Radiological properties of MAGIC normoxic polymer gel dosimetry

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Abstract. For a polymer gel dosimeter to be of use in radiation dosimetry, it should display water-equivalent radiological properties. In this study, the radiological properties of the MAGIC (Methacrylic and Ascorbic acid in Gelatin Initiated by Copper) normoxic polymer gels were investigated. The mass density (ρ) was determined based on Archimedes’ principle. The weight fraction of elemental composition and the effective atomic number (Z_{eff}) were calculated. The electron density was also measured with 90° scattering angle at room temperature. The linear attenuation coefficient (µ) of unirradiated gel, irradiated gel, and water were determined using Am-241 based on narrow beam geometry. Monte Carlo simulation was used to calculate the depth doses response of MAGIC gel and water for 6MV photon beam. The weight fractions of elements composition of MAGIC gel were close to that for water. The mass density was found to be 1027 ± 2 kg m⁻³, which is also very close to mass density of muscle tissue (1030 kg m⁻³) and 2.7% higher than that of water. The electron density (ρ_e) and atomic number (Z_{eff}) were found to be 3.43 × 10²⁹ e m⁻³ and 7.105, respectively. The electron density measured was 2.6% greater than that for water. The atomic number was very close to that for water. The prepared MAGIC gel was found to be water equivalent based on the study of element composition, mass density, electron density and atomic number. The linear attenuation coefficient of unirradiated gel was very close to that for water. The µ of irradiated gel was found to be linear with dose 2-40 Gy. The depth dose response for MAGIC gel from a 6 MV photon beam had a percentage dose difference to water of less than 1%. Therefore it satisfies the criteria to be a good polymer gel dosimeter for radiotherapy.

1. Introduction
Recent advances in radiotherapy treatment techniques such as conformal radiotherapy enable radiation treatments to be tailored to the tumor shape. This is advantageous as treatment outcomes can be enhanced due to a reduced absorbed dose to healthy tissue. However, these new treatments place great demands on dosimetry techniques due to the complex nature of the radiation dose distributions used. To completely verify these complex dose distributions before treatment starts, three-dimensional (3D) dosimetry system is needed. Dosimeters currently in use, such as ionization chambers and thermoluminescent (TLD) dosimeters, have limitations as they only measure the dose at a single point, and radiographic films only measure a 2D distribution. Various works have shown that polymer gel could be used as dosimeter to acquire 3D dose distribution [2, 3]. Gel dosimeters consist of a gel infused with radiation sensitive materials. Upon irradiation free radicals released during the radiolysis...
of the water within the gel initiate polymerization and cross-linking of the monomers. The amount of free radicals released is proportional to the dose received by the gel dosimeter and the resultant amount of polymer formed is therefore also proportional to dose until an upper limit is reached. Oxygen is an efficient scavenger of free radicals and must be removed from polymer gel dosimeters prior to irradiation or the polymerization process will be inhibited [4-6]. This results in the requirement for specialized equipment to prevent penetration of oxygen to polymer gel mixture and has been a disadvantage of using polymer gel dosimeters. Fong et al. [1] reported a polymer gel formulation which contains oxygen scavengers and can be manufactured in normal atmospheric conditions. This formulation consists of methacrylic acid, copper sulphate, ascorbic acid, hydroquinone, gelatin and water and is given the acronym MAGIC gel.

For a material to be used as radiation dosimetry, it should display water-equivalent radiological properties. The radiological properties including effective atomic number, number of electrons per gram, mass density and electron density should be same as radiological properties of water or tissue [7, 8]. Several studies have been done to investigate water equivalency of different polymer gel dosimetry for photon and electron beam dosimetry [1, 9-18]. MAGIC gel dosimeter has previously been investigated for its radiological interaction properties and radiological water equivalence [1, 10].

In the present work, we have evaluated the water equivalency and radiological attenuation properties of MAGIC gel by calculating the weight fraction of element composition, mass density, effective atomic number, number of electron per gram, electron density and the linear attenuation coefficient of unirradiated and irradiated MAGIC gel dosimetry. The depth doses for MAGIC gel and water were also calculated using Monte Carlo simulation.

2. MATERIALS AND METHODS

2.1. MAGIC gel preparation
The MAGIC gel was prepared based on the formulation proposed in the literature by Fong et al. [1]. The chemical materials used to produce the MAGIC gel and their concentrations are as follows: gelatin type A (300 bloom) (8%), ascorbic acid (0.0367%), copper sulphate (0.002%), methacrylic acid (8%) and HPLC grade distilled water (83.9%).

