Physica Medica 63 (2019) 105–111

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

Study of the formulation optimization and reusability of a MAGAT gel dosimeter

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ARTICLE INFO

Keywords:
Gel dosimetry
MAGAT
Reusable gel dosimeter

ABSTRACT

Purpose: This study aims to optimize the formulation of a methacrylic acid gelatine and tetrakis (hydroxymethyl) phosphonium chloride (MAGAT) gel dosimeter to achieve acceptable dosimetric characteristics and the lowest final costs. This study also evaluates the reusability of the dosimeter.

Methods: The MAGAT gel dosimeter formulation was optimized. Tetrakis (hydroxymethyl) phosphonium chloride (THPC) concentrations (2, 5, 8, 10, 20, and 65 mM), methacrylic acid (MA) concentrations (2.0, 2.5, 3.0, 3.5, and 4.0% w/w) and gelatin concentrations (4.36, 6.45, 8.36, and 10.45% w/w) were evaluated to provide an adequate dosimetric response. The final dosimeter formulation linearity and dose rate dependence were evaluated. The reutilization methodology of the optimized gel formulation, but containing 2 mM of THPC, which was previously irradiated with a dose of 2 Gy, is also presented.

Results: The optimized mass concentration of the dosimeter consists of 88.60% deionized water, 8.36% gelatin, 3.00% of MA and 0.04% THPC (5 mM). It presents a linear response for doses up to 10 Gy with a 1.16 $Gy^{-1} s^{-1}$ sensitivity. A maximum sensitivity variation of less than 4.0% was found when varying the dose rate of the radiation beams from 300 to 500 cGy/min. It was possible to reuse the dosimeter, however the sensitivity decreased by 15% from the first to the second irradiation.

Conclusions: A low-cost MAGAT gel dosimeter with optimized formulation that responds to radiation in a dose range of 0 to 10 Gy with small dose-rate dependence is presented. The MAGAT gel can be reused after a 2 Gy irradiation.

1. Introduction

In 1984, Gore et al. [1] proposed that radiation-induced changes in a Fricke solution could be evaluated by Nuclear Magnetic Resonance (NMR). Consequently, the researchers presented the idea of using Magnetic Resonance Imaging (MRI) to collect spatial dose distribution information. However, ferric ions in Fricke solutions and even in Fricke gels diffuse in the dosimeter, limiting their spatial resolution for dose distribution measurements [2]. To overcome this limitation, polymer gel dosimeters based on acrylic monomers infused in a gel matrix were developed [3,4]. The first two main classes of polymer gel dosimeters that become available were the polyacrylamide based gels (PAG, nPAG) [5] and the methacrylic acid (MA) based gel dosimeters (MAGIC, nMAG or MAGAT) [6 7]. More recently, other polymer gel dosimeter were developed [8–12].

The unique three dimensional dosimetry possibility made the gel dosimeters the ideal tool for checking the increasingly conformal dose delivery, which is a characteristic of emerging radiotherapy treatment. This possibility was strengthened with the development of plastic radiochromic dosimeters, such as PRESAGE [13] that can be read by an optical computed tomography (CT) scanner. Although these dosimeters represent a new class of easy-handle 3D dosimeters, the MRI readout technique was used in the majority of evaluations of gel dosimeters at least until 2017 [14].

The methacrylic acid gelatine and tetrakis (hydroxymethyl) phosphonium chloride (MAGAT) polymer gel dosimeter is composed of a gel

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https://doi.org/10.1016/j.ejmp.2019.05.018
Received 26 September 2018; Received in revised form 23 May 2019; Accepted 25 May 2019
Available online 12 June 2019

matrix made of water and gelatin, where the MA monomers and the antioxidant agent tetrakis (hydroxymethyl) phosphonium chloride (THPC) are placed. It was used in this study owing to the lesser toxicity of methacrylic monomers when compared to polyacrylamide monomers [6]. Moreover, MAGAT gel was evaluated as the most tissue-equivalent dosimeter among the MA-based dosimeters [15], and this characteristic makes it a promising dosimeter for use in the clinical setting. Two formulations of MAGAT gels have been proposed in the literature [16,17] to provide the highest dosimeter sensitivity.

In the first part of this study, MAGAT gel formulation was optimized to achieve acceptable dosimetric characteristics and the lowest final cost. A comparison between the performances of the several formulations evaluated will be based on the sensitivity of the dose response curve and higher sensitivity results in a superior gel dosimeter [18]. Although a divergence from linearity has been observed for some gels [7], the assumption and analyses of the linear region at low doses was used in several studies in the literature [19–22].

The second part of this study evaluated the reusability of MAGAT polymer gel dosimeters. The development of reusable polymeric gels can make the management of the technique easier, because otherwise it would be necessary to dispose of the material while respecting chemical and environmental recommendations. The introduction of a simple methodology to re-use the dosimeter could facilitate its management and increase the clinical applicability of the technique. In the radiochromic gel dosimetry area, reusable dosimeters are already available [23,24], emphasizing the need for similar reusable polymer gel dosimeters.

