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Dosimetry study of diagnostic X-ray using doped iodide normoxic polymer gels

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HIGHLIGHTS

- mGy range for diagnostic radiology was developed using gel dosimeter.
- NIPAM and MAGAT based gels were used to evaluate diagnostic X-ray CT radiation dose.
- NIPAM doped iodide gel was verified for diagnostic radiation doses measurement.

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ABSTRACT

In radiotherapy, polymer gel dosimeters are used for three-dimensional (3D) dose distribution. However, the doses are within the Gy range. In this study, we attempted to develop a low-dose 3D dosimeter within the mGy range for diagnostic radiology. The effect of the iodinated compound was used as a dose enhancement sensitizer to enhance the dose sensitivity of normoxic polymer gel dosimeters. This study aims to use *N*-isopropylacrylamide(NIPAM)-based and methacrylic acid (MAGAT)-based gels to evaluate the potential dose enhancement sensitizer, as well as to compare two gels that may be suitable for measuring diagnostic radiation doses. The suitable formulation of NIPAM gel [5% (w/w) gelatin, 5% (w/w) NIPAM, 3% (w/w) *N*,*N*′-methylenebisacrylamide (BIS), 5 mM tetrakis (hydroxymethyl) phosphonium chloride (THPC), and 87% (w/w) deionized distilled water] and MAGAT gel (4% MAA, 9% gelatin, 87% deionized water, and 10 mM THPC) were used and loaded with clinical iodinated contrast medium agent (Iobitridol, Xenetix® 350). Irradiation was conducted using X-ray computed tomography. The irradiation doses ranged from 0 mGy to 80 mGy. Optical computed tomography was the employed gel measurement system. The results indicate that the iodinated contrast agent yields a quantifiable dose enhancement ratio. The dose enhancement ratios of NIPAM and MAGAT gels are 3.35 ± 0.6 and 1.36 ± 0.3, respectively. The developed NIPAM gel in this study could be suitable for measuring diagnostic radiation doses.

1. Introduction

In 1993, a type of polymer gel, the polyacrylamide gel (PAG), was introduced to replace Fricke gel with acrylic monomer (Maryanski et al., 1993). Maryanski et al. (1996) also introduced a new type of gel, the BANG® gel serial (BANG-1 to 3, MGS Research Inc.), which is composed of gelatin, acrylamide, BIS, and nitrogen. Improvements to BANG gel lessened monomer toxicity and increased gel sensitivity.

Several vinyl monomers, such as acrylamide, methacrylic acid (MAGAT), and *N*-isopropylacrylamide (NIPAM), have been used in polymer gel dosimeters. Huang et al. (2013) recently examined the characteristics of the chemical structure of a NIPAM dosimeter, as well as its ^{13}C-NMR, ^{1}H-NMR, and FT-Raman spectra, which were irradiated 0 Gy to 20 Gy. De Deene et al. (2000) reported that the dose sensitivity of the polymer gel dosimeter was lower for low doses (below 1 Gy). Hence, several studies have attempted to use various formulations to enhance gel sensitivity; nevertheless, the effect of dose enhancement remains limited. Fernandes et al. (2008a, 2008b) used MAGIC gel to mix formaldehyde, but radiation sensitivity increased by only 10.5%. Meesat et al. (2009) compared various halide ions to examine the variations in dose sensitivity for different radiation energies. The researchers found that the iodinated contrast medium agent exhibited the best dose

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enhancement. Marques et al. (2010) added gold nanoparticles to MAGIC-f gel dosimeter as radiation sensitizer. The dose enhancement effect of the MAGIC-f gel dosimeter was effectively enhanced. Jirasek et al. (2010) increased the solubility of BIS in the NIPAM gel dosimeter by adding a co-solvent (e.g. isopropanol), resulting in heightened dose sensitivity. Hayashi et al. (2012) demonstrated that the dose sensitivity of the MAGAT gel dosimeter is enhanced through the addition of inorganic salts. Table 1 showed the comparison of dose-enhancement effect of various polymer gel dosimeter.

In an attempt to obtain information on dose distribution from polymer gels, researchers have investigated several readout tools, including magnetic resonance imaging (MRI); X-ray computed tomography (CT), and optical CT (Hsieh et al., 2012). In this study, the optical CT scanner is used to provide an inexpensive and simple alternative imaging modality (Gore et al., 1996; Chang et al., 2011).

With the advances in medical technology, the use of ionization for radiation diagnosis and radiotherapy has gradually increased. Consequently, the absorbed dose of patients has relatively increased. Table 2 lists the diagnostic equipment of polymer gel dosimeter as measured by several research groups (Antoniou et al., 2008; Hill et al., 2008; Sarabipour et al., 2006). In 2008, the MAGAT gel dosimeter was irradiated via interventional radiology (Hill et al., 2008). The gel demonstrated a linear dose response beyond a 25 cGy threshold. However, the dose range remains higher than the diagnostic CT reference recommended by the American College of Radiology (ACR) CT Accreditation Program (Table 3). In the present study, we used various polymer gel dosimeters doped with radiation sensitizer (iodinated contrast medium) to evaluate diagnostic X-ray CT radiation dose. In addition, the formulations of the polymer gel dosimeter that could result in higher linearity and sensitivity were identified.

