

Determine the Dose Distribution Using Ultrasound Parameters in MAGIC-f Polymer Gels

Dose-Response:
An International Journal
January-March 2016:1-7
© The Author(s) 2016
DOI: 10.1177/1559325815625647
dos.sagepub.com



Hossein Masoumi¹, Manijhe Mokhtari-Dizaji¹, Azim Arbabi², and Mohsen Bakhshandeh³

Abstract

In this study, using methacrylic and ascorbic acid in gelatin initiated by copper (MAGIC-f) polymer gel after megavoltage energy exposure, the sensitivity of the ultrasound velocity and attenuation coefficient dose-dependent parameters was evaluated. The MAGIC-f polymer gel was irradiated under 1.25 MeV cobalt-60, ranging from 0 to 60 Gy in 2-Gy steps, and received dose uniformity and accuracy of $\pm 2\%$. After calibration of the ultrasonic systems with a frequency of 500 kHz, the parameters of ultrasound velocity and attenuation coefficient of the irradiated gel samples were measured. According to the dose–response curve, the ability of ultrasonic parameters was evaluated in dose rate readings. Based on a 4-order polynomial curve, fitted on the dose–response parameters of ultrasound velocity and attenuation coefficient and observed at 24 hours after irradiation, ultrasonic parameters had more sensitivity. The sensitivity of the dose–velocity and dose–attenuation coefficient curves was observed as 50 m/s/Gy and 0.06 dB/MHz/Gy over the linear range of 4 to 44 Gy, respectively. The ultrasonic parameters at 5°C, 15°C, and 25°C on the gel dosimeter after 0 to 60 Gy irradiation showed that readings at 25°C have higher sensitivity compared to 15°C and 5°C. Maximum sensitivity time and temperature readings of the MAGIC-f ultrasonic parameters were concluded 24 hours after irradiation and at a temperature of 25°C.

Keywords

polymer gel, MAGIC-f, radiation dosimetry, velocity, attenuation coefficient

Introduction

A conventional dosimeter is used to measure the dose at a point or in a plane, which may have some limitations. For example, the dimensions of the ionization chamber in high-dose or low-resolution thermoluminescent dosimetry may not be suitable for 3-dimensional (3D) dosimetry. Therefore, it is recommended to use a dosimeter that has these restrictions and to measure the dose levels more accurately in the 3 dimensions to be used in the areas.¹

For the dosimetry methods based on gel, magnetic resonance imaging (MRI) was used to read the dose. Due to the influence of free radicals generated from the radiation dose to other parts of the gel, dose map changes occurred, and to solve the problem, a polymer gel, created by ionizing radiation, was proposed.²⁻⁶ In the polymer gels, monomers become polymer chains, which are determined by the parameter values for R_2 (T_2 relaxation time spin–spin and $R_2 = 1/T_2$), and using MRI to measure the dose levels.⁷⁻¹⁰ But these types of gels have problems, such as toxicity and the presence of oxygen in the gel

environment (oxygen is caused by entrapment of free radicals produced by the ionizing radiation and prevents the polymerization reaction of monomers by radicals), and due to the presence of oxygen, these cannot be used in typical environments.^{11,12} Since 2001, a new polymer gel called methacrylic and ascorbic acid in gelatin initiated by copper (MAGIC) has been proposed in which most of the problems of previous gels were eliminated, making it suitable for

¹ Medical Physics Department, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran

² Radiotherapy and Oncology Department, Faculty of Medical Sciences, Shahid Beheshti University of Medical Sciences and Health Services, Tehran, Iran

³ Radiology Technology Department, Faculty of Paramedical Sciences, Shahid Beheshti University of Medical Sciences and Health Services, Tehran, Iran

Corresponding Author:

Manijhe Mokhtari-Dizaji, Department of Medical Physics, Tarbiat Modares University, Chamran-Aleahmad Cross, Tehran 1411713116, Iran.
Email: mokhtarm@modares.ac.ir



measuring the dose in a normal environment.¹³ The superiority of the MAGIC gel dosimeter over other proposed gels, such as polyacrylic acid gel (PAG), bus acid nitro gel (BANG), and bis, acrylamid, nitrous oxide and agarose (BANANA), in terms of sensitivity, accuracy, and response area proved significant in some specifications.^{14,15} Given the fact that accurate measurement of the dose response is dependent on the gel material, another study was conducted on the design and evaluation of various combinations of the MAGIC gel dosimeter in order to optimize the clinical application of the gel.^{16,17} The use of formaldehyde increased sensitivity and melting temperature in the MAGIC polymer gel.¹⁸