2. Materials and Methods

The optimization of MAGAT gel components concentrations was performed to achieve a formulation with acceptable dosimetric characteristics and with the lowest final costs to respond to irradiation in a dose range up to 10 Gy. We considered an acceptable sensitivity to be around 1.0 Gy^{-1} s^{-1}, which means a proportional response between R2 and dose, and corresponds to a value that can be achieved using MA based gels [25]. Then, the reusability of the dosimeter was evaluated. Basically, to reuse the polymer gel dosimeter, it was necessary to melt the dosimeter and refrigerate it again.

The gel dosimeter studied was a MAGAT-type gel dosimeter with 2 mM of THPC. Its formulation at the beginning of this study was based on the gelatin and MA concentrations of MAGIC-f gels [26], but its antioxidant agent was changed for THPC [7]. In this way, the initial mass concentration of chemicals in the dosimeter was 85.60% ultrapure deionized water, 8.36% of a bovine 250 bloom gelatin (Gelita®), 6.00% MA (Sigma®) and 0.04% (or 2 mM) THPC (Sigma®).

2.1. Dosimeter preparation

The general dosimeter preparation used in this study is described below; however, the chemical concentrations used are going to be detailed on the optimization of dosimeter composition and on the reutilization studies sections. The dosimeter preparation started by heating water to 50 °C in a beaker and was followed by slow gelatin addition under continuous agitation. When the gelatin was completely dissolved and melted, the solution was cooled to 35 °C and the other chemicals were added (MA and THPC). The solution was stirred for at least 5 min more. After that, the gel was stored in transparent plastic calibration vials (120 mm in length and 10.25 mm in diameter) and refrigerated at 7 °C for at least 12 h in a domestic refrigerator.

2.2. Irradiations

All dosimeter irradiations were conducted using a 6-MV LINAC (Siemens Primus, Siemens Medical Systems, Concord, CA, USA). The calibration vials were transported from the gel dosimeter laboratory to the hospital in a thermal bag and were left in the LINAC room for 30 min before irradiation in order to thermally equilibrate room temperature before irradiation. A fixed 100 cm source surface distance (SSD) setup was used. The vials were positioned in an acrylic support under 1.5 cm of acrylic plates for dose buildup, and 5 cm of acrylic plates were also used under the vials for guaranteeing backscatter (Fig. 1). All calibration vials used for generating dose–response curves that were compared in the study were irradiated together. A minimum field size of 20 × 20 cm^2 was used for irradiation, but larger field sizes were used when the number of vials was large, and they were not encompassed by that field. The doses were delivered in increments of 2 Gy. After each irradiation, the vials receiving that dose were removed, and the others were left in the LINAC to be irradiated with another 2 Gy dose. This procedure was repeated until the vials were irradiated with 2, 4, 6, 8 and 10 Gy. The delivered doses were calculated based on the LINAC commissioning and dosimetric quality control checks performed following international recommendations [27] and using ionization chambers.

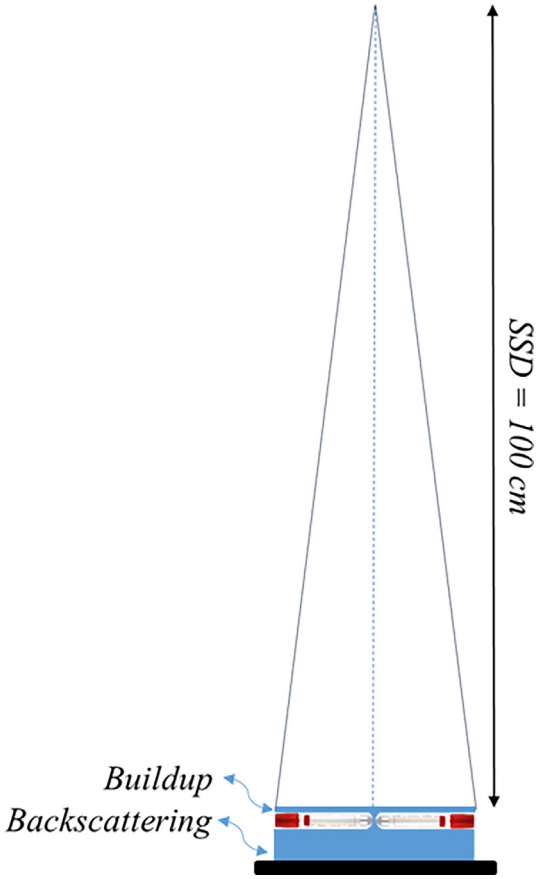

Fig. 1. Irradiation configuration consisting of a 100 cm SSD setup. Irradiated vials were positioned in acrylic support with 1.5 cm of buildup and 5 cm of backscattering material.