Table 1
Comparison of dose enhancement ratio in polymer gel dosimeter.

Author	Type of gel	Radiation sensitizer	Percent of dose enhancement (%)
Fernandes et al.	MAGIC gel	Formaldehyde	10.5
Meesat et al.	PAG gel	Iodinated contrast agent	45
Marques et al.	MAGIC-f gel	Gold nanoparticles	106
Hayashi et al.	MAGAT gel	Inorganic salts	284

Table 2
Measurement tools in diagnostic equipment that uses polymer gel dosimeters (Antoniou et al., 2008; Hill et al., 2008; Sarabipour et al., 2006).

Year	Vinyl monomers	Gel type	Irradiation instrument	Measurement tool
2005	Methacrylic acid	MAGIC	CT	MRI
2006	Polyacrylamide	PAG	CT	Optical CT
2008	Polyacrylamide	PAG	CT	MRI
2008	Methacrylic acid	MAGAT	Fluoroscopy	MRI
2009	Methacrylic acid	MAGIC	CT	CT

Table 3
Recommended diagnostic CT reference levels derived from the analysis of data gathered from the first three years of the ACR CT Accreditation Program (McCollough et al., 2011).

Examination	Reference levels(CTDI-vol) (mGy)
CT head	75
CT adult abdomen	25
CT pediatric abdomen	20

2. Material and method

2.1. Preparation of NIPAM gel dosimeter

Senden et al. (2006) proposed the *N*-sopropylacrylamide (NIPAM) polymer gel, which is based on a less toxic monomer. According to Chang et al. (2011) NIPAM gel is composed of 5% gelatin (Sigma-Aldrich), 5% NIPAM (Sigma Aldrich), 3% BIS (Merck), 5 mM THPC (Sigma Aldrich), and 87% deionized water. Gelatin was added to distilled water for 10 min at room temperature. The gelatin solution was stirred and heated to 45 °C using an electric heater until the solution became clear and transparent. With continuous stirring, NIPAM and BIS were poured into the gelatin solution and dissolved after approximately 15 min. Subsequently, THPC was added to the solution and continuously stirred for 2 min. Finally, the gel solution was transferred to Pyrex screw test tubes (16 mm diameter, 100 mm length) and then stored in a refrigerator for 3 h prior to irradiation.

2.2. Preparation of MAGAT gel dosimeter

MAGAT gel was prepared according to Hurley et al. (2005). In addition, various gelatin concentrations of the MAGAT gel dosimeter formulation were observed. Gelatin was added to distilled water and heated to 45 °C. To observe a clear solution, the mixed solution was allowed to swell for 10 min. The solution was then cooled down to 35 °C. Methacrylic acid was subsequently added to the solution and continuously stirred for 25 min. Finally, THPC was added to the solution as an antioxidant and mixed for 2 min. The MAGAT solutions were transferred individually to Pyrex screw test tubes and stored in a refrigerator for 3 h prior to irradiation. Table 4 shows the formulations of NIPAM and MAGAT dosimeters. Furthermore, the clinical iodinated contrast medium agent (Xenetix® 350 injectable solution, Guerbet) was used as radiation sensitizer.

2.3. Irradiation of gels

All samples were irradiated at 24 °C in a clinical linear accelerator (Varian 21EX). A 6 MV linear accelerator was used to irradiate the gel, with a field size of 10 cm × 10 cm, dose rate of 400 cGy/min, and source to axis distance of 100 cm. The vial containing the gel was placed at the center of the 30 cm × 30 cm PMMA phantom. The irradiation doses were 0.5 Gy, 1 Gy, 1.5 Gy, 2 Gy, and 2.5 Gy. After being irradiated, the gels were stored in a refrigerator for 3 h (NIPAM and MAGAT) for subsequent optical laser measures. All samples were irradiated to evaluate diagnostic radiation via a spiral CT (Discovery ST, GE) with 10 cm × 8 cm gelatin phantom. The output tube voltage was 120 kVp, the tube current was 100 mA to 400 mA, the slice thickness was 10 mm, and the scan time was 0.5 s × circle^{-1}. The dose delivered ranged from 0 mGy to 80 mGy. Gaining the best dose response and sensitivity, the linearity and sensitivity of the doped iodinated contrast agent polymer gel dosimeter were observed at different dose ranges. Fig. 1 explains the purpose of polymer gel dosimeter irradiation.

Table 4
Formulations of polymer gel dosimeters.

Gel-type	Gelling agent (w/w %)	Monomer (w/w %)	Cross-linker (w/w %)	Oxygen scavenger (mM)
NIPAM	Gelatin (5)	NIPAM (5)	BIS (3)	THPC (5)
MAGAT-1	Gelatin (4)	MAA (9)	–	THPC (10)
MAGAT-2	Gelatin (6)	MAA (9)	–	THPC (10)
MAGAT-3	Gelatin (8)	MAA (9)	–	THPC (10)