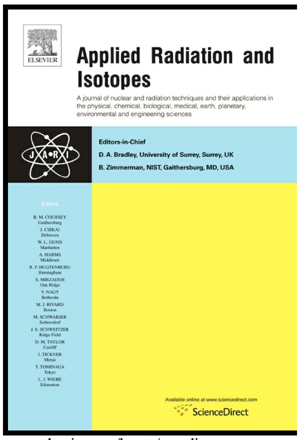
Author's Accepted Manuscript



www.elsevier.com/locate/apradiso

Polymer gel dosimeter based on itaconic acid

Facundo Mattea, David Chacón, José Vedelago, Mauro Valente, Miriam C. Strumia

PII: S0969-8043(15)30125-1
DOI: http://dx.doi.org/10.1016/j.apradiso.2015.07.042
Reference: ARI7071

To appear in: *Applied Radiation and Isotopes*

Received date: 8 June 2015
Accepted date: 25 July 2015

Cite this article as: Facundo Mattea, David Chacón, José Vedelago, Maurc Valente and Miriam C. Strumia, Polymer gel dosimeter based on itaconic acid *Applied Radiation and Isotope*: http://dx.doi.org/10.1016/j.apradiso.2015.07.042

Polymer gel dosimeter based on itaconic acid

Facundo Mattea[a,b], David Chacón[b,c], José Vedelago[d,b], Mauro Valente[b,d], Miriam C. Strumia[e]

a Facultad de Ciencias Químicas, Universidad Nacional de Córdoba, Córdoba, CONICET, Argentina.

b Laboratorio de Investigación e Instrumentación en Física Aplicada a la Medicina e Imágenes por Rayos X (LIIFAMIR^X)- Facultad de Matemática, Astronomía y Física, Universidad Nacional de Córdoba, Córdoba, Argentina

c Departamento de Física, Universidad Nacional, Heredia, Costa Rica.

d Facultad de Matemática, Astronomía y Física, Universidad Nacional de Córdoba, Córdoba, Argentina; Instituto de Física Enrique Gaviola, Córdoba; CONICET, Argentina

e Facultad de Ciencias Químicas, Universidad Nacional de Córdoba, Córdoba, Argentina Instituto Multidisciplinario de Biología Vegetal; CONICET, Argentina.

Tel: +54 351 433-4050 ext. 448, e-mail: fmattea@gmail.com

Keywords: Polymer Gel, Itaconic Acid, Dosimetry, Raman Spectroscopy

ABSTRACT

A new polymeric dosimeter based on itaconic acid and N, N'-methylenebisacrylamide was studied. The preparation method, compositions of monomer and crosslinking agent and the presence of oxygen in the dosimetric system were analyzed. The resulting materials were irradiated with an X-ray tube at 158 cGy/min, 226cGy min and 298 cGy/min with doses up to 1000 Gy. The dosimeters presented a linear response in the dose range 75-1000 Gy, sensitivities of 0.037 Gy-1 at 298 cGy/min and an increase in the sensitivity with lower dose rates. One of the most relevant outcomes in this study was obtaining different monomer to crosslinker inclusion in the formed gel for the dosimeters where oxygen was purged during the preparation method. This effect has not been reported in other typical dosimeters and could be attributed to the large differences in the reactivity among these species.

1.- INTRODUCTION

Diagnostic radiology and radiotherapy are the most used techniques to detect and treat several tumors and cancer diseases. One of the key aspects for a successful radiological treatment is the evaluation of the real dose administrated to the carcinogenic tissue and the risk of damaging the surrounding tissue. In that regard, knowing in advance the 3D dose distribution improves significantly the quality of the radiological procedure. Common dosimeters, such as the ionization chamber, thermoluminescent dosimeters and films, cannot measure the 3D dose distribution because of their limitations to maintain spatial dose information (Ibbott, 2004). One of the best methods so far is the use of polymer gel dosimeters (Sellakumar et al., 2007). Despite of some early studies proving the use of polymers for radiation purposes (Alexander et al., 1954; Hoecker and Watkins, 1958) it was not until 1993 when Maryanski et al. proposed the first dosimeter based on polyacrylamide (PAG) (Maryanski et al., 1993). From that year to the present different systems have been proposed, such as BANG (Maryanski et al., 1994), MAGIC (Fong et al., 2001), MAGAT (De Deene et al., 2002) , PAGAT (Venning et al., 2005), N-isopropylacrylamide (NIPAM) (Senden et al., 2006) and 2- Hydroxyethyl methacrylate (HEMA) (Lepage et al., 2001; Trapp et al., 2005). In these systems acrylic monomers, crosslinking agents and in most of the cases an oxygen inhibiter like Tetrakis-phosphonium chloride (THPC) are homogenously dissolved in an aqueous gel matrix. Ionizing radiation induces the formation of free radicals from water radiolysis to initiate the polymerization and gel formation reactions between the monomers and crosslinking agents, thus producing changes in the physical properties of the material. The amount of formed polymer / hydrogel is related to the absorbed dose by the polymer gel (Baldock et al., 2001). The degradation of the spatial dose information resulting from diffusion mechanisms, which represents the main limitation for Fricke gel dosimetry (Davies and Baldock, 2008; Vanossi et al., 2008), is considerably reduced by the use of polymers. Therefore irradiation and dose measurements can be carried out on different times. The changes in the material's properties can be measured by several techniques, for example magnetic resonance imaging (MRI) (Maryanski et al., 1993), optical CT scanner (Gore et al., 1996; Wuu and Xu, 2011), Raman spectroscopy (Rintoul et al., 2003), ultrasound (Mather et al., 2002) and x-ray tomography (CT) (Hilts et al., 2000).

In the present study a new polymeric system is studied consisting in itaconic acid (ITA), N,N'-methylenebisacrylamide (BIS), an aqueous gelatin solution and THPC as oxygen scavenger. The monomers ITA and BIS have been already studied for hydrogel formation and the polymerization induced by other radical initiation methods has been already proved (Caykara and Akcakaya, 2007). The effect of changes of the concentration of the different species in the sensitivity and dosimetric efficiency for doses from 0 to 1000 Gy was studied by means of Raman spectroscopy and by optical methods.

