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Original paper

Sensitivity enhancement of methacrylic acid gel dosimeters by incorporating iodine for computed tomography scans

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ABSTRACT

Purpose: Polymer gel dosimeters provide three-dimensional absorbed dose information and have gradually become a popular tool for quality assurance in radiotherapy. This study aims to incorporate iodine into the MAGAT-based gel as radiation sensitizer and investigate whether it can be used to measure the radiation dose and slice thickness for CT scans.

Methods: The nMAGAT(I) gel was doped with 0.03, 0.05, and 0.07-M iodine. The absorbed dose was delivered using a CT scanner (Alexion 16, Toshiba Medical Systems, Japan) with tube voltages of 80, 100, 120, and 135 kVp. The irradiated nMAGAT(I) gel was read using a cone beam optical CT scanner to produce dose-response curves. The nMAGAT(I) gel was used to obtain the slice sensitivity profile (SSP) and the CT dose index (CTDI) for quality assurance of CT scans.

Results: The 0.07-M iodine-doped nMAGAT(I) gel exhibited maximum sensitivity with the dose enhancement ratio of 2.12. The gel was chemically stable 24 h after its preparation, and the polymerization process was completed 24–48 h after the irradiation. For CT quality assurance, the full width at half maximum measured by the nMAGAT(I) gel matched the nominal slice thickness of CT. The CTDI at center, CTDI at peripheral, and weighted CTDI obtained by the nMAGAT(I) gel differed from those obtained by the ionization chamber by −4.2%, 3.1%, and 0.7%, respectively.

Conclusions: The nMAGAT(I) gel can be used to assess radiation doses and slice thickness in CT scans, thus rendering it a potential quality assurance tool for CT and other radiological diagnostic applications.

1. Introduction

Polymer gel dosimeters provide information on three-dimensional radiation dose distribution and exhibit favorable dose-response linearity, tissue equivalence, energy and dose rate dependence. Therefore, they have gradually become a popular tool for quality assurance in clinical radiotherapy [1,2]. However, a relatively low dose sensitivity of the polymer gel dosimeters makes them unsuitable for dose assessment in radiological diagnostics at present. Computed tomography (CT) is widely used as a first-line diagnostic modality in radiology. The average CT dose index (CTDI) for body scans is 21 mGy in the U.S., which is only about one percent of the radiotherapy dose per fraction [3]. Therefore, for quality assurance in the radiodiagnostic dose range, increasing the dose sensitivity of the polymer gel dosimeters for CT scans is imperative [4].

After irradiation, monomers in an aqueous gel matrix are polymerized; the extent of polymerization is directly proportional to the radiation dose. The sensitivity of a gel dosimeter is thus defined as the dose response per unit dose. Polymer gels prepared using various formulas show different linearity and sensitivity levels. Several studies have focused on improving the dose response of polymer gels to radiation, including optimization of gel recipes and addition of radiation sensitizers. The polyacrylamide gel (PAG) has a linearity range of 0.5–10 Gy and a relatively high sensitivity level of 0.860 HU/Gy [5]. However, the sensitivity varies considerably between different PAG formulas [6,7]. Chang et al. [8] used *N*-isopropylacrylamide monomers to prepare the NIPAM gel which exhibited a linearity range of 1–20 Gy and sensitivity of 0.254 HU/Gy. This study found that a further increase of the amount of monomers elevated the sensitivity to 0.569 HU/Gy. Shih et al. [9] showed that the DEMBIG gel, comprising 2-

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(dimethylamino) ethyl acrylate as monomers, exhibited a favorable linearity from 1 to 25 Gy with an average sensitivity of 0.459 HU/Gy.

Co-solvents can be added to increase the sensitivity of polymer gels as well. The sensitivity of MAGIC polymer gels was originally reported to be 0.380 HU/Gy [10]. By mixing formaldehyde with the MAGIC gel, Fernandes et al. [11] observed that the melting point of the gel increased to 69 °C and its sensitivity increased by 12.5%. Jirasek et al. [12] incorporated glycerol of various weight percentages into the NIPAM gel and observed that adding 50% glycerol to 6% total monomer increased the sensitivity level to 0.480 HU/Gy. Meesat et al. [13] used the dose enhancement ratio (DER), which is the ratio between the sensitivity of polymer gels with co-solvents and that without co-solvents, to evaluate the iodine-doped PAG gel. The results showed that DER was 1.82. Other high atomic number substances can also be added to the gel. The DERs of 0.5-mM bismuth-doped PAG and NIPAM were 1.34 and 1.18 [14], respectively, whereas the gadolinium-doped PAG gel had a DER of 2.53 [15]. However, these experiments were conducted in the energy range of radiotherapy. There is little information about the incorporation of co-solvents into the gel dosimeter in the radiodiagnostic energy range.