2.2 Density measurements
The density of the gel can be determined from Archimedes' principle [19]. A volumetric glass flask was filled with gel at room temperature (23°C). The density of the MAGIC gel was determined by the following equation:

\[ \rho_{gel} = \frac{m_{gel}}{V_{gel}} \]

Where \( \rho_{gel} \) is the density of the gel, \( m_{gel} \) is the mass of gel in the flask, \( V_{gel} \) is the volume of the flask filled with gel. The uncertainty in the mass density of the gel was calculated as the standard error in the mean value.

2.3 Element composition measurements
Since the formula of a compound expresses the ratio of the numbers of its constituent atoms, a formula also conveys information about the relative masses of the elements it contains. But in order to make this connection, we need to know the relative weight fraction of the different elements in each compound.
The chemical compounds used to produce the MAGIC gel were gelatin type A (300 bloom) (C_{17}H_{32}N_{5}O_{6}), ascorbic acid (C_{6}H_{8}O_{6}), copper sulphate (Cu SO_{4}.5H_{2}O), methacrylic acid (H_{2}C(CH_{3})CO_{2}H) and HPLC grade water. The weight fraction was determined for carbon (C), hydrogen (H), oxygen (O), nitrogen (N), copper (Cu II) and sulphur (S) in each compound above using the following equation:

\[ Weight \ fraction = \frac{mass \ of \ each \ element \ in \ the \ whole \ compound}{mass \ of \ whole \ compound} \]

2.4. Effective atomic number (Z_{eff}) measurement

The effective atomic number (Z_{eff}) was calculated by summation of weight fractional proportion (w_k) of each atom in MAGIC gel multiplied by the atomic number (Z_k) of the atom as shown in the following equation [1]:

\[ Z_{eff} = \sum_{k} w_k Z_k \]

2.5 Linear Attenuation Coefficient Measurements

For linear attenuation coefficient measurement, the polymer gel was poured into polystyrene spectrophotometry cuvettes with parallel flat sides and the total thickness of 1.2 cm. The gel in cuvettes were irradiated to different doses (2 Gy to 40 Gy) at a dose rate of 250 cGy per minute using a 6 MV photon beam with source to surface distance (SSD = 100 cm) from linear accelerator (Siemens Primus, USA).

The linear attenuation coefficient of unirradiated gel, irradiated gel, and de-ionised water were made separately at room temperature using narrow beam geometry (School of Physics, University Sains Malaysia). Measurements were carried out with a similar set-up used previously [20] as shown in figure 1. The radiation source used was Am-241 (Amersham, Sydney) with an activity of 1.67 GBq, which has a major photopeak at 59.5 keV [21]. Transmitted radiation was detected using XR-100T-CdTe detector (E G & G Ortec, Atlanta USA). The PX2T power supply and amplifier were used with coarse gain of 50 and unipolar pulse with shaping time of 3 \mu s. The live time used was 2000 s. The spectrum was analyzed on a personal computer with Aptec MCA Application Multichannel Analyser software (Canberra Industries, Meriden USA). The background counts were obtained without the Am-241 source. The Am-241 source was placed in the source holder. Then a lead collimator (1 mm diameter) was placed in the collimator holder and counts (I_0) without the sample was obtained. Radiation counts were then obtained with empty cuvettes in the radiation path to correct for the attenuation due to cuvette walls. Cuvette containing unirradiated gel was placed in the radiation path and the count was obtained. The irradiated gel of various doses was placed in the radiation path separately and radiation counts were obtained for each one. For the measurement of the linear attenuation coefficient of deionised water, radiation counts were obtained through cuvettes filled with deionised water. Background counts were subtracted from the recorded counts for each of the measurement above. Then the count of the empty cuvettes was subtracted from this resultant count to obtain I. The following equation was used to determine the linear attenuation coefficient of MAGIC gel:

\[ I = I_0 e^{-\mu x} \]