2.- MATERIALS AND METHODS

2.1. Gel Dosimeter Preparation

Different compositions and procedures were used to manufacture the dosimeters. Itaconic acid (≥ 99% purity) and BIS (99% purity) purchased from Sigma Aldrich® were used as monomer and crosslinking agent respectively. An aqueous solution of Gelatin 300 Bloom purchased from FLUKA and a buffer solution with equimolar quantities of sodium phosphate monobasic and sodium phosphate dibasic, both with analytical grade and a total concentration of 2M were used as to prepare the support matrix of the dosimeters. The phosphate buffer solution was used instead of water to avoid the gelatin rupture because of the low pH value obtained when ITA was added to the solution. For the dosimeter preparation, first the gelatin was mixed with the buffer solution at ambient temperature and heated up to 50ºC for 30 minutes, then the temperature was lowered to 37 ºC to avoid polymerization of the monomers during the dosimeter preparation. Afterwards, BIS was mixed for 15 minutes, then the ITA was incorporated and stirred for another 15 minutes. Finally, 10% of the buffer volume with THPC was incorporated at 37ºC and the mixture was stirred for 30 minutes. The final solution was used to fill poly-methyl methacrylate box shaped vessels (cuvette) of 10x10x44 mm^3, no air was left at the top of the vessels to avoid the effects associated with the presence of oxygen above the THPC antioxidant capacity. The dosimeters were stored for 24hr at 4ºC until irradiation for stabilization purposes. For the experiments without oxygen, N_2 (>99.999% purity) was bubbled during the mixing of the monomers and the whole setup was sealed to avoid the incorporation of O_2. The final concentration of gelatin 300 Bloom: and THPC where 5% w/w and 0.1% w/w respectively. These values were already tested in a feasibility study of the ITA-BIS system and selected according to typical values used by other authors (Chang et al., 2011b; Deene et al., 2006).

2.2. Dosimeter Irradiation

Samples irradiations were carried out in a conventional X-ray tube with a W anode available at LIIFAMIR$^{\otimes}$ facilities. The tube is connected to a generator with a maximum power of 3 kW that provides electrical current values from 5 to 60 mA, and voltage values from 20 to 60 kV. Different beam configurations can be achieved with this setup. In most of the irradiation experiments an electrical current of 44 mA and voltage of 44 kV were used, obtaining a dose rate of an approximate dose of 298 cGy/min. To measure the absolute dose rate a calibrated Farmer type ionization chamber (PTW-Freiburg TN 30013) was used, in water-equivalent phantoms. The samples were rotated at 6 rpm during the irradiation experiments in order to obtain a homogeneous absorbed dose.

2.3. Dosimeter Characterization

The degree of polymerization or gel formation in the irradiated dosimeters was studied by means of three different methods. A chemical description and quantification was performed by Raman Spectroscopy with a Labram HR (Horiba Jobin-Yvan) Raman spectrometer using a 632.8 He-Ne Laser with a 6.3 mV power. Spectra of the irradiated dosimeters were analyzed by comparing the area of some of the characteristic peaks for the stretching of C=C bonds in the ITA and BIS molecules. Also optical variations on the cuvette dosimeters were analyzed by means of a Shimadtzu spectrophotometer UV-260 by measuring changes on the optical absorbance at wavelengths from 290 nm to 550 nm. A wavelength ranging from 426 nm to 436 nm was used for comparing the irradiated dosimeters with non-irradiated ones. Finally, a series of dosimeters irradiated at different doses were lyophilized for 12 hs, then sputtered with a 5 nm chrome layer in an argon atmosphere, and scanning electron microscope images of the surface of these samples were acquired with a scanning electron microscope (FE-SEM Sigma, Carl Zeiz) using an acceleration voltage of 8 kV.

3.- RESULTS AND DISCUSSION

3.1. Dose response

In an initial study, the feasibility of using itaconic acid and N, N'- methylenebisacrylamide in a gelatin based matrix to evaluate and quantify dose distributions during typical X-ray irradiation applications was proved (Mattea et al., 2015). Nevertheless a thorough study of the limiting dose ranges, effects of changes on the composition of the different compounds present in the dosimeters and the dependence of the dosimeter's behavior with dose rates were not previously performed and are informed within this article. In the first approach of testing the potentiality of this material as a polymeric dosimeter for therapeutic applications, relatively high doses were necessary to obtain a reliable response, especially when optical methods were used to characterize the results. Doses ranging from 0 to 175 Gy were assayed obtaining linear responses for doses higher than 75 Gy. Also, a value of 30 Gy was observed as a minimum threshold to obtain a recordable change in the optical density of the ITA-BIS dosimeters after their irradiation. In this study the maximum dose assayed was 1000 Gy and at this high dose values a linear response was achieved. Figure 1 shows the dosimeters irradiated at doses ranging from 0 to 1000 Gy.

(FIGURE 1)

These dosimeters were characterized by mean of FT-Raman spectroscopy and UV-Vis spectroscopy and the results are presented in Figure 2 and Figure 3 respectively.

(FIGURE 2)

A linear response was observed in the ΔOD measurements for dose values ranging from 75 to 1000 Gy with a R^2 value of 0.996 and with a sensitivty of 0.037 Gy^{-1}.

(FIGURE 3)

The reported results from Raman spectra were obtained from the characterization method consisting on comparing the area of the charactistics peaks for the stretching of the C=C bond in the ITA and BIS molecules to the area of the stretching of the C=C bond in the ITA molecules in the non irradiated dosimeters. In that regard, the dissapearance of C=C bond after the irradiation in each compound can provide information about the degree of polymerization and about the type of polymer or gel formed during the irradiation. All the experimental data obtained by this characterization method was fitted with the following mathematical expression:

$$\frac{INT}{INT_{ITA0}} = 100 - a\,(1 - e^{-b\,DOSE})$$

A similar expression to fit the formation of new C-C bonds in a polymeric dosimeters based on N-isoprpylacrylamide and BIS was presented by Huang et al. (Huang et al., 2013).

In Figure 4 SEM images of the surface's morphhology of dosimenters irradiated at doses ranging from 0 to 1000 Gy can be obseved.