Among various polymer gels, the MAGAT gels, in which methacrylic acid (MAA) serves as the monomer, demonstrated a higher sensitivity level of 0.850 HU/Gy [16]. Chuang et al. [4] used nMAG gels to measure 300-mm CTDI and slice sensitivity profile (SSP) simultaneously for multiple detector CT. However, at least 200-mGy absorbed dose was required to trigger polymerization. Baxter et al. [17] used 32 consecutive CT scans of the gel to investigate the dose for typical CT imaging protocols. In this study, iodine was incorporated in the MAGAT-based gel as the radiation sensitizer. Subsequently, the linearity and sensitivity were assessed and the question of whether it can be used to measure the radiation dose and slice thickness for CT scans was investigated.

2. Materials and methods

2.1. Gel preparation

The nMAGAT gel was prepared under normal atmospheric conditions with 4% gelatin and 9% MAA according to Hurley et al's recipe [18]. After gelatin and monomers were mixed evenly, radiocontrast agents (Xenetix 350, Guerbit, France) with an iodine concentration of 350 mg/ml were added and stirred at 35 °C for 10 min to produce 0.03-M, 0.05-M, and 0.07-M iodine-doped gel solution. Subsequently, 10-mM tetrakis(hydroxymethyl) phosphonium chloride was added as oxygen scavenger. The iodine-doped nMAGAT gel is referred to as the nMAGAT(I) gel. Table 1 lists the composition of the nMAGAT(I) gel. The prepared gel solution was poured into 15-cm-length and 2-cm-diameter acrylic tubes having a parafilm-lined screw cap. The gel tubes were then stored at 4 °C refrigerator for solidification. The cooling process can reduce the chemical reaction rate and avoid spontaneous heat-induced polymerization [19].

2.2. Gel irradiation

The gel-containing tube was taken out of the refrigerator for one hour and inserted into the center of a self-made polymethyl methacrylate (PMMA) cylindrical phantom with a length of 15 cm and a diameter of 16 cm. The phantom was placed at the isocenter of a CT scanner (Alexion 16, Toshiba Medical Systems, Japan) and scanned at the room temperature of 20 °C, as shown in Fig. 1. Consecutive scans in the axial mode were performed to deliver different doses to the gel. The scanning parameters included tube voltages of 80, 100, 120, and 135 kVp, 4.8-mm Al equivalent filtration, tube current of 150 mA, slice thickness of 1 cm, and scanning time of 1 s.

Table 1
Composition of the nMAGAT(I) gel.

Composition	Weight percentage (%)
Gelatin	4
Methacrylic acid (MAA)	9
Distilled water	87
THPC	10 mM
Iodine	0.03 M, 0.05 M, 0.07 M

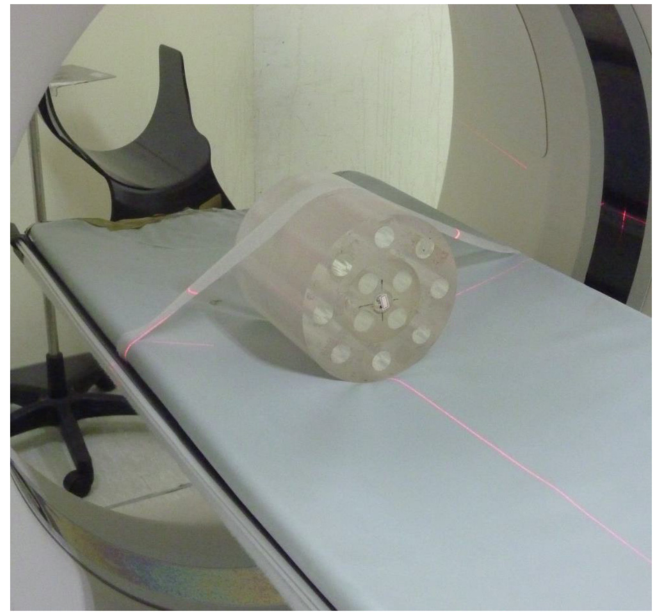

Fig. 1. Irradiation of the 15-cm-length and 16-cm-diameter PMMA phantom. The gel tube was inserted into the phantom center and the phantom was placed at the isocenter of the CT gantry.

