Effect of Sulfuric Acid Concentration on Radiological Properties of Genipin Gel Dosimeter

Amer Al-Jarrah, Azhar A.R, Iskandar S.M, Nik Noor Ashikin Nik Abrazak, Baker Ababneh, Ehsan Taghizadeh Tousi, and Lum Liang Soo

Abstract—In this study, the effect of sulfuric acid on the radiological properties of genipin (GP) polymer dosimeter was investigated and its water equivalence evaluated for use in radiotherapy. Elemental composition of polymer gel dosimeter determines its radiological properties, while water equivalency is a significant property that controls the competency of a dosimeter. Several techniques were employed to determine the water equivalency of the GP gel dosimeter, and the mass density (ρ), effective atomic number (Z_{eff}), electron density (ρ_e), linear attenuation coefficient (μ) of pre and post irradiation gel, and water. The variation in mass density and electron density between the gels formulations did not exceed 0.001gcm^{-3} and $0.002 \text{ x}10^{23}\text{e cm}^{-3}$, respectively. Effective atomic number was found to be consistent with the energy range for water (over 0.2-20MeV), although it also exhibited values higher than water values by 2% for energies below 200keV. In addition, linear attenuation coefficient (μ) for water, pre irradiated gel and 10Gy irradiated gel batch (B) were deduced to be 0.2054, 0.2059 and 0.2082, respectively. The variation of μ for irradiated gel shows an exponential relation between μ and absorbed dose with regulation value of 0.99.

Keywords—Effective atomic number, linear attenuation coefficient, polymer gel dosimeter

I. INTRODUCTION

GENIPIN is a naturally occurring crosslinking reagent produced from geniposide. [1]. Over the years, apart from its use in herbal medicine, Genipin has shown more promising distinctive characteristics compared to other crosslinkers such as its biocompatibility and low cytotoxicity [2, 3]. From early on, several studies have investigated the characteristics and applications of Genipin. Using NMR spectroscopy, Djerassi (1960) analysed the chemical structure of Genipin (GNP), which was found to possess a molecular formula of C11H14O5 [4]. Genipin has also been crosslinked with amino acid to create stable crosslinked products with dark blue pigments [5]. Recently, Jordan [6] introduced the application of genipin gel as 3D dosimeter. From then on, there have been various researches carried out to evaluate the

Amer Al-Jarrah, Azhar A.R, Iskandar S.M, Nik Noor Ashikin Nik Abrazak, Baker Ababneh, Ehsan Taghizadeh Tousi, are with School of Physics, Universiti Sains Malaysia, Penang, Malaysia.
Lum Liang Soo, and Mount Miriam Hospital, Penang, Malaysia.
E-mail: aljarrah8@yahoo.com

application of Genipin in radiotherapy applications. For example, Jordan (2009) reported that Genipin–gelatin have an adequate response for radioactive dosage up to 50Gy. Other studies showed that the dark blue pigment of gel bleaches out upon irradiation as an indication of absorbed dose [7]. In addition, it was demonstrated that the bleaching process allows the mapping of absorbed dose distribution in three dimensions (3D) with sufficient stability and sensitivity for doses up to100Gy [8].

Furthermore, the radiological properties of a potential radiation dosimeter is required to be analogous to those of water [9]. This implies that the material should react similarly as water upon irradiation, within a given mass or thickness. This signifies the material is characterized by the same effective atomic number (Zeff), electron and mass densities as water [10][11]. Since water equivalency is regarded as a fundamental property of dosimeter in radiotherapy treatment, polymer gel dosimeter is proposed as a potential tool capable of satisfying the necessary requisites in this field [12]. Other intrinsic feature of Polymer gel dosimeters includes flexibility in shape and substance. Moreover, polymer gel dosimetry technique has the capability of mapping the absorbed dose distribution in three dimensions(3D) with high spatial resolution compared to the one-dimensional (1D) or two-dimensional (2D) dosimeters such as ion chambers, diodes or TLD's and films [13]. Furthermore, the polymer gel is capable of evaluating total volume in one attempt [14][15].