To read the dose in gel dosimetry, MRI, computed tomography (CT), and OCT methods can be used. Magnetic resonance imaging is more expensive than other imaging methods, but if it were inexpensive, it would be a quick and easy method for obtaining information about the dose–response curve.¹⁹ Radiofrequency power is widely applied to the gel, which causes warming of the gel by about 1°C to 3°C. Given that the rate of transverse relaxation (T_2) in the gel dosimeter is temperature dependent, it remarkably built up a low percentage of error in the measured dose.^{20,21}

The advantages of using CT imaging for the gel dosimeter readings over MRI are due to the low cost, lack of sensitivity to low temperatures during imaging, and the low number of artifacts in the images. But there are problems in reading CT imaging of gel dosimetry such as low sensitivity of CT responses to low dose.²²⁻²⁶ A reading method based on optical computed tomography (OCT) has problems. Using OCT readings of such optical artifacts depends on the shape and extent of the gel opacity. In addition, the depth of this imaging technique is limited and depends on the amount of radiation and staining gels (8 cm).²⁷⁻³²

Recently, very limited attention has been paid to the ultrasonic methods for determining the dose used to extract the physical–acoustical parameters. Mather et al determined dose values of the MAGIC polymer gel using the parameters of velocity, attenuation coefficient, and transmitted signal intensity.³³ Atkins et al, using MAGIC polymer gel, studied the parameters of the ultrasound velocity, attenuation coefficient, density, and acoustic impedance in the range of 0 to 50 Gy absorbed dose.³⁴ Khoei et al have investigated the dose dependence of both ultrasound bulk attenuation and broadband ultrasound attenuation for the polyacryl amide gelatin tetrakis hydroxyl methyl phosphonium chloride (PAGAT) gel dosimeter.³⁵ Siti et al developed a new method for the evaluation of radiotherapy, 3D polymer gel dosimeters using ultrasound to assess the significant structural changes that occur following irradiation of the dosimetry.³⁶ Ultrasonic wave can be considered in determining the dose due to easy access, relatively low time and cost, and the dynamic and high-resolution images produced compared to MRI, CT, and OCT but still requires extensive studies to evaluate its ability. In this study, the sensitivity of the MAGIC-f polymer gel has been used, which in terms of stability and melting point of the polymer gel is better than the other methods. The ultrasonic parameters including

velocity, attenuation coefficient, and the qualitative index of the MAGIC-f polymer gel were studied in an absorbed dose range of 0 to 60 Gy in 2-Gy steps. By examining the dose–response curve of the ultrasonic parameters, the efficiency of this method and the sensitivity of the polymer gel will yield a range of absorbed doses. In this study, time interval and optimum temperature readings were extracted.

Materials and Methods

To make a MAGIC-f polymer gel,¹⁸ the materials including animal gelatin (Gelatin sheets 4072; Merck Co, Darmstadt, Germany), formaldehyde (Doctor Mojallali Chemical Complex, Tehran, Iran), ascorbic acid, methacrylic acid, hydroquinone monomethyl ether stabilized (Merck Co), copper sulfate, and twice-distilled water were prepared. In this study, the method of preparing 50 mL of MAGIC-f polymer gel is as follows: First, 4.1 g gelatin is added to 40.5 mL twice-distilled water at room temperature and the temperature is increased to 45°C, while stirred at the same time. After dissolving the gelatin, the temperature was lowered to about 35°C, and at this temperature, 17.6 mg ascorbic acid, 1 mg of copper sulfate, and 1.5 mL of formaldehyde (37% solution in 10% methanol) were added. After 5 minutes, 2.95 g methacrylic acid was added to the solution. Simultaneously, the solution was stirred and then poured into the sample container. The samples then remained refrigerated for 24 hours at a temperature of 10°C.

After 24 hours,¹⁸ the samples were removed from the refrigerator to reach the room temperature of the laboratory (22.5°C \pm 0.2°C) and were transferred to the radiotherapy department for irradiation. The samples were irradiated under 1.25 MeV of energy using a cobalt-60 machine (cobalt teletherapy unit, Theratron 780 C; AECL, Ottawa, Ontario, Canada). For each individual dose, gels were irradiated in the absorbed dose range of 0 to 60 Gy in 2-Gy steps. The cobalt-60 radiation field size was 10 \times 10 cm² at a distance of 80 cm from the surface of the gel, and the calculated dose was set at a depth of 1 cm from the surface of the gel and received a dose uniformity and accuracy of \pm 2% (Dosigray Dosisoft 4.103.18L).

After calibration of the ultrasound system, parameters were read including ultrasound velocity (m/s) and attenuation coefficient (dB/MHz) on the gel samples using an ultrasonic measuring device (Sonost 2000; Osteosys Co, Ltd, Seoul, Korea) with a frequency of 500 kHz at 3, 24, 36, and 48 hours after irradiation. In this study, each sample was read 3 times to reduce the error readings to below 10%.