2.3. MRI acquisition and analyses

MRI was acquired 24 h after irradiation to guarantee that the polymerization reactions were complete [28]. During this time, the vials were stored in the MRI scanner room to achieve thermal equilibrium with the scanner room temperature. A multi-spin echo sequence consisting of seven echo times multiples of 22.35 ms and a repetition time of 1400 ms in a Phillips 3T MRI scanner was used (Achieva, Philips, Best, Netherlands). All images were acquired using a field of view (FOV) of 130 × 120 × 120 mm^3, slice thickness of 2 mm and slice spacing of 2 mm. The relaxation rate mean value of the gel samples and

Table 1
MAGAT gel formulations used for the studies performed to optimize dosimeteŕs formulation: THPC concentration study, MA concentration study, and gelatin concentration study. For all studies, water was added to complete the formulation.

Components	THPC study	MA study	Gelatin study
Gelatin (% w/w)	8.36	8.36	4.36, 6.45, 8.36, 10.45
MA (% w/w)	6.00	2.00, 2.50, 3.00, 3.50, 4.00	3.00
THPC [1] (mM)	2, 5, 8, 10, 20, 65	5	5

1. Equivalent to 0.04% w/w.

their respective standard deviations were evaluated using in-house developed software in MATLAB®. The standard deviation of R2 values are presented as the error bars in all dose–response curves presented in this study. Considering that the calibration vials were 12 cm in length, approximately 30 axial images were acquired of each vial. At a minimum, the central 15 images were analyzed for each dose point presented in the dose response curves.

2.4. Optimization of dosimeter composition

Starting from the original composition presented previously for the MAGAT gel, THPC was the first component that had its concentration optimized in the gel composition. The THPC molarities studied were 2 mM, 5 mM, 8 mM, 10 mM, 20 mM and 65 mM (Table 1). However, owing to the small variation in molarity, the rounding mass concentration of THPC of 0.04% weight by weight (w/w) is valid for all of the studied gel formulations.

The melting temperature of the gels with different THPC concentrations was estimated by heating the gel samples (80 ml of gel) inside a plastic container in a hot water bath. The bath was achieved using a beaker filled with water and heated by a hotplate. This setup was used to provide heat in a more homogeneous fashion to the dosimeter. A digital thermometer placed inside the dosimeter was used to estimate the geĺs melting temperature, which was considered as the temperature at which the gelatin starts to lose its original rigid shape.

The THPC concentration of 5 mM presented the highest sensitivity and was chosen to continue the study. MA was the second optimized component in the gel dosimeter. Its mass concentration was varied from 2.0% to 4.0% in increments of 0.5% and all the reductions of MA in the dosimeter were counterbalanced by the addition of deionized water to the recipe (Table 1).

The last optimized component in the formulation was gelatin. Its mass concentration was varied in 2% increments from 4.36% to 10.36%. The formulation used the optimized results achieved previously for THPC and MA concentrations of 5 mM and 3% w/w, respectively. The composition of the evaluated dosimeters is presented in Table 1.

To verify the dosimetric performance of the optimized gel formulation, two important dosimetric characteristics were evaluated. The first one was the linearity response for doses up to 20 Gy. Special attention was given to doses from 0.5 Gy to 2.0 Gy. For this dose region, the dosimeters were irradiated in increments of 0.5 Gy. For the rest of the doses, up to 20 Gy, increments of 2 Gy were used. The second dosimetric characteristic was the dose rate dependence. In this study, the dosimeters were irradiated from doses of 2 to 10 Gy in increments of 2 Gy at different dose rates (200 cGy/min, 300 cGy/min, 400 cGy/min, and 500 cGy/min). The different dose rates were achieved by varying the SSD, in accordance with the inverse square law. The irradiation details for these two experiments are summarized in Table 2.

2.5. Reutilization study

To evaluate the possibility of reusing the gel dosimeter, a preliminary study was performed with the optimized gel formulation, but using 1 mM of THPC, which allows for melting the dosimeter at a lower temperature and facilitates the methodology.

The reutilization study started by preparing six calibration vials and an 80-ml jar filled with a new MAGAT gel sample according to the procedure described in Section 2.1. All chemical concentrations were based on the optimized formulation, except for the THPC concentration. The calibration vials were irradiated following the same setup as described before (Section 2.2), with doses from 2 to 10 Gy in increments of 2 Gy, to obtain the reference geĺs response for the first irradiation in the usual methodology. The 80-ml container was irradiated with 2 Gy using parallel opposed beams to achieve a homogeneous dose distribution in the gel. After irradiation, the calibrations vials and the jar were stored in the MRI room, to maintain the same thermal history for both dosimeters. One day later, the 80-ml container was taken to the laboratory and submitted to the reutilization methodology to receive the second irradiation scheme.