(FIGURE 4)

From these images it is clear that for doses below 50 Gy a very small amount of the ITA-BIS hydrogel is formed, and after the freeze drying process only the structure of the gelatin can be observed as fibers or rods. At higher doses the surface of the irradiated samples selected for the SEM analysis becomes smother and homogeneos, indicating that a larger concentration of hydrogel is present after the irradiation. Finally, at 1000 Gy every part of the surface of the sample is smooth and homogeneous only presenting subtle height differences. In a similar study of a N-isopropylacrylamide (NIPAM) –BIS based dosimeter (Huang et al., 2013) the authors observed that at the two highest doses the material presented very similar homogenous and smooth morphology and because of that, they concluded that the saturation point of that system was reached. In the present study it is not possible to assert that the saturation point was met just from the SEM analysis. Nevertheless, considering the results of the ΔOD analysis together with SEM images it is possible to conclude that 1000 Gy it's still below the saturation limit of the ITA-BIS system. Moreover, comparing the slope of the ΔOD analysis in different dose intervals (100 Gy to 1000 Gy, 100 Gy to 500Gy and 250 Gy to 1000 Gy) there is only a maximun difference of 6% among them, thus indicating that at 1000 Gy the behavior of the ΔOD with an increase of dosis is still on the linear section of the sigmoidal typical behavior for polymer based dosimeters.

3.2. Effects of changes in %T

Different compositions were assayed to study the dose response of the ITA-BIS dosimeters, Table 1 summarizes the different concentrations used in this study, %T and %C are total mass percent of monomers in the gel system and the mass percent of the monomer mixture that acts as a crosslinking agent, respectively. In the present study a dosimeter concentration of 4.6T and 34C was taken as reference value for the variable analysis assays. This value was previously tested (Mattea et al., 2015) and it was selected to keep a molar ratio between the monomers and crosslinker of 2:1 and a relatively high concentration of total monomers considering the solubility limits of the monomers.

(TABLE 1)

The optical behavior of the 4.6T, 34C dosimeters can be observed in Figure 3. The dosimetric system ITA-BIS presented a sigmoidal behavior like other polymeric dosimeters, however the initial dose neccesary to obtain a clear distinguishale and reliable response by optical methods was relatively high compared with other polymeric dosimeters (Basfar et al., 2015; Chen et al., 2014). The effect of changes in the total reactive material concentration can be observed in Figure 5 and Figure 6.

(FIGURE 5)

Both compounds, monomer and crosslinker, are being consumed proportionally at every studied %T, which indicates the formation of an homogeneous material at different doses. For concentations below 4T the response of the ITA-BIS dosimeters was not good enough for dosimetric purposes and the maximum extent of the polymerization and gelification reactions only involves aproximately 15% of the reactive compounds.

(FIGURE 6)

From the Raman characterization it can be observed that a great increase in the reaction degree was achieved by increasing the total concentration from 4.6T to 5.2T. However, this effect was not clearly observed in the optical density characterization, as it can be apreciated in Figure 6, reporting that only a relatively small increase on the sensitivity of material was achieved. Increasing the total concentration to values higher than 5.2T was not possible because of the solubiltiy limits of BIS and ITA compounds.

3.3. Effects of O_2 inhibition.

The presence of oxygen during the polymerization and hydrogel formation has the same outcome that for other types of radical polymerization inhibitors, and it has been proved to have a severe impact over the performance of polymeric dosimeters (Hepworth et al., 1999). The use of oxgyegn scavengers such as THPC has simplified the preparation of polymeric dosimeters, however there are some issues to be investigated about the effect of this substance over the gelatin matrix, like the reaction with the amine groups of the gelatine matrix and the increase of the gelatin cross-linking (Jirasek et al., 2006). Actually, Sedaghat et al. showed results where the concentration of THPC could lead to changes in the accuracy and reproducibility of normoxic dosimeters (Sedaghat et al., 2012). For the experiments reported in the present study, a comparison between dosimeters prepared with THPC at atmospheric conditions and in a N_2 atmosphere has been done to check if the typical antioxidant concentration was suitable for the ITA-BIS based material. The results are depicted in Figure 7.

(FIGURE 7)

Raman analysis of these results provides useful information on the effect of oxygen present in the dosimeters when 5mM of THPC is present as oxygen scavenger. A clear effect on the consumption of ITA molecules was observed when O_2 was removed from the dosimeters, oxygen even at low concentrations has a higher impact on the reaction of the less reactive monomers in the system. These reults suggests that a different structure of hydrogel could be formed during the irradiation. What is more, by comparing these results, where information about the vynil group consumption was evaluated, with the optical changes observed in these dosimeters (Figure 8) it becomes clear that a different hydrogel was obtained where more BIS relative to ITA was incorporated into de hydrogel matrix.

(FIGURE 8)

This effect is not new, in fact it is well known that O_2 acts as plymerization inhibitor and limits the length of polymer chains during the polymerization (Billmeyer, 1984). This effect leads to a less crosslinked matrix with a less significant incoporation of BIS in the formed hydrogel and despite of observing a similar reduction in the intensisty of the raman spectra area corresponding to the vynil groups of the monomers, a less dense material is obtained with different light absorption.

3.4. Effects of Dose Rate

There are some different reports on how dose rate affects the dosimetric sensitivity on polymeric dosimeters, a high dose rate produces a higher concentration of water radicals which, depending on the concentration of monomers, could enhance the polymerization and gel formation reactions. For the NIPAM-BIS system for example, Huang et al. (Huang et al.,

2013) reported a decrease of 33% in the dose sensitivity with an increase in the dose rate from 200 cGy/min to 600 cGy/min. On the other hand, Chang et al. (Chang et al., 2011a) observed the oposite effect, an increase of almost 33% in the sensititvty when the dose rate was varied from 100 cGy/min to 500 cGy/min, in both cases the experimentes were carried out under 6 MV X-ray energy. Also Senden et al. (Senden et al., 2006) studied the NIPAM-BIS dosiemter at two different dose rates of 55 cGy/min and 272 cGy/min observing no significant difference among the results, but concluding that further studies would be necessary to claim such effect. In the present study the results with variations in the dose rate can be observed in Figures 9 and 10. It has to be pointed out that the linear energy transfer, and associated ionization density, for kilovoltage and megavoltage X-ray beams may differ. Thus, the reported results obtained for variations of dose rates might not be directly comparable with high energy beams. But, no extreme differences would be obtained, qualitatively and also quantitatively.

(FIGURE 9)

(FIGURE 10)

The sensitivity calculated from the slope of the optical absorbance cruves are 0.037 at 298 cGy/min, 0.071 at 226 cGy/min and 0.096 at 158 cGy/min, observing a 61% increase in the sensitivity.

