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Improvement of the sensitivity of PASSAG polymer gel dosimeter by urea

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ABSTRACT

The severe toxicity in compound of polymer gel dosimeters has been reported as one of their major limitations for utilization in clinical applications. Recently, PASSAG polymer gel dosimeter has been introduced as a safe polymer gel dosimeter. Despite the excellent dosimetric results reported for this gel dosimeter, its R_2-dose sensitivity is relatively low. Therefore, the present study is aimed to improve the sensitivity of PASSAG gel dosimeter by adding urea to its structure. Moreover, it was tried to obtain the optimal amount of urea for the new gel dosimeter. After preparation of the PASSAG-U (PASSAG and Urea) gel dosimeters, they were irradiated using 6 MV photon energy and their responses were read by a 1.5 T MRI scanner. Then, the R_2-dose response and the R_2-dose sensitivity of the PASSAG-U gel dosimeters with various percentages of the urea were assessed at a 0–10 Gy dose range, various scanning temperatures (15–24 °C), and post irradiation times (1–30 days). The radiological properties of PASSAG-U gel dosimeters confirmed soft tissue and water equivalence of the new gel dosimeters. Compared to the PASSAG gel dosimeter, the R_2-dose sensitivities of PASSAG-U gel dosimeters with 1%, 3%, and 5% urea were improved by 12.14%, 25.15%, and 27.90%, respectively. Although the addition of urea improves the R_2-dose sensitivity of the gel dosimeter, it leads to the degradation of dose resolution (especially for 5% urea). Moreover, the dosimetric evaluation of characteristics related to the PASSAG-U gel dosimeters with various urea concentrations resulted to following conclusions: 1) the optimal amount of urea was determined 3%; 2) there was a stability in the R_2 values for 18–22 °C scanning temperatures; 3) there was a temporal stability at the response of PASSAG-U gel dosimeters from 14 to 30 days after irradiation; 4) the R_2-dose sensitivity of PASSAG-U gel dosimeters varied over post irradiation time.

1. Introduction

Modern techniques used in radiation therapy are capable of delivering a conformal dose distribution and precise to tumor as well as lower dose to surrounding normal tissues (Sellakumar and Samuel, 2010). Because of high dose gradient between the tumor and normal tissue in these techniques, any error or inaccuracy at dose delivery can cause either an inadequate dose to the target volume or a high dose to the adjacent normal tissues (Abtahi et al., 2016). Therefore, three dimensional (3D) verification of dose distribution during irradiation in these modern radiotherapeutic techniques is necessary (Khezerloo et al., 2017a, 2018).

The use of conventional dosimeters (such as film, diode, ion chamber, thermoluminescent dosimeter, etc.) for the measurement of 3D dose distribution is almost impossible (Oldham et al., 2003; Farhood et al., 2018a). In this regard, gel dosimetry systems can be used to measure the accurate 3D dose distribution with high spatial resolution (Oldham et al., 2003; Yan et al., 2005). The 3D dosimetric systems (based on chemical mechanisms) are classified in three main groups: 1) ferric dosimeters, 2) polymer gel dosimeters, and 3) PRESAGE (radiochromic dosimeter) (Khezerloo et al., 2017b).

The polymer gel dosimetry system was first introduced by Maryanski et al. (1993). Thereafter, some studies on improvement and optimization of the polymer gel dosimeters were carried out (Trapp et al., 2005; De Deene et al., 2002; Lepage et al., 2001). Despite many benefits of these dosimetric systems, they are not routinely used in clinic (Yao et al., 2017). The severe toxicity in compound of polymer gel dosimeters has been reported as one of their major limitations for utilization in clinical applications (Waldenberg et al., 2017). To resolve this problem, several less toxic monomers have been presented by researchers (Pappas et al., 1999; Senden et al., 2006; Abtahi, 2016).

In our recent study, we introduced PASSAG polymer gel dosimeter, as the safest polymer gel dosimeter so far (Farhood et al., 2018a). The monomer used in the structure of this new gel is a safe substance with

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LD_{50} > 16,000 mg/kg, genetic and carcinogenicity toxicity tests with negative responses, and eco-friendly. The radiological properties of PASSAG gel dosimeter showed that this gel dosimeter can be considered as a water or soft tissue equivalent material in most practical conditions (Farhood et al., 2018b). In addition, the PASSAG gel dosimeter has an excellent linear R_2-dose response in 0–15 Gy dose range, less dependency to the scanning temperature (18–24 °C), independence of R_2-dose response to different photon energies (6 and 18 MV) and dose rates (100–400 cGy/min) in 0–10 Gy dose range (Farhood et al., 2018a, Farhood et al., 2018b). However, a main disadvantage of the PASSAG gel dosimeter is its relatively low R_2-dose sensitivity. The "response–dose sensitivity" quantity in polymer gel dosimeters is defined as slope of the linear region of the gel dosimeter response to absorbed dose values.

In the present study, we improved sensitivity of the PASSAG gel dosimeter by adding urea to its structure and this new formula was named PASSAG-U (PASSAG and Urea). Moreover, it was tried to obtain the optimal amount of urea for the new gel dosimeter. Using Magnetic Resonance Imaging (MRI) technique, properties of temperature dependence and temporal stability of the PASSAG-U gel dosimeters were also assessed.

