Dosimetric Evaluation of MAGICA Polymer Gel Doped with Bismuth Nanoparticles under 6 MV Photon Irradiation

Shiva Shoobkolaei (MSc)[1,2]*, Nader Riyahi Alam (PhD)[1]*, Ali Shabestani Monfared (PhD)[2]

[1]Department of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences (TUMS), Tehran, Iran
[2]Cancer Research Center, Health Research Institute, Babol University of Medical Sciences, Babol, Iran

ABSTRACT

Background: Polymer gels provide high-resolution Three-Dimensional (3D) dosimetry and serve as valuable tools for quality assurance in radiotherapy.

Objective: The current study aimed to synthesize a Methacrylic Acid with Gelatin, Initiated by Copper, and Agarose (MAGICA) added polymer gel dosimeter doped with Bismuth Nanoparticles (BiNPs) and to evaluate its dosimetric performance under clinical megavoltage irradiation systematically.

Material and Methods: In this experimental study, we prepared MAGICA gels containing BiNPs at concentrations of 0.05, 0.1, and 0.2 mM, along with control gels. These gels were then simultaneously irradiated with 6 MV photon beams from a clinical linear accelerator. The dosimetric responses were quantified using T_2-weighted magnetic resonance imaging (MRI).

Results: All samples exhibited a stable linear R_2–dose response, and the incorporation of BiNPs enhanced the dosimetric sensitivity. Analysis of the Dose Enhancement Factor (DEF) yielded values of 1.05, 1.09, and 1.08 for the 0.05, 0.1, and 0.2 mM BiNP concentrations, respectively. This enhancement is attributed to increased local energy deposition and production of hydroxyl radicals via water radiolysis.

Conclusion: BiNP-doped MAGICA gel provides improved dosimetric performance and reproducibility, establishing it as a robust platform for 3D dose verification and a promising candidate for preclinical radiotherapy optimization.

Keywords

Radiation Dosimeters; Polymer Gel; Bismuth; Nanoparticles; Sensitivity; Radiotherapy

Introduction

Radiation therapy plays a central role in cancer treatment by delivering high-energy ionizing radiation, such as X-rays or electron beams, to destroy tumor cells by inducing DNA damage. In modern radiotherapy, advanced techniques, such as Three-Dimensional Conformal Radiation Therapy (3DCRT), Intensity Modulated Radiation Therapy (IMRT), Volumetric Modulated Arc Therapy (VMAT), and Stereotactic techniques, as well as the recently developed Magnetic Resonance Imaging Linear Accelerator (MRI-Linac) systems, enable precise radiation dose delivery to complex tumor volumes and minimize exposure to surrounding healthy tissues. These technological advances underscore the crucial role of accurate dosimetry and verification

*Corresponding author:
Nader Riyahi Alam
Department of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences (TUMS), Tehran, Iran
E-mail: riahialam@gmail.com

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in ensuring safe and effective treatment delivery [1]. Precise dosimetry is a cornerstone of radiotherapy quality assurance and treatment optimization, providing reproducible and reliable quantification of absorbed ionizing radiation within the target volume. Continuous advances in medical dosimetry have further enhanced the accuracy of dose measurement and the overall reliability of radiation therapy [2, 3].

Traditionally, dosimetry has been performed using one-dimensional detectors, such as ionization chambers and silicon diodes [4, 5], or two-dimensional detectors, such as radiochromic films and Electronic Portal Imaging Devices (EPID) [6]. Despite continuous improvements in these devices, a realistic assessment of dose distribution within a volumetric space requires the use of a Three-Dimensional (3D) dosimeter, which has attracted considerable interest in recent years. This tool allows precise analysis of complex radiation fields and enables end-to-end verification of the entire treatment process, from dose planning to final delivery [7].

One of the earliest types of gel dosimeters was the Fricke gel, which operates based on radiation-induced changes in ferric ion concentration [8]. However, the limited stability of these ions led to diffusion and the formation of concentration gradients within the gel, reducing spatial uniformity. To achieve improved chemical and spatial stability, a new generation of dosimeters based on radiation-induced polymerization was developed [9]. The normoxic MAGIC gel, composed of methacrylic acid, ascorbic acid, and gelatin with a copper initiator, remains stable under normal environmental conditions and exhibits a precise dose response. Due to these advantages, it has been widely investigated for 3D dosimetry in radiotherapy [10]. To further enhance its reproducibility and stability, agarose was introduced as a stabilizing agent, leading to the development of the improved MAGICA formulation [11]These modifications enhance the gel's dynamic response, improve its uniformity, and strengthen its chemical robustness, making MAGICA a reliable tool for 3D dosimetry in research and clinical applications [12].