Gel dosimeters comprise of gel matrix combined with sensitive radiation materials. The monomers in the gel matrix are polymerized as a function of the absorbed dose after irradiation [16]. The polymerization rate is controlled by several factors that include polymer gel composition, irradiation energy, irradiation dose rate, and irradiation temperature [12, 17, 18]. Thus, most of its properties are influenced by its elemental composition (gel matrix and monomers). Several studies have assessed the water equivalency of dosimetric materials through its compositions by conducting a comparative analysis between some parameters and the corresponding values for water: effective atomic number (Zeff); mass energy absorption coefficient; mass stopping power; mass density (ρ); and electron density (ρe) [17, 19, 20]. Based on the study carried out by Jordan (2009), Gorjiara et al., (2011) examined the radiological

properties of photon and electron beam dosimetry of genipin gel. The present study explores the effect of sulfuric acid concentration of genipin gel on its radiological properties by calculating the effective atomic number, electron neutrality, and measuring mass density and linear attenuation coefficient.

II. MATERIAL AND METHODS

Based on a study carried out by Davies, Bosi [21], the genipin gel was found to be composed of gelatin, genipin, Milli-Q water and sulfuric acid. The compositional concentrations in the final gel comprise 50mM genipin, 100mM sulphuric acid and 4% w/w gelatin.

A. Genipin Gel Preparations

The impact of sulfuric acid concentration variations on the radiological properties of genipin gel was explored in this study. The ingredients required for thr preparation of the polymer gel was divided into four batches (A, B, C and D) as listed in Table 1. Each batch consists of gelatin type A (300 blooms, G2500, Sigma-Aldrich), genipin (G4796, Sigma-Aldrich), Milli-Q water and sulfuric acid. In batch A, The sulfuric acid concentration was 50mM, while genipin and gelatin concentrations were kept at 75μM and 4g w/w, respectively. For all experiments, gels were prepared using the certain steps. Firstly, a sealed flask containing Milli-Q water placed in water bath at 45°C. Thereafter, the gelatin was added, and then the solution stirred with a magnetic bar, until the gelatin totally melted, then a clear solution was obtained. Afterwards, Genipin was added, and the water path temperature increased to 70°C. The resultant mixture was stirred lightly to prevent bubbles formation in gel for an additional five hours. Sulfuric acid was subsequently added to the reaction flask, and the solution stirred for 10 minutes more. Finally, the gel was poured directly into PMMA standard Cuvette, sand ealed with cap tops. The gels were cooled in a refrigerator overnight.

TABLE I
THE COMPOSITIONS BY WEIGHT OR CONCENTRATION OF THE POLYMER GEL DOSIMETERS INVESTIGATED

Components	Batches Weight fraction			
	A	B	C	D
Water (w/w)%	95.75	95.25	94.87	94.39
Gelatin (w/w)%			4	
Genipin μM			75	
Sulfuric acid mM	50	100	150	200

B. Density measurements

For density measurements, twenty ml of each batch kept at room temperature (23± 0.5) °C were utilized. The mass density (ρ) for each polymer gel formulation was measured four times with a calibrated 5 milliliter micropipette and analytical balance to an accuracy of ±0.0001gm/ml so the

measurements could be averaged. The density for each formulation is listed in table (2).

C. Calculations of the element composition of each polymer gel formulation

The elemental mass fractions calculated for each polymer gel formulation are listed in tables (2).

TABLE II
ELEMENTAL COMPOSITIONS AND MASS DENSITIES OF GEL FORMULATIONS

Medium	H (%)	C (%)	N (%)	O (%)	S (%)	p^a(g/cm3)
Water	0.11190	0.00000	0.00000	0.88810	0.00000	1.000
GP A	0.11042	0.02029	0.00696	0.86276	0.00155	1.002
GP B	0.10998	0.02029	0.00696	0.86164	0.00311	1.002
GP C	0.10966	0.02029	0.00696	0.86141	0.00467	1.003
GP D	0.10922	0.02029	0.00696	0.86029	0.00622	1.003

[a] *density at 23C°*

D. Calculations of effective atomic number (Zeff) and electron density

After identifying the elemental composition and the mass density of each polymer gel formulation, the effective atomic number (Zeff) and electron density (ρe) were calculated. The effective atomic number (Zeff) depends on the elemental composition of the mixture as well as the type and energy of the radiation beam (Podgorsak, 2005). In turn, the interactions between photon beam and matter depend on Zeff and electron density (ρe) of that matter (Taylor et al., 2008). Therefore, this study shows the effect of genipin gel formulations on its effective atomic number as a function of energy. In addition, comparative analysis of Zeff for muscle and fat was carried out based on the results of previous studies. The effective atomic number, Zeff, was calculated using formula (1)

$$Z_{eff} = \sqrt[m]{\sum_{i=1}^{n} a_i Z_i^m} \tag{1}$$

Where a_i and Z_i are the electron fraction and atomic number of ith element, respectively (Kron et al., 1993). According to Mayneord formula, m is an empirical number which is assumed to be 2.94 (Khan, 2010), while the electron density(ρ_e) and the number of electron per gram (n_e) were calculated expressions (2) and (3).

$$\rho_e = \rho . N_A . \sum \omega_i . \left(\frac{Z_i}{A_i}\right) \tag{2}$$

$$n_e = \frac{\rho_e}{\rho} \tag{3}$$

Where, ρ is the mass density of material and NA is Avogadro's number, while ωi and Ai are the mass fraction and atomic mass of ith element, respectively.