4.- CONCLUSIONS

A new dosimetric system composed by itaconic acid and N,N'- methylenebisacrylamide was studied for X-ray dosimetric purposes. The irradiation with a X-ray source was performed from 0 Gy to 1000 Gy using a dose rate of 298 cGy/min. Also the influence of dose rate was studied obtaining an increase in the dose sensitivity of 61% when the dose rate was decreased from 298 CGy/min to 158 cGy/min. Two different aproaches were used to analize the amount and quality of the polymer formed during the irradiation. First by measuring the optical density changes of the dosimeters irradiated with different doses observing a linear behaviour between 75 Gy and 1000 Gy. On a second hand, the dosimeters were analyzed by Raman spectroscopy looking for chemical differences that provides information on the consumption of the different species during the polymerization induced by the X-ray irradiation. A different consumption rate was observed for the monomer and the crosslinking agent when the dosimeters were prepared in the absence of oxygen. One of the main differences between the ITA-BIS system and other typical polymeric dosimeters, such as NIPAM-BIS, PAG, etc. is the relative reactivity of the monomer and crosslinking agent. In the studied system the ITA molecules have less probability to react and to form part of the gel ITA-BIS matrix. Therefore, these molecules have a high sensivity to changes that could inhibit the polymerization reactions, such as O_2 inhibition, or a chemical inhibition. As a consequence, a different structure of the hydrogel could formed within the dosimeter and with a different optical atenuation. On of the main motivations to analyze the effect of traces of O_2, in a normoxic dosimeter, was the to evaluate the high threshold dose value required to obtain the polymerization. Presumptions regarded an inhibition effect or inherent characteristics of the dosimetric material. No differences were observed in the dose threshold within the dosimeters when O_2 was removed, which is a typical oxygen effect in polymer gel dosimeters (De Deene et al., 2002). THPC was always added to the dosimeters and the effects of THPC in polymer dosiemters were expected, such as the reduction in the consumption of the monomers in the presence of THPC (Sedaghat et al., 2012).

Acknowledgments

This study was partially financed by the Argentinean Government by means of the PIP 112-

20110101029 and PIP 11420090100398 projects, and the PICT 2011-0654 FONCyT Res 140/12 and PICT 2008/0398 ANPCyT projects. The authors would also like to thank PME (2006) 1544 grants for Raman measurements in LANN of SNM and the Universidad of Costa Rica for the financial support.

REFERENCES

Alexander, P., Charlesby, A., Ross, M., 1954. The Degradation of Solid Polymethylmethacrylate by Ionizing Radiation. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 223, 392-404.

Baldock, C., Harris, P.J., Piercy, A.R., Healy, B., 2001. Experimental determination of the diffusion coefficient in two-dimensions in ferrous sulphate gels using the finite element method. Australas. Phys. & Eng. Sci. Med. 24, 19-30.

Basfar, A.A., Moftah, B., Rabaeh, K.A., Almousa, A.A., 2015. Novel composition of polymer gel dosimeters based on N-(Hydroxymethyl)acrylamide for radiation therapy. Radiation Physics and Chemistry 112, 117-120.

Billmeyer, F.W., 1984. Part 2. Polymerization, Textbook of polymer science, 3rd ed. John Wiley & Sons, New York, pp. 55-68.

Caykara, T., Akcakaya, I., 2007. Swelling behaviors of ionic poly(N,N-dimethylacrylamide-co-acrylamide) hydrogels in various media. Journal of Applied Polymer Science 104, 2140-2145.

Chang, K.-Y., Shih, T.-Y., Hsieh, B.-T., Chang, S.-J., Liu, Y.-L., Wu, T.-H., Wu, J., 2011a. Investigation of the dose characteristics of an n-NIPAM gel dosimeter with computed tomography. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 652, 775-778.

Chang, Y.-J., Hsieh, B.-T., Liang, J.-A., 2011b. A systematic approach to determine optimal composition of gel used in radiation therapy. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 652, 783-785.

Chen, Y.-L., Hsieh, B.-T., Chiang, C.-M., Shih, C.-T., Cheng, K.-Y., Hsieh, L.-L., 2014. Dose verification of a clinical intensity-modulated radiation therapy eye case by the magnetic resonance imaging of N-isopropylacrylamide gel dosimeters. Radiation Physics and Chemistry 104, 188-191.

Davies, J.B., Baldock, C., 2008. Sensitivity and stability of the Fricke–gelatin–xylenol orange gel dosimeter. Radiation Physics and Chemistry 77, 690-696.

De Deene, Y., Hurley, C., Venning, A., Vergote, K., Mather, M., Healy, B.J., Baldock, C., 2002. A basic study of some normoxic polymer gel dosimeters. Physics in Medicine and Biology 47, 3441.

Deene, Y.D., Vergote, K., Claeys, C., Wagter, C.D., 2006. The fundamental radiation properties of normoxic polymer gel dosimeters: a comparison between a methacrylic acid based gel and acrylamide based gels. Physics in Medicine and Biology 51, 653.

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. Physics in Medicine and Biology 46, 3105.

Gore, J.C., Ranade, M., Maryañski, M.J., Schulz, R.J., 1996. Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: I. Development of an optical scanner. Physics in Medicine and Biology 41, 2695.

Hepworth, S.J., Leach, M.O., Doran, S.J., 1999. Dynamics of polymerization in polyacrylamide gel (PAG) dosimeters: (II) modelling oxygen diffusion. Physics in Medicine and Biology 44, 1875.

Hilts, M., Audet, C., Duzenli, C., Jirasek, A., 2000. Polymer gel dosimetry using x-ray computed tomography: a feasibility study. Physics in Medicine and Biology 45, 2559.

Hoecker, F.E., Watkins, I.W., 1958. Radiation polymerization dosimetry. The International Journal of Applied Radiation and Isotopes 3, 31-35.

Huang, Y., Hsieh, L., Chang, Y., Wang, T., Hsieh, B., 2013. Characterization of the chemical stability of irradiated N-isopropylacrylamide gel dosimeter. Radiation Physics and Chemistry 89, 76-82.

Ibbott, S.G., 2004. Applications of gel dosimetry. Journal of Physics: Conference Series 3, 58.

Jirasek, A., Hilts, 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. Physics in Medicine and Biology 51, 1891.

