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Investigation of the Tissue Equivalence of Some Polymer Gel Dosimeters: A Monte Carlo Study

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Abstract

The radiological properties of four polymer gel dosimeters-MAGIC, MAGAS, MAGAT, and PAGAT-used in radiotherapy dosimetry were investigated in this study. Two independent Monte Carlo codes, EGSnrc and PENELOPE, were employed to simulate photon and electron radiation transport. Mass attenuation coefficients, mass stopping powers, CSDA ranges, interaction cross sections (interaction probabilities), and depth-dose distributions were calculated for each gel over the energy range of 10 keV to 30 MeV and compared against one another and against soft tissue. The total mass attenuation coefficients, interaction probabilities, mass stopping powers, and CSDA ranges of the polymer gels were found to agree closely with those of soft tissue, with differences of only 0.05% - 0.1% across the entire energy range. Depth-dose curves for monoenergetic 6 MeV electron and photon beams, evaluated over depths of 0.05 - 20 cm, showed deviations of approximately 1% or less between the gels and soft tissue. These results demonstrate that all four polymer gels exhibit strong radiological equivalence to soft tissue, with MAGAT showing the closest agreement. Accordingly, MAGIC, MAGAS, MAGAT, and PAGAT gels can be considered reliable soft-tissue-equivalent dosimeters for radiotherapy applications.

Subject Areas

Applied Physics

Keywords

Polymer Gel Dosimetry, Monte Carlo Simulation, EGSnrc, PENELOPE, Tissue Equivalence, Radiotherapy

1. Introduction

In radiotherapy, the primary objective is to deliver a prescribed dose of radiation to a tumor or lesion within a patient while minimizing the dose delivered to the surrounding healthy tissue. Conventional radiation dosimeters, such as ionization chambers and thermoluminescent dosimeters (TLDs), measure absolute dose only at single points. Owing to their small physical size, TLDs can achieve relatively high spatial resolution in dose measurement. Film dosimeters, in turn, offer high spatial resolution in one- and two-dimensional planes. Although three-dimensional (3D) dose distributions can be obtained by positioning film dosimeters in multiple planes and layers, this approach is difficult and time-consuming. The need for a dosimetry technique capable of full 3D imaging of radiation dose distributions has therefore led to the development of gel dosimetry.

The first study of the chemical changes produced by radiation in aqueous solutions, and particularly the use of such changes for radiation dosimetry, was conducted by Day and Stein in 1950 [1]. Later, a high-energy radiation dosimeter based on the radiation-induced polymerization of a liquid was suggested by Hoecker and Watkins in 1958 [2]. Since then, extensive research has been carried out on radiation-sensitive gels, and various formulations have been developed. A new type of tissue-equivalent medium for magnetic resonance imaging of the 3D dose distributions produced by ionizing radiation was developed [3].

A study of polymer gel dosimetry using MRI, applied to treatment plans for stereotactic radiosurgery and high-dose-rate brachytherapy, was carried out [4]. An effective MAGAT (MAA, gelatin, and THPC) polymer gel dosimeter was fabricated by varying the composition of its chemical components, and the relationship between gel components and dose response was investigated [5]. The MAGAS (methacrylic acid, gelatin, and ascorbic acid) normoxic polymer gel dosimeter for clinical radiotherapy dosimetry was investigated [6]. The radiological properties of the MAGIC (methacrylic acid (MAA) and ascorbic acid (AscA) in gelatin, initiated by copper) normoxic polymer gel were investigated, and Monte Carlo simulation was used to calculate the depth-dose response of MAGIC gel and water for a 6 MV photon beam [7]. The PAGAT (polyacrylamide, gelatin, and tetrakis(hydroxymethyl)phosphonium chloride) normoxic polymer gel dosimeter was investigated, in which the concentrations of the gel's chemical components were varied and its response to ionizing radiation was evaluated using MRI [8]. The radiological properties of the PRESAGE and PAGAT polymer dosimeters were investigated, and their water equivalence was determined for use in radiotherapy dosimetry using Monte Carlo modeling [9]. A Monte Carlo study of the water and tissue equivalence of a new PRESAGE formulation for 3D proton beam dosimetry was carried out [10]. Different properties of polymer gel dosimeters, such as their composition, which determines their accuracy, and their use as 3D dosimeters in radiotherapy, were investigated [11]. A review study of tissue-equivalent gel dosimeters was conducted, covering their properties, advantages, limitations, applications, and recent developments, as well as methods to enhance their

stability, safety, and cost-effectiveness [12].

The main objective of this study is to investigate the radiological tissue equivalence of several polymer gel dosimeters by comparing their radiological properties-including interaction cross sections, mass attenuation coefficients, mass stopping power, and depth-dose distributions-with those of soft tissue, using the PENELOPE and EGSnrc Monte Carlo codes.