In addition, a regularly calibrated Farmer-type ionization chamber (FC65-P, Scanditronix Wellhofer North America, USA) was inserted into the phantom center and irradiated under the aforementioned conditions to obtain the absorbed dose. The total standard uncertainty (coverage factor $k = 1$) of the ionization chamber was 0.5%. It is worth noting that the PMMA phantom contains several holes each with a diameter of 20 mm for CTDI head measurements. The holes that were not used were filled with 20-mm PMMA rods to ensure electron equilibrium in the phantom during radiation exposure.

2.3. Gel characteristic evaluation

The nMAGAT(I) gels doped with 0.03, 0.05, and 0.07-M iodine were given various absorbed doses of 16.9, 31.6, 48.8, 63.1, 94.7, 126, 178, 252, and 315 mGy at 120 kVp and 150 mAs. Twenty-four hours after the irradiation, an optical CT scanner (VISTA, Modus Medical Devices Inc., USA) was used to read the gel in order to create dose-response curves. The sensitivity, which is defined as the slope of the dose-response curve, was evaluated, and the DER, which is defined as the ratio between the sensitivity of nMAGAT(I) gel and that of nMAGAT gel, was thus calculated. Moreover, post-preparation times of 3, 6, 12, 24, 48, and 72 h had been allotted before the gel was irradiated, and post-irradiation times of 12, 24, 48, 72, and 120 h were allotted before the gel was read to evaluate the stability of the nMAGAT(I) gel. Measurements were repeated three times for each dose point; the mean and standard deviation were calculated.

To determine the energy dependence, the nMAGAT(I) gel with the optimal iodine concentration was irradiated using a tube current of 150 mA and tube voltages of 80, 100, 120, and 135 kVp, respectively. Consecutive scans were performed to achieve a dose range of 16.9–365.5 mGy. The dose–response curves were linearly fitted and the sensitivity levels evaluated. The type A uncertainty of the gel dosimetry in this study includes the fluctuation of CT output, preparation and preservation of the gel, errors in dose response fitting, etc. The type B uncertainty is related to both random errors and bias which cannot be determined from repeated measurements. In our experiment, the total standard uncertainty (coverage factor $k = 1$) of the nMAGAT(I) gel was approximately 5%.

2.4. Gel reading

The VISTA cone beam optical CT scanner was used to read the gel at the room temperature of 22 °C. The scanner includes a diode array light source with a wavelength of 633 nm as well as a sink with a diameter of 9.5 cm and height of 13 cm. After the light passed through the irradiated gel tube, a collimator was used to remove the stray light before it was received by a charge-coupled camera. Subsequently, the optical linear attenuation coefficient map was reconstructed using the VistaRecon software (Modus Medical Devices Inc., USA). A circular region of interest (ROI) was drawn on the center of the gel tube with a radius of 0.5 cm to calculate the mean and standard deviation.

2.5. Slice thickness and CT dose index assessments

The nMAGAT and nMAGAT(I) gel tubes were inserted into the center of the home-made PMMA phantom (Fig. 1) and scanned 10 consecutive times using a tube voltage of 120 kVp, tube current of 150 mA, and nominal slice thickness of 1 cm, respectively. The SSP was obtained through the long axis of the gel tube, and the full width at half maximum (FWHM) was measured to represent the slice thickness of the CT scan.

For CT dose assessments, a tube voltage of 135 kVp, tube current of 220 mA, scan time of 0.75 s, and slice thickness of 6 mm were applied according to the annual quality assurance procedure of the CT scanner. The nMAGAT(I) gel tubes were inserted into the 3, 6, 9, and 12 o'clock positions as well as the center of the PMMA phantom for 10 consecutive scans. The weighted CTDI ($CTDI_w$) was calculated as follows:

$$CTDI_w = \frac{1}{3}CTDI_c + \frac{2}{3}CTDI_p, \tag{1}$$

where $CTDI_c$ and $CTDI_p$ are the CTDI measured at the central and peripheral regions of the PMMA phantom, respectively. A 10-cm-long pen-shaped ionization chamber (RaySafe, Unfors, Sweden) was also used to measure the weighted CTDI for comparison. Its total standard uncertainty (coverage factor $k = 1$) was 0.5%.