Lepage, M., Jayasakera, P.M., Bäck, S.Å.J., Baldock, C., 2001. Dose resolution optimization of polymer gel dosimeters using different monomers. Physics in Medicine and Biology 46, 2665.

Maryanski, M.J., Gore, J.C., Kennan, R.P., Schulz, R.J., 1993. NMR relaxation enhancement in gels polymerized and cross-linked by ionizing radiation: A new approach to 3D dosimetry by MRI. Magnetic Resonance Imaging 11, 253-258.

Maryanski, M.J., Schulz, R.J., Ibbott, G.S., Gatenby, J.C., Xie, J., Horton, D., Gore, J.C., 1994. Magnetic resonance imaging of radiation dose distributions using a polymer-gel dosimeter. Physics in Medicine and Biology 39, 1437.

Mather, M.L., Whittaker, A.K., Baldock, C., 2002. Ultrasound evaluation of polymer gel dosimeters. Physics in Medicine and Biology 47, 1449.

Mattea, F., Romero, M.R., Vedelago, J., Quiroga, A., Valente, M., Strumia, M.C., 2015. Molecular structure effects on the post irradiation diffusion in polymer gel dosimeters. Applied Radiation and Isotopes 100, 101-107.

Rintoul, L., Lepage, M., Baldock, C., 2003. Radiation Dose Distribution in Polymer Gels by Raman Spectroscopy. Applied Spectroscopy 57, 51-57.

Sedaghat, M., Bujold, R., Lepage, M., 2012. Preliminary studies on the role and reactions of tetrakis(hydroxymethyl)phosphonium chloride in polyacrylamide gel dosimeters. Physics in Medicine and Biology 57, 5981.

Sellakumar, P., James Jebaseelan Samuel, E., Supe, S.S., 2007. Water equivalence of polymer gel dosimeters. Radiation Physics and Chemistry 76, 1108-1115.

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. Physics in Medicine and Biology 51, 3301.

Trapp, J.V., Leach, M.O., Webb, S., 2005. Preliminary dose response study of a gel dosimeter using 2-Hydroxyethyl Methacrylate (HEMA). Australas. Phys. & Eng. Sci. Med. 28, 172-174.

Vanossi, E., Carrara, M., Gambarini, G., Mariani, M., Valente, M., 2008. Study of polymer gel for dose imaging in radiotherapy. Radiation Measurements 43, 442-445.

Venning, A.J., Hill, B., Brindha, S., Healy, B.J., Baldock, C., 2005. Investigation of the PAGAT polymer gel dosimeter using magnetic resonance imaging. Physics in Medicine and Biology 50, 3875.

Wuu, C.-S., Xu, Y., 2011. 3-D dosimetry with optical CT scanning of polymer gels and radiochromic plastic dosimeter. Radiation Measurements 46, 1903-1907.

FIGURE CAPTIONS

Figure 1.- ITA-BIS dosimeters irradiated with doses from 0 to 1000 Gy.

Figure 2.- Raman spectroscopy analysis for vinyl C=C groups in ITA and BIS molecules relative to the initial C=C groups in ITA molecules, in dosimeters with 4.6T 34C irradiated at doses ranging from 0 to 1000 Gy

Figure 3.- Radiological sensitivity obtained by means of UV-Vis absorbance measurements in dosimeters with 4.6T 34C irradiated at doses from 0 to 1000 Gy.

Figure 4. – SEM images of ITA-BIS dosimeters irradiated at different total dosis from 0Gy to 1000 Gy, obtained with an acceleration voltage of 8Kv and a magnification of 40k x.

Figure 5.- Raman spectroscopy analysis for vinyl C=C groups in (a) ITA molecules and (b) BIS molecules, for dosimeters with different total monomer concentrations (5.2T, 4.6T, 4.0 T and 3T) and a fixed monomer to crosslinker ratio (34C).

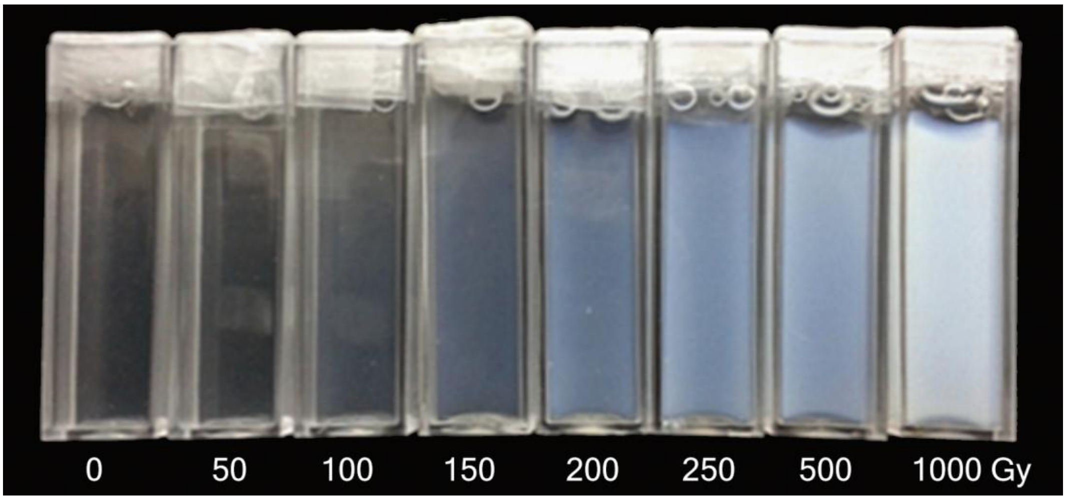
Figure 6. – Sensitivity obtained from the slope of the linear regressions calculated from the UV-Vis spectroscopy characterization of ITA-BIS dosimeters with different %T values (3T, 4T, 4.6T and 5.2 T)