2. Materials and methods

2.1. Formulation and preparation of PASSAG-U polymer gel dosimeter

In this work, the formulation of conventional 2-Acrylamido-2-Methy-1-PropaneSulfonic acid (AMPS) Sodium Salt-based polymer gel dosimeter was improved. The PASSAG gel dosimeter recipe presented by Farhood et al. (2018b) was considered as a basis and then the new gel dosimeter (PASSAG-U) was generated by adding the urea to the structure of basis gel dosimeter.

The chemical components used in the PASSAG-U gel dosimeter include: AMPS (Merck, ≤ %100), NaOH (Merck, ≤ %100), urea (Merck, Germany), N, N-Methylene-Bis-Acrylamide (Bis) (≥99.5%, Sigma Aldrich, USA), gelatin from porcine skin (type A, 300 Bloom, Sigma Aldrich, USA), HPLC grade pure water (Obtained from Direct-Q 3 UV water purification system, Millipore, France), and Tetrakis hydroxyl methyl phosphonium chloride (THPC) (80% solution in water, Sigma Aldrich, USA).

To obtain the optimal formulation of the PASSAG-U gel dosimeter, different amounts of the urea were used (0%, 1%, 3%, and 5% (w/w)). The chemical concentrations applied in this work are listed in Table 1. According to the data presented in Table 1, the new gel formulations were prepared in three rounds and in each round, the water and urea amounts were changed; as the amount of water was decreased by adding the urea in each step, and the amounts of other chemical components were constant. Fig. 1 shows the chemical structure of urea substance used in the composition of PASSAG-U gel dosimeter.

The PASSAG-U gel dosimeters were fabricated as follows: 1) the urea amount (1%, 3%, or 5%) was entirely dissolved in 80% of the water at room temperature; 2) the monomer of AMPS sodium salt was generated at room temperature and for this aim, some NaOH material was added to a specific concentration of AMPS at 10% of the water, and

Table 1
The PASSAG and PASSAG-U gel compositions and concentrations in four rounds.

	Round 1	Round 2	Round 3	Round 4
Urea	0 wt%	1 wt%	3 wt%	5 wt%
Water	89 wt%	88 wt%	86 wt%	84 wt%
Gelatin	5 wt%	5 wt%	5 wt%	5 wt%
AMPS sodium salt	3 wt%	3 wt%	3 wt%	3 wt%
Bis	3 wt%	3 wt%	3 wt%	3 wt%
THPC	10 mM	10 mM	10 mM	10 mM

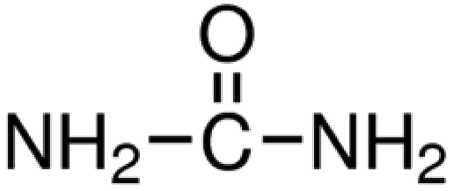

Fig. 1. Chemical structure of urea substance used in the structure of PASSAG-U gel dosimeter.

salt solution with pH 7 was obtained; 3) the gelatin was swelled in the solution obtained from the first step for 10 min, before its temperature reaches to 50 °C; 4) while stirring continuously, the crosslinker (Bis) was dissolved in the solution obtained from the third step for 15 min; 5) the AMPS sodium salt)monomer(was added to the mixture resulting from forth step at 37 °C; 6) the antioxidant (THPC) was blended with 10% of the water, and then it was added to the final mixture at 35 °C. The obtained PASSAG-U gel dosimeters were transparent and clear, and transferred into the glass tubes with dimension of 12 mm outer dimeter and 60 mm length. Then, the lids of the vials were closed with their caps and sealed by parafilm. Finally, these gel tubes were stored for 24 h at 4–5 °C in a refrigerator.

2.2. Radiological properties of new gel dosimeter

At first, the mass densities of the un-irradiated PASSAG-U gel dosimeters were obtained. Then, the electron density (ρ_e), number of electrons per gram (n_e) and the effective atomic number (Z_{eff}) of the new gel dosimeters were calculated to evaluate radiological properties by using the following equations:

$$\rho_e = \rho . N_A . \sum w_i . \left(\frac{Z_i}{A_i}\right) \quad (1)$$

$$n_e = \left(\frac{\rho_e}{\rho}\right) \quad (2)$$

$$Z_{eff} = \sqrt[2.94]{\sum_{i=1}^{n} a_i . Z_i^{2.94}} \quad (3)$$

where N_A denotes Avogadro's number, w_i denotes weigh fraction of the i-th element of atomic mass (A_i) and atomic number (Z_i), and a_i denotes the relative electron fraction of the i-th element.

2.3. Irradiation process of new gel dosimeter

The irradiation of gel samples was carried out by 6 MV X - rays emitted from Siemens Primus linear accelerator (linac) (Siemens AG, Erlangen, Germany) in Yasrebi Radiation Oncology Center (Kashan, Iran) approximately 24 h after manufacturing the PASSAG-U gel dosimeters. The gel samples were positioned in the central part and distance of 50 mm from the wall of a water phantom with dimension of 50 × 50 × 40 cm^3. The properties of the irradiation field include: field size of 40 × 40 cm^2, source to axis distance of 100 cm, gantry angle of 270°. A 1–10 Gy dose range (by step of 1 Gy) with 200 cGy/min dose rate was delivered to different separate gel samples and one vial was not irradiated (the reference/control vial).

