Co-solvents are another type of additive that has been investigated for improving the effectiveness of gels that use Bis as a crosslinker [27]. Glycerol and isopropanol are two co-solvents that can be added to dosimeter recipes so that higher levels of Bis can be dissolved, leading to increased dose sensitivity due to increased crosslink density in the polymer. The motivation for trying to increase the dose sensitivity is so that new recipes can be developed that are suitable for x-ray CT readout.

4. Environmental Factors
A number of environmental factors during polymer gel manufacture affect the resultant dose response of the gels.

4.1. Temperature
DeDeene et al [28] reported on the effects of temperature history on polymer gel manufacture. They manufactured a series of gels and allowed them to cool under a range of conditions, including gels cooled in a fridge (with and without a water bath) and gels cooled under ambient conditions (see figure 2a). Figure 2b illustrates the cooling rate and time required to reach thermal equilibrium for the three different classes of gel cooling. Figure 3 illustrates the resulting variation in polymer gel response for nPAG, nMAG, and VIPAR gels. As can be seen, nPAG gels are less susceptible (7% variation at 10 Gy) to rates of gel cooling during the solidification process than are nMAG gels (67% at 10 Gy).
Polymer gel cooling rates are affected not only by their surrounding atmosphere, as demonstrated above, but also by the size of the gel. Figure 4 illustrates the variations in cooling rate within different regions of the gel for large (4L) gel volumes. The effect is observable irrespective of the presence of a water bath, although in this case the effect is mitigated. The discontinuity present in the cooling rate is due to the phase transition of the gel, hence affecting the rate of flow of convection currents. From figure 4 it can be seen that care must be taken in cooling large volumes of gel, with attempts made to minimize any differences in cooling rate in different regions of the gel volume.

DeDeene et al. [28] further investigated the effects of cooling rate on the accuracy of polymer gel dosimetry. They used a simple irradiation (depth dose) to compare ion chamber and gel measurements. Using 4 batches of gel they were able to establish absolute errors associated with gel measurements of the depth dose. Figure 4 illustrates the results and indicates that a maximum average dose difference of 0.5 Gy exists between gel and ion chamber measurements. Results indicate that, despite the given uncertainty in gel response due to different manufacture cooling rates, accurate dosimetry can still be performed under controlled conditions.
Figure 4: Cooling rates as a function of position within the gel volume of large (4L) volumes of gel. Gels cooled in fridge (a) without and (b) with water bath [28].

Figure 5: (a) Depth dose cure measured using 4 batches of polymer gel and an ion chamber. (b) Dose difference between gel and ion chamber measurements for the curves in (a) [28].

5. Impurities in the Manufacture Process
The purity of the constituents used in polymer gel manufacture can affect, for example, the rate of oxygen scavenging when an antioxidant is used to de-oxidize the gel [30]. A simple example is illustrated in figure 6. The rate of oxygen scavenging in tap water is significantly slower than the scavenging rate in deionized and purified water (figure 6a), illustrating the advantage of using deionized water in the manufacture process. Even with deionized water, the total time to scavenge oxygen in polymer gel is non-negligible, as is illustrated in figure 6b. With optimized scavenger concentrations (4.65 mM [30]), scavenging time is on the order of 1 hr. Hence, it can be recommended that polymer gels are not irradiated prior to this wait time.
6. Effects of THPC Concentration on Polymer Gel Dose Response

The concentration of THPC present within a polymer gel not only affects the oxygen scavenging rate, as seen above, but also the dose-response of the gel. Figure 7 illustrates the effects of THPC concentration on polymer gel dose response. Clearly, too low a THPC concentration will result in not all oxygen being scavenged from the gel and the resultant dose-response will be either flat (unreactive gel) or will exhibit a threshold effect, where gel response is observed only after a certain dose. At a given THPC concentration (4.65 mM) the threshold effect will disappear and maximal polymer gel dose-response will be observed. Above this concentration, however, gel dose-response appears to weaken, likely due to the additional reaction of THPC with gelatin, causing increased gel crosslinking.