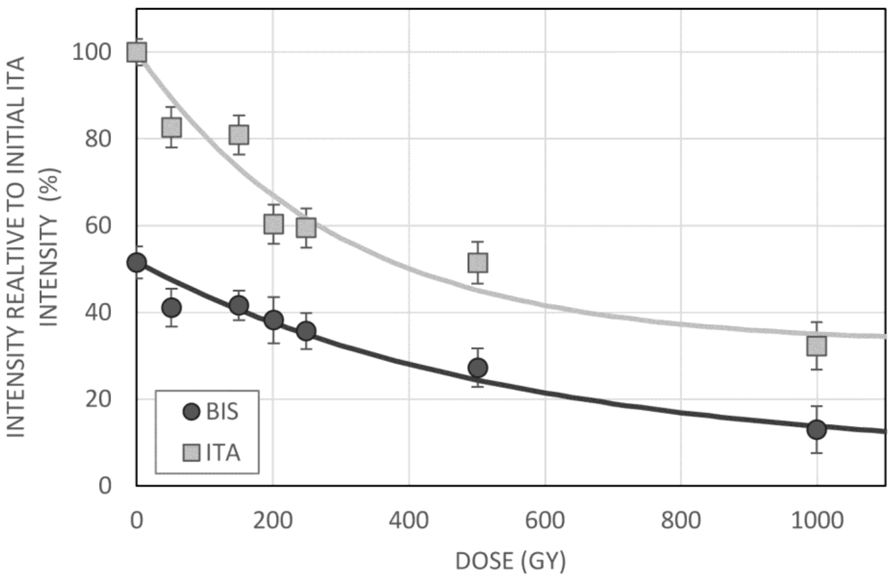
Figure 7. – Raman analysis of ITA-BIS dosimeters with and without a N_2 atmosphere irradiated with doses ranging from 0 to 250 Gy.

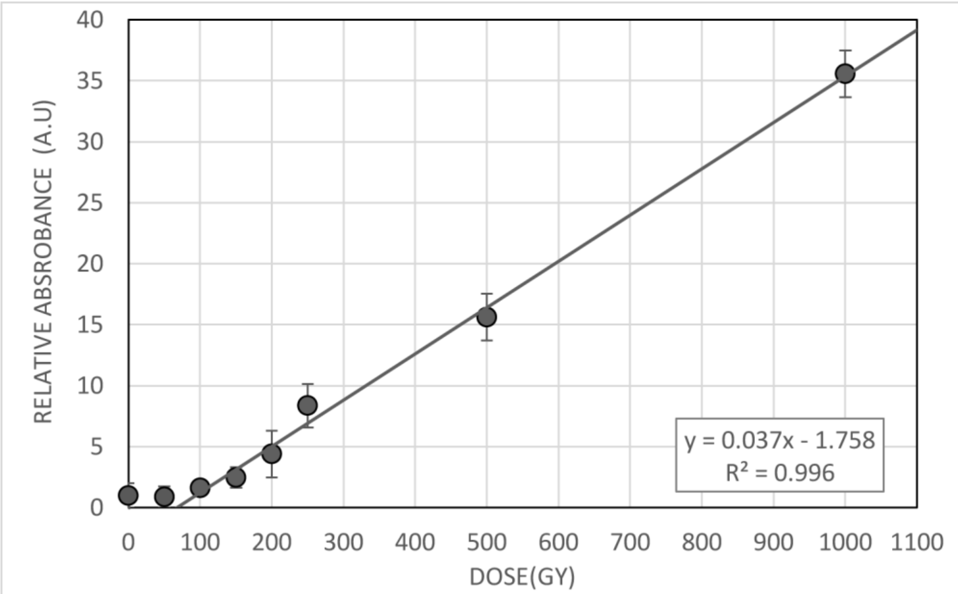
Figure 8. – Optical analysis of ITA-BIS dosimeters with and without a N_2 atmosphere irradiated with doses ranging from 0 to 250 Gy.

Figure 9. – Raman analysis of 4.6T ITA-BIS dosimeters irradiated with different dose rates from 0 to 250 Gy.

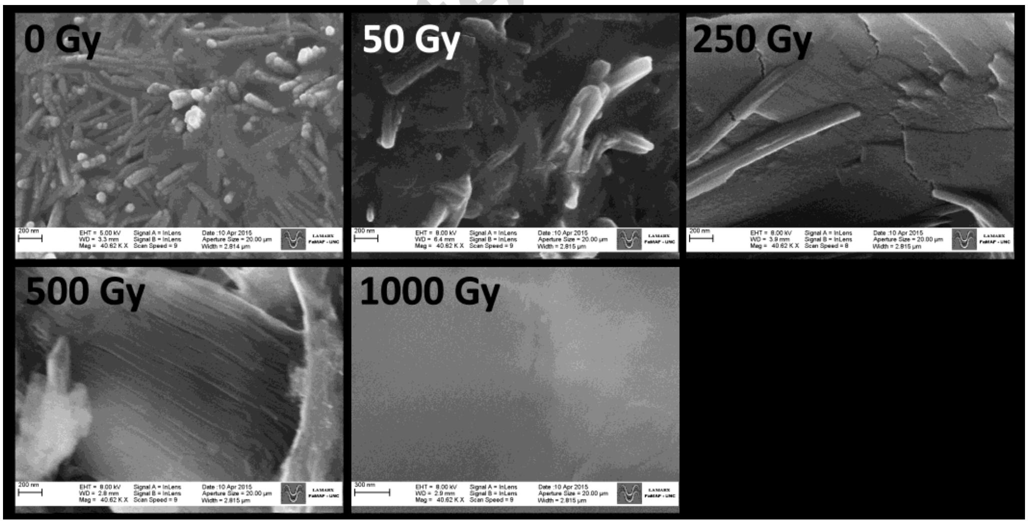
Figure 10. – Optical analysis of 4.6T ITA-BIS dosimeters irradiated with different dose rates from 0 to 250 Gy.