2. Materials and Method

Eelectron and photon transport in MAGIC, MAGAS, MAGAT, and PAGAT polymer gel dosimeters was simulated using the EGSnrc and PENELOPE Monte Carlo codes. The elemental compositions of the polymer gels under study were taken from previously published data: MAGIC [7], MAGAS [6], MAGAT [5], and PAGAT [8]. The composition of soft tissue (Tissue, Soft (ICRP)) was obtained from the NIST database. The chemical and elemental compositions of all materials of interest are summarized in **Table 1**.

2.1. PENELOPE-Based Simulations

ENELOPE Monte Carlo code was used to calculate mass attenuation coefficients, cross-sections, and depth-dose distributions for photon beams, as well as stopping powers, CSDA ranges, and depth-dose distributions for electron beams of interest in all the materials under study [13]. The *material.exe* was used to generate the necessary material files from the elemental compositions and mass densities (**Table 1**) of the polymer gel dosimeters, while the tables.exe program was used to calculate the stopping power and CSDA range of incident electrons. The *penmain.exe* program was used to calculate depth-dose distributions for electrons and photons. The parameters used for electron and photon transport were as follows: EABS (1): 1.00E+05 eV, EABS (2): 1.00E+04 eV, EABS (3): 1.00E+05 eV, C_1: 5.00E-02, C_2: 5.00E-02, WCC: 5.00E+03 eV, WCR: 5.00E+03 eV, NSIMSH: 1.00E+08. Where, EABS (1:3) are electron, photon and positron absorption energy, C_1 and C_2 are elastic scattering parameters, WCC and WCR are cut off energy losses for inelastic collision and bremsstrahlung emission, and NSIMSH is the number of simulation shower. Depth-dose calculations were performed using a cylindrical gel phantom with a diameter of 5 cm and a length of 20 cm. A 2×2 cm^2 field on the phantom surface was irradiated using a conical beam generated by a point source positioned on the central axis (Z) at a source-to-surface distance of 100 cm (SSD = 100 cm).

2.2. EGSnrc-Based Simulations

EGSnrc Monte Carlo Code was used to calculate depth-dose distributions for electron and photon beams in all materials of interest [14]. The *egs-gui* program was used to generate cross-sectional data for the polymer gel dosimeters based on the elemental compositions and mass densities listed in **Table 1**. The DOSRZnrc program was used to calculate dose distributions along the axial (Z) and radial (r) directions. The parameters used for electron and photon transport in each pro-

gram were as follows: ECUT: 0.521 MeV, PCUT: 0.001 MeV, electron-step algorithm: PRESTA II, bremsstrahlung angular sampling: KOCH-MOTZ, electron impact ionization: off, bremsstrahlung cross sections: Bethe-Heitler, boundary crossing algorithm: EXACT, SMAX: 1e10, Rayleigh scattering: on, photon-electron angular sampling: on, bound Compton scattering: norej, atomic relaxations: on, photon cross sections: xcom, ESTEPE: 0.25, Xımax: 0.5, and number of histories: 1×10^8. In the DOSRZnrc program, depth-dose curves were generated by defining a cylindrical gel phantom with a diameter of 5 cm and a length of 20 cm. A 2×2 cm^2 field on the phantom surface was irradiated using a conical beam generated by a point source positioned on the central axis, incident from the front of the phantom, at a distance of 100 cm (SSD = 100 cm).

Table 1. Elemental composition of soft tissue and elected polymer gel dosimeters.

	MAGIC	MAGAS	MAGAT	PAGAT	Soft Tissue (ICRP)
H	0.1067	0.1047	0.1042	0.1059	0.104472
C	0.0843	0.0844	0.0854	0.0681	0.232190
N	0.01392	0.0115	0.0115	0.0242	0.024880
O	0.7994	0.7984	0.7928	0.8008	0.630238
Na	-	-	-	-	0.001130
Mg	-	-	-	-	0.000130
P	-	-	0.0015	0.0002	0.001330
S	0.00000256	-	-	-	0.001990
Cl	-	-	0.0017	0.0002	0.001340
K	-	-	-	-	0.001990
Ca	-	-	-	-	0.000230
Fe	-	-	-	-	0.000050
Cu	0.00000508	-	-	-	---
Zn	-	-	-	-	0.000030
Total	**1.004**	**0.999**	**0.997**	**0.999**	**1.000**
Density (g/cm^3)	1.027	1.038	1.032	1.026	1.000

3. Results and Discussion

A. Mass attenuation coefficient

The mass attenuation coefficient, comprising its photoelectric, Compton, and pair-production components, was calculated for MAGIC, MAGAS, MAGAT, and PAGAT polymer gels over the 10 keV - 30 MeV energy range. The results were compared with one another and with soft tissue. The photoelectric, Compton, and pair-production attenuation coefficients were plotted as a function of energy (Figure 1). For a more detailed evaluation, the total mass attenuation coefficient and the following additional parameters were plotted separately.