However , Manohara et al., (2008) emphasized on the use of formula (4) to determine Zeff because it is applicable for all kinds of materials, compounds as well as mixtures for all photon energies with corresponding mass attenuation coefficient, $\left(\frac{\mu}{\rho}\right)_i$ in terms of the molar fraction, f_i :

$$Z_{eff} = \frac{\sum_i f_i \; A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_j f_j \; \frac{A_j}{Z_j}\left(\frac{\mu}{\rho}\right)_j} \tag{4}$$

E. Linear Attenuation Coefficient Measurements

Irradiations of gel were carried out using a linear accelerator (PRIMUS, Siemens, Germany), with SAD =100cm, field size= 10×10 cm2, dose rate= 300cGy/min and the depth was chosen at 5cm using parallel opposed beams technique. For background measurement, one sample of each batch was left unirradiated. PMMA standard Cuvette with thickness of 1.2 cm was filled with gel and subsequently placed in a Perspex holder at the mid-region of Solid water phantom. Afterwards, the gel were irradiated to a range of different doses (2 - 30Gy) using 6 MV photon beam.

The linear attenuation coefficient of polymer gel were obtained in narrow beam geometry using a point 241Am radioisotope source with 450 mCi activity and gamma photon energy 59.54 keV along with NaI (T1) detector (ORTEC, 2010) coupled to multichannel analyzer (School of Physics, University Sains Malaysia).

The linear attenuation coefficients (μ) were then calculated using Beer Lambert's law

$$\mu = ln\left(\frac{I_0}{I}\right) \times \frac{1}{x} \tag{5}$$

where I0 and I are incident and transmitted intensities (counts) at a specific energy and x is thickness of absorber.

Furthermore, Al-Bahri and Spyrou (1998) highlight that using a Compton scattering technique, electron density (ρe) of the samples can be obtained according to the following equation:

$$\frac{[N_{scat}]_S}{[N_{scat}]_w} = \frac{[\rho_e]_S}{[\rho_e]_w} \tag{6}$$

where $[N_{scat}]$ is the number of counts under the Compton scattering peak and s and w indicate sample and water, respectively. Since the electron density of water is known (3.34x 1023 e.m-3),the samples densities could be calculated through the previous relation.

III. RESULTS AND DISSECTION

A. Elemental mass fraction and mass densities of gel formulations

The elemental mass fraction and densities of water and each gel formations are shown in Table 2. Also listed is the corresponding effect of sulfuric acid concentration on the elemental mass fractions and mass densities of gel.

Variations in mass fraction of gelatin and sulfuric acid demonstrated considerable effect on the gel density and elemental mass fractions of GP gel. However, the values of gel density were observed to be close to water density because more than 95% of gel is composed of water.

B. Effective atomic number and electron density

The effective atomic numbers, electron density and number of electron per gram of each gel formulations were calculated using equations 1, 2 and 3, respectively, and their results listed in Table 3. Based these calculations, the electron density was observed to decease with increase in weight fraction of sulfuric acid, possibly attributable to decrease in oxygen mass fraction. Conversely, the effective atomic increased with increase in sulfuric acid fraction due to the presence of sulfur atoms which possess relatively higher atomic number compared to other GP components.

TABLE III

ELECTRON DENSITY AND EFFECTIVE ATOMIC NUMBER OF GENIPIN POLYMER GEL, WATER, MUSCLE, AND FAT.