0
50
100
150
200
250
500
1000 Gy

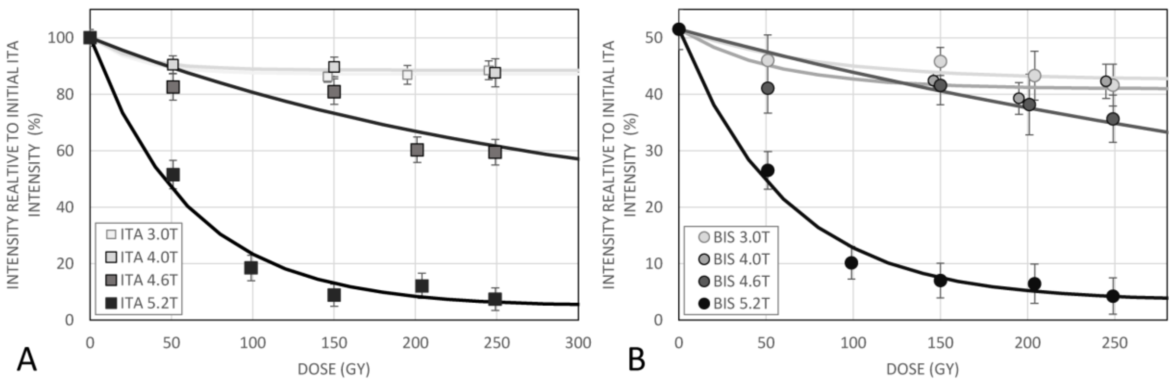

INTENSITY REALTIVE TO INITIAL ITA INTENSITY (%)
100
80
60
40
20
0
0
200
400
600
800
1000
DOSE (GY)
BIS
ITA



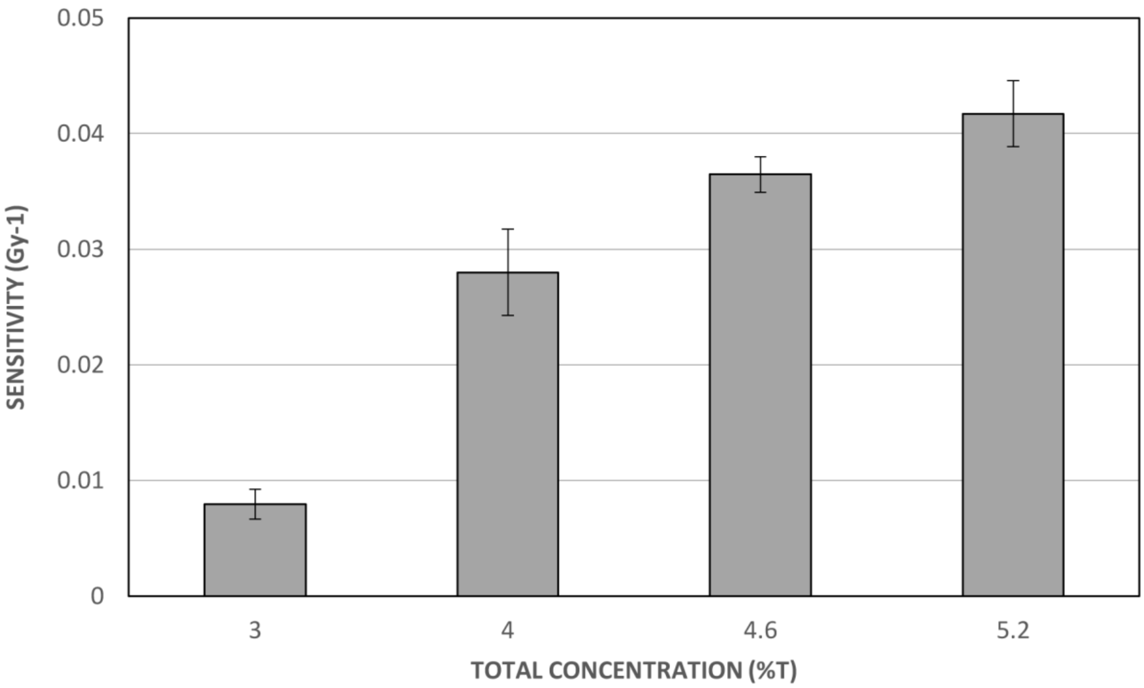
RELATIVE ABSROBANCE (A.U)
0
5
10
15
20
25
30
35
40
0 100 200 300 400 500 600 700 800 900 1000 1100
DOSE(GY)
y = 0.037x - 1.758
R² = 0.996