In recent years, the performance of polymer gel dosimeters has focused on enhancing their sensitivity and dose response. One of the most effective approaches involves the incorporation of high atomic number (high-Z) nanoparticles [13-16]. These nanoparticles have been extensively investigated for radiation dose enhancement [17] and increased local energy deposition primarily through physical interactions, such as the photoelectric effect, Compton scattering, and pair production. The resulting increase in absorbed dose can be quantified using the Dose Enhancement Factor (DEF), which provides a direct measure of the amplification of radiation effects in the presence of nanoparticles [17, 18].

Among various high-Z nanoparticles, Bismuth Nanoparticles (BiNPs) [19] have recently gained considerable attention as promising radiosensitizers due to their high atomic number (Z=83), strong X-ray attenuation capability, excellent biocompatibility, and relatively low cost compared with Gold Nanoparticles (AuNPs) [20, 21]. Furthermore, BiNPs exhibit unique dual functionality that enables both diagnostic imaging and therapeutic enhancement, positioning them as attractive candidates for theranostic applications [22].

The radiation sensitization induced by BiNPs has been analyzed through Monte Carlo simulations in various geometrical configurations and materials under various irradiation modalities, including kilovoltage X-rays [23], brachytherapy sources such as ^{192}Ir [24], and megavoltage photon beams [25]. Results from these simulations demonstrated that BiNPs can significantly increase local energy deposition and radiosensitivity, with the magnitude of enhancement influenced by nanoparticle concentration and photon energy, primarily due to the Z^4/E^3 dependence of the

photoelectric effect at the atomic level (where Z is the atomic number and E is the photon energy).

Given the promising radiosensitizing potential of BiNPs and the high spatial resolution of polymer gel dosimetry, further studies are warranted to explore their combined use. This study aimed to incorporate BiNPs into the MAGICA polymer gel dosimeter to evaluate their potential in enhancing the dosimetric response and radiation sensitivity of the gel system. The work assesses the feasibility and performance of the BiNPs–MAGICA composite as a novel 3D dosimeter for use in verifying megavoltage photon radiotherapy.

Material and Methods

Materials

In this experimental study, MAGICA polymer gel dosimeters were prepared and irradiated to evaluate the radiosensitizing effects of BiNPs. The normoxic MAGICA polymer gel dosimeter was developed using a slightly modified version of the composition [10], notably with agarose incorporated. All chemicals utilized throughout the process were analytical grade and of high purity. These included gelatin (porcine skin, type A, 300 Bloom, Sigma-Aldrich, USA), agarose (low EEO, Bioreagent, Sigma-Aldrich, USA), hydroquinone, ascorbic acid (AA), copper (II) sulfate ($CuSO_4$) (all from Sigma-Aldrich, USA), and methacrylic acid (MAA, 99.9%, Merck, Germany). Ultrapure deionized water (Milli-Q, Purelab Flex UV, Elga Lab-Water, UK) was used as the solvent.

BiNPs (28 nm, Nano kimiagaran Co.) were obtained as dry powder and dispersed in 1% of the total ultrapure water by ultrasonic agitation before incorporation into the gel. The detailed composition of the MAGICA gel is presented in Table 1.

Synthesis of MAGICA Polymer Gel Dosimeter Doped with BiNPs

Gelatin was added slowly to 60% of the total ultrapure water at room temperature and magnetically stirred for about 30 minutes, while the temperature was raised to 50 °C to obtain a homogeneous solution. Simultaneously, agarose was dissolved in 30% of the total water at 80 °C in a separate container under continuous stirring until fully dissolved. Both solutions were then cooled to around 50 °C, combined, and stirred until a uniform final solution was obtained.

Hydroquinone, previously dissolved in 2% of the total water, was added to the mixture, which was then allowed to cool to 35 °C. Ascorbic Acid (AA) and copper (II) sulfate ($CuSO_4$), each dissolved in 2% of the total water and serving as oxygen scavengers, were sequentially introduced under gentle stirring. After 5 minutes, Methacrylic Acid (MAA) was added, and the solution was stirred until

Table 1: Chemical component of the MAGICA gel dosimeter

Component	Chemical formula	Concentration (w/w) %
Ultrapure deionized water	H_2O	82.3
Porcine gelatin	$C_{17}H_{32}N_5O_6$	8
Agarose	$(C_{12}H_{18}O_9)$ n	5.0
Methacrylic acid	$C_4H_6O_2$	9
Hydroquinone	$C_6H_6O_2$	2.0
Ascorbic acid	$C_6H_8O_6$	0.0352
Copper sulfate	$CuSO_4$	0.0015

complete homogeneity was achieved.

The resulting gel solution was divided into four equal portions. The pre-prepared BiNP suspension, sonicated in 1% ultrapure water at concentrations of 0.05, 0.1, and 0.2 mM, was added to three portions of the gel, while the fourth portion served as the control (pure gel) and received 1% ultrapure water. All portions were thoroughly stirred to ensure uniform dispersion of the components.

For each gel composition, four independent batches were prepared, and for each batch, six vials were used: five vials for irradiation at different doses and one vial as an unirradiated control. The gels were then poured into 9.5 mL glass vials, sealed with Parafilm, and wrapped in aluminum foil to protect them from light. All samples were stored at 5 °C for 24 hours before irradiation [26].