2.4. Gel dosimeter reading and data processing

A 1.5 T MRI scanner (Siemens Avanto, Germany) was used to read the responses of PASSAG and PASSAG-U gel dosimeters during 30 days after irradiation (1, 10, 14, 17, 20, 25, and 30 days after irradiation). A standard RF head coil was utilized to record the signals. In the present project, a 32-echo Carr–Purcell–Meiboom–Gill pulse sequence was applied and the MRI scanning parameters have been listed in Table 2.

Table 2
MRI scanning parameters used in the current study.

Features	Properties
First echo time (TE)	22 ms
Space between echoes (ES)	22 ms
Repetition time (TR)	4000 ms
Matrix size	232 × 256
Feld of view	27 × 30 cm^2
Slice thickness	2 mm
Number of averages	2
Pixel band-width	100 Hz

To obtain the R_2 maps and the R_2-dose curves of gel samples, the methods presented in our previous studies were used (Farhood et al., 2018a, Farhood et al., 2018b). Moreover, the sensitivity of gel dosimeter (α) (the slope of the response-dose curve) was calculated by differentiating the R_2-dose curve.

The temperature dependence of PASSAG and PASSAG-U gel dosimeters during scanning was assessed at the temperatures of 15, 18 (room temperature), 20, 22, and 24 °C. For this purpose, 44 gel samples were applied (for each gel formula, 11 gel samples were used) and these gel samples were exposed with dose values of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 Gy. At first, the gel samples were fixed in a water container with dimensions of 24 × 18 × 12 cm^3 and were transferred to the room scanning. The temperature of room scanning was then adjusted on one of the temperatures mentioned above and this process was repeated for each of the five temperatures evaluated. The gel samples were kept within the water container for 1–2 h, to equilibrate the temperature of the water container with the room temperature. It is notable that before and instantly after each scanning, the temperature of the water container was measured by a thermometer; as it did not show any change rather than the pre-set room temperature.

3. Results and discussion

3.1. The elemental compositions and radiological properties

The details of elemental compositions of PASSAG and PASSAG-U gel dosimeters, soft tissue and water are summarized in Table 3. Moreover, the radiological properties (ρ_e, n_e, and Z_{eff}) for these materials are tabulated in the 9–11 columns of Table 3.

The results (Table 3) demonstrate that by adding the urea to the PASSAG formulation, variations in the elemental compositions between the PASSAG and PASSAG-U gel dosimeters with different percentages of the urea were not remarkable (< 3%). However, it is seen that the amounts of oxygen and carbon between the PASSAG-U gel dosimeters and soft tissue/water are not almost similar. Since cross sections these two elements (oxygen and carbon) for interactions of gamma rays are almost same (Abtahi et al., 2014), the sum of oxygen and carbon content (Table 3, column 7) in the PASSAG-U gel dosimeters is almost similar to those of soft tissue/water. Also, since the amount of hydrogen between soft tissue/water and the PASSAG-U gel dosimeters is almost same, they can be considered as potential useful dosimeters for neutron dosimetry.

The radiological properties of PASSAG gel dosimeter are almost equivalent to those of the PASSAG-U gel dosimeters (Table 3). Furthermore, the data presented in Table 3 confirm soft tissue and water equivalence of the PASSAG-U gel dosimeters; as from practical point of view, these gel dosimeters can be considered as a soft tissue/water equivalent material.

3.2. R_2-dose response and R_2-dose sensitivity

The response–dose curves of PASSAG and PASSAG-U gel dosimeters with 1%, 3%, 5% urea for 1 day after irradiation are shown in Fig. 2.

The results obtained from these four curves show linear R_2-dose responses for these gel dosimeters in 0–10 Gy dose rage. The following equations (4)–(7)demonstrate the variation of the R_2 of the PASSAG and PASSAG-U gel dosimeters with the 1%, 3%, and 5% urea as a function of absorbed dose value, respectively. For a more detailed analysis of R_2-dose responses of above-mentioned gel dosimeters, goodness of the fit parameters related to these curves were tabulated in Table 4; as these data show an exact mono-polynomial fitting for the PASSAG and the PASSAG-U gel dosimeters with 1%, 3%, 5% urea in 0–10 Gy dose range.