Where I is the intensity of the beam, I_0 is the intensity of the beam incident on the material and x is the thickness of material through which the beam has passed.
In theory, Compton scattering takes place when a photon strikes an effectively free electron which is at rest. However, this situation is only an approximation when the binding energy of the electrons involved is small compared to the energy of the incident photons. If narrow beam geometry is adopted and a detector is placed at some angle from a radiation source in order to detect photons which are deflected by an object, the number of the scattered photons detected can be used to estimate the electron density of the object. The electron density was determined by:

\[
\frac{[N]_{\text{gel}}}{[N]_{\text{wat}}} = \frac{[\rho_e]_{\text{gel}}}{[\rho_e]_{\text{wat}}}
\]

where \([N]\) is the number of scattered photons detected. \((\rho_e)_{\text{gel}}\) and \((\rho_e)_{\text{wat}}\) are the electron density of gel and water, respectively. The electron density of water is \(\rho_e = 3.34 \times 10^{29} \text{ e m}^{-3}\) which is usually used as the reference material [22]. The electron density of MAGIC gel was determined at room temperature using narrow beam geometry. The main components of the experimental set-up were a scanner, radiation source, detector and multi channel analyser (MCA).

The detector was moved 90° from the source. The 90° scattering angle was selected because the best resolution can be obtained at this angle [23]. The background counts were obtained without the Am-241 source. Cuvette containing unirradiated gel was placed in the center of sample holder and the radiation count \([N]_{\text{gel}}\) was obtained. Then in the same fashion the radiation counts \([N]_{\text{wat}}\) for water were obtained through cuvettes filled with deionised water. Background counts were subtracted from the recorded counts for each of the measurement above.

2.6 Monte Carlo depth dose simulation
In order to compare dose response of MAGIC gel and water to megavoltage energy, depth doses were calculated for 6MV photon beam using Monte Carlo simulation. The EGSnrc/BEAMnrc and EGSnrc/DOSXYZnrc codes were used to perform the dose calculation [24, 25]. The BEAMnrc software was used to simulate Primus Linear accelerator head geometry (Siemens Primus, USA) and to generate phase space file. PEGS4 (EGS preprocessor) was used to calculate cross sectional data by using the element composition and the mass density of MAGIC gel as the inputs to PEGS4 software. The electron cut-off energy (ECUT) was set to 0.7 MeV while the photon cut-off energy (PCUT) was set to 0.01 MeV [26]. The beam parameters used were a 100 cm SSD with a 10x10 cm² field size. A total of 800 million histories were run in the accelerator head calculations. A phase space was scored in a plane perpendicular to the beam axis at 100 cm distance from the target. Dose calculations in DOSXYZnrc were performed using a water phantom with the dimensions 20x20x15 cm³ and the phantom was positioned at an SSD of 100 cm. For depth-dose calculations the voxel size was 0.5x0.5 cm³ in the x and y plane and 0.2 cm in the longitudinal direction (z-depth direction).
3. Results and Discussion
A polymer gel dosimeter to be used in radiation dosimetry should display water-equivalent properties. The suitable method for evaluating water-equivalence is to measure the mass density, electron density and effective atomic number. The weight fraction of elemental composition obtained from this study for carbon, hydrogen, oxygen, nitrogen, sulfur and copper (II) in MAGIC gel is shown in table 1.

Table 1. The composition of MAGIC gel, water, human muscle tissue and fat (weight fractions denoted as $w_i$).

| Material   | $w_C$  | $w_H$  | $w_O$  | $w_N$  | $w_S$  | $w_{Cu(ii)}$ |
|------------|--------|--------|--------|--------|--------|-------------|
| MAGIC      | 0.0843 | 0.1067 | 0.7994 | 0.01392| 2.56 x 10^{-6}| 5.08 x 10^{-6}|
| Water      | 0.000  | 0.1111 | 0.8889 | 0.00   | 0.00   | 0.00         |
| MAGIC a    | 0.075  | 0.1062 | 0.8021 | 0.0139 | 2.58 x 10^{-6}| 5.08 x 10^{-6}|
| MAGIC b    | 0.086  | 0.1048 | 0.7987 | 0.0115 | 2.56 x 10^{-6}| 5.09 x 10^{-6}|
| Muscle a   | 0.123  | 0.1020 | 0.7298 | 0.0350 | 0.00   | 0.00         |
| Fat b      | 0.5732 | 0.1120 | 0.3031 | 0.0110 | 6.0 x 10^{-5}| 0.00         |

The weight fractions of elements composition given were close to that for water. From the literature, the weight fractions of elements composition calculated in this study were different from previous study done by Fong et al. [1] and Venning et al. [10]. This small difference can be attributed to the change in concentration of some main chemical compounds in MAGIC gel, where the quantity of water was increased and the amount of methacrylic acid was reduced. Hydroquinone was also excluded because there was still very small amount of hydroquinone (100-250 ppm) in the methacrylic acid to prevent auto-polymerization on the shelf.