Irradiation Procedure

Prepared gel vials (BiNPs-doped gels at concentrations of 0.05, 0.1, and 0.2 mM, along with control gels) were irradiated using a 6 MV photon beam from a medical linear accelerator (Primus LINAC, Siemens Healthineers, Germany). All vials were positioned vertically in a Plexiglas holder. This holder was placed inside a 40×34×35 cm^3 water phantom. Each vial had a height of 4.2 cm, with its center positioned 2.1 cm from the top of the vial.

Irradiation was performed using two parallel-opposed 40×40 cm^2 fields at a Source-to-Axis Distance (SAD) of 100 cm. The dose rate was set to 200 MU/min (corresponding to 200 cGy/min, based on a calibration of 1 cGy per MU at the reference point in water). Delivered doses were 2, 4, 6, 8, and 10 Gy, while one vial from each group was kept unirradiated as a background reference. After irradiation, all samples were stored at 4 °C to minimize thermal effects and prevent post-irradiation polymerization, ensuring dosimetric stability before MRI readout.

MRI Readout and Data Analysis

After irradiation, all polymer gel dosimeters were stored for 24 hours to allow completion of post-irradiation polymerization and cross-linking, ensuring stabilization of the final dose-dependent R_2 values [10]. Prior to imaging, the samples were kept in the MRI room for four hours to minimize temperature-induced variations in the spin–spin relaxation rate ($R_2=1/T_2$). Temperature was controlled at 4 °C during storage and prior to MRI readout to ensure reproducible R_2 measurements. MRI scans were conducted on a 1.5 T system (MAGNETOM Avanto; Siemens Healthineers, Germany) using a body coil, as illustrated in Figure 1a.

The R_2 values were used as the dosimetric parameter due to their high sensitivity, wide dynamic range, and superior signal-to-noise

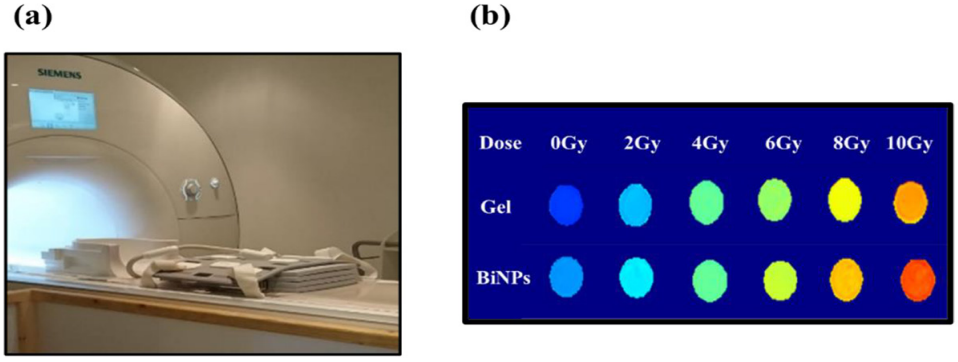

Figure 1: MRI imaging and corresponding R_2 map of MAGICA gel dosimeters. (**a**) Representative view of 1.5 T MRI imaging. (**b**) R_2 map of pure MAGICA gel and gels containing 0.1 mM BiNPs, irradiated with 6 MV photon beam at doses of 0–10 Gy. (MRI: Magnetic Resonance Imaging)

ratio compared with T_1-weighted imaging [27]. Accordingly, T_2-weighted images were acquired using a multi-spin-echo sequence with 16 echo times. MRI acquisition parameters were: Repetition Time (TR) =3000 ms, Echo Spacing (TEs) =22 ms, Field of View (FOV) =250 mm², matrix size=256×256 (pixels), slice thickness =4 mm, and Number of Excitations (NEX) =2. Calibration vials were scanned alongside the BiNPs-containing gels to minimize intersample temperature variations during acquisition.

R_2 maps were reconstructed from DICOM data using MATLAB (R2023b, MathWorks, USA), and mean R_2 values were extracted from Regions of Interest (ROIs) within each vial, excluding edge voxels (Figure 1b). Dose–response curves were plotted as mean R_2 versus absorbed dose to evaluate the linear dose–response behavior of the gel dosimeters. R_2 values were calculated using the mono-exponential model:

$$S_i=S_0.e^{-R_2\times TE} \qquad (1)$$

where S_i and S_0 are the signal intensities at the i-th echo time and TE=0, respectively.

For each independent batch, the R_2–dose slope and DEF were calculated separately for each replicate. The final DEF values were obtained by averaging the three replicates, ensuring independent consideration of each measurement and accurate representation of variability.

Statistical Analysis

All measurements were conducted in triplicate, and the results are reported as mean ± Standard Deviation (SD). The Shapiro–Wilk test was applied to assess normality.