Before each reading, the device was calibrated with a standard sample. Then, the ultrasound device was connected to a personal computer (Intel Pentium 3, RAM 384 MB) with Sonost 2000 software (version 2.01.12, Copyright 2006; Osteosys Co, Ltd). The parameters of ultrasound velocity, attenuation coefficient, and qualitative index of the MAGIC-f polymer gel were measured before and after irradiation with 0 to 60 Gy absorbed doses in 2-Gy steps. The dose–response curve for the parameters of the ultrasound velocity and

attenuation coefficient in the range of absorbed doses was plotted. According to the dose–response curve, the effect of the ultrasonic parameters on absorbed dose rate readings will be discussed.

In this study, to examine the appropriate time interval readings with the ultrasound method and the optimum temperature readings with the most sensitivity, samples were reviewed at 3, 24, 36, and 48 hours after irradiation. To study the temperature readings, the gel samples were investigated after irradiation at 5°C, 15°C, and 25°C, and then the sensitivity parameters of ultrasound velocity and attenuation coefficient were measured at the temperatures mentioned previously.

Results

Figure 1 shows the dose–response curve for the ultrasound velocity and attenuation coefficient parameters from 0 to 60 Gy absorbed doses of 2-Gy steps. In this diagram, the coefficient of variation in the parameters at any dose is less than 4%. The curve is fitted on points of order 4. Fitting coefficients at various times are longer than 0.98. In Figure 1, curve-fitting equations to separate reading times are calculated.

Ultrasound velocity change during irradiation at 24 hours after 0 to 60 Gy absorbed doses is 26 m/s. These changes are 23 m/s at 3 and 36 hours after irradiation and 21 m/s at 48 hours after irradiation. Attenuation coefficient changes are calculated as 2.4 dB/MHz/mm at 24 hours after irradiation and 2.3 dB/MHz/mm at 3, 36, and 48 hours after irradiation. Based on 4-order curves fitted on the dose–response parameters of ultrasound velocity and attenuation coefficient that were observed at 3, 24, 36, and 48 hours after irradiation, we concluded that 24 hours after irradiation, the parameters have higher sensitivity. So the best time for reading the ultrasound parameters was measured to be 24 hours after irradiation.

By examining the dose–response curve for ultrasound velocity during the first 24 hours after irradiation (Figure 1A), it was observed that between the doses of 4 and 44 Gy, it is almost linear. By examining the linear range of the response curve (Figure 2), the correlation coefficient in the linear range of the diagram is 0.998 and the sensitivity of the dose velocity is 50 cm/s/Gy. The sensitivity of ultrasound velocity in the range of 46 to 60 Gy is 9 cm/s/Gy, with a correlation coefficient of 0.939. From 46 Gy absorbed dose, the curve was saturated for reading ultrasound velocity.

By examining the dose–response curve for the attenuation coefficient parameter at 24 hours after irradiation (Figure 1B), it was observed that between the doses of 4 and 44 Gy, it is almost linear. By examining the linear range of the response curve (Figure 3), the correlation coefficient in the linear range of the curve is 0.992 and the sensitivity of the dose-attenuation coefficient curve is 0.06 dB/MHz/Gy. The sensitivity of the dose-attenuation coefficient curve in 46 to 60 Gy absorbed dose is 0.01 dB/MHz/Gy with a 0.997 correlation coefficient. From the 46 Gy absorbed dose, the curve was too saturated for reading the attenuation coefficient.