The reutilization methodology began by heating the closed jar containing the irradiated gel at a constant temperature of 45 °C in a digital oven with automatic temperature control (M3, Bravac®) for 30 min. After that, the melted gel was separated into three different beakers. The first beaker received just the reused gel, and the second and third beakers received a re-addition of the same amount of MA and THPC from the initial preparation, respectively. Six calibration vials were prepared using the content of each beaker. They were placed in a domestic refrigerator at 7 °C for 24 h and were finally irradiated with the same doses of the reference sample following the usual irradiation methodology (Section 2.2). After irradiation, these vials were also stored in the MRI room with the previously irradiated gels and one day after the MRI acquisition of all the vials was completed.

Two cautions were taken during the heating process: the first one did not provide much heat so that the evaporation or flash point temperature of the chemicals could be achieved. The second one did not expose the dosimeter to temperatures at which gelatin molecules could degrade [29]. Thus, the optimized formulation with 5 mM of THPC presenting a melting temperature higher than 50 °C, could not be melted without harming its gelatin molecules. To achieve a reusable dosimeter with a formulation closer to the optimized one, we repeated this procedure for the gel with 2 mM of THPC, owing to its lower melting temperature. All other chemicals concentrations were kept the same as in the optimized formulation. The reutilization methodology

Table 2
Delivered doses and dose rate used in linearity of response and dose-rate dependence studies for MAGAT gel optimized formulation.

	Linearity of response study	Dose rate dependence study
Delivered dose	0.5 Gy to 2.0 Gy (steps of 0.5 Gy) 2.0 Gy to 20 Gy (steps of 2 Gy)	2.0 Gy to 10 Gy (steps of 2 Gy)
Dose rates (cGy/min)	200	200, 300, 400, 500

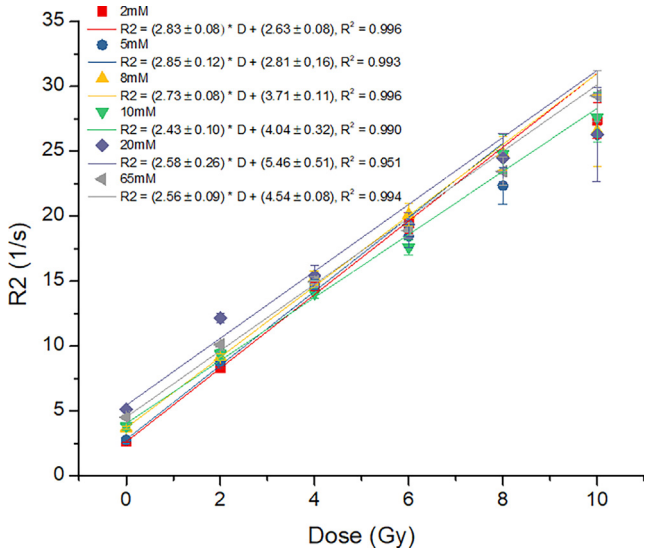

Fig. 2. Dose-response curves for gels with THPC concentrations of 2 mM, 5 mM, 8 mM, 10 mM, 20 mM and 65 mM. Lines correspond to linear regressions of all data (p less than 0.05).

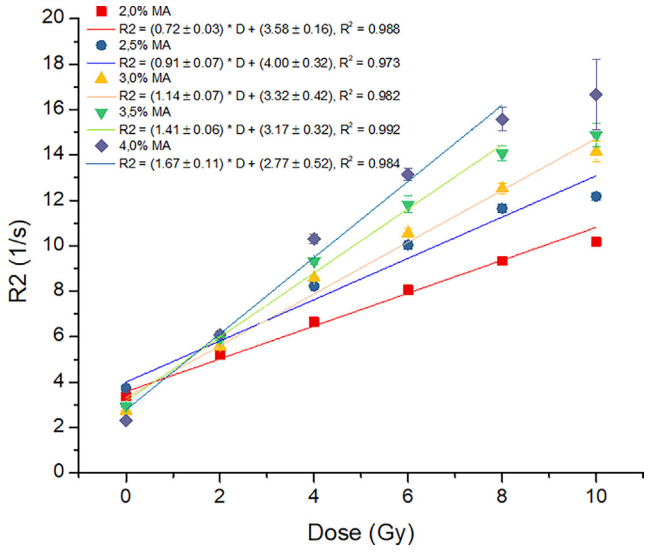

Fig. 3. Dose-response curves for MA concentrations of 2, 2.5, 3, 3.5, and 4% w/w. Lines correspond to linear regressions of all data (p less than 0.05), but for MA concentrations of 3.5% and 4.0%, R2 values for 10 Gy dose were excluded from fitting, because saturation is observed in response.

was the same as presented before, but after the melting process of the dosimeter, just THPC was re-added to the gel.

3. Results

3.1. Optimization of dosimeter composition

The influence of the THPC concentration on the dose–response curve is presented in Fig. 2. The dosimeteŕs sensitivity increases weakly when the THPC concentration increases from 2 mM to 5 mM, but for higher THPC concentrations the dosimeteŕs sensitivities are lower than the value achieved for 5 mM THPC gel.