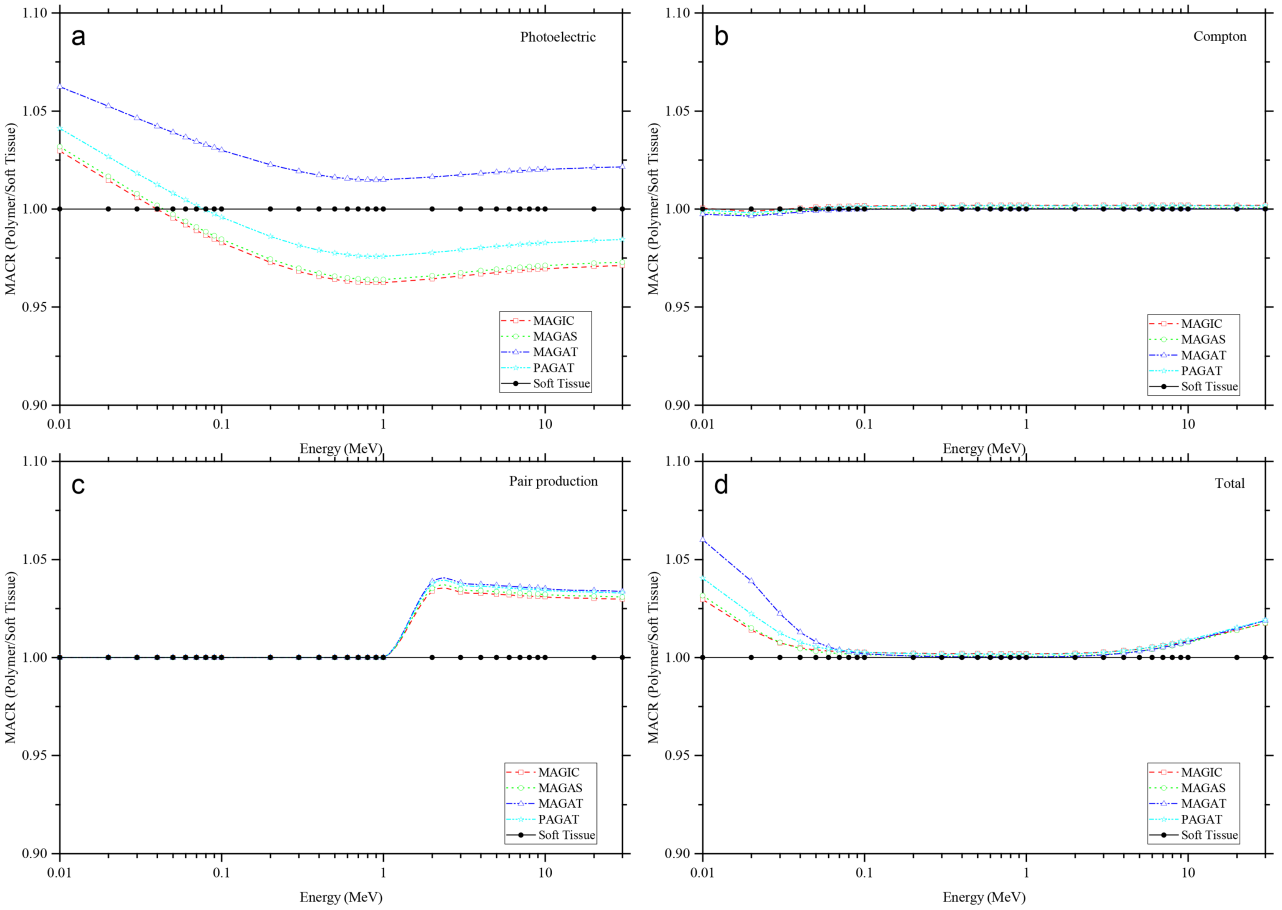


Figure 1. Mass attenuation coefficient ratio (MACR) of selected polymer gel dosimeters relative soft tissue, (a): Photoelectric mass attenuation coefficient ratio, (b): Compton mass attenuation coefficient ratio, c: Pair production mass attenuation coefficient ratio, and (d): total mass attenuation coefficient ratio.

As shown in Figure 1, in the photoelectric energy domain, the mass attenuation coefficients of MAGIC, MAGAS, MAGAT, and PAGAT gels were found to be 5% lower, 5% lower, 5% higher, and 2% lower than that of soft tissue, respectively. In the Compton scattering domain, the mass attenuation coefficients of all investigated polymer gels were found to be very close to that of soft tissue, with only minor differences observed. In the pair production domain, the mass attenuation coefficients of all investigated polymer gels were found to be approximately 5% higher than that of soft tissue. Consequently, the total mass attenuation coefficients of all investigated polymer gels were found to closely match those of soft tissue, with differences ranging from 0.05% to 1%.