One-way ANOVA was used to compare the groups, followed by Tukey's post-hoc test for pairwise comparisons, using GraphPad Prism 9.5.1. Statistical significance was defined as a *P*-value<0.05.

Results

Pure MAGICA gel samples were examined at different radiation doses from 0 to 10 Gy to evaluate the effect of irradiation on the polymerization process. With increasing dose, visual changes in the gel were observed as increased opacity and reduced transparency, indicating the progression of radiation-induced polymerization.

The response of MAGICA gel to irradiation was measured based on the transverse relaxation time (T_2) in non-irradiated samples, both in the absence and presence of BiNPs. Minor variations were observed in T_2 before irradiation, likely due to slight interactions between the gel components and the nanoparticles. By converting T_2 to the transverse relaxation rate $R_2=1/T_2$, pure MAGICA gel exhibited linear behavior over the dose range of 0–10 Gy, with R_2 increasing uniformly with dose ($R^2=0.996$).

The R_2–dose response of the pure gel and BiNP-loaded gels at different concentrations is presented in Figure 2. The BiNP-loaded gels also showed a similar linear response, but the slope of the R_2–dose curve was higher in the presence of nanoparticles.

Gel sensitivities were calculated from the slopes of the R_2–dose response curves. Sensitivity values for the pure MAGICA gel and BiNP-loaded gels at concentrations of 0.05, 0.1, and 0.2 mM were 1.04, 1.10, 1.14, and 1.13 $Gy^{-1}.s^{-1}$, respectively. A significant increase in sensitivity was observed for all BiNP-loaded gels compared with the pure gel ($P<0.001$), as illustrated in Figure 3a.

The DEF was calculated as the ratio of the R_2–dose slope of BiNP-loaded gels to that of the pure gel and is presented as a bar graph in Figure 3b. DEF values for concentrations of 0.05, 0.1, and 0.2 mM were 1.05±0.005, 1.09±0.005, and 1.08±0.006, respectively, with the highest DEF observed at 0.1 mM. The difference in DEF between the pure and BiNP-loaded gels was statistically significant ($P<0.001$).

Discussion

The response of MAGICA gel to irradiation

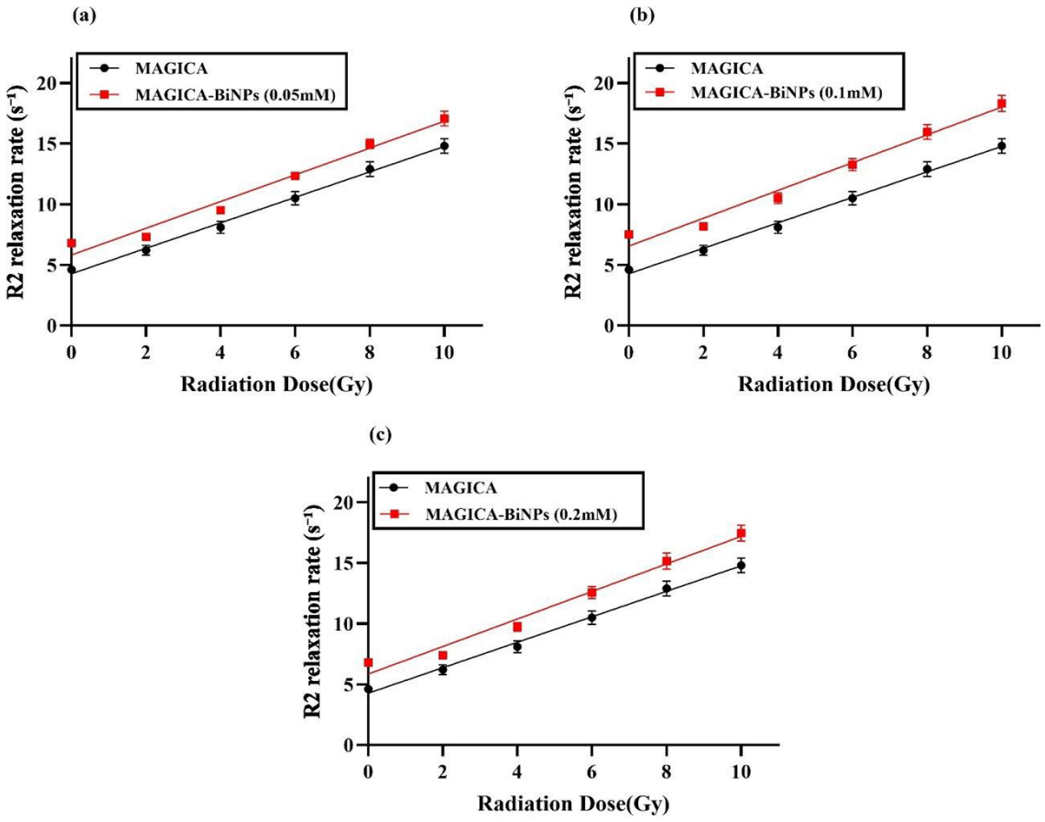

Figure 2: Impact of BiNP concentration on the R_2–dose response of MAGICA gel. (**a–c**) R_2–dose response curves of MAGICA gels doped with BiNPs at concentrations of 0.05 mM (**a**), 0.1 mM (**b**), and 0.2 mM (**c**), illustrating the relationship between absorbed dose and R_2 values following irradiation with a 6 MV photon beam in the dose range of 0–10 Gy.