Another important characteristic of the dosimeter that is altered when the THPC concentration increases is the geĺs melting temperature (Table 3).

Considering the highest sensitivity and the suitable melting temperature for an easy-handle dosimeter at room temperature, the 5 mM THPC concentration was chosen to continue the optimization study.

The study evaluating different MA concentrations showed that by increasing the MA concentration, the dosimeter sensitivity increases (Fig. 3). However, for the two highest MA concentrations, saturation in the dosimeteŕs response was observed for doses higher than 8 Gy. Based on this, an MA mass concentration of 3% was chosen as the optimized one in order to maintain a higher sensitivity and avoid the saturation of the response.

By varying the gelatin concentration in the dosimeter, it is possible to see two different behaviors (Fig. 4). For the two lowest mass concentrations, the dose–response curves are linear only for dose values up to 6 Gy (Fig. 3) and the curves present the highest sensitivities. For the two largest gelatin concentrations, the dose–response curves sensitivities are lowest, but the curves are linear for the whole dose range evaluated. Therefore, to save chemicals in the gel composition and to

Table 3
Melting temperature estimated for MAGAT gel dosimeters containing THPC concentrations of 2, 5, 8, 10, and 20 mM.

THPC concentration (mM)	2	5	8	10	20
Melting temperature (°C)	37	52	70	71*	78*

* Maximum temperature achieved for sample; however, dosimeter gelatin was still rigid, meaning that melting temperature is higher than this value.

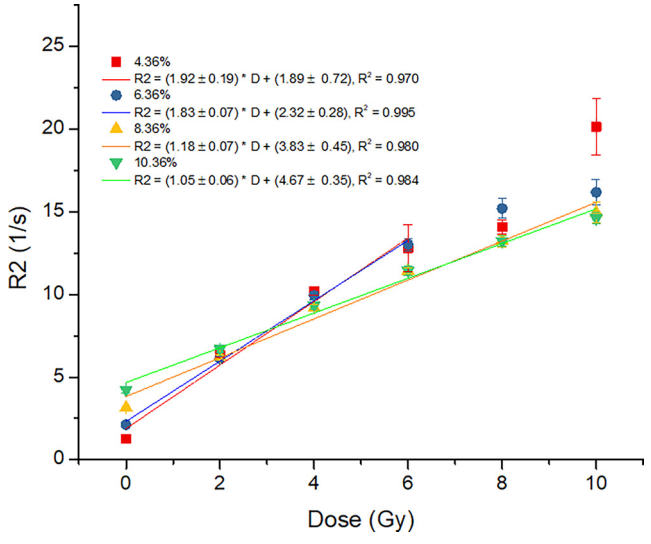

Fig. 4. Dose-response curves for gelatin concentrations of 4.36, 6.36, 8.36 and 10.36% w/w. Lines correspond to linear regressions of all data (p less than 0.05), but for gelatin concentrations of 4.36% and 6.36%, R2 values for 8 and 10 Gy doses were excluded from fitting.

avoid compromising the previous results, a gelatin concentration of 8.36% was chosen as the best value of the gelatin concentration.

Finally, the optimized mass concentration of the dosimeter achieved in this study consists of 88.60% deionized water, 8.36% gelatin, 3.00% MA and 0.04% THPC (5 mM). The dosimetric response of this recipe is presented in Fig. 5 for doses up to 20 Gy and its dose rate dependence is presented in Fig. 6.

3.2. Reutilization study

In the preliminary study using the 1 mM THPC gel, we found that only the gel with the re-addition of THPC responded to irradiation (Fig. 7).

As presented before, the gel formulation used for the final re-utilization study contains 2 mM of THPC because, among the tested THPC concentrations, this is the only one that could be melted without

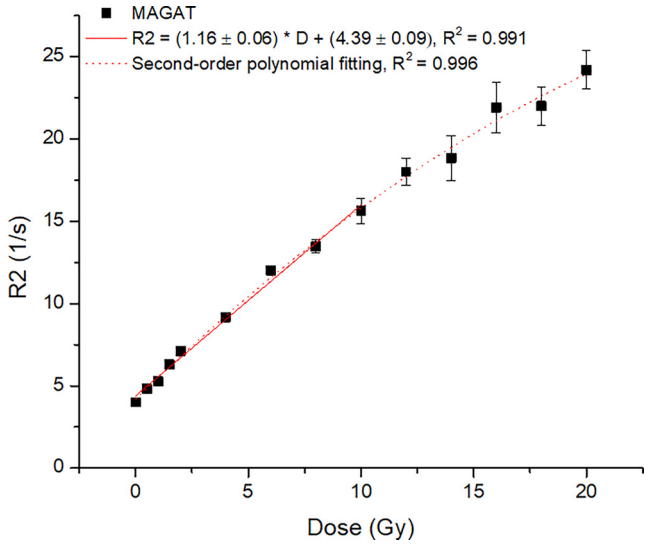

Fig. 5. Dose-response curves for doses up to 20 Gy for optimized formulation of dosimeter.