B. Mass stopping power and CSDA range

The mass collision stopping power and mass radiative stopping power of electrons in MAGIC, MAGAS, MAGAT, and PAGAT polymer gels were calculated over the energy range of 10 keV to 30 MeV and compared with one another as well as with soft tissue. The results obtained are presented in Figure 2.

As shown, the mass collision stopping power, total mass stopping power, and CSDA range of all polymer gels investigated were found to be in close agreement

(with only minor differences) with those of soft tissue across the 0.01 - 30 MeV energy range. In contrast, the mass radiative stopping power of all polymer gels examined was found to be approximately 4% higher than that of soft tissue over the same energy range. Consequently, the total mass stopping power and range of all polymer gels studied were found to be in excellent agreement with soft tissue, exhibiting only a 0.05% difference.

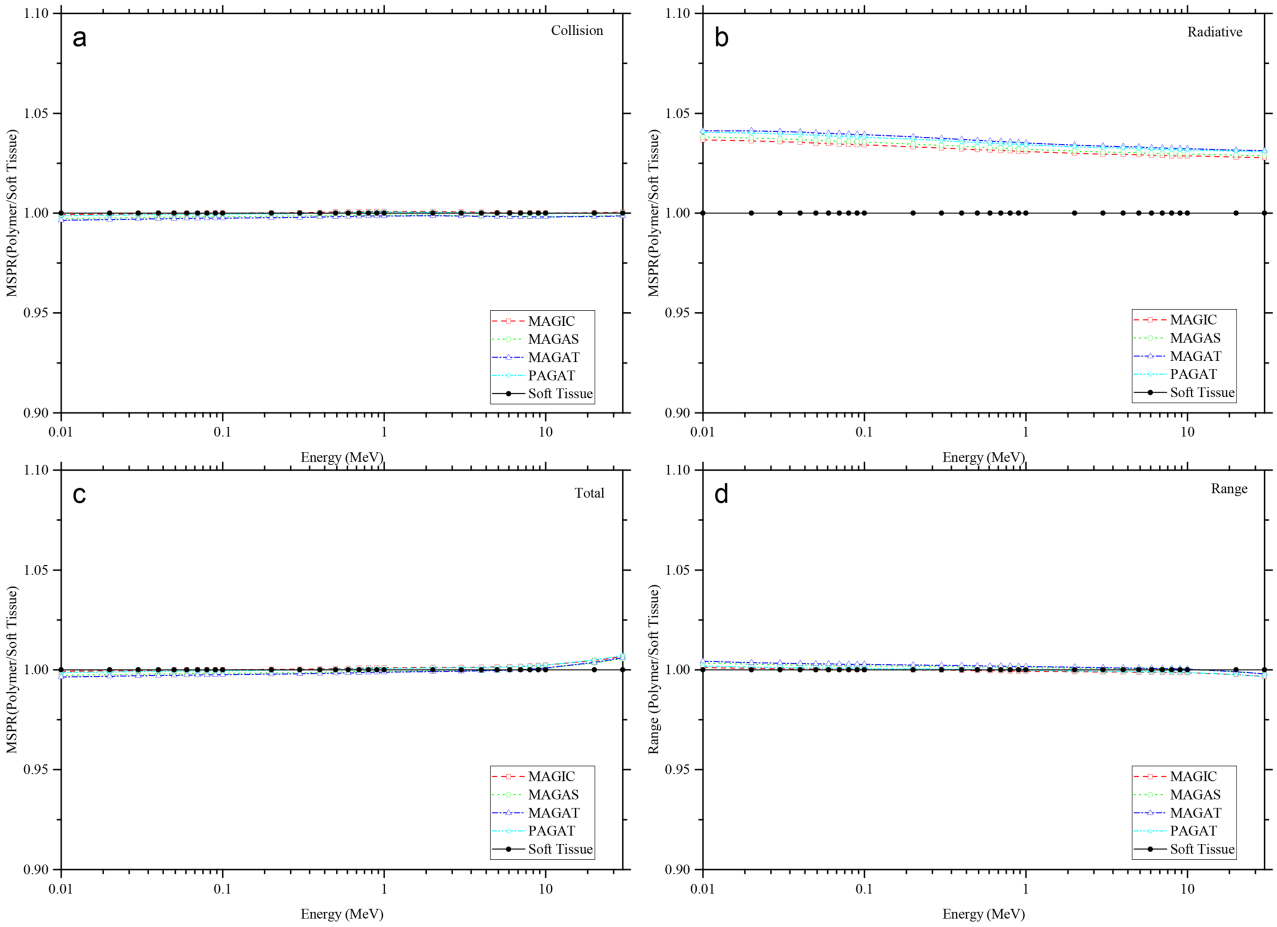


Figure 2. Mass stopping power ratio (MSPR) of electrons of selected polymer gel dosimeters relative soft tissue (a): mass collision stopping power ratio, (b): mass radiative stopping power ratio, (c): total mass stopping power ratio, and (d): CSDA range ratio.