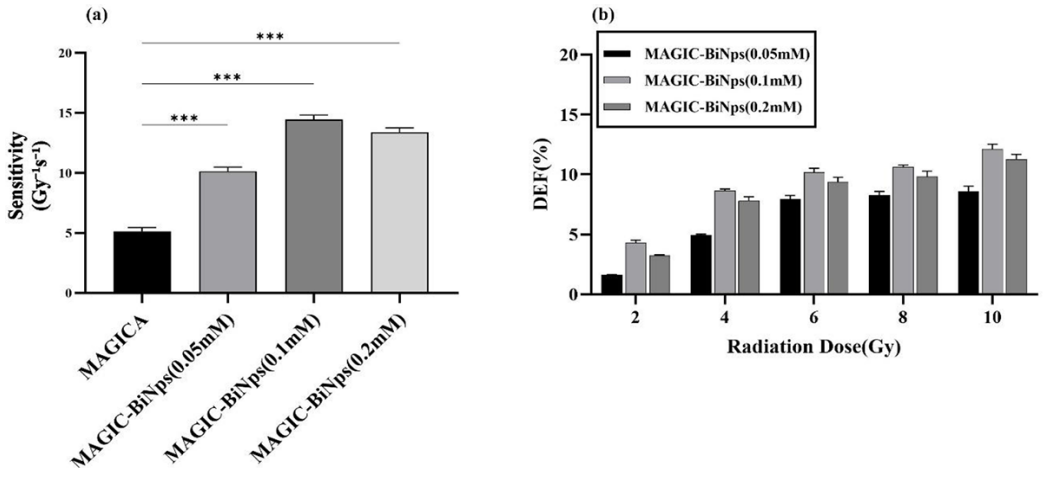

Figure 3: Sensitivity and dose enhancement of MAGICA gel loaded with BiNPs. (**a**) Mean gel sensitivity for pure gel and BiNP-loaded gels at concentrations of 0.05, 0.1, and 0.2 mM irradiated with a 6 MV photon beam. (**b**) DEF of BiNP-loaded gels at the same concentrations relative to pure gel over 2–10 Gy, irradiated with a 6 MV photon beam. Error bars indicate SD; *P*-value<0.001.

originates from radicals formed through water radiolysis, particularly hydroxyl radicals (OH•), hydrogen atom radicals (H•), and hydrated electrons (e^-_{aq}). These radicals react with Methacrylic Acid (MAA) monomers, initiating a chain polymerization process [27]. As the reaction progresses, active radicals transfer between polymer chains, leading to network growth and increased crosslink density. The densification of the polymer network correlates directly with measurable changes in the transverse relaxation rate (R_2) on MRI images, such that R_2 increases with absorbed dose [28]. In the absence of irradiation, MAGICA gel exhibits chemical and physical stability, and minor pre-irradiation changes, including slight opacity or small R_2 fluctuations, are considered baseline values [29].

At megavoltage energies, (6 MV) commonly applied in clinical radiation therapy, Compton scattering is the predominant photon interaction with matter [30]. Because this interaction depends on electron density, the incorporation of BiNPs, which have a higher atomic number and density than soft tissue, increases local electron density within the gel. This enhancement promotes Compton scattering and the production of secondary electrons, which deposit additional energy in the microscopic volumes surrounding the nanoparticles. These low-energy electrons further stimulate polymerization, leading to increased local dose, elevated R_2 values, and a steeper gel dose–response curve. This physical mechanism underlies the observed DEF in BiNP-doped gels. It should be noted that at megavoltage energies, only modest DEF values are expected, which is consistent with the described physical mechanisms.

In this study, the R_2–dose response curves for both pure and BiNP-doped gels were linear; however, the presence of nanoparticles significantly increased the slope of the curves, indicating enhanced gel sensitivity. The sensitivity of pure MAGICA was 1.04 $Gy^{-1}.s^{-1}$, whereas BiNP-doped gels with concentrations of 0.05, 0.1, and 0.2 mM exhibited sensitivities of 1.10, 1.14, and 1.13 $Gy^{-1}.s^{-1}$, respectively. These differences were statistically significant (P-value<0.001).