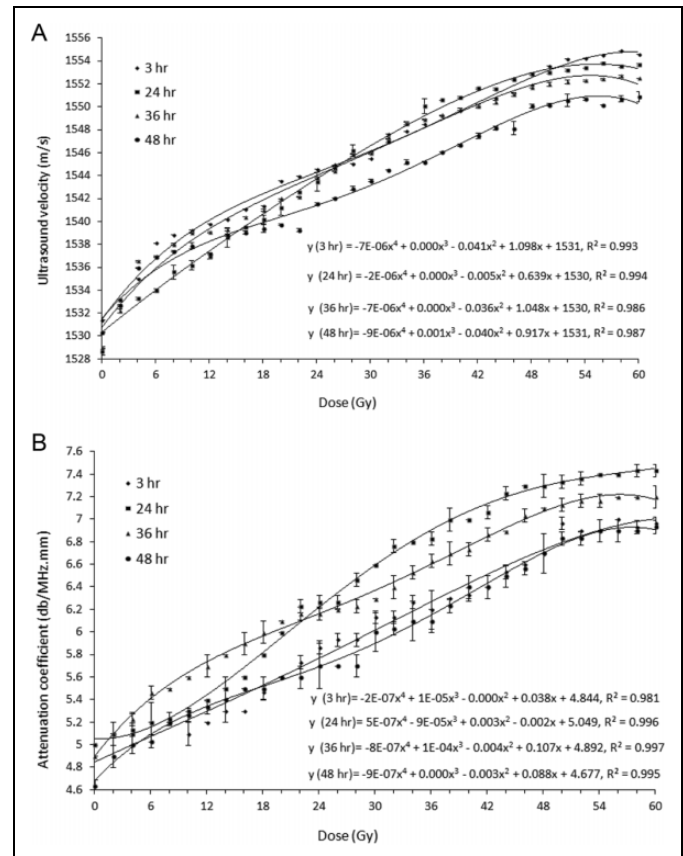


Figure 1. Dose–response curve for parameters of (A) ultrasound velocity (m/s) and (B) attenuation coefficient (dB/MHz/mm) at 3, 24, 36, and 48 hours after irradiation. Based on average, standard deviation in all measurements is less than 4%. The curve is fitted on points of order 4. Fitting coefficients at various times are longer than 0.98.

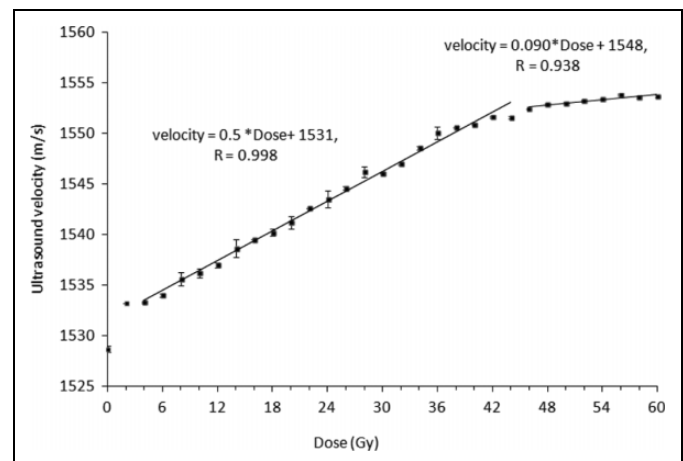


Figure 2. Sensitivity curve in the range of 4 to 44 Gy for ultrasound velocity (m/s). Reading was done 24 hours after irradiation. The linear regression function and the correlation coefficient in the 4 to 44 Gy absorbed dose with sensitivity of 50 cm/s/Gy and in the 46 to 60 Gy absorbed dose with sensitivity of 9 cm/s/Gy are shown.

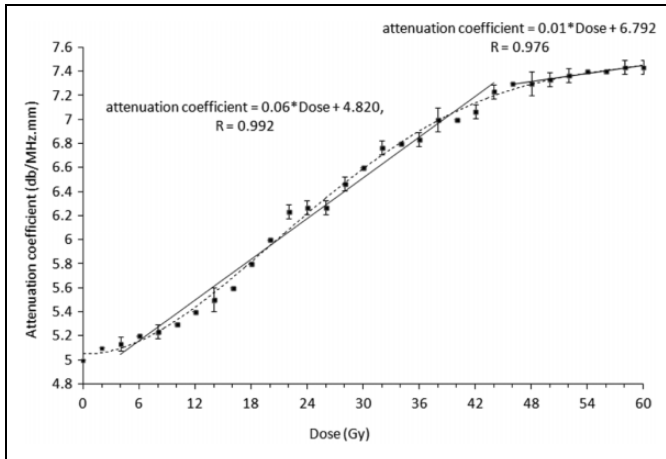


Figure 3. Sensitivity curve in the range of 4 to 44 Gy for attenuation coefficient (dB/MHz/mm/Gy). Reading was done 24 hours after irradiation. The linear regression function and the correlation coefficient in 4 to 44 Gy absorbed dose with sensitivity of 0.06 dB/MHz/mm/Gy and in 46 to 60 Gy absorbed dose with sensitivity of 0.01 dB/MHz/mm/Gy are shown.