C. Interaction Cross-Section (Interaction Probability)

The interaction cross-sections represented by the photoelectric, Compton, and pair production cross-sections of the MAGIC, MAGAS, MAGAT, and PAGAT polymer gels were calculated over the energy range of 10 keV to 30 MeV and compared with one another as well as with soft tissue. The results obtained are presented in **Figure 3**.

As shown, in the photoelectric domain, the interaction cross-sections of the MAGIC, MAGAS, MAGAT, and PAGAT gels were found to be 5% lower, 3% lower, 2% higher, and 3% lower, respectively, than soft tissue over the 1 - 30 MeV energy range. In the Compton domain, the interaction cross-sections of the

MAGIC and PAGAT polymer gels were found to be 2% lower than soft tissue over the 0.01 - 30 MeV energy range, whereas those of the MAGAS and MAGAT gels were found to be 0.75% lower than soft tissue over the same energy range. In the pair production domain, the interaction cross-sections of the MAGIC, MAGAS, MAGAT, and PAGAT gels were found to be 2%, 3%, 4%, and 2.5% higher, respectively, than soft tissue over the 2 - 30 MeV energy range. Consequently, the total interaction cross-section of all polymer gels investigated was found to be in close agreement with soft tissue, with differences ranging from 0.002% to 6%.

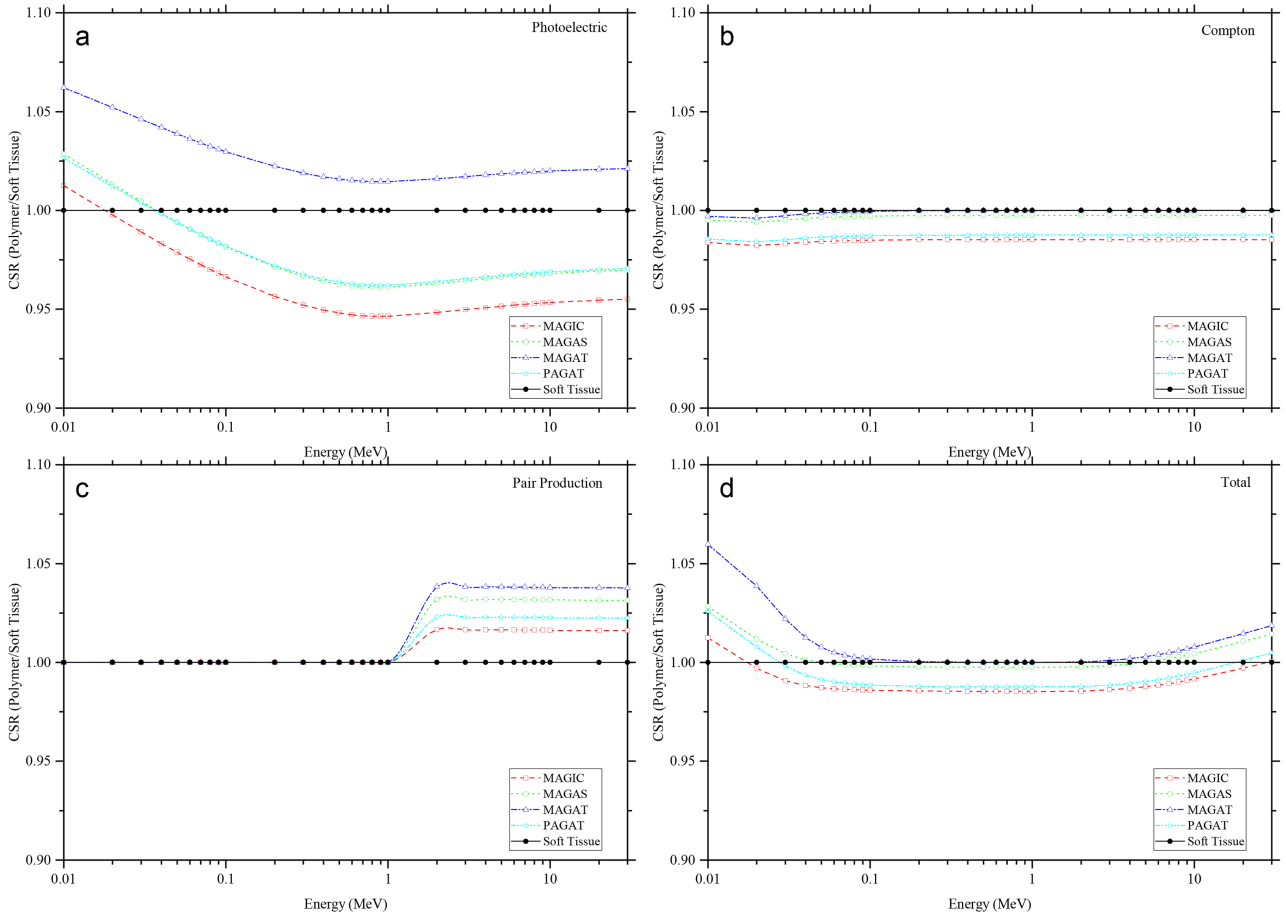


Figure 3. Cross-section (Interaction Probability) ratio of selected polymer gel dosimeters relative to soft tissue, (a): Photoelectric cross-section ratio, (b): Compton cross-section ratio, (c): Pair production cross-section ratio, and (d): total cross-section ratio.