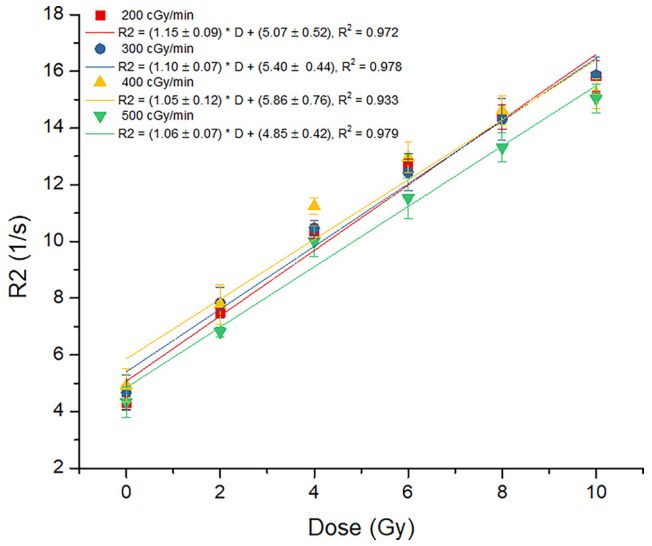

Fig. 6. Dose-response of optimized formulation of dosimeter curves for irradiations with dose rates of 200, 300, 400 and 500 cGy/min.

harming the geĺs gelatin molecules. To show how this gel compares to the 5 mM of THPC gel, Fig. 8 is a plot of the dose responses of both gel formulations.

The dose–response curves of the first and second irradiations for the 2 mM THPC dosimeter are presented in Fig. 9. The second irradiation data corresponds to the response of the gel samples from the same batch used at the first irradiation, that were submitted to the presented methodology for the dosimeteŕs reutilization after receiving a dose of 2 Gy in a previous irradiation. It can be seen that for the first irradiation the dosimeteŕs response is linear with the dose; however, for the second irradiation, a linear and second-order polynomial fitting were presented, as the R^2 value of the polynomial fitting is better than the linear one.

4. Discussions

4.1. Optimization of dosimeter composition

In the MAGAT gel composition optimization study, the first evaluated component was THPC. The dosimeteŕs sensitivity varied by less

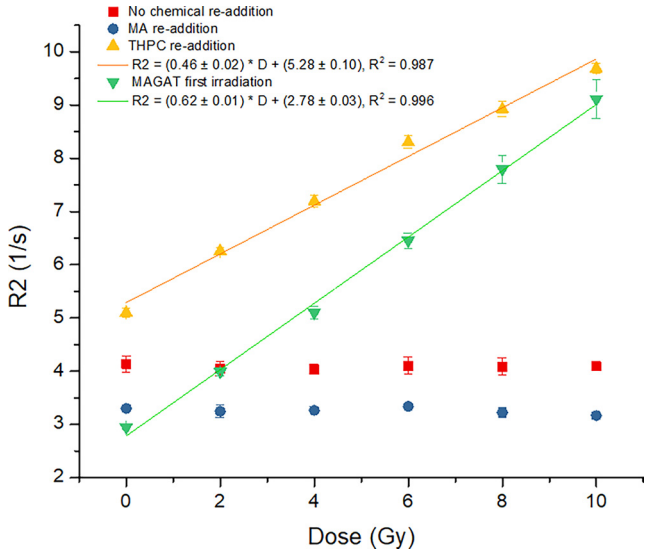

Fig. 7. Dose response curves achieved for 1 mM THPC gel in preliminary study of reutilization methodology.

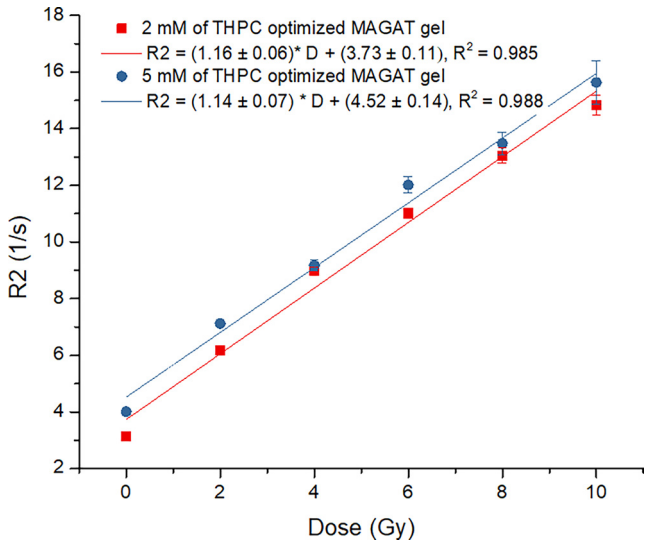

Fig. 8. Comparison of dose–response curves for optimized formulations of MAGAT gel with 5 mM of THPC and gel with same concentration of all chemicals but with THPC reduced to 2 mM.