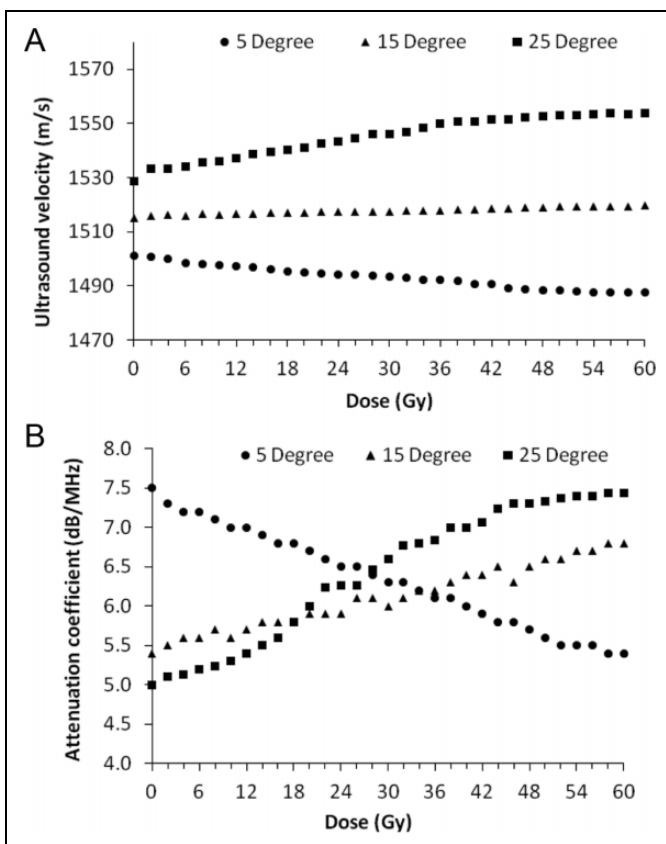


Figure 4. A, Ultrasound velocity (m/s) and (B) attenuation coefficient (dB/MHz) of the gel dosimeter at 5°C, 15°C, and 25°C from 0 to 60 Gy absorbed doses with 2-Gy steps.

In Figure 4, the parameters of the ultrasound velocity and attenuation coefficient are presented at 5°C, 15°C, and 25°C in gel dosimeter after irradiation of 2 Gy increments from

absorbed doses of 0 to 60 Gy. Figure 4 shows that the readings of the ultrasonic parameters at 25°C are more sensitive relative to 5°C and 15°C.

In Table 1, the percentage change in ultrasonic parameters of gel from 0 to 60 Gy absorbed doses with 10-Gy steps, followed by 10°C increase in temperature from 5°C to 15°C and 15°C to 25°C, and so 20°C increase in temperature from 5°C to 25°C is shown.

Table 1 showed that with a change in temperature from 5°C to 15°C and 15°C to 25°C, the ultrasound velocity in gel dosimetry is increased 0.9% (14 m/s) before irradiation and 2.2% (34 m/s) after a 60 Gy absorbed dose. With the 20°C change in temperature from 5°C to 25°C, the ultrasound velocity in gel dosimetry is increased 1.8% (28 m/s) before irradiation and 4.4% (66 m/s) after a 60 Gy absorbed dose. The attenuation coefficient with a 10°C change in temperature from 5°C to 15°C is decreased 28.0% (2.1 dB/MHz) before irradiation and increased 25.9% (1.4 dB/MHz) after a 60 Gy absorbed dose. With a 10°C change in temperature from 15°C to 25°C, the attenuation coefficient is decreased 7.4% (0.4 dB/MHz) before irradiation and increased 9.3% (4.9 dB/MHz) after a 60 Gy absorbed dose. With a 20°C change in temperature from 5°C to 25°C, the attenuation coefficient is decreased 33.3% (2.5 dB/MHz) before irradiation and increased 37.7% (2.0 dB/MHz) after a 60 Gy absorbed dose. The results show that the gel temperature reading is an important parameter in measuring ultrasonic parameters.

Discussion

Since 2002, very few studies have been proposed on alternative methods of ultrasonic imaging techniques other than MRI in the extraction of a dose–response curve.^{33,34,37} In these studies, PAG and MAGIC gel dosimetry types were used under different absorbed doses, and ultrasonic and mechanical parameters were extracted from the gels. In some of these studies, the results of performing ultrasound techniques in MRI readings were compared with the parameters of the absorbed dose. However, additional reporting that definitively compares the sensitivity of ultrasound to MRI has not been reported yet. Mather et al³³ studied 0 to 50 Gy absorbed doses of MAGIC polymer gel using the parameters of velocity, attenuation coefficient, and transmitted signal intensity. Using the ultrasound parameters of velocity, attenuation coefficient, and signal intensity across the gel, they managed to estimate the 0 to 50 Gy doses. In this study, dose rate sensitivity was 1.8×10^{-4} s/m/Gy for ultrasound velocity, 3.9 dB/m/Gy for attenuation coefficient, and 3.2 V/Gy for transmitted signal intensity. All parameters showed a high sensitivity in the absorbed dose of 15 Gy. The results show that with increasing dose, the reduced rate of the values is inconsistent with the results of our study.