The electron density and mass density are the most important issue that must be considered for any dosimeter to be used in external radiotherapy treatment [10]. The mass density ($\rho$), electron density ($\rho_e$) and effective atomic number ($Z_{eff}$) of the MAGIC gel are given in table 2.

Table 2. Mass density, electron density, number of electron per gram and, effective atomic number ($Z_{eff}$) for MAGIC gel, water, human muscle tissue and fat

| Material   | $\rho$ (kg m$^{-3}$) | $\rho_e$ ($\times 10^9$ e m$^{-3}$) | $\rho_e/\rho$ ($\times 10^{10}$ kg$^{-1}$) | $Z_{eff}$ |
|------------|----------------------|----------------------------------|----------------------------------|----------|
| MAGIC      | 1027±2               | 3.43                             | 3.348                            | 7.10     |
| MAGIC a    | 1060                 | 3.51                             | 3.310                            | 7.07     |
| MAGIC b    | 1037±5               | 3.44                             | 3.323                            | 7.30     |
| Water      | 1000                 | 3.34                             | 3.34                             | 7.22     |
| Muscle a   | 1030                 | 3.44                             | 3.31                             | 6.93     |
| Fat b      | 916                  | 3.05                             | 3.33                             | 6.33     |

The mass density was found to be 1027 ± 2 kg m$^{-3}$, which is also very close to mass density of muscle tissue (1030 kg m$^{-3}$) and 2.7% higher than that of water and this was attributed to its high gelatine and monomer concentration. The obtained mass density differs from the previous studies done by Fong et al. [1] (1060 kg m$^{-3}$), and Venning et al. [10] (1037 ± 5 kg m$^{-3}$). The observed differences in mass density are most likely due to the difference in preparation and measuring techniques. The electron density ($\rho_e$) and effective atomic number ($Z_{eff}$) were found to be $3.43 \times 10^9$ e m$^{-3}$ and 7.105,
respectively. The electron density measured was 2.6% greater than that for water. The effective atomic number was close to that for water with small difference with the previous studies [1, 10]. This difference can be attributed to the change in the weight fraction of elemental composition.

Figure 2 shows the variation of linear attenuation coefficient (LAC) with absorbed dose based on the measurement using irradiated samples. Excellent correlation ($r = 0.993$) was found between linear attenuation coefficient and absorbed dose. It was found that the linear attenuation coefficient of unirradiated gel was very close to water. The measured linear attenuation coefficient (LAC) for unirradiated MAGIC gel and water was found to be $0.84 \pm 0.04$ cm$^{-1}$ and $0.85 \pm 0.02$ cm$^{-1}$, respectively. There was a linear relationship between linear attenuation coefficient and absorbed dose for MAGIC gel up to 40 Gy. So an increase in absorbed dose of MAGIC polymer gel leads to an increase in linear attenuation coefficient. This increase in linear attenuation coefficient is linked to the change in density of the irradiated gel [10].

![Figure 2](image2.jpg)

**Figure 2.** The variation of linear attenuation coefficient (LAC) with absorbed dose.

The depth dose curves for MAGIC gel and water that calculated using Monte Carlo simulation are shown in figure 3. The dose reduction with depth of MAGIC gel is very similar to that of water. The maximum difference of percentage depth dose of gel with that for water was found to be 1%. Result obtained was consistent with the previous study done by Venning et al. [10].

![Figure 3](image3.jpg)

**Figure 3.** Monte Carlo calculated relative depth dose curves for MAGIC gel and water.
4. Conclusion
MAGIC normoxic polymer gel dosimeter has been investigated for its radiological water equivalence by investigating the element composition, mass density, electron density, number of electron per gram, effective atomic number, and linear attenuation coefficient of unirradiated gel. MAGIC gel can be considered a radiological water equivalent dosimeter since almost all of its radiological properties differ by less than 2.7% from that of water. The $\mu$ of irradiated gel was found to be linear with dose, up to 40 Gy. The Monte Carlo simulation for 6 MV photon beam was used to calculate the percentage depth dose for MAGIC gel and water and it was found that the dose reduction with depth of gel was very similar to that of water with difference less than 1%. It may be concluded that MAGIC gel can be considered water equivalent for depth dose measurements of 6 MV photon beam.

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