Figure 7: Effect of THPC concentration on nPAG polymer gel dose response [30].

7. Effect of temperature on gelation

Gelatin is composed from small chains of amino acids extracted from natural sources such as the porcine skin. The physics and chemistry of gelation is a field of research in itself and the reader is referred to this literature for further details [31-36]. Here, we only provide the general concepts and their impact on the performance of the dosimeter. Gelatin chains are water soluble such that they dissolve readily in water heated to ~ > 35°C. Upon cooling, the chains form coils and undergo a helix
transformation by association of three different chains. This process is not instantaneous but proceeds over a time scale of several hours. A three-dimensional network is obtained, which will subsequently prevent the diffusion of polymer formed upon irradiation. For magnetic resonance experiments, gelatin serves another role; it determines the initial transverse relaxation rate ($R_2$) value of the system ($R_{2,0}$), and therefore the range of $R_2$ values of the dosimeter from the unirradiated to the fully polymerized state. The lower the gelatin concentration, the lower $R_{2,0}$ and the larger the range of $R_2$ values. Continued gelation implies that the value of $R_{2,0}$ will change as a function of time. As described in Section 2, the rate of polymer formation depends on the amount of gelatin in the recipe, but it is not clear whether the morphology of the gelatin network also influences the polymerization rate. An additional consideration is the temperature history of gelatin. In fact, it was observed in 2000 that the strength of the gelatin network decreases with an increase in the temperature of the gelatin solution [37], which was corroborated by measurements of the elastic modulus of this material [38]. The value of $R_{2,0}$ is correlated with the rigidity of the gelatin network so the reproducibility of polymer gel dosimeters requires a fine control on the manufacturing process.

8. Physical factors affecting dose response

The quantity of polymer formed for a given absorbed dose and the number and size of the precipitated polymer particles depends on the type of monomers and on the rate of polymerization of each formulation (i.e., how much polymer is formed for a given dose). The polymer that forms must cause a detectable change in the properties that can be probed by an imaging modality.

8.1. MRI

In the case of MRI, the polymer must affect at least one of the relaxation rates (i.e., the longitudinal, $R_1$, or the transverse, $R_2$, relaxation rate), the diffusion of water molecules or the magnetization transfer between the polymer protons and the water protons (for a review, see [40]). Briefly, three main factors must be considered. First, the rigidity and the immobilization of protons on the polymer will increase the relaxation rate of neighboring water molecules either by dipolar relaxation or by chemical exchange. The latter effect will be modulated by the chemical composition of the polymer (and indirectly of its constituent monomers) as well as the solubility of the polymer.

8.2. Optical CT

Optical CT relies on absorption and scattering of light due to interaction with the precipitated polymer particles [41]. When a large number of particles is present in the gel, multiple scattering can make gel readout difficult. As a result, a recent cone-beam optical CT study [42] with a NIPAM-based dosimeter used a lower total monomer concentrations than is typical in for recipes for MRI readout (4%T rather than 6%T). The resulting reduction in the amount of polymer lowered the sensitivity into the linear performance range of the scanner and improved the accuracy of the dosimetry. The optical clarity of the gel solution before irradiation is very important when using optical CT, as is background optical density drift, which can occur over time due to impurities [43]. There are opportunities to optimize gel recipes and manufacturing procedures to improve initial and background clarity.

8.3. X-ray CT

When imaging with x-ray CT, gel composition is by far the largest single contributor in determining polymer gel dose response. As can be seen from figure 8a, polymer gel dose response varies considerably when changing gel composition from anoxic PAG to normoxic PAG and normoxic NIPAM polymer gel. The reduced dose response of normoxic gel formulations is disadvantageous for x-ray CT polymer gel dosimetry, which is typically hindered by a low dose resolution. Hence, recent efforts have been concentrated on improving dose sensitivity when imaged with x-ray CT. One line of attack in this regard is increasing the crosslinker concentration within the gel via a co-solvent capable of increasing the solubility of the bisacrylamide crosslinker (~3% solubility in water) within polymer gel. One co-solvent that shows promise is isopropanol. Figure 8b illustrates polymer gel dose
response, measured using x-ray CT, when gels are manufactured using 10% T 50 %C NIPAM-based dosimeters varying co-solvent concentrations [44]. The use of co-solvents in polymer gel dosimetry remains an open area of research.