$$R2 = 0.185 \times Dose + 1.971 \quad (4)$$

$$R2 = 0.208 \times Dose + 2.512 \quad (5)$$

$$R2 = 0.232 \times Dose + 3.636 \quad (6)$$

$$R2 = 0.237 \times Dose + 5.072 \quad (7)$$

According to the data of equations (4)–(7), the R_2-dose sensitivities of the PASSAG and the PASSAG-U with 1%, 3%, and 5% urea are 0.185 ± 0.019, 0.208 ± 0.018, 0.232 ± 0.013, and 0.237 ± 0.015 s^{-1} Gy^{-1}, respectively. The above results demonstrate that by increasing the urea concentration, the sensitivity of PASSAG-U gel dosimeters increase; as the improvement of R_2-dose sensitivity is remarkable for the PASSAG-U gel dosimeters with 3% and 5% urea. Compared to the PASSAG gel dosimeter, the R_2-dose sensitivities of PASSAG-U gel dosimeters with 1%, 3%, and 5% urea were improved by 12.14%, 25.15%, and 27.90%, respectively. It is notable that adding the urea to the PASSAG formulation leads to a more acceleration in the polymerization reaction of the polymer gel dosimeters. The optimal amount of urea was determined 3%, because after this urea concentration, the R_2-dose sensitivity of PASSAG-U gel dosimeters does not remarkable altered (< 3%). The more important reason for this choice was that the addition of urea leads to the degradation of dose resolution (especially for 5% urea). To describe precisely, it can be mentioned although the increasing the urea improves the R_2-dose sensitivity of the gel dosimeter, adding this substance to the gelatin leads to the denaturation of its structure (especially proteins), which results in the monomers/crosslinkers do not disperse uniformly at all the mixture of gel. When the gel sample irradiates, radicals induced by water radiolysis initiate the process of monomers' polymerization and subsequently, regions from the irradiated gel sample that have received the same dose value do not exhibit the same generated polymers. In addition, as seen from Fig. 2, R_2-intercept value ($R_{2,0}$) increases by

Table 3
The elemental compositions (% by weight) and radiological properties for the PASSAG, PASSAG-U gel dosimeters with different percentages of urea, soft tissue, and water.

Material type	W_H	W_C	W_O	W_N	W_S	W_{C+O}	ρ (gr/cm^3)	ρ_e (× 10^{23})	n_e (× 10^{23})	Z_{eff}
PASSAG	10.54	5.46	80.73	1.60	0.42	86.19	1.04	3.45	3.31	7.53
PASSAG-U, 1%	10.50	5.66	80.11	2.07	0.42	85.77	1.04	3.45	3.31	7.52
PASSAG-U, 3%	10.41	6.06	78.86	3.00	0.42	84.92	1.05	3.48	3.31	7.51
PASSAG-U, 5%	10.32	6.46	77.62	3.93	0.42	84.08	1.05	3.48	3.31	7.50
Soft tissue	10.2	14.3	70.8	3.4	0.3	85.1	1.04	3.44	3.31	7.34
Water	11.2	–	88.8	–	–	88.8	1.00	3.34	3.34	7.51

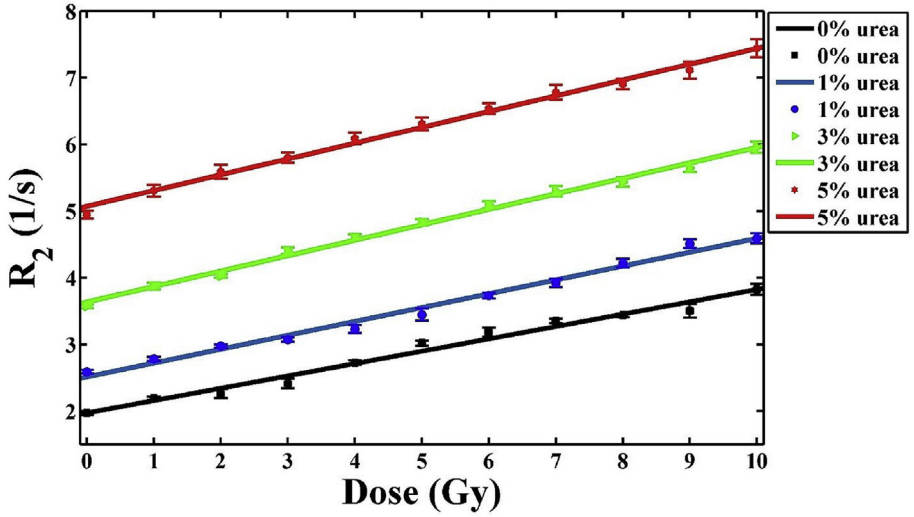

Fig. 2. The R_2-dose response of PASSAG and PASSAG-U gel dosimeters for various percentages of urea at 1 day after irradiated by 6 MV photon energy with 200 cGy/min dose rate and 18 °C scanning temperature. Error propagation method was applied to obtain the error bars (Knoll, 2000).

Table 4
Goodness of the linear fit to R_2-dose data of the PASSAG and PASSAG-U gel dosimeters with different percentages of urea.

Parameters	PASSAG	PASSAG-U, 1%	PASSAG-U, 3%	PASSAG-U, 5%
SSE	0.070	0.061	0.033	0.043
R-square	0.982	0.987	0.994	0.993
Adjusted R-square	0.980	0.986	0.994	0.992
RMSE	0.088	0.082	0.061	0.069

increasing the urea and it leads to the increased standard deviation of R_2 values; so that this is not because of chemical mechanisms, but because of statistics (De Deene and Baldock, 2002). So, according to Equation (8) (Baldock et al., 2001), these effects cause an increase in standard deviation of the response (R_2) of the gel dosimeters (σ_{R2}) and it also affects the dose resolution (D_{Δ}^{p}) (leads to its degradation). In is noteworthy that these adverse effects were more severe in high dose values.