Mather et al¹⁹ studied the absorbed dose rate using the physical parameters of ultrasound velocity and attenuation coefficient in radiation-sensitive gels (MAGIC and PAG). In the present study, the dependence of ultrasound velocity and attenuation coefficient was investigated with dose increments from 0 to 60 Gy. The sensitivities of the ultrasonic attenuation

Table 1. Percentage Change in Ultrasonic Parameters of Gel From 0 to 60 Gy Absorbed Dose With 10-Gy Steps Followed by 10°C Increase in Temperature From 5°C to 15°C and 15°C to 25°C, and so 20°C Increase in Temperature From 5°C to 25°C.

Absorbed Dose, Gy	5°C-15°C		25°C-15°C		25°C-5°C	
	Velocity, m/s	Attenuation Coefficient, dB/MHz	Velocity, m/s	Attenuation Coefficient, dB/MHz	Velocity, m/s	Attenuation Coefficient, dB/MHz
0	0.9	-28.0	0.9	-7.4	1.8	-33.3
10	1.2	-20.0	1.3	-5.4	2.6	-24.3
20	1.5	-11.9	1.6	1.7	3.1	-10.4
30	1.6	-4.8	1.9	10.0	3.5	4.8
40	1.8	-6.7	2.1	9.4	4.0	16.7
50	2.1	-17.9	2.2	11.1	4.4	31.0
60	2.2	-25.9	2.2	9.3	4.4	37.7

coefficient at a frequency of 4 MHz, based on the MAGIC gel and the PAG gel absorbed doses, were 4.7 ± 0.3 dB/m/Gy and 3.9 ± 0.3 dB/m/Gy, respectively. The ultrasound velocities in MAGIC gel and PAG gel were 0.178 ± 0.006 m/s/Gy and -0.44 ± 0.02 m/s/Gy, respectively, for each Gy absorbed dose. The ultrasonic attenuation coefficient showed a significant increase with absorbed dose. From these findings, it is concluded that the use of ultrasonic parameters for polymer gel dosimetry is sufficiently sensitive.

Atkins et al³⁴ extracted the ultrasonic characterization of MAGIC gel using the pulse-echo method. They measured the ultrasound velocity, attenuation coefficient, and density of the gel at different temperatures and doses, and a nearly nonlinear relationship was obtained between the absorbed dose and ultrasound attenuation coefficient. The attenuation coefficient was constant for doses lower than 10 Gy.

The ultrasound velocity at 25°C was equal to 1550.3 ± 1.5 m/s, and dose sensitivity was estimated as 0.14 ± 0.03 m/s/Gy. The ultrasound velocity and attenuation coefficient vary with temperature, so that at the temperature of 15°C, velocity was measured as 1535.4 ± 0.8 m/s, with -0.08 ± 0.01 m/s/Gy sensitivity. Also, density varies with temperature and dose. At the temperature of 26°C, density and its dose sensitivity were achieved at 1028.9 ± 0.3 kg/m³ and 0.178 ± 0.004 kg/m³/Gy, respectively.^{33,34,38}

In this study, the sensitivity of the MAGIC-f polymer gel, which has a higher sensitivity, stability, and melting point than MAGIC polymer gel,¹⁸ was used to measure the ultrasonic parameters. The gel was studied at 3, 24, 36, and 48 hours after irradiation. The results of the present study are based on extracting the ultrasonic MAGIC-f gel characterizations including ultrasound velocity and attenuation coefficient. The results showed that the best time for readings of the gel is 24 hours after irradiation, because at this time, the gel has the most sensitive ultrasound parameters related to dose. This could be due to changes related to the gel structure because the gel requires this amount of time to achieve a stable structure. Four-order curves were fitted on the dose response in the range of absorbed dose of 0 to 60 Gy with 2-Gy steps. Fitting coefficients at various times in all responses of the ultrasonic readings related to dose are higher than 0.98.

In the dose-response curve of ultrasonic parameters, there are linear relationships between doses of 4 and 44 Gy with ultrasound velocity and attenuation coefficient (correlation coefficient >0.99). Curve sensitivity of dose ultrasound velocity and attenuation coefficient parameters was obtained as 50 m/s/Gy and 0.06 dB/MHz/Gy, respectively. The results obtained in this study, compared with results obtained by Atkins et al³⁴ and Mather et al,^{19,20,33} show a higher sensitivity and a wider range of the dose-response curve that is linear.

In the present study, in addition to ultrasound velocity, attenuation coefficient parameters were investigated at 5°C, 15°C, and 25°C. The results showed that the readings at 25°C compared to 15°C and 5°C have a higher sensitivity. Gel temperature at reading time is an important parameter in measuring ultrasonic parameters. Atkins et al³⁴ investigated the ultrasound velocity change in the gel dosimeter with 0 to 30 Gy irradiation and at temperatures of 15°C, 20°C, and 25°C and showed that by increasing the temperature, the ultrasound velocity would increase 5 m/s. The results are fully compatible with the results of our study.