3. Results

3.1. Iodine concentration

Fig. 2 illustrates the relationship between the optical linear attenuation coefficient and absorbed dose when iodine concentrations were 0, 0.03, 0.05, and 0.07 M, respectively. The R-squared values of the dose–response curves exceeded 0.940 for all concentrations, indicating that the nMAGAT(I) gel exhibits good linearity at the dose range from 31.6 mGy to 315 mGy. As the concentration increased, the sensitivity of the nMAGAT(I) gel increased. When the iodine concentration reached 0.07 M, the sensitivity approached the highest value of 2.48×10^{-4} cm^{-1}/mGy, and the DER was 2.12. Accordingly, the iodine concentration of 0.07 M was used in the following experiments.

3.2. Gel stability

Fig. 3 shows the time-response curves for 31.6, 63.1, 94.7, and 126.2 mGy with the post-preparation times of 3, 6, 12, 24, 48, and 72 h. The light attenuation coefficient was measured 24 h after the irradiation. The nMAGAT(I) gel was chemically stable 24 h after its

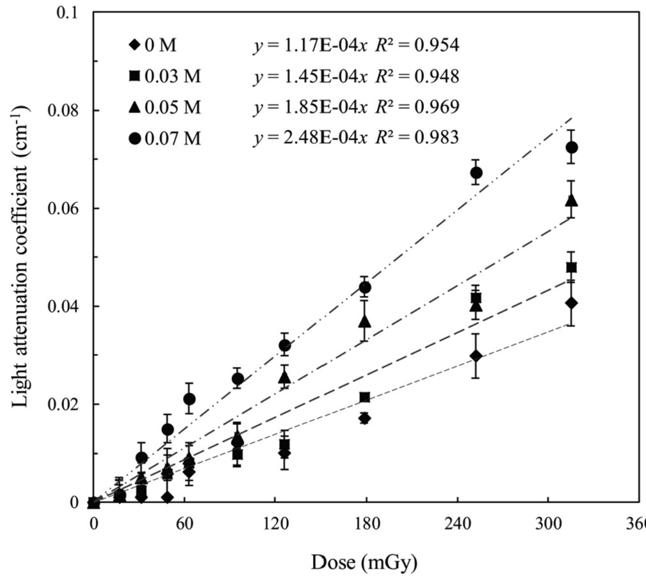

Fig. 2. Dose-response curves for 0, 0.03, 0.05, and 0.07-M iodine concentrations. The iodine concentration of 0.07 M yielded the highest sensitivity level. The error bars represent one standard deviation from the mean of three replicates.

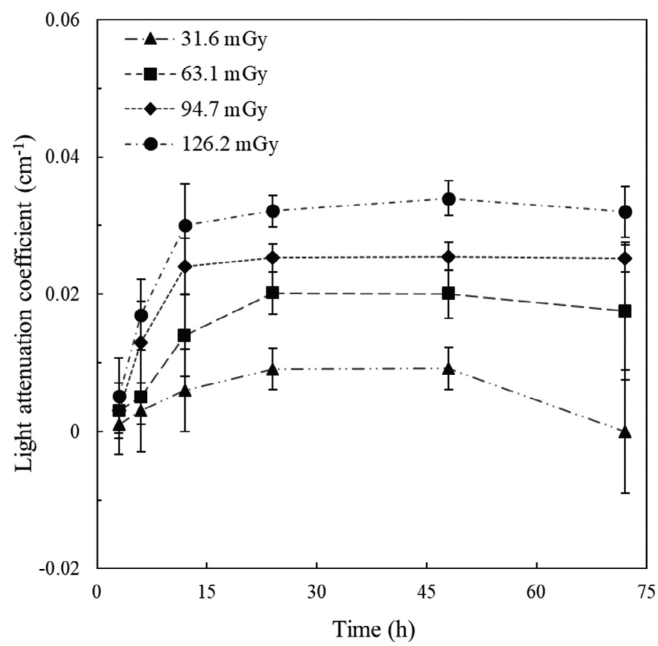

Fig. 3. Time-response curves of the irradiated nMAGAT(I) for 31.6, 63.1, 94.7, and 126.2 mGy with various post-preparation times. The nMAGAT(I) gel was stable 24 h after preparation; the stability decreased when irradiated more than 48 h after preparation. The error bars represent one standard deviation from the mean of three replicates.

preparation. However, when the gel had the post-preparation time of more than 48 h before the irradiation, the stability decreased and the standard deviation of the attenuation coefficient measurements increased significantly. Thus, the nMAGAT(I) gel should be irradiated within 24–48 h after its preparation.