$$D_{\Delta}^{p} = k_p \sqrt{2} \frac{\sigma_{R_2}}{\alpha} \tag{8}$$

In a recent study (Anaraki et al., 2018), we used different concentrations of the urea to improve the R_2-dose sensitivity of NIPAM gel dosimeter. Our findings showed that the optimal amount of urea is 3% for U-NIPAM gel dosimeter; as this urea concentration increased the sensitivity of improved gel dosimeter almost 37%. Also, various materials for increasing the response-dose sensitivity of polymer gel dosimeters have been suggested by researchers. For instance, use of sucrose at formulation of polyacrylamide-based gel dosimeters showed that this substance improves the sensitivity of mentioned gel dosimeters (Yoshioka et al., 2010). In other study, by adding 3% formaldehyde to MAGIC gel dosimeter, the sensitivity of this gel dosimeter increased about 10% (Fernandes et al., 2008). Moreover, improving the dose sensitivity of methacrylic acid- and acrylamide-based gel dosimeters by inorganic salt has been reported (Chacón et al., 2018; Hayashi et al., 2012). Another method to increase the response-dose sensitivity of polymer gel dosimeters is altering the chemical concentrations of their monomers or/and crosslinkers; for example, it was shown the sensitivity of VIPAR gel dosimeter improves by changing the monomer (N-vinylpyrrolidone) and crosslinker (Bis) amounts in co-solvent solutions (Kozicki et al., 2017).

Referring also to Table 2 of Ref. (Farhood et al., 2019), it is realized that the response-dose sensitivity of optimized PASSAG-U gel dosimeter is more or almost the same with those of VIPAR, PABIG, BANG, U-NIPAM and acrylamide-based gel dosimeters, but less than those of methacrylic based gel dosimeters.

3.3. Temperature dependence

As mention previously, the R_2-dose responses of PASSAG and PASSAG-U gel dosimeters at five temperatures during scanning were assessed and the obtained results are shown in Fig. 3.

According to the data presented in Fig. 3, there are small variations at the response (R_2) of the all gel dosimeters (PASSAG and PASSAG-U) during 15–24 °C scanning temperatures for low and moderate dose values, and these R_2 differences increase for high dose values. In a more detailed analysis of the results, the PASSAG and PASSAG-U gel dosimeters with 1% urea showed a decreasing trend at their responses with increment of the scanning temperature, while the opposite trend was seen in the PASSAG-U gel dosimeter with 5% urea. For PASSAG-U gel dosimeter with 3% urea, it was observed a R_2 value stability over scanning temperature (15–24 °C). Based on the above results, it was be mentioned that the presence of urea in the composition of PASSAG gel dosimeters can lead to a change in the response (R_2) of these gel dosimeters over the scanning temperature. In the recent study on U-NIPAM gel dosimeters (Anaraki et al., 2018), their temperature dependence of R_2 - dose response was investigated in 0–6 Gy dose range and 0–4% urea concentrations. The findings showed that the R_2 values of gel dosimeters decrease with increasing the scanning temperature. In the analysis of the findings of that study with the results of current study, it was found that the results between two study for the dose values up to 6 Gy and the urea concentrations up to 3% were almost same. From practical point of view, it was reported that a temperature increase of 1–3 °C can be happened during a long-term scanning of the gel dosimeters and this temperature increase can be due to the RF power absorption in the gel dosimeter (De Deene, 2004). Our results revealed that increasing the scanning temperature up to 4 °C from room temperature (between 18 and 22 °C) has no considerable effect on the R_2 values of PASSAG-U gel dosimeters ($< 5\%$).

Evaluation of the R_2-dose sensitivity of PASSAG and PASSAG-U gel dosimeters as a function of urea concentration and scanning temperature (Fig. 4) demonstrated that for a certain scanning temperature, an increasing trend at the sensitivity of gel dosimeters is observed over the urea concentration, so that the highest and the lowest amounts of R_2-dose sensitivity were related to 5% and 0% urea, respectively. Moreover, the instability in R_2-dose sensitivity of all gel dosimeters was