Environmental factors, such as temperature of polymer gel during irradiation or x-ray CT imaging, have shown to have negligible effect on resultant gel dose response. This fact adds to the general ease of use of the technique, as these factors are not of utmost importance when performing x-ray CT polymer gel dosimetry [45]. Furthermore, imaging parameters such as tube current, voltage, slice thickness etc also have a negligible affect on the resulting polymer gel dose response sensitivity. However, they will affect the dose resolution of the resulting measurements in that these parameters all affect the noise within the CT images. Hence, recommendations have been made on using these parameters to minimize the noise in CT images of irradiated polymer gel [45].

---

**Figure 8:** (a) Polymer gel dose response measured with x-ray CT imaging for (i) anoxic PAG, (ii) normoxic PAG, and (iii) normoxic NIPAM polymer gel. (b) Gel dose response for gels manufactured with 10% total monomer / crosslinker concentration and varying concentrations of isopropynol co-solvent. Anoxic PAG dose response shown for comparative purposes. (b) Taken from) [44].

9. **Is there a one-size-fits-all polymer gel dosimeter recipe?**

The answer is no because storing and reading out dose is not strictly a polymer chemistry issue. It has been shown that different gel formulations can have a better dose resolution within a specified dose range but can have a worse dose resolution within a different dose range [46]. Moreover, the appropriate recipe also depends on the type of detection system (MRI, optical CT, x-ray CT) and on the details of the image acquisition protocol for each system. Clearly, an appropriate recipe must be selected that matches the type of dosimetry needed (i.e., the range of doses, the dose rate, etc.), the precision required and the stability of the dosimeter.

10. **Acknowledgments**

M.L. acknowledges support from the Canada Research Chair program and from the Natural Sciences and Engineering Research Council of Canada (NSERC). M.L. is a member of the FRSQ-funded Centre de Recherche Clinique Étienne-Le Bel.

K.M. acknowledges support from the Canada Institutes for Health Research (CIHR) and from NSERC.

A.J. acknowledges support from NSERC, the Canadian Foundation for Innovation (CFI) and the British Columbia Knowledge Development Fund (BCKDF).
References

[1] Fong P M, Keil D C, Does M D, Gore J C 2001 Polymer gels for magnetic resonance imaging of radiation dose distributions at normal room atmosphere Phys. Med. Biol. 46 3105-13

[2] Maryanski M J, Gore J C, Kennan R P, Schulz R J 1993 NMR Relaxation enhancement in gels polymerized and cross-linked by ionizing radaiton: a new approach to 3D dosimetry by MRI Magn. Res. Imaging 11 253-8

[3] Senden R J, De Jean P, McAuley K B, Schreiner L J 2006 Polymer gel dosimeters with reduced toxicity: a preliminary investigation of the NMR and optical dose response using different monomers Phys. Med. Biol. 51 3301-14

[4] Pappas E, Maris T, Angelopoulou A, Paparigopoulou M, Sakelliou L, Saidilos P, Voyiatzi L, Vlachos L 1999 A new polymer gel for magnetic resonance imaging (MRI) radiation dosimetry Phys. Med. Biol. 44 2677–84

[5] Gore J C, Kang Y S, Schulz R J 1984 Measurement of radiation-dose distributions by Nuclear Magnetic-Resonance (NMR) Imaging Phys. Med. Biol. 29 1189-97

[6] Adamovics J, Maryanski M J 2006 Characterisation of PRESAGE™: A new 3-D radiochromic solid polymer dosemeter for ionising radiation Radiation Protection Dosimetry 120 107-12