than 17% for all concentrations evaluated, presenting a mean value of 2.66 ± 0.17 $Gy^{-1}s^{-1}$. It can be seen that the sensitivity increases from 2 to 5 mM owing to the higher antioxidant effect that a higher THPC concentration exerts [7]. However, the sensitivity decreases at THPC concentrations higher than 5 mM, because in solution, THPC dissociates into formaldehyde, leading to the formation of more crosslinking in the gelatin matrix [30]. This results in stiffer gels, where the diffusion of monomers is more difficult and the polymerization rate or the dosimeteŕs response is decreased. In addition, the increase in gelatin crosslinking results in a higher gel melting temperature (Table 3). The response of the gel containing 65 mM of THPC was evaluated as an extrapolation data of a high THPC concentration gel to confirm the previous theory in the used formulation.

The 5 mM THPC concentration exhibits the highest sensitivity among the concentrations studied because it presents a balance between the benefits of the higher antioxidant power of THPC and the production of a dosimeter that does not limit the monomeŕs diffusion. Choosing the highest sensitivity response of the dosimeter containing 5 mM of THPC to continue the study opened the possibility of reducing

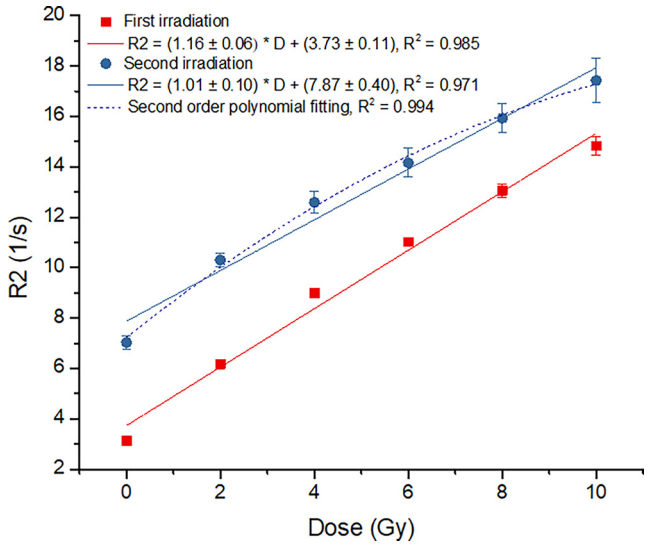

Fig. 9. Dose-response curves for same gel sample containing 2 mM of THPC irradiated twice. Second irradiation results were achieved using reutilization methodology proposed.

the other component concentration, in order to reduce the costs of the dosimeter. This THPC concentration is different from the 10 mM used in the other two studies that optimized the formulation of a MAGAT gel [16,17] and is also different from the ideal THPC concentration for PAGAT gels (4.65 mM) found by Jirasek *et al.* [30].

The increase in the dosimeteŕs sensitivity achieved by increasing the MA concentration (Fig. 2) was expected because MA is the dosimeter monomer and its concentration may be directly related to the dosimeter response [7,17]. However, by increasing the MA concentration, the uncertainties associated with the dose also increases, especially at higher doses. In addition, response saturation is observed for doses higher than 8 Gy for MA mass concentrations of 3.5% and 4.0%.

The lowest sensitivities verified for the dosimeters containing 8.36% and 10.45% gelatin in the composition (Fig. 3) occurs first because by increasing the gelatin concentration, the gel stiffness increases as well. This also makes the diffusion of monomers more difficult and reduces the polymer chain growth. The second reason is that the higher gelatin concentration increases the rate of termination reactions by radical transfer to gelatin, reducing the geĺs sensitivity.

The optimized dosimeteŕs formulation achieved in this study presents a 50% reduction in the MA concentration. Because it is the most expensive component of the dosimeter, a significant reduction in the final price of the dosimeter was achieved. Moreover, the reduction in the concentrations of the components also increases the water equivalence of the dosimeter [15], making it more interesting for clinical dosimetry.

This formulation, when used following the proposed methodology and the scanning parameters presented, possesses a relative dose resolution (or a minimal detectable dose difference within 95% level of confidence relative to the operational dose range) of 0.13 Gy [2,31]. The known sources of uncertainties in the dosimeter response are well described [32] and were controlled in this study, in this condition, the physicochemical mechanisms should not contribute to more than a total error of 2% in the dose measurement [33], and the scanner related sources of uncertainty may be kept well below 3% [34,35], resulting in a combined uncertainty of 3.6%.