The initial increase in sensitivity up to 0.1 mM reflects a uniform and effective distribution of nanoparticles within the gel. The slight decrease in sensitivity at 0.2 mM is likely due to nanoparticle aggregation and radical scavenging effects, which reduce polymerization efficiency [31]. Consistent with previous studies on other metallic nanoparticles [32], higher concentrations can lead to competition between free radicals and monomers, resulting in a minor reduction in both the slope of the R_2–dose curve and the DEF. Within the 0–10 Gy dose range, increasing BiNP concentration from 0.05 to 0.1 mM markedly increased the slope of the R_2–dose curve and the DEF. Even at low concentrations, BiNPs promote secondary electron production and additional water radiolysis, generating more radicals and accelerating polymerization. These effects collectively enhance the gel's local dose response and sensitivity.

Previous studies [16,20,21,29,32-34] have consistently shown that incorporating nanoparticles enhances both the sensitivity and dose response of polymer gels. Sabbaghizadeh et al. (2017) reported that adding AgNPs increased the dosimetric response of PAGAT gel by 11.82% [32]. Khosravi et al. (2016) observed DEF values ranging from 1.014 to 1.161 for various concentrations of AuNPs in MAGICA gel [29]. Farahani et al. (2020) found that BiNPs significantly increased the dose response in nPAG gels for Ir-192, while a smaller effect was observed for Co-60, highlighting the energy dependence of nanoparticle-mediated dose enhancement [20]. Similarly, Alqathami et al. (2016) reported higher DEFs for bismuth-based nanoparticles at kilovoltage compared to megavoltage energies [33]. Alyani Nezhad et al. (2021) demonstrated that Bi_2O_3 nanoparticles in GENIPIN gel under low-energy (50 kV) irradiation

substantially increased the local dose through the photoelectric effect [21]. Sathiyaraj et al. (2018) reported maximum DEFs of 1.34 and 1.18 for BiNPs in PAGAT and NIPAM gels, respectively, under 1.25 MeV gamma irradiation at 0.5 mM concentration [34]. Additionally, Shoobkolaei et al. (2026) quantitatively compared AuNPs and PtNPs in MAGICA gels under 6 MV irradiation, reporting dose enhancement factors of 9.88% for AuNPs and 12.04% for PtNPs [16].

Importantly, this study provides a dosimetric evaluation of MAGICA polymer gel doped with varying concentrations of BiNPs under clinical 6 MV photon irradiation, extending previous studies on nanoparticle-enhanced gel dosimetry. The effects of BiNP concentration on gel sensitivity and R_2–dose response were systematically assessed, offering quantitative insight into the behavior of these high-Z nanoparticles under clinically relevant conditions.

Conclusion

This study demonstrated that doping the MAGICA polymer gel with BiNPs effectively enhances gel sensitivity and the DEF under clinical 6 MV photon irradiation. The R_2–dose response remained linear, with the slope increasing at 0.1 mM, indicating maximal sensitivity, while a slight decrease at 0.2 mM likely resulted from nanoparticle aggregation and radical scavenging. These findings confirm that high-Z nanoparticles facilitate secondary electron production and accelerate polymerization within the gel. Overall, the MAGICA–BiNP system offers a promising platform for preclinical dosimetry and may serve as a reference for evaluating BiNP-mediated dose enhancement in tumor radiosensitization during radiotherapy.

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Authors' Contribution

S. Shoobkolaei and N. Riyahi Alam conceptualized the study and developed the methodology. S. Shoobkolaei performed the software implementation, formal analysis, data curation, visualization, and prepared the original draft of the manuscript. S. Shoobkolaei and N. Riyahi Alam conducted the validation process. The investigation was carried out by S. Shoobkolaei and A. Shabestani Monfared. Resources were provided by N. Riyahi Alam, A. Shabestani Monfared, and M. Khobi. N. Riyahi Alam reviewed and edited the manuscript. Supervision was provided by N. Riyahi Alam and A. Shabestani Monfared. N. Riyahi Alam was responsible for project administration and funding acquisition. All authors have read and approved the final version of the manuscript.

Ethical Approval

No ethical approval was required, as the study did not involve humans or animals.

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Conflict of Interest

None

Data Availability Statement

All data produced from this study are available from the corresponding author on reasonable request.

References

1. Salman MD, Radzi YM, Rahman AA, Oglat AA, Dheyab MA. Advancements and applications of dosimetry techniques in modern medical radiation therapy: a comprehensive review. *J Radioanal Nucl*

Chem. 2024;**333**:3713-37. doi: 10.1007/s10967-024-09517-3.