[7] DOSGEL 2006 J. Phys. Conf. Ser., 56

[8] Fuxman A M, McAuley K B, Schreiner L J 2003 Modeling of free-radical crosslinking copolymerization of acrylamide and N,N_-methylenebis(acrylamide) for radiation dosimetry Macromol. Theory Simul. 12 647–62

[9] McAuley K B 2004 The chemistry and physics of polyacrylamide gel dosimeters: why they do and don’t work J. Phys.: Conf. Ser. 3 29-33

[10] McAuley K B 2006 Fundamentals of polymer gel dosimeters J. Phys.: Conf. Ser. 56 35-44

[11] Durmaz S, Okay O 2000 Phase separation during the formation of poly(acrylamide) hydrogels Polymer 41 5729–35

[12] Maryanski M, Audet C, Gore J C 1997 Effects of crosslinking and temperature on the dose response of a BANG polymer gel dosimeter Phys. Med. Biol. 42 303-11

[13] Babic S, Schreiner L J 2006 An NMR relaxometry and gravimetric study of gelatin-free aqueous polycrylamide dosimeters, Phys. Med. Biol. 51 4171–87

[14] Warman J M, Luthjens L H, de Haas M P 2008 In-situ radiation dosimetry based on radio-fluorogenic copolymerization, proc. DOSGEL 2008, 303-7

[15] De Deene Y, Vergote K, Claey s C, De Wagner C 2006 The fundamental radiation properties of normoxic polymer gel dosimeters : a comparison between a methacrylic acid based gel and acrylamide based gels Phys. Med. Biol. 51 653-73

[16] Lepage M, Whittaker A K, Rintoul L, Back S A J, Baldock C 2001 The relationship between radiation-induced chemical processes and transverse relaxation times in polymer gel dosimeters Phys. Med. Biol. 46 1061-74

[17] Fuxman A M, McAuley K B and Schreiner L J 2005 Modelling of polycrylamide gel dosimeters with spatially non-uniform radiation dose distributions Chem. Eng. Sci. 60 1277–93

[18] Karlsson A, Gustavsson H, Månsson S, McAuley K B, Bäck S A J 2007 Dose integration characteristics in normoxic polymer gel dosimetry investigated using sequential beam irradiation Phys Med. Biol. 52 4697-706

[19] Katchalsky A, Blauer G 1951 Kinetics of methacrylic acid polymerization in aqueous solution Trans. Faraday Society 47 1360-70

[20] Eliassaf J, Silberberg A, Katchalsky A 1955 Negative Thixotropy of Aqueous Solutions of Polymethacrylic Acid Nature 4493 1119

[21] Moussaid A, Schosseler F, Munch J P, Candau S J 1993 Structure of polyacrylic acid and polymethacrylic acid solutions: a small angle neutron scattering study J. Phys. II France 3
[22] Hayashi S-I, Munenori Y, Usui S, Haneda K, Takahiro T 2008 The role of gelatin in a methacrylic acid based dosimeter, Proc. DOSGEL 2008, 5th International Conference on Radiotherapy Gel Dosimetry 94-96

[23] Salomons G J, Park Y S, McAuley K B, Schreiner L J 2002 Temperature increases associated with polymerization of irradiated PAG dosimeters Phys. Med. Biol. 47 1435–1448

[24] Bamford CH and Shiiki Z 1968 Free-radical template polymerization Polymer 9 595-8

[25] Polowinski S 2002 Template polymerisation and co-polymerisation Prog. Polym. Sci. 27 537-77

[26] Fernandes J P, Pastorello B F, de Aurojo D B, Baffa O 2008 Formaldehyde increases MAGIC dosimeter melting point and sensitivity Phys. Med. Biol. 53 N53-N58

[27] Koeva V I, Csaszar E S, Senden R J, McAuley K B and Schreiner L J 2008 Polymer gel dosimeters with increased solubility: a preliminary investigation of the NMR and optical dose-response using different crosslinkers and co-solvents Macromol. Symp. 261 157-66