The main dosimetric characteristics of this optimized recipe include the linear response for doses up to 10 Gy with a 1.16 $Gy^{-1}s^{-1}$ sensitivity and a maximum dose deviation of ± 6%. For higher doses up to 20 Gy, a saturation in the response is observed and a higher uncertainty is associated with the R2 values, because this is the second-order polynomial fitting that is most adequate to encompass all the data (Fig. 4). Second, a maximum sensitivity variation of 9% was found when changing the dose rate of the radiation beams from 200 to 500 cGy/min, but if we consider the dose rate variation from 300 to 500 cGy/min, this dependence decreases to less than 4% (Fig. 5).

This study was designed for a straightforward optimization process and did not evaluate if the THPC concentration had any effect on the MA variation study or if the THPC and MA concentration had any influence on the gelatin concentration study.

4.2. Reutilization study

In the preliminary study, we found that the re-addition of THPC to the recycled gel was necessary (Fig. 7). None of the other tested gels responded to the irradiation owing to the oxygen inhibition of the polymerization.

The reutilization study could not be performed with the final optimized formulation achieved because it presents a high melting point (52 °C) and this temperature could not be provided to the dosimeter without harming the gelatin molecules, because they start to degrade at temperatures higher than 40 °C and reach complete degradation at 200 °C [29]. The solution found for this problem was to reduce the THPC concentration to 2 mM, reducing its melting temperature to 37 °C. This was acceptable on this study, because when comparing the dose response of the optimized gel containing 2 mM of THPC with the dose response of the optimized gel containing 5 mM of THPC (Fig. 7) a difference of less than 2% was found among their sensitivities. In addition, this gel presents a higher relative dose resolution (0.20 Gy) when compared to the 5 mM THPC optimized gel [2]. When we look for other studies available at the literature, the use of 2 mM of THPC for PAGAT gels resulted in a gel that presents inhibition of its response due to a too slow O_2 consumption [30]. For MA based gels the situation is different, gels prepared in anoxic conditions with 0.5, 2 and 3.5 mM of THPC responded to irradiation [36], and for normoxic preparation conditions, the inhibition occurred only for gels with less than 1 mM of THPC [37].

The MAGAT gel reutilization was verified after a previous 2 Gy irradiation when using the proposed methodology (Fig. 9). A gel dosimeter sensitivity of 1.16 $Gy^{-1}s^{-1}$ was found for the first irradiation of the sample, while a sensitivity of 1.01 $Gy^{-1}s^{-1}$ was found for the second irradiation of the same sample, corresponding to a sensitivity reduction of less than 15%. It is possible to see that a higher uncertainty is associated with the R2 values for all evaluated doses of the reused gel, resulting in a worsening of the relative dose resolution for the second irradiation of the dosimeter (0.33 Gy) [2].

Considering the reduction in the quality of the linear fitting of the reused gel, which was 1.5% smaller than for the first usage, a second-order polynomial fitting was also used. It presented a higher value (R^2 = 0.994); however, the relative dose resolution for the gel in this case was 0.57 Gy, indicating that for dosimetry purposes, the linear fitting was the most adequate.

The types of uncertainties associated with the reused dosimeter may be the same as discussed before for the optimized formulation. However, for the reutilization study, the dosimeter was melted after the first irradiation and the physical–chemical uncertainties must be higher than those proposed before. By doubling the physical–chemical uncertainty, an estimated combined uncertainty of 5% is achieved for the reused dosimeter.

If we analyze the value of R2 at 0 Gy change from the first to the second irradiation, it can be seen that its value increases from 3.1 s^{-1} to 7.0 s^{-1}, showing that the heat provided to melt the dosimeter did not break the polymer chains of the first irradiation. However, there was still an excess of monomers molecules available for polymerizing at the second irradiation, even with the proposed 50% reduction in the MA concentration after the optimization study.

The proposed methodology for gel dosimeter reutilization was evaluated only for first uniform irradiation with a 2 Gy dose. The

evaluation of a non-uniform irradiation and other doses delivered at the first irradiation will be the subject of further study.

5. Conclusions

The first part of this study optimized the formulation of a MAGAT gel dosimeter. The achieved final composition consisted of 88.60% deionized water, 8.36% gelatin, 3.00% MA, and 0.04% THPC (5 mM). This formulation presented a reduction of 50% in the MA concentration which corresponds to a significant reduction in the costs for fabricating the dosimeter. The evaluated dosimetric characteristics of this formulation are that it responds to radiation in a dose range of 0 to 10 Gy and presents a dose rate dependence on its response of less than 4% when varying the dose rate from 300 to 500 cGy/min.

When altering the concentration of THPC in the optimized MAGAT gel formulation from 5 mM to 2 mM, it is possible to reuse the dosimeter with the proposed methodology with an estimated loss of less than 15% in sensitivity. The possibility of reusing the dosimeter can facilitate the dosimeteŕs clinical use, because it will reduce the disposal of chemicals and the costs of dosimetric tests. However, the 3D performance of the reused dosimeter was not investigated in this study.

Acknowledgments

This work was supported by grant 2014/03370-6, São Paulo Research Foundation (FAPESP), Brazil. Partial support was received from CAPES, Brazil and CNPq, Brazil.

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