D. Depth-Dose

1) Electron Beam

The normalized PENELOPE Monte Carlo depth-dose curves for MAGIC, MAGAS, MAGAT, and PAGAT polymer gels, along with soft tissue, for the electron beam are presented in **Figure 4(a)**. As shown, a difference of 1.5% was observed over the 0.1 - 1.1 cm depth range, and a difference of 1% - 5% was observed over the 1.1 - 3.4 cm depth range. Similarly, the normalized EGSnrc Monte Carlo depth-dose curves for the same materials and beam are presented in **Figure 4(b)**,

showing a difference of 0.5% over the 0.05 - 1.1 cm depth range and a difference of 1% - 6% over the 1.15 - 3.4 cm depth range between the polymer gels and soft tissue. Furthermore, the depth-dose curves of the polymer gels were found to be in close agreement with one another in both the EGSnrc and PENELOPE simulations.

2) Photon Beam

The normalized PENELOPE Monte Carlo depth-dose curves for MAGIC, MAGAS, MAGAT, and PAGAT polymer gels, along with soft tissue, for the photon beam are presented in Figure 4(c). As shown, the dose differences between each gel and soft tissue did not exceed 1% over the 0.1 - 2.3 cm depth range, and remained within 0.85% - 1% over the 2.3 - 20 cm range, indicating that all four gels are nearly tissue-equivalent for this beam.

