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Characteristics of a normoxic polymethacrylic acid gel dosimeter for a 72-MeV proton beam

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ABSTRACT

The characteristics of a normoxic polymethacrylic acid gel dosimeter for a 72-MeV proton beam were evaluated. A polymer gel dosimeter was synthesized using gelatin, methacrylic acid, hydroquinone, tetrakis(hydroxymethyl) phosphonium chloride, and highly purified distilled water. The dosimeter was manufactured by placement in a polyethylene (PE) container. Irradiated dosimeters were analyzed to determine the transverse relaxation time (T2) using a 1.5-T MRI. A calibration curve was obtained as a function of the absorbed dose.

A Bragg curve made by irradiating the gel with mono-energy was compared with the results for a parallel plate ionization chamber. The spread-out Bragg peak (SOBP) range and distal dose fall-off (DDF) were comparatively analyzed by comparing the irradiated gel with a spread-out Bragg peak against with the ion chamber.

Lastly, the gel's usefulness as a dosimeter for therapeutic radiation quality assurance was evaluated by obtaining its practical field size, flatness, and symmetry, through comparison of the profiles of the gel and ion chamber.

1. Introduction

Dosimeters for the estimation of the dose of a proton beam include ion chambers [1], diamond [2], diode [3] and film [4] detectors. However, point dosimeters such as ion chambers, diamond detectors, and diodes have difficulties in obtaining data on continuous radiation dose distributions around the target.

In contrast, films are useful for measuring doses in small irradiation fields, since they have the advantage of visual verification of the 2-dimensional dose distribution, and have outstanding spatial resolution. However, when several sheets of film are overlapped in order to measure the spatial dose distribution, the accuracy suffers in terms of directional-dependency.

Recently, polymer gel dosimeters have been used as a tool for the 3-dimensional measurement of radiation doses using the principle of the transition of a monomer into a polymer in proportion to the radiation dose [5,6]. Compared with typical dosimeters, the characteristics of gel dosimeters are independent of the direction of irradiation. In addition, they are receiving attention as a 3-dimensional dosimeter for dose estimation in radiation therapy, as they feature tissue-equivalent materials and volume.

Gels used for charged particle beams include BANG [7,8], Polyacrylamide gel [9], and Ferrous sulfate gel [10]. Jirasek irradiated a gel with a 74-MeV proton beam, and observed the LET effect at the Bragg peak using Raman spectroscopy [9]. According to the report by Heufelder [8], when a 68-MeV proton beam is applied to BANG-1 gel, the dose at the Bragg peak is small, about 25%–30% that of the ion chamber. This is related to a report by Bäck [10], which showed that when a 132-MeV proton beam is applied to ferrous sulfate gel, the dose is underestimated by about 15%–20% in comparison to an ion chamber.

In this study, the beam range, spread-out Bragg peak (SOBP), and distal dose fall-off (DDF) were analyzed by comparison with an ion chamber, and an ensuing quenching effect was observed. The dosimetric characteristics of normoxic polymer gel were verified using a 72-MeV proton beam.

2. Materials and methods

2.1. Gel preparation

Substances that compose normoxic polymethacrylic acid gel are listed in the following. In order to establish a matrix, gelatin (300 bloom, Sigma-Aldrich, USA) and monomer methacrylic acid

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(MAA, Sigma-Aldrich, USA), which polymerizes in accordance with the radiation dose, were used. Hydroquinone (HQ, Sigma-Aldrich, USA) was used as pre-polymerization preventer in order to prevent polymerization prior to irradiation, and tetrakis (hydroxymethyl) phosphonium chloride (THPC, Sigma-Aldrich, USA) was used as an anti-oxidant in order to remove any oxygen in the gel solution [11].

The process and conditions of synthesis of normoxic polymer gel are as follows (Fig. 1). After placing highly purified distilled water into a flask, gelatin equivalent to 6% of the total mass was added. At this time, the gelatin was dissolved by applying heat while maintaining stirring at a speed that does not produce foam in the reaction flask. Before the gelatin was completely dissolved, methacrylic acid equivalent to 8% of the total mass was dissolved. 0.05 mM hydroquinone and 10 mM tetrakis, an anti-oxidant, were also dissolved.

When the gelatin was completely dissolved and reached a temperature of 50 °C, heating was stopped, and the temperature of the gelatin solution was cooled to 43 °C by placing the reaction flask in a water tank. The gel was then placed in a container made of polyethylene (PE). The dimenions of the gel containers were 9.5-cm in diameter and 15 cm in length, and $12 \times 12 \times 17$ cm^3. All the processes of gel synthesis were performed in ambient air using a 5-liter glass flask. The gel container was left at room temperature for more than 1 h to remove any air bubbles in the solution generated during the synthesis process, prior to solidifying the solution into a gel by placing it in refrigerator at a temperature of 4 °C.