Conclusion

In this study, the MAGIC-f polymer gel has been used, which in terms of sensitivity, stability, and melting point of the polymer gel is better than the other options. The dose-response curves for ultrasound velocity and attenuation coefficient of the polymer gel in absorbed dose range of 0 to 60 Gy in 2-Gy steps indicate the ability of this technique in reading the absorbed dose. Maximum sensitivity time and temperature readings of the MAGIC-f gel ultrasonic parameters were concluded 24 hours after irradiation and at a temperature of 25°C.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study

was supported by a PhD thesis funded by the Faculty of Medical Sciences of Tarbiat Modares University.

References

1. Khan FM. *The Physics of Radiation Therapy*. 5th ed. Baltimore, MD: William and Wilkins; 2014: Chapter 19; 415-416.
2. Gore JC, Kang YS, Schulz RJ. Measurement of radiation dose distributions by nuclear magnetic resonance (NMR) imaging. *Phys Med Biol*. 1984;29(10):1189-1197.
3. Maryanski MJ, Schulz RJ, Ibbott GS, et al. Magnetic resonance imaging of radiation dose distributions using a polymer-gel dosimetry. *Phys Med Biol*. 1993;39(9):1437-1455.
4. Maryanski MJ, Schulz RJ, Gore GS. Three dimensional dose distributions for 160 MeV protons using MRI of the tissue-equivalent BANG polymer gel dosimeter. *PTCOG Newslett*. 1994;14:10-11.
5. Maryanski MJ, Gore JC, Schulz RJ, Kennan RP. NMR relaxation enhancement in gels polymerized and cross-linked by ionizing radiation: a new approach to 3D dosimetry by MRI. *Magn Reson Imaging*. 1993;11(2):253-258.
6. De Deene Y, De Wagter C, Van Duyes B, et al. Validations of MR-based polymer gel dosimetry as a preclinical three-dimensional verification tool in conformal radiotherapy. *Magn Reson Med*. 2000;43(1):116-125.
7. Haraldsson P, Bäck SA, Magnusson P, Olsson LE. Dose response characteristics and basic dose distribution data for a polymerization-based dosimeter gel evaluated using MR. *Br J Radiol*. 2000;73(865):58-65.
8. De Deene Y, Hurley C, Venning A, et al. A basic study of some normoxic polymer gel dosimeters. *Phys Med Biol*. 2002;47(19): 3441-3463.
9. Baldock C, Burford RP, Billingham N, et al. Experimental procedure for the manufacture and calibration of polyacrylamide gel (PAG) for MRI radiation dosimetry. *Phys Med Biol*. 1998;43(3): 695-702.
10. Baldock C, Rintoul L, Keevil SF, Pope JM, George GA. Fourier transform Raman spectroscopy of polyacrylamide gel (PAGs) for radiation dosimetry. *Phys Med Biol*. 1998;43(12): 3617-3627.
11. Sittig M. *Handbook of Toxic and Hazardous Chemicals and Carcinogens*. 6th ed. Trenton, NJ: Noyes Publications; 2013: 65-68.
12. Mc Jury M, Oldham M, Cosgrove VP. Radiation dosimetry using polymer gels: methods and applications. *Br J Radiol*. 2000; 73(873):919-929.
13. Fong PM, Keil DC, Does MD, Gore JC. Polymer gels for magnetic resonance imaging of radiation dose distributions at normal room atmosphere. *Phys Med Biol*. 2001;46(12): 3105-3113.
14. De Deene Y, Vergote K, Claey's C, De Wagter C. The fundamental radiation properties of normoxic polymer gel dosimeters: a comparison between a methacrylic acid based gel and acrylamide based gels. *Phys Med Biol*. 2006;51(3):653-673.
15. Hurley C, Venning A, Baldock C. A study of normoxic polymer gel dosimeter comprising methacrylic acid, gelatin and tetrakis (hydroxymethyl) phosphonium chloride (MAGAT). *Appl Radiat Isot*. 2005;63(4):443-456.
16. Luci JJ, Whitney HM, Gore JC. Optimization of magic gel formulation for three dimensional radiation therapy dosimetry. *Phys Med Biol*. 2007;52(10):n241-n248.
17. Adinehvand K, Zahmatkesh MH, Aghamiri MR, Akhlaghpour S. Verification of dose rate and energy dependence of MAGICA polymer gel dosimeter with electron beams. *Iran J Radiat Res*. 2008;6(1):31-36.
18. Fernandes J, Pastorello B, Araujo D, Baffa O. Formaldehyde increases MAGIC gel dosimeter melting point and sensitivity. *Phys Med Biol*. 2008;53(4):53-58.
19. Mather ML, De Deene Y, Whittaker A K, Simon G, Rutgers R, Baldock C. Investigation of ultrasonic properties of PAG and MAGIC polymer gel dosimeters. *Phys Med Biol*. 2002;47(24): 4397-4408.
20. Marini G, Pavan TZ, Baggio AL. Doppler images of heterogeneous gel dosimeter phantom by multi-frequency vibration. *Pan American Health Care Exchanges (PAHCE) Conference*. 2011: 347-349.
21. Chu KC, Jordan KJ, Battista JJ, Van Dyk J, Rutt BK. Polyvinyl alcohol-fricke hydrogel and cryogel: two new gel dosimetry systems for low Fe³⁺ diffusion. *Phys Med Biol*. 2000;45(4): 955-969.
22. Hilt's M, Duzneli C, Robar J. Polymer gel dosimetry using x-ray computed tomography: feasibility and potential application to stereotactic radiosurgery. DOSGEL 99; International Workshop on Radiation Therapy Gel Dosimetry. 1999:139-141.
23. Hilt's M, Audet C, Duzneli C, Jirasek A. Polymer gel dosimetry using X-ray computed tomography: a feasibility study. *Phys Med Biol*. 2000;45(9):2559-2571.
24. Hilt's M, Jirasek A, Duzneli C. Effects of gel composition on the radiation induced density change in PAG polymer gel dosimeters: a model and experimental investigations. *Phys Med Biol*. 2004; 49(12):2477-2490.
25. Trapp JV, Back SA, Lapage M, Michael G, Baldock C. An experimental study of the dose response of polymer gel dosimeters imaged with X-ray computed tomography. *Phys Med Biol*. 2001;46(11):2939-2951.
26. Trapp JV, Michael G, De Deene Y, Baldock C. Attenuation of diagnostic energy photons by polymer gel dosimeters. *Phys Med Biol*. 2002;47(23):4247-4258.
27. Oldham M, Siewerdsen JH, Shetty A, Jaffray DA. High resolution gel-dosimetry by optical CT and MRI scanning. *Med Phys*. 2001; 28(7):1436-1445.
28. Novotny JJ, Sapevacek V, Dvorak P, Novotny J, Cechak T. Energy and dose rate dependence of BANG-2 polymer gel dosimeter. *Med Phys*. 2001;28(11):2379-2386.
29. De Deene Y, Venning A, Hurley C, Healy BJ, Baldock C. Dose-response stability and integrity of the dose distribution of various polymer gel dosimeters. *Phys Med Biol*. 2002;47(14): 2459-2470.
30. De Deene Y, Vergote K, Claey's C, De Wagter C. The fundamental radiation properties of normoxic polymer gel dosimeters: a comparison between a methacrylic acid based gel and acrylamide based gels. *Phys Med Biol*. 2006;51(3):653-673.