[28] De Deene Y, Pitomvils G, Visalatchi S 2007 The influence of cooling rate on the accuracy of normoxic polymer gel dosimeters. Phys. Med. Biol. 52 2719–28

[29] Papadakis E, Maris T G, Zacharopoulou F, Pappas E, Zacharakis G, Damilakis J 2007 An evaluation of the dosimetric performance characteristics of n-vinylpyrrolidone-based polymer gels Phys. Med. Biol. 52 5069–83

[30] Jirasek A, Hils M, Shaw C, Baxter P 2006 Investigation of tetrakis hydroxymethyl phosphonium chloride as an antioxidant for use in x-ray computed tomography polyacrylamide gel dosimetry Phys. Med. Biol. 51 1891

[31] Djabourov M, Leblond J, Papon P 1988 Gelation of aqueous gelatin solutions. I. structural investigation J. Phys. France 49 319-32

[32] Djabourov M, Leblond J 1987 Thermally reversible gelation of the gelatin-water system Am. Chem. Soc. Symp. Ser. 350 211-23

[33] Maquet J, Théveneau H, Djabourov M, Leblond J, Papon P 1986 State of water in gelatin solutions and gels: An 1H NMR investigation Polymer 27 1103-10

[34] Djabourov M, Maquet J, Theveneau H, Leblond J, Papon P 1985 Kinetics of gelation of aqueous gelatin solutions Br. Polym. J. 17 169-74

[35] Rees D A 1969 Structure, conformation, and mechanism in the formation of polysaccharide gels and networks Adv. Carbohydrate Chem. Biochem. 24 267-332

[36] Eagland D, Pilling G, Wheeler R G 1975 Studies of the collagen fold formation and gelation in solutions of a monodisperse alpha gelatin Discuss. Faraday Soc. 57 181-200

[37] De Deene Y, Hanselaer P, de Wagter C, Achten E, De Neve W 2000 An investigation of the chemical stability of a monomer/polymer gel dosimeter Phys. Med. Biol. 45 859-78

[38] Normand V, Muller S, Ravey J, Parker A 2000 Gelation kinetics of gelatin: A master curve and network modeling. Macromolecules 33 1063-71

[39] Lepage M, Whittaker A K, Rintoul L, Bäck S Å J, Baldock C 2001 The relationship between chemical processes and transverse relaxation times in polymer gel dosimeters Phys. Med. Biol. 46 1061-74

[40] Lepage M, Gore J C 2004 Contrast mechanisms in magnetic resonance imaging J. Phys.: Conf. Ser. 3 78-86

[41] Maryanski M J, Zastavker Y Z, Gore J C 1996 Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: II Optical properties of the BANG polymer gel Phys. Med. Biol. 41 2705-17

[42] Olding T, Holmes O, Schreiner L J 2008 Development of a quality assurances scattering phantom for cone beam optical CT Prelim. Proc. 5th Int. Conf. Radiother. Gel Dosim., Crete, Greece 169-73

[43] Lopatiuk-Tirpak O, Langen K M, Meeks S L, Kupelian P A, Zeidan O A, Maryanski M J
2008 Performance evaluation of an improved optical computed tomography polymer gel dosimeter system for 3D dose verification of static and dynamic phantom deliveries Med. Phys. 35 3847-59

[44] Hilts M, Jirasek A, Duzenli C 2005 Technical considerations for implementation of x-ray CT polymer gel dosimetry Phys Med Biol. 50 1727 – 45

[45] Koeva V I, McAuley K B, Jirasek A, Schreiner L J. 2008 Preliminary investigation of the NMR, optical and x-ray CT dose-response of polymer gel dosimeters with cosolvents and increased crosslinker levels. Prelim. Proc. 5th Int. Conf. Radiother. Gel Dosim., Crete, Greece.

[46] Baldock C, Lepage M, Bäck S Å J, Murry P J, Porter D, Kron T 2001 Dose resolution in radiotherapy polymer gel dosimetry: Effect of echo spacing in MRI pulse sequence Phys. Med. Biol. 46 449-60.