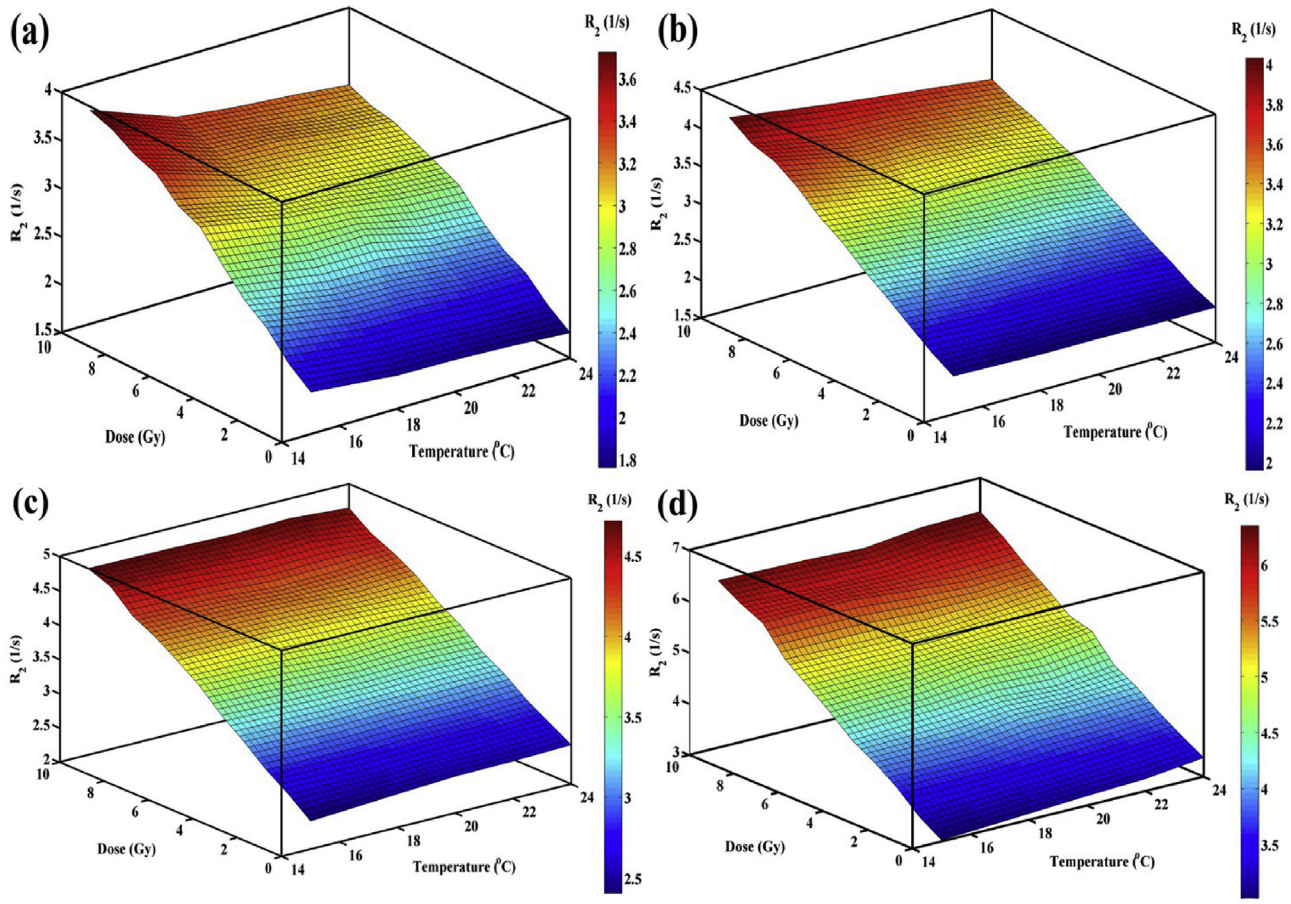

Fig. 3. The R_2-dose response of PASSAG and PASSAG-U gel dosimeters with various percentages of urea as a function of scanning temperature. (a) 0% urea, (b) 1% urea, (c) 3% urea, and (d) 5% urea.

remarkable for 15–18 °C scanning temperatures. There is the R_2-dose sensitivity stability for all gel dosimeters during 18–22 °C scanning temperatures, as the differences of R_2-dose sensitivities for most evaluated points were less than 5%. On the other hand, the findings revealed that for 0%, 1%, and 3% urea concentrations, the R_2-dose sensitivities of gel dosimeters decline with increment of the scanning temperature. Anaraki et al. (2018) reported that for a certain scanning temperature, the R_2-dose sensitivity of U-NIPAM gel dosimeters increases with increasing the urea concentration. Also, they represented that for a certain urea concentration, the R_2-dose sensitivity of these gel

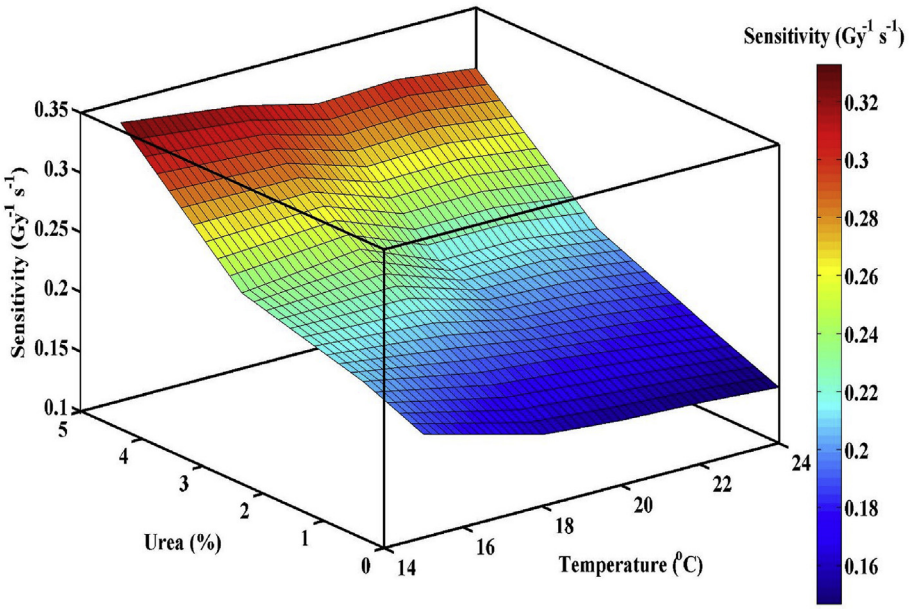

Fig. 4. The R_2-dose sensitivity of PASSAG and PASSAG-U gel dosimeters as a function of urea concentration and scanning temperature.