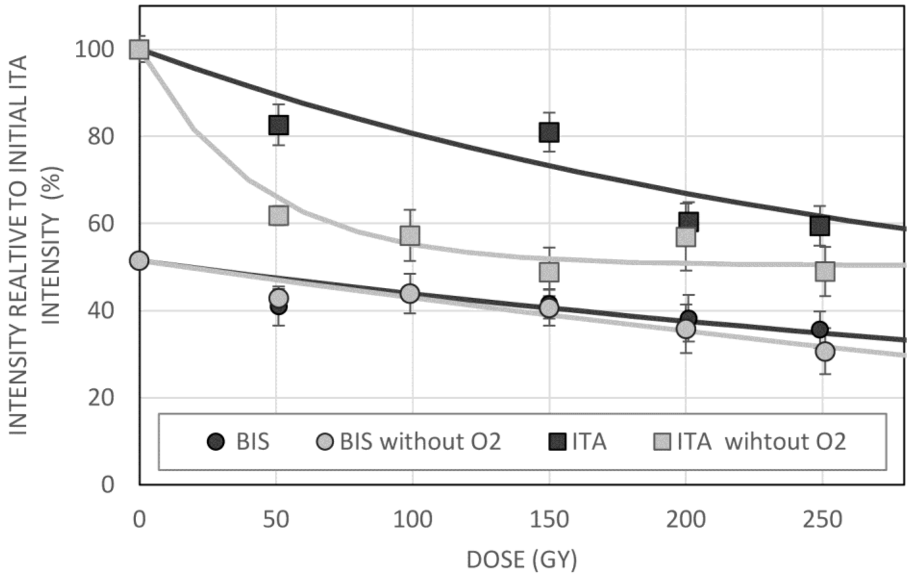
0 Gy
50 Gy
250 Gy
500 Gy
1000 Gy

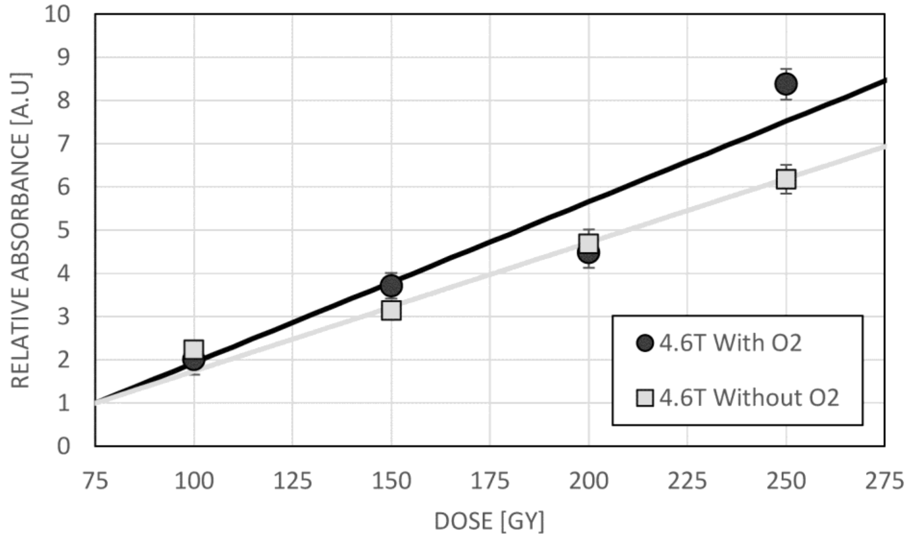


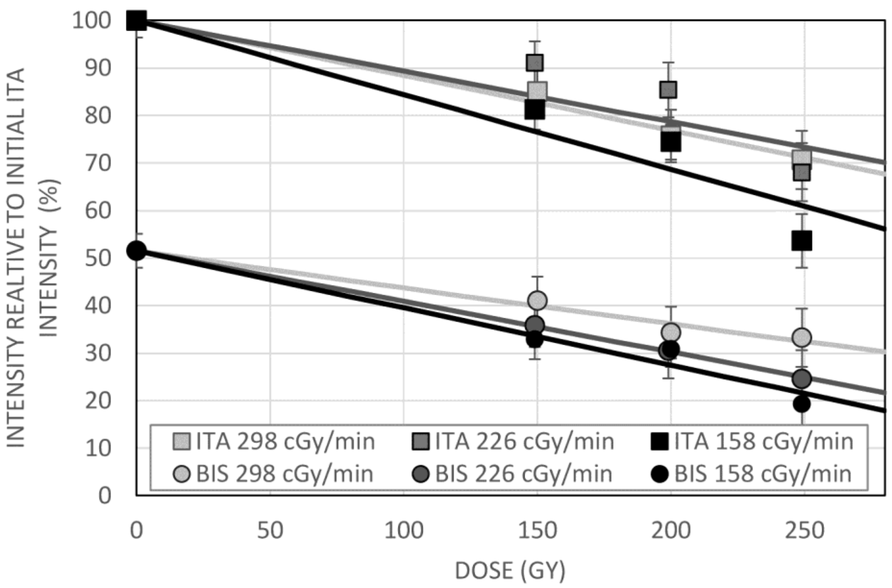
INTENSITY REALTIVE TO INITIAL ITA INTENSITY (%)
DOSE (GY)
ITA 3.0T
ITA 4.0T
ITA 4.6T
ITA 5.2T
A
INTENSITY REALTIVE TO INITIAL ITA INTENSITY (%)
DOSE (GY)
BIS 3.0T
BIS 4.0T
BIS 4.6T
BIS 5.2T
B



SENSITIVITY (Gy-1)
TOTAL CONCENTRATION (%T)
3
4
4.6
5.2


INTENSITY REALTIVE TO INITIAL ITA INTENSITY (%)
100
80
60
40
20
0
0
50
100
150
200
250
DOSE (GY)
BIS
BIS without O2
ITA
ITA wihtout O2


RELATIVE ABSORBANCE [A.U]
10
9
8
7
6
5
4
3
2
1
0
75
100
125
150
175
200
225
250
275
DOSE [GY]
4.6T With O2
4.6T Without O2


INTENSITY REALTIVE TO INITIAL ITA INTENSITY (%)
DOSE (GY)
ITA 298 cGy/min
ITA 226 cGy/min
ITA 158 cGy/min
BIS 298 cGy/min
BIS 226 cGy/min
BIS 158 cGy/min
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250

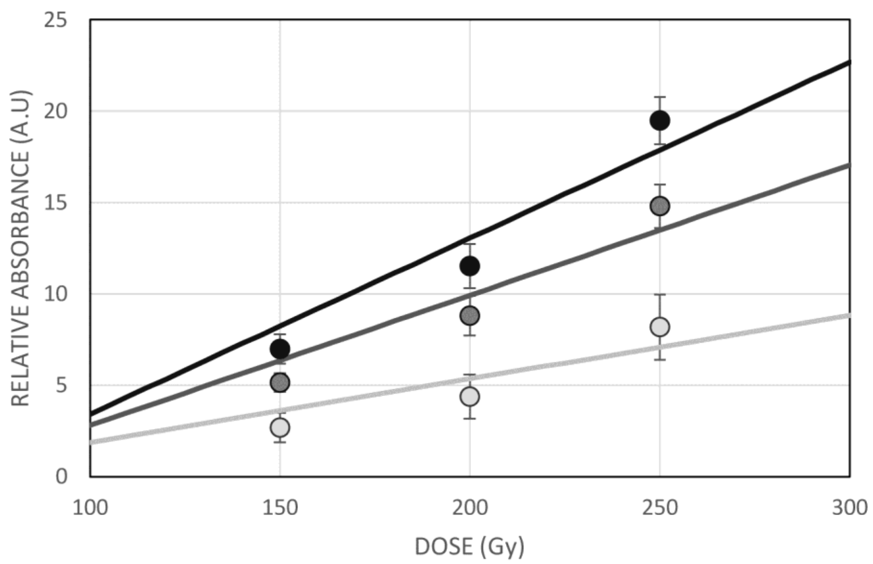

RELATIVE ABSORBANCE (A.U)
DOSE (Gy)
0
5
10
15
20
25
100
150
200
250
300

Table 1.- Dosimeter compositions and preparation methods.

%T w/w	%C w/w	METHOD DETAILS	DOSE RANGE (Gy)	GOALS
3	34		0 - 250	Inhibitors effect, %T effect
4	34	Standard	0 - 250	%T effect
4.6	34	Standard	0 - 1000	%T effect, reference value
5.2	34	Standard	0 - 250	%T effect
4.6	34	N_2 atmosphere	0 -250	O_2 effect, THPC efficiency
4.6	34	Standard	0-250	Dose rate effect

highlight

- A novel polymer gel dosimeters based on itaconic acid is presented and characterized
- The typical linear trend of the dose behavior in a specific dose range was found
- It is reported that different gel structures were formed when oxygen and an antioxidant were present
- Absorbed dose is univocally correlated with optic absorbance and Raman spectroscopy
- Itaconic acid appears as a reliable radiation dosimeter that may be further improved