Fig. 4 shows the time-response curves for 31.6, 63.1, 94.7, and 126.2 mGy with the post-irradiation times of 12, 24, 48, 72, and 120 h. Polymerization of the nMAGAT(I) gel gradually stabilized 24 h after the irradiation. Between 24 and 72 h, only slight polymerization continued in the gel, causing a difference in the light attenuation coefficients of

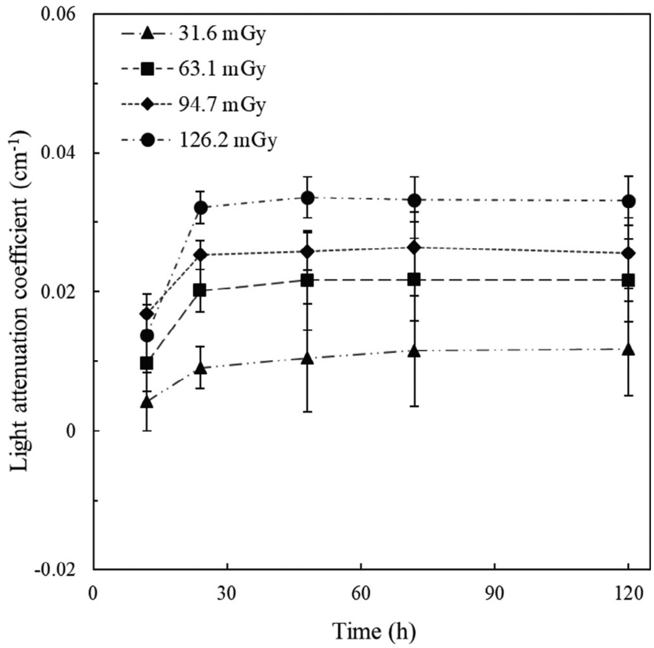

Fig. 4. Time-response curves of the irradiated nMAGAT(I) gel for 31.6, 63.1, 94.7, and 126.2 mGy with various post-irradiation times. Polymerization stabilized 24 h after the irradiation. No continued polymerization or fading was observed. The error bars represent one standard deviation from the mean of three replicates.

less than 2%, and the response did not show significant changes even up to 120 h. These results signify that the nMAGAT(I) gel is not affected by delayed polymerization and regression. In the subsequent experiments, the post-preparation time and post-irradiation time were fixed at 24 h.

3.3. Energy dependence

Fig. 5 shows the dose-response curves of the nMAGAT(I) gel

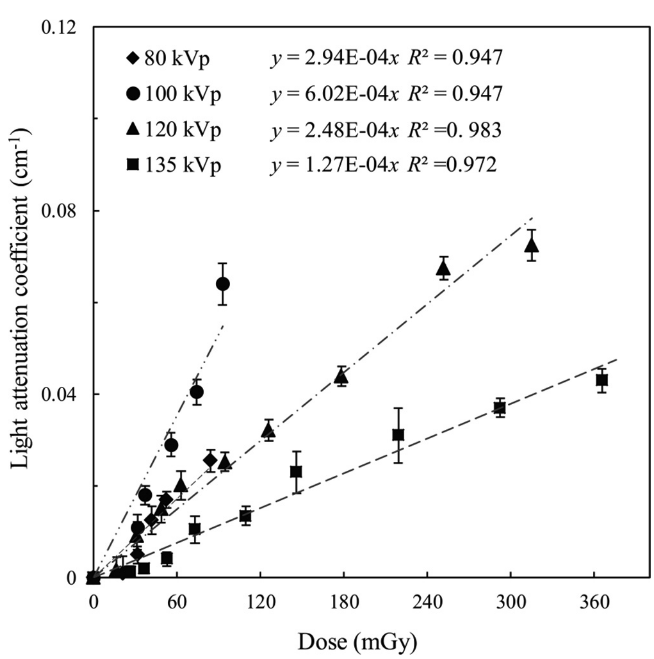

Fig. 5. Dose-response curves of the nMAGAT(I) gel irradiated at 80, 100, 120, and 135 kVp. The nMAGAT(I) gel yielded the highest sensitivity at 100 kVp. The error bars represent one standard deviation from the mean of three replicates.