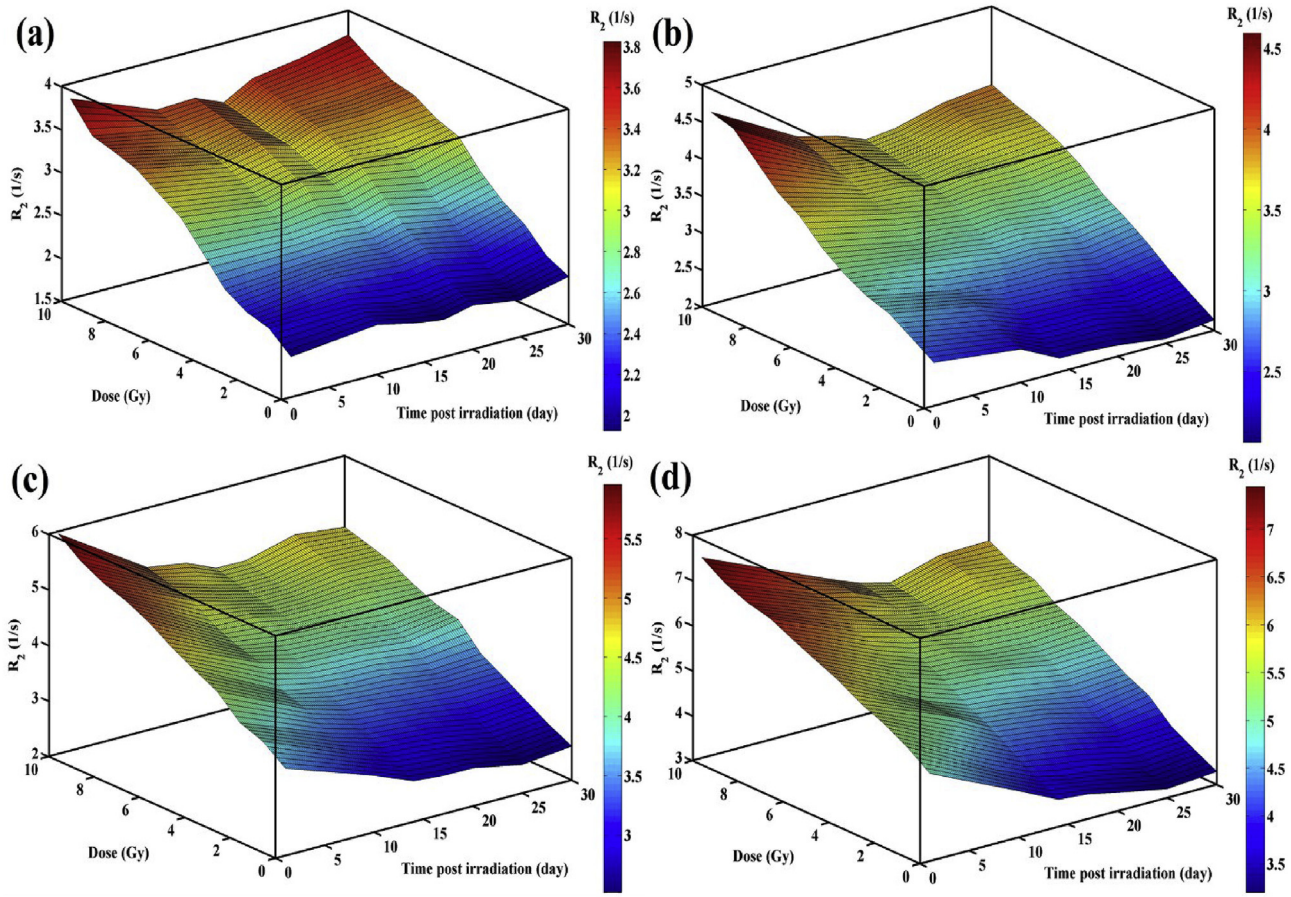

Fig. 5. The R_2-dose response of PASSAG and PASSAG-U gel dosimeters with various percentages of urea as a function of time post irradiation at 18 °C scanning temperature. (a) 0% urea, (b) 1% urea, (c) 3% urea, and (d) 5% urea.

dosimeters is stable between 18 and 21 °C scanning temperatures (Anaraki et al., 2018).

3.4. Temporal stability

The R_2-dose responses of PASSAG and PASSAG-U gel dosimeters with various percentages of the urea were investigated for 1, 10, 14, 17, 20, 25, and 30 days after irradiation and the obtained data are demonstrated in Fig. 5.

The results obtained from Fig. 5 show a temporal stability at the response of PASSAG-U gel dosimeters from 14 to 30 days post irradiation time. The temporal instability of gel dosimeters can be attributed to continuing the polymerization reactions in these gel dosimeters by long-lived radicals, process of monomers' auto polymerization, and structural changes of the gelatin (De Deene et al., 2000, 2002; De Deene, 2004). However, the amount of the auto polymerization of gel dosimeters (unirradiated and irradiated) is different from each other, which its reason may be because of difference in the content of monomers (Anaraki et al., 2018). Moreover, adding the urea to the PASSAG formula causes more instability at the response of gel dosimeters (Abtahi et al., 2014; Gambarini et al., 2001); as these post irradiation time instabilities were remarkable for 3% and 5% urea concentrations. In a recent study (Anaraki et al., 2018), it was shown a temporal instability for U-NIPAM gel dosimeters up to 10 days post irradiation time. Also, it has been reported that the post irradiation time instability of U-NIPAM gel dosimeters increases with increment of the urea concentration (Anaraki et al., 2018).