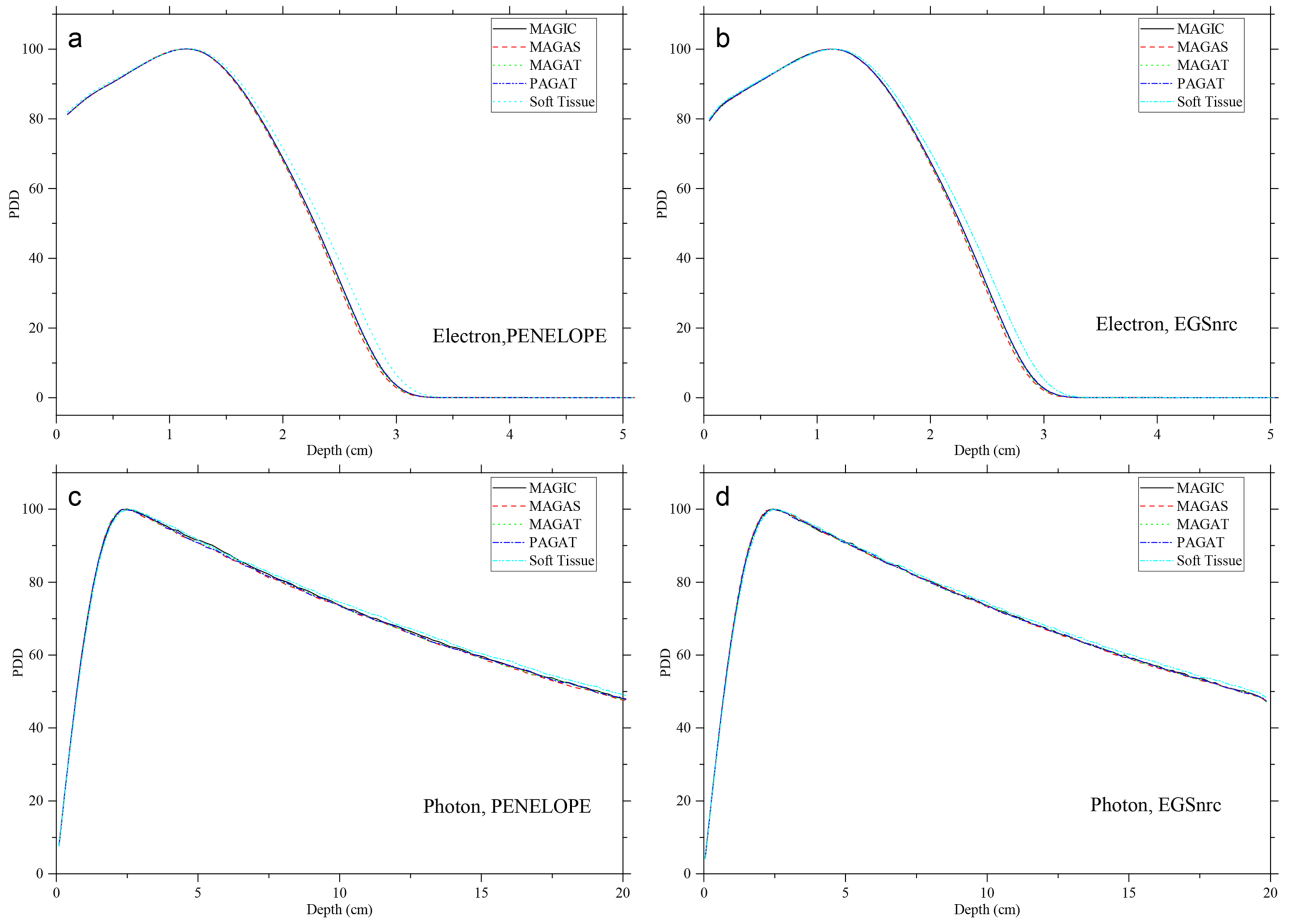


Figure 4. PENELOPE and EGSnrc Monte Carlo depth-dose curves of selected polymer gel dosimeters relative to soft tissue, for 6 MeV electron and 6 MeV photon beams.

Similarly, the normalized EGSnrc Monte Carlo depth-dose curves for the same materials and beam are presented in Figure 4(d), showing a difference of 0.5% over the 0.05 - 2.45 cm depth range and a difference of 0.5% - 1% over the 2.45 - 20 cm depth range. Furthermore, the depth-dose curves of the polymer gels were

found to be in close agreement with one another in both the EGSnrc and PENELOPE simulations. A comparison of the normalized depth-dose curves between the two Monte Carlo codes (PENELOPE and EGSnrc) for the MAGIC polymer gel, for both electron and photon beams, was also performed (Figure 5), revealing a difference of 0.5% across the entire depth range (0.05 - 20 cm).