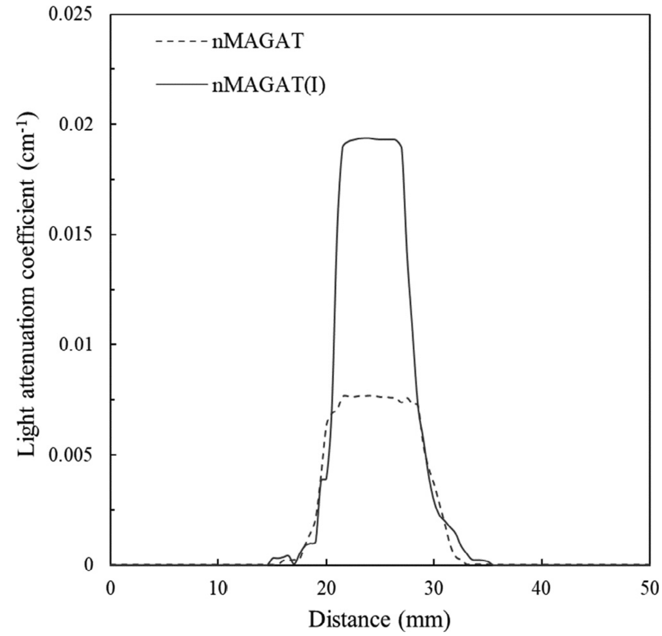

Fig. 6. SSP of 10-mm nominal slice thickness measured by the nMAGAT(I) and nMAGAT gels. The FWHM values were 9.5 and 12.5 mm, respectively.

obtained at various tube voltages. The light attenuation coefficient increased with increase in the absorbed dose; the *R*-squared values of the linear fitting all exceeded 0.940. At the tube voltages of 80, 100, 120, and 135 kVp, the sensitivity levels were 2.94×10^{-4}, 6.02×10^{-4}, 2.48×10^{-4}, and 1.27×10^{-4} cm^{-1}/mGy, respectively. The tube voltage of 100 kVp generated the most favorable sensitivity. This is because the most probable X-ray energy of CT just matches the *k*-edge of iodine (33.2 keV), thus greatly enhancing the probability of the photoelectric effect. As the tube voltage continued to increase, the sensitivity decreased because Compton scattering gradually dominates. The probability of the Compton effect is independent of the atomic number. Therefore, iodine has limited effects on increase in energy imparted to the gel.

3.4. Measuring slice thickness of CT scans

Fig. 6 shows the SSP of CT scans for the nominal slice thickness of 10 mm measured using the nMAGAT and nMAGAT(I) gels. At the center of the irradiation field, the average light attenuation coefficient obtained by the nMAGAT(I) gel was 2.08 times higher than that obtained by the nMAGAT gel. The nMAGAT(I) gel was more sensitive and generated stronger signals than the nMAGAT gel. The FWHM values of the two gels were 9.5 and 12.5 mm. The higher signal-to-noise ratio of the nMAGAT(I) gel make it more accurate in the slice thickness measurements.

3.5. Assessing radiation doses of CT scans

Table 2 presents $CTDI_c$, $CTDI_p$, and $CTDI_w$ measured using the ionization chamber and nMAGAT(I) gel at 135 kVp. The dose-response curve in Fig. 5 (solid square) was applied to convert the light

Table 2
CTDI measurements using the ionization chamber and nMAGAT(I) gel.

Position	Ion chamber (mGy)	nMAGAT(I) (mGy)	Difference
$CTDI_c$	65.94	63.19	−4.2%
$CTDI_p$	68.19	70.28	3.1%
$CTDI_w$	67.44	67.92	0.7%

attenuation coefficient to the absorbed dose. The nMAGAT(I) gel slightly underestimated $CTDI_c$ by 4.2%. For the $CTDI_p$, the absorbed doses were measured at the 3, 6, 9, and 12 o'clock positions surrounding the PMMA phantom. The mean value obtained by the nMAGAT(I) gel did not significantly differ from that obtained using the ionization chamber. For the $CTDI_w$, the result of the nMAGAT(I) gel differed from that of the ionization chamber by less than 1%. By using the paired *t*-test, no significant differences for $CTDI_w$ (p-value = 0.65) can be found between the ion chamber and nMAGAT(I) gel.

4. Discussion

This study used iodine as the radiation sensitizer because of its high atomic number, which greatly induces the photoelectric effect (proportional to Z^4) in the energy range of radiological diagnosis. Meesat et al. [13] demonstrated that iodine ion (I^-) can scavenge the free radicals produced by the radiolysis of water and quench the polymerization process. The iodine atoms provided in the radiocontrast agent in this study are covalently bound to molecules. Therefore, no scavenge effect was observed. The iodine concentrations of 0.03, 0.05, and 0.07 M increase the effective atomic number of the gel from 7.59 to 11.2, 12.2, and 13.0, respectively [20]. Further increase of the concentration will compromise the tissue equivalence of the gel [21]. Therefore, 0.07-M iodine is considered as a suitable concentration for dose measurements.