Also, assessment of the post irradiation time effect on the response of PASSAG-U gel dosimeters (Fig. 5) demonstrated that the R_2 values decline over post irradiation time and this decrease was considerable for short post irradiation times. It is noteworthy that this decreasing trend of the R_2 values was observed for the gel samples irradiated by low dose values or the unirradiated gel samples. These variations in the response of PASSAG-U gel dosimeters can be because of hardening of gelatin matrix of these gel dosimeters by urea. In addition, urea can decrease auto polymerization of monomers through scavenging free radicals and subsequently, it causes decreasing the R_2 values of gel dosimeters over time (Anaraki et al., 2018).

Other results (Fig. 6) demonstrated that the R_2-dose sensitivity of PASSAG-U gel dosimeters varies over post irradiation time; as these improvements in the sensitivity were 3.89–12.14%, 25.15–41.23%, and 27.90–82.52% for the PASSAG-U gel dosimeters with 1%, 3%, and 5% urea, respectively. Moreover, the most improvements in the sensitivity of the PASSAG-U gel dosimeters with 1% (12.14%), 3% (41.23%), and 5% (82.52%) were belonged to 1, 10, and 10 days after irradiation, respectively. In addition, the R_2 - dose sensitivity of PASSAG-U gel dosimeters, for a certain post irradiation time, increased with increasing the urea concentration; as these increases in sensitivity were remarkable for the longer post irradiation times. Moreover, the findings showed a R_2 - dose sensitivity stability for the PASSAG-U gel dosimeters from 10 to 20 days after irradiation.

4. Conclusion

In the present study, the sensitivity of PASSAG gel dosimeter was improved by adding the urea to its structure and this new formula was called PASSAG-U. Compared to the PASSAG gel dosimeter, the R_2-dose sensitivities of PASSAG-U gel dosimeters with 1%, 3%, and 5% urea were improved by 12.14%, 25.15%, and 27.90%, respectively. The dosimetric evaluation of characteristics related to the PASSAG-U gel

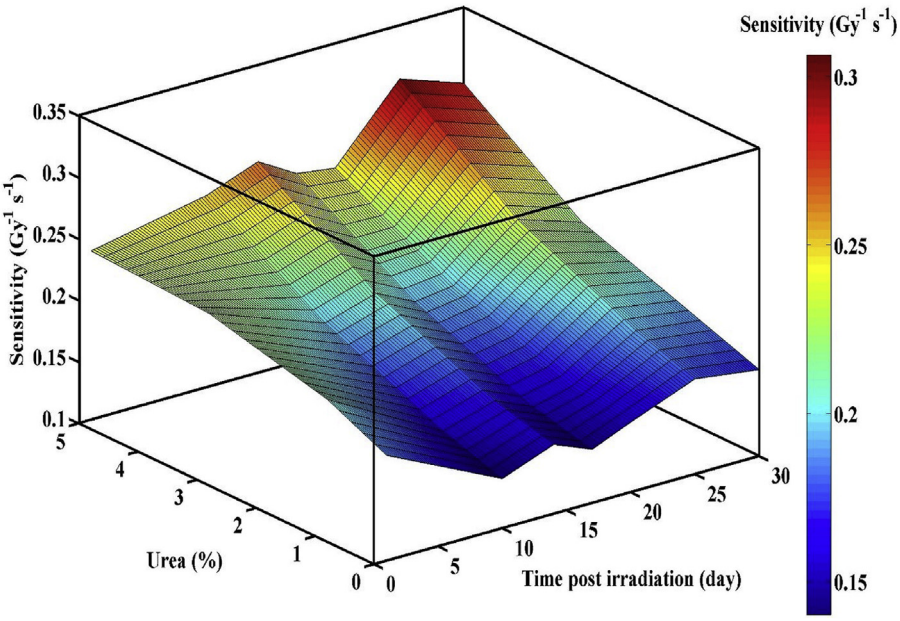

Fig. 6. The R_2-dose sensitivity of PASSAG and PASSAG-U gel dosimeters as a function of urea concentration and time post irradiation at 18 °C scanning temperature.

dosimeters with various urea concentrations resulted to the following conclusions: 1) the radiological properties of PASSAG-U gel dosimeters confirmed soft tissue and water equivalence of the new gel dosimeters; 2) the optimal amount of urea was determined 3%; 3) there were an excellent linear R_2-dose responses for the PASSAG-U gel dosimeters in 0–10 Gy dose range; 4) there was a stability in the R_2 values for 18–22 °C scanning temperatures; 5) there was a temporal stability at the response of PASSAG-U gel dosimeters from 14 to 30 days post irradiation time; 6) the R_2 - dose sensitivity of PASSAG-U gel dosimeters varied over post irradiation time; as these improvements in the sensitivity were 3.89–12.14%, 25.15–41.23%, and 27.90–82.52% for the PASSAG-U gel dosimeters with 1%, 3%, and 5% urea, respectively.

Finally, it can be concluded that although the addition of urea improves the R_2-dose sensitivity of PASSAG gel dosimeter, it leads to the degradation of dose resolution (especially for 5% urea). Therefore, the use of other suitable material substances for increasing the response-dose sensitivity of PASSAG polymer gel dosimeter can be proposed as a subject for further work.

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