31. Karlsson A, Gustavsson HS, Manson S, McAuley KB, Bäck SA. Dose integration characteristics in normoxic polymer gel dosimetry investigated using sequential beam irradiation. *Phys Med Biol.* 2007;52(15):4697-4706.
32. Crescenti RA, Bamber JC, Bush NL, Webb S. Characterization of dose-dependent Young's modulus for a radiation-sensitive polymer gel. *Phys Med Biol.* 2009;54(4):843-857.
33. Mather ML, Whittaker AK, Baldock C. Ultrasound evaluation of polymer gel dosimeters. *Phys Med Biol.* 2002;4(9):1449-1458.
34. Atkins TJ, Humphrey VF, Duck FA. Investigation of ultrasonic properties of MAGIC gels for pulse-echo gel dosimetry. The 6th international conference on 3D radiation dosimetry. *J Phys Conf Ser.* 2010;250:1-5.
35. Khoei S, Trapp JV, Langton CM. Ultrasound attenuation computed tomography assessment of PAGAT gel dose. *Phys Med Biol.* 2014;59(15):n129-n137.
36. Siti KAR, Iskandar SM, Azhar AR, Ramzun MR, Halimah MK. Acoustic evaluation of hema polymer gel dosimeter phantoms. *Adv Mater Res.* 2014;895(169):169-173.
37. Crescenti RA, Bamber JC, Oberai AA, et al. Quantitative ultrasonic elastography for gel dosimetry. *Ultrasound Med Biol.* 2010;36(2):268-275.
38. Maryanski MJ, Zastavker YZ, Gore JC. Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: II. Optical properties of the BANG polymer gel. *Phys Med Biol.* 1996;41(12):2705-2717.