The stability of the nMAGAT(I) gel gradually decreases when the post-preparation time exceeds 48 h. This may be because oxygen gradually penetrates into the gel through the screw cap and tube wall. The increase in oxygen content inhibits polymerization process [22], and subsequently decreases gel sensitivity. Massillon et al. [23] reported that the initial response of the polymer gel may be faded after 100 h of its irradiation. In this study, the nMAGAT(I) gel had slightly delayed polymerization during 24 to 72 h of post-irradiation time, and no regression was observed up to 120 h. However, in order to avoid additional uncertainty or bias, it is recommended that we should not extend the time between irradiation and reading process.

De Deene et al. [24] assessed the properties of the nMAG gel and reported that the dosimeter had an energy dependence of less than 3%. The nMAGAT(I) gel contains 0.07-M iodine, and *k*-edge absorption in it facilitates the favorable generation of additional photoelectrons, characteristic X-ray, and Auger electrons, which all tend to deposit their energy locally. However, the iodine atoms also increase the effective atomic number of the gel, which considerably increases the energy dependence [20,25]. In the present study, the nMAGAT(I) gel exhibits a maximum sensitivity ratio of 4.74 in the energy range of CT scans. The significant energy dependence urges us to establish a dose-response curve for each specific tube voltage before CT dose measurements. Additionally, different dose-response curves are required for different filters and after replacement of the X-ray tube.

Currently, the most commonly used ionization chamber for CTDI measurements has a length of only 10 cm, which cannot fully cover the width of detectors in modern CT scanners. Consequently, CTDI generally underestimates the energy deposition and absorbed dose of scanning regions. Chuang and Wu [4] measured a 30-cm SSP and CTDI simultaneously using the nMAG gel to consider scattered radiation in a larger irradiation field. However, the nMAG gel is relatively insensitive and could not accurately assess radiation dose near the edge of the field. The nMAGAT(I) gel introduced in this study is more sensitive to radiation than the nMAG gel. Future research will investigate the capability of dose profile and radiation dose assessments by using the nMAGAT(I) gel for other clinical radiological applications.

The limitation of using nMAGAT(I) gel in clinical radiodiagnostic practice is the minimum detectable dose (MDD). MDD is defined as the dose resolution as the dose approaches zero [26]. That is $2.77\sigma_D$ for 95% confidence interval (CI) and $1.44\sigma_D$ for 68% CI. Baldock et al. [26] demonstrated the MDD of the PAG gel to be 155 mGy for 68% CI, whereas Chuang et al. [4] showed the MDD of the nMAG gel to be 113 mGy. Although the nMAGAT(I) gel has the MDD of 66 mGy for 68% CI, it still needs multiple radiation exposures from radiodiagnostic imaging modalities. That is the reason ten consecutive CT scans are required in the SSP and CTDI measurements. For further reducing MDD of the gel dosimeter, post-image processing procedures of the gel reading system have to be investigated to increase the signal-to-noise ratio in dose images.

5. Conclusion

Gel dosimeters offer three-dimensional dose information and exhibit favorable tissue equivalence, dose linearity, and energy dependence. They have become an increasingly popular tool in radiation therapy. In this study, the nMAGAT(I) gel doped with 0.07-M iodine revealed a good linearity in the dose range of 31.6–315 mGy. The sensitivity level was effectively increased and the DER approached 2.12. The nMAGAT(I) gel exhibited stable chemical properties 24 h after its preparation, and no delayed polymerization and regression can be found. In clinical applications, the nMAGAT(I) gel was used to assess radiation doses from CT scans and to analyze the slice thickness of SSP; such a gel dosimeter has the potential to serve as a quality assurance tool for CT and other radiological diagnostic applications.

Acknowledgments

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Competing interests

The authors declare that no competing interests exist.