2. Angelou C, Patallo IS, Doherty D, Romano F, Schettino G. A review of diamond dosimeters in advanced radiotherapy techniques. *Med Phys.* 2024;**51**(12):9230-49. doi: 10.1002/mp.17370. PubMed PMID: 39221583. PubMed PMCID: PMC11656300.
3. Karger CP, Elter A, Dorsch S, Mann P, Pappas E, Oldham M. Validation of complex radiotherapy techniques using polymer gel dosimetry. *Phys Med Biol.* 2024;**69**:06TR1. doi: 10.1088/1361-6560/ad278f. PubMed PMID: 38330494.
4. Rosenfeld AB, Biasi G, Petasecca M, Lerch MLF, Villani G, Feygelman V. Semiconductor dosimetry in modern external-beam radiation therapy. *Phys Med Biol.* 2020;**65**(16):16TR01. doi: 10.1088/1361-6560/aba163. PubMed PMID: 32604077.
5. Pereira Neves L, Perini AP, Caldas LV. A review of ionization chambers developed for use at the Brazilian IPEN calibration laboratory. *Braz J Phys.* 2024;**54**:167. doi: 10.1007/s13538-024-01533-8.
6. De Freitas Nascimento L, Gasparini A. Review of real time 2D dosimetry in external radiotherapy: advancements and techniques. *Radiat Meas.* 2025;**180**:107344. doi: 10.1016/j.radmeas.2024.107344.
7. Sasaki M, Ikushima H, Sugimoto W, Kitagawa K. Long-term stability of a three-dimensional dose verification system. *Radiol Phys Technol.* 2020;**13**(1):83-91. doi: 10.1007/s12194-020-00554-7. PubMed PMID: 32006217.
8. Gore JC, Kang YS, Schulz RJ. Measurement of radiation dose distributions by nuclear magnetic resonance (NMR) imaging. *Phys Med Biol.* 1984;**29**(10):1189-97. doi: 10.1088/0031-9155/29/10/002. PubMed PMID: 6494247.
9. Maryanski MJ, Gore JC, Kennan RP, Schulz RJ. NMR relaxation enhancement in gels polymerized and cross-linked by ionizing radiation: a new approach to 3D dosimetry by MRI. *Magn Reson Imaging.* 1993;**11**(2):253-8. doi: 10.1016/0730-725x(93)90030-h. PubMed PMID: 8455435.
10. Fong PM, Keil DC, Does MD, Gore JC. Polymer gels for magnetic resonance imaging of radiation dose distributions at normal room atmosphere. *Phys Med Biol.* 2001;**46**(12):3105-13. doi: 10.1088/0031-9155/46/12/303. PubMed PMID: 11768494.
11. Adinehvand VK, Zahmatkesh MH, Aghamiri MR, Akhlaghpour S, Bagheri S. Verification of dose rate and energy dependence of MAGICA polymer gel dosimeter with electron beams. *Int J Radiat Res.* 2008;**6**(1):31-6.
12. Behrouzkia Z, Zohdiaghdam R, Khalkhali HR, Mousavi F. Evaluation of Gold Nanoparticle Size Effect on Dose Enhancement Factor in Megavoltage Beam Radiotherapy Using MAGICA Polymer Gel Dosimeter. *J Biomed Phys Eng.* 2019;**9**(1):89-96. doi: 10.31661/jbpe.v9i1Feb.1019. PubMed PMID: 30881938. PubMed PMCID: PMC6409369.
13. Dong X, Tian Y, Wang F, Chen C, Wang Y, Ma J. Gold-Nanoparticle-Enhanced Radio-Fluorogenic Hydrogel Sensor for Low Radiation Doses in Clinical Radiotherapy. *Polymers (Basel).* 2022;**14**(22):4841. doi: 10.3390/polym14224841. PubMed PMID: 36432968. PubMed PMCID: PMC9694710.
14. Salman MD, Md Radzi Y, Ashour NI, Oglat AA, Rahman AA. Characteristics of a novel poly(methyl methacrylate-gel) dosimeter doped with copper oxide nanoparticles for radiotherapy applications. *Polym Bull.* 2025;**82**:10031-50. doi: 10.1007/s00289-025-05863-8.
15. Soliman YS, Capron M, Pontoni D, Krisch M, Pellicioli P. Study of a gel dosimeter based on Ag nanoparticles for applications in radiation therapy with synchrotron X-rays at ultrahigh dose rate compared to 60Co γ-rays. *Radiat Phys Chem.* 2025;**227**:112351. doi: 10.1016/j.radphyschem.2024.112351.
16. Shoobkolaei S, Alam NR, Monfared AS, Khobi M, Farahani S. Platinum and gold nanoparticles as radiosensitizers in megavoltage radiotherapy: Quantitative assessment via MRI polymer gel dosimetry. *Radiat Phys Chem.* 2026;**241**:113475. 10.1016/j.radphyschem.2025.113475.
17. Kuncic Z, Lacombe S. Nanoparticle radio-enhancement: principles, progress and application to cancer treatment. *Phys Med Biol.* 2018;**63**(2):02TR01. doi: 10.1088/1361-6560/aa99ce. PubMed PMID: 29125831.
18. Schuemann J, Bagley AF, Berbeco R, Bromma K, Butterworth KT, Byrne HL, et al. Roadmap for metal nanoparticles in radiation therapy: current status, translational challenges, and future directions. *Phys Med Biol.* 2020;**65**(21):21RM02. doi: 10.1088/1361-6560/ab9159. PubMed PMID: 32380492.
19. Shahbazi-Gahrouei D, Choghazardi Y, Kazemzadeh A, Naseri P, Shahbazi-Gahrouei S. A review of bismuth-based nanoparticles and their applications in radiosensitising and dose enhancement for cancer radiation therapy. *IET Nanobiotechnol.* 2023;**17**(4):302-11. doi: 10.1049/nbt2.12134.