Material	ρ (g cm^{-3})	ρ_e (x10^{23}e cm^{-3})	$\rho e /\rho$ (x10^{23}g^{-1})	Z_{eff}	$\left(\frac{\rho_e}{\rho}\right)^{material}_{water}$
GP A	1.002	3.344	3.337	7.415	0.998
GP B	1.002	3.343	3.336	7.447	0.998
GP C	1.003	3.345	3.335	7.478	0.998
GP D	1.003	3.344	3.334	7.509	0.997
Water	1.000	3.343	3.343	7.412	1.000
Muscle[a]	1.040	3.445	3.313	7.462	0.991
Fat[a]	0.916	3.059	3.339	6.332	0.999

[a](Venning et al., 2005a)

However, for a broad energy array ranging from 10KeV to 20 MeV, there is bound to be an impact on photon interaction with matter i.e. photoelectric effect. Compton interaction and pair production; To study this effect, effective atomic number were calculated using equation 4, while the mass attenuation coefficients for each element were obtained from NIST x-ray database (Hubbell and Seltzer, 2004) . Figure 1 shows the effective atomic number for each gel formulations comparison with water in two scales as a function of photons energy
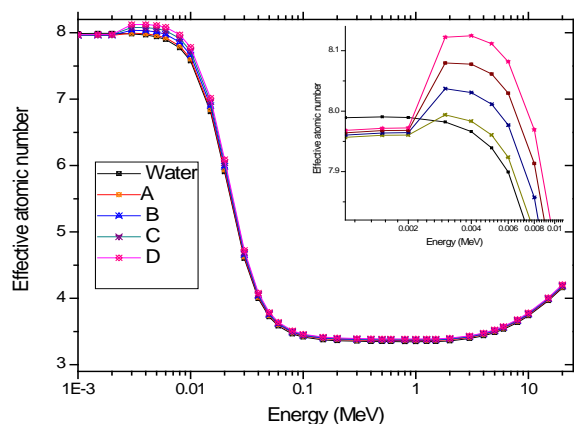
Fig. 1 The effective atomic number for each gel formulations comparison with water in two scales as a function of photons energy.

The results show consistency in values of Zeff for most of the GP gel formulation with water above 100keV, although some values were slightly higher than water value over the energy range 2-100keV, possibly due to the sulfur atoms. Photoelectric interaction is probable the dominant factor in this energy range which is affected by high atomic number element. In contrast, the electron density for GP gel was evaluated using a Compton scattering technique, which conforms to the calculated values. Both values along with percentage error are listed in Table iv.

TABLE IV
THE PERCENTAGE ERROR BETWEEN CALCULATED AND EVALUATED VALUES OF ELECTRON DENSITY FOR EACH GP GEL FORMULATIONS

		GP gel formulations			
		A	B	C	D
Electron density	Calculated	3.344	3.343	3.345	3.344
	Evaluated	3.367	3.36	3.356	3.343
Percentage error		0.688%	0.509%	0.329%	0.0300%

C. Linear attenuation coefficients

Figure 2 shows an exponential relation between the doses of the irradiated samples and the linear attenuation coefficient of GP batch B. The attenuation coefficients were obtained in

narrow beam geometry using 241Am point source, which has a major photon peak at 59.54 keV.

Similarly, the linear attenuation coefficient for water was evaluated using the same geometry at 59.54 keV, table 5 shows the linear attenuation coefficient were obtained by Xcom data base and experimental value with Percentage error.
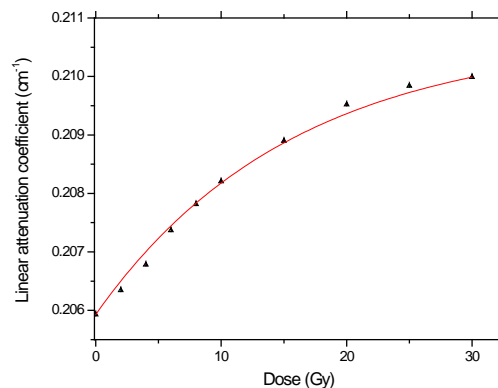

Fig. 2 The variation of linear attenuation coefficient with absorbed dose.

TABLE V
CALCULATED (XCOM) AND EXPERIMENTAL LINEAR ATTENUATION COEFFICIENTS (□) OF THE WATER AT

linear attenuation coefficient (cm^{-1}) at 59.54 keV.		Percentage error
Xcom	Experimental	
0.2066	0.2054	0.58%

IV. CONCLUSION

As observed, the GP gel dosimeter exhibited radiological properties similar to water. This was confirmed from the values of mass and electron densities, effective atomic number, and linear attenuation coefficient. A similar study conducted by Gorjiara et al., (2011) also recorded that GP gel can be considered a water equivalent dosimeter. According to this study, the effect of variation in elemental composition (sulfuric acid) on water equivalency of GP gel was observable in the values obtained for mass and electron densities of gel. Furthermore, more than 95% of gel composition is water, so that most of its radiological properties is analogous to that of water.

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