References

[1] Kozicki M, Jaszczak M, Maras P, Dudek M, Clapa M. On the development of a VIPAR (nd) radiotherapy 3D polymer gel dosimeter. Phys Med Biol 2017;62:986–1008.
[2] Shih TY, Wu J, Shih CT, Lee YT, Wu SH, Yao CH, et al. Small-field measurements of 3D polymer gel dosimeters through optical computed Tomography. PLoS ONE 2016;11:e0151300.
[3] Martin CJ, Huda W. Intercomparison of patient CTDI surveys in three countries. Radiat Prot Dosimetry 2013;153:431–40.
[4] Chuang CC, Wu J. Dose and slice thickness evaluation with nMAG gel dosimeters in computed tomography. Sci Rep 2018;8:2632.
[5] Hilts M, Audet C, Duzenli C, Jirasek A. Polymer gel dosimetry using x-ray computed tomography: a feasibility study. Phys Med Biol 2000;45:2559.
[6] Trapp J, Bäck SÅJ, Lepage 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;46:2939.
[7] Hilts M, Jirasek A, Duzenli 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;49:2477.
[8] Chang KY, Shih TY, Hsieh BT, Chang SJ, Liu YL, Wu TH, et al. Investigation of the dose characteristics of an n-NIPAM gel dosimeter with computed tomography. Nucl Instrum Methods Phys Res A 2011;652:775–8.
[9] Shih TY, Shih CT, Chang YJ, Chun YY, Hsieh BT, Chang SJ, et al. Evaluating the characteristics of a novel DEMBIG gel dosimeter using computed tomography. IEEE Trans Nucl Sci 2013;60:716–21.
[10] Hill B, Venning A, Baldock C. The dose response of normoxic polymer gel dosimeters measured using X-ray CT. Br J Radiol 2005;78:623–30.
[11] Fernandes JP, Pastorello BF, de Araujo DB, Baffa O. Formaldehyde increases MAGIC gel dosimeter melting point and sensitivity. Phys Med Biol 2008;53:N53.
[12] Jirasek A, Hilts M, Berman A, McAuley K. Effects of glycerol co-solvent on the rate and form of polymer gel dose response. Phys Med Biol 2009;54:907.
[13] Meesat R, Jay-Gerin JP, Khalil A, Lepage M. Evaluation of the dose enhancement of iodinated compounds by polyacrylamide gel dosimetry. Phys Med Biol 2009;54:5909.
[14] Sathiyaraj P, Jebaseelan Samuel EJ. Application of bi-nanoparticle on dose enhancement effect in two different polymer gel dosimeter using spectrophotometer. J Cancer Res Ther 2018;14:662–5.
[15] Santibanez M, Guillen Y, Chacon D, Figueroa RG, Valente M. Feasibility of dose enhancement assessment: Preliminary results by means of Gd-infused polymer gel dosimeter and Monte Carlo study. Appl Radiat Isot 2018;141:210–8.
[16] Brindha S, Venning A, Hill B, Baldock C. Experimental study of attenuation

properties of normoxic polymer gel dosimeters. Phys Med Biol 2004;49:N353.
[17] Baxter P, Jirasek A, Hilts M. X-ray CT dose in normoxic polyacrylamide gel dosimetry. Med Phys 2007;34:1934–43.
[18] Hurley C, Venning A, Baldock C. A study of a normoxic polymer gel dosimeter comprising methacrylic acid, gelatin and tetrakis (hydroxymethyl) phosphonium chloride (MAGAT). Appl Radiat Isot 2005;63:443–56.
[19] De Deene Y. Essential characteristics of polymer gel dosimeters. J Phys Conf Ser 2004;3:34.
[20] Sellakumar P, Samuel EJJ, Supe SS. Water equivalence of polymer gel dosimeters. Radiat Phys Chem Oxf Engl 1993;2007(76):1108–15.
[21] Taylor ML, Franich RD, Trapp JV, Johnston PN. The effective atomic number of dosimetric gels. Australas Phys Eng Sci Med 2008;31:131–8.
[22] Baldock C, De Deene Y, Doran S, Ibbott G, Jirasek A, Lepage M, et al. Polymer gel dosimetry. Phys Med Biol 2010;55:R1.
[23] Massillon JG, Minniti R, Soares CG, Maryanski MJ, Robertson S. Characteristics of a new polymer gel for high-dose gradient dosimetry using a micro optical CT scanner. Appl Radiat Isot 2010;68:144–54.
[24] De Deene Y, Vergote K, Claeys 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;51:653–73.
[25] Un A. Water and tissue equivalency of some gel dosimeters for photon energy absorption. Appl Radiat Isot 2013;82:258–63.
[26] Baldoc C, Lepage M, Back SA, Murry PJ, Jayasekera PM, Porter D, et al. Dose resolution in radiotherapy polymer gel dosimetry: effect of echo spacing in MRI pulse sequence. Phys Med Biol 2001;46:449–60.