PubMed PMID: 37139612. PubMed PMCID: PMC10288357.

20. Farahani S, Alam NR, Haghgoo S, Shirazi A, Geraily G, Gorji E, Kavousi N. The effect of bismuth nanoparticles in kilovoltage and megavoltage radiation therapy using magnetic resonance imaging polymer gel dosimetry. *Radiat Phys Chem*. 2020;**170**:108573. doi: 10.1016/j.radphyschem.2019.108573.
21. Alyani Nezhad Z, Geraily G, Hataminia F, Parwaie W, Ghanbari H, Gholami S. Bismuth oxide nanoparticles as agents of radiation dose enhancement in intraoperative radiotherapy. *Med Phys.* 2021;**48**(3):1417-26. doi: 10.1002/mp.14697. PubMed PMID: 33387376.
22. Yang C, Guo C, Guo W, Zhao X, Liu S, Han X. Multifunctional bismuth nanoparticles as theranostic agent for PA/CT imaging and NIR laser-driven photothermal therapy. *ACS Appl Nano Mater*. 2018;**1**:820-30. doi: 10.1021/acsanm.7b00255.
23. Hossain M, Su M. Nanoparticle location and material dependent dose enhancement in X-ray radiation therapy. *J Phys Chem C Nanomater Interfaces.* 2012;**116**(43):23047-52. doi: 10.1021/jp306543q. PubMed PMID: 23393610. PubMed PMCID: PMC3563421.
24. Gebremariam T, Geraily G, Longo F, Gholami S. Radiation dose escalation by injecting bismuth, gold and platinum nanoparticles into a tumour during high dose rate 192Ir brachytherapy: a Monte Carlo study. *Radiat Environ Biophys*. 2025;**64**(2):303-10. doi: 10.1007/s00411-025-01127-1. PubMed PMID: 40261354.
25. Abolaban F, Nisbet A. Radiation dose enhancement in megavoltage radiation therapy using Au, Gd, Pt, Ag, and Bi nanoparticles of various concentration level. *Biointerface Res Appl Chem.* 2022;**12**(2):2404-14. doi: 10.33263/BRIAC122.24042414.
26. De Deene Y, Pittomvils G, Visalatchi S. The influence of cooling rate on the accuracy of normoxic polymer gel dosimeters. *Phys Med Biol*. 2007;**52**(10):2719-28. doi: 10.1088/0031-9155/52/10/006.: 17473347.
27. Baldock C, De Deene Y, Doran S, Ibbott G, Jirasek A, Lepage M, McAuley KB, Oldham M, Schreiner LJ. Polymer gel dosimetry. *Phys Med Biol*. 2010;**55**(5):R1-63. doi: 10.1088/0031-9155/55/5/R01. PubMed PMID: 20150687. PubMed PMCID: PMC3031873.
28. De Deene Y. Review of quantitative MRI principles for gel dosimetry. *J Phys Conf Ser.* 2009;**146**:012033. doi: 10.1088/1742-6596/164/1/012033.
29. Khosravi H, Rahmani F, Hashemi B. Gel dosimetry: The effect of gold nanoparticles on the dose enhancement in the external radiation therapy. *Nanomed Res J*. 2016;**1**:31-8. doi: 10.7508/nmrj.2016.01.005.
30. Podgoršak EB. Radiation physics for medical physicists. Berlin, Heidelberg: Springer; 2016. p. 277-376.
31. Ertl HH, Feinendegen LE, Heiniger HJ. Iodine-125, a tracer in cell biology: physical properties and biological aspects. *Phys Med Biol*. 1970;**15**(3):447-56. doi: 10.1088/0031-9155/15/3/005. PubMed PMID: 5485455.
32. Sabbaghizadeh R, Shamsudin R, Deyhimihaghighi N, Sedghi A. Enhancement of Dose Response and Nuclear Magnetic Resonance Image of PAGAT Polymer Gel Dosimeter by Adding Silver Nanoparticles. *PLoS One.* 2017;**12**(1):e0168737. doi: 10.1371/journal.pone.0168737. PubMed PMID: 28060829. PubMed PMCID: PMC5218462.
33. Alqathami M, Blencowe A, Geso M, Ibbott G. Quantitative 3D Determination of Radiosensitization by Bismuth-Based Nanoparticles. *J Biomed Nanotechnol.* 2016;**12**(3):464-71. doi: 10.1166/jbn.2016.2183. PubMed PMID: 27280244.
34. 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**(3):662-5. doi: 10.4103/0973-1482.187295. PubMed PMID: 29893336.