Chemical element analysis was conducted, and the density and effective atomic number of the synthesized normoxic polymer gel were compared with those of soft tissue, muscle, and water. The results are illustrated in Table 1. At 1.02 g/m^3, the density of the gel was greater than that of water, but lower than that of muscle. In addition, the effective atomic number of the gel was 7.10, closer to that of water than that of soft tissue or muscle.

2.2. Calibration curve of normoxic polymer gel dosimeter

The calibration curve for dosimeters needs to be made by assessing the extent of the dose reaction according to the radiation absorption dose. Most dosimeters, including film and thermoluminescent dosimeter (TLD), are known to be energy-dependent [14–17].

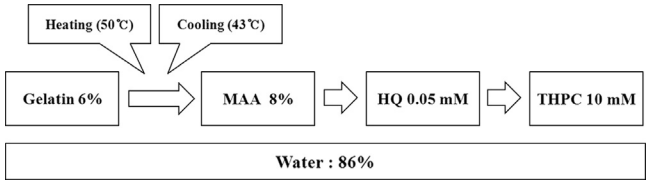

Fig. 1. Synthesis of polymethacrylic acid gel MAA: Methacrylic acid, HQ: Hydroquinone, THPC: Tetrakisphosphonium chloride.

Table 1
Elemental composition (% weight fraction), density (g cm^{-3}) and effective atomic number (Z_{eff}) of gel, soft tissue, muscle, and water.

Material	W_H	W_C	W_N	W_O	O/C	O/N	C/N	ρg cm^{-3}	Z_{eff}
Gel	10.55	7.37	1.1	80.98	10.98	73.61	6.70	1.02	7.10
Soft tissue [12]	10.2	14.30	3.40	70.80	4.95	20.82	4.20	1.06	6.86
Muscle [13]	10.99	12.30	3.50	72.90	5.92	20.82	3.51	1.04	6.92
Water	11.20			88.80				1.00	7.21

All dimensions of elemental compositions are % weight fractions.
ρ: density.
Z_{eff}: effective atomic number.

It has been disclosed that although polymer gel dosimeters are also dependent on the energy of the photon beam, the dose reaction curve is linear at absorption doses of less than 8 Gy [18–20].

Unlike a photon beam, which undergoes exponential reduction after a build-up region, in the case of an ion beam, there is a need to assess the calibration curve of the dosimeter according to the energy of the ion beam due to the linear energy transfer (LET) effect. For this purpose, an experiment with the following structure was performed.

A 72-MeV proton beam was used to irradiate the gel dosimeter. The range of the proton beam is the distance from the phantom surface to the 90% distal dose fall-off, and the water equivalent range is about 4.9 to 5.1 cm. A collimator with a diameter of 50 mm made of brass alloy material (60% Cu–40% Zn) was used for the exponential relationship estimation of the 72-MeV proton beam accelerated with a therapeutic cyclotron (Proteus 235 Proton therapy system, IBA, Belgium). Results were obtained at a distance of 100 mm from the collimator to the gel dosimeter (Fig. 2).

According to the IAEA Technical Reports Series No. 398, since values are more stable at the mid-SOBP than those for a relative dose at the Bragg peak position for mono-energy, it is recommended to read the relative dose value at that position for higher reliability [21]. Therefore, the SOBP was made by attenuating the energy using an energy modulator. The calibration curve was measured within the absorption dose range of 1–8 Gy.

2.3. Dose estimation

2.3.1. Bragg curve

The gel was irradiated at room temperature using the setup illustrated in Fig. 2 in order to estimate the depth dose of the gel dosimeter for the proton beam. In addition, a water phantom (WP 300 3D Water Phantom, IBA, Belgium) was placed at the position of the gel in order to compare the depth dose of the gel dosimeter and ion chamber. A parallel plate chamber (Markus-type, PTW model 34045) was used for the ion chamber.

In order to compare the depth of two dosimeters, a conversion was made to the water-equivalent depth (WED) for the gel (Eq. (1)).

$$WED\ (g\ cm^{-2}, cm) = d(cm) \times \rho(g\ cm^{-3}) \quad (1)$$

d is the depth at each of the dosimeters, and ρ is the density.

2.3.2. Spread-out Bragg peak

Protons are accelerated by means of a therapeutic cyclotron and passed through a nozzle. The SOBP is made with reiterated energy using the energy modulator within the nozzle. The SOBP made in this method was measured with both an ion chamber and

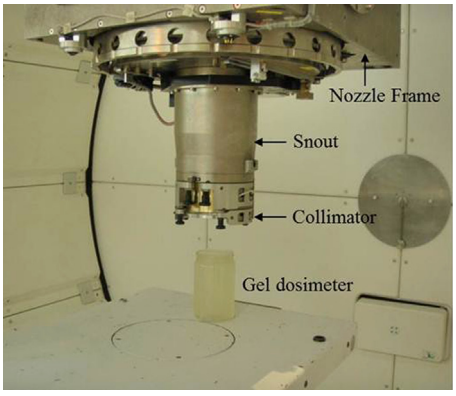

Fig. 2. Gel dosimeter was irradiated using a therapeutic proton beam.