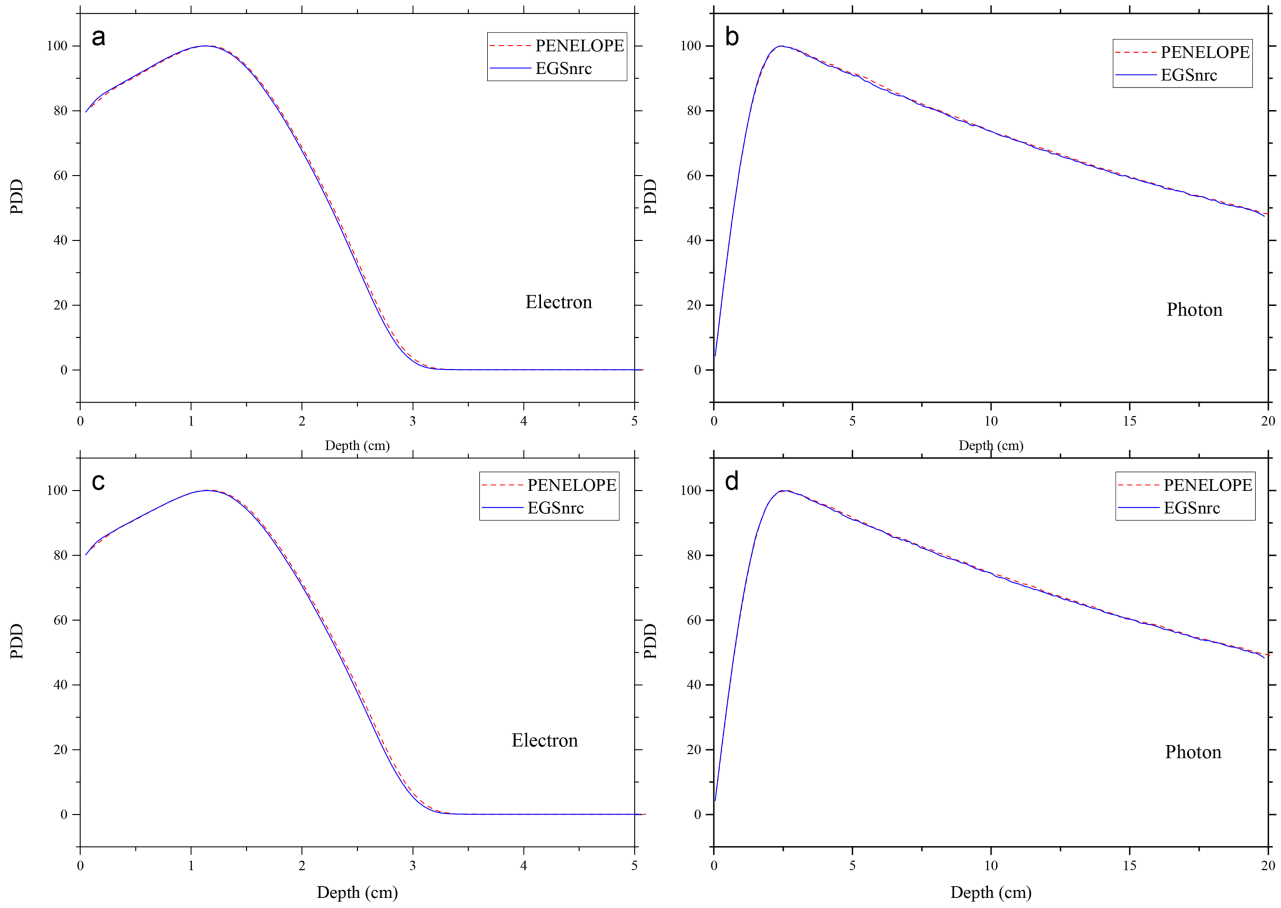


Figure 5. PENELOPE and EGSnrc Monte Carlo depth-dose curves of MAGIC polymer gel dosimeter, for 6 MeV electron and 6 MeV photon beams.

4. Conclusions

Polymer gel dosimeters have emerged as a promising tool for three-dimensional dose verification in radiotherapy, owing to their ability to closely mimic the radiological properties of human soft tissue while offering spatially continuous dose information-an advantage over conventional point or planar detectors. In the current work, a comprehensive investigation of the soft-tissue equivalence of MAGIC, MAGAS, MAGAT, and PAGAT polymer gels was carried out using two independent Monte Carlo codes (EGSnrc and PENELOPE) and two radiation beam types (electron and photon), allowing for cross-validation of the results across simulation platforms.

Mass attenuation coefficients, stopping power, interaction cross sections, and

depth-dose curves of the polymer gels of interest were calculated and compared with those of soft tissue across a broad range of energies relevant to diagnostic and therapeutic applications. The total mass attenuation coefficient results for soft tissue were found to be in close agreement with those of the polymer gels (0.05% - 0.1% difference) over the energy range of interest, and particularly over the 1 - 10 MeV range-the energy region most relevant to megavoltage photon radiotherapy. The total interaction cross sections of all polymer gels investigated were found to be in close agreement with soft tissue (0.002% - 6% difference), reflecting consistent photon and electron interaction probabilities across the elemental composition of the gels. The total mass stopping power and CSDA range results for soft tissue were found to be in close agreement with those of the polymer gels (0.05% difference) over the energy range of interest, indicating comparable electron energy-loss and penetration behavior.

Furthermore, the difference between the depth-dose curves of soft tissue and the polymer gels for 6 MeV electron and photon beams, over the 0.05 - 20 cm depth range, was found to be approximately 1% or less, confirming close dosimetric agreement even under realistic clinical beam energies and depths. The consistency of these findings across both Monte Carlo codes further reinforces the robustness of the results, reducing the likelihood that the observed agreement is an artifact of a specific simulation algorithm.

These results demonstrate that all polymer gels examined in this study were radiologically close to soft tissue across the full range of physical quantities investigated, with the MAGAT gel showing the closest agreement overall. Consequently, the respective polymer gels can be considered reliable radiological soft-tissue equivalents, supporting their continued use in three-dimensional dosimetric verification, quality assurance, and validation of complex treatment delivery techniques such as IMRT, VMAT, and stereotactic radiosurgery.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Day, M.J. and Stein, G. (1950) Chemical Effects of Ionizing Radiation in Some Gels. *Nature*, **166**, 146-147. https://doi.org/10.1038/166146a0

[2] Hoecker, F.E. and Watkins, I.W. (1958) Radiation Polymerization Dosimetry. *The International Journal of Applied Radiation and Isotopes*, **3**, 31-35. https://doi.org/10.1016/0020-708x(58)90053-x

[3] Maryanski, M.J., Schulz, R.J., Ibbott, G.S., Gatenby, J.C., Xie, J., Horton, D., *et al.* (1994) Magnetic Resonance Imaging of Radiation Dose Distributions Using a Polymer-Gel Dosimeter. *Physics in Medicine and Biology*, **39**, 1437-1455. https://doi.org/10.1088/0031-9155/39/9/010

[4] Maryanski, M.J., Ibbott, G.S., Eastman, P., Schulz, R.J. and Gore, J.C. (1996) Radiation Therapy Dosimetry Using Magnetic Resonance Imaging of Polymer Gels. *Medical Physics*, **23**, 699-705. https://doi.org/10.1118/1.597717

[5] Razak, N.N.A., Rahman, A.A., Kandaiya, S., Mustafa, I.S., Mahmoud, A.A. and Yahaya, N.Z. (2016) Optimisation of the MAGAT Gel Dosimeter Compositions. *Internatuinal Journal of Radiation Research*, **14**, 305-311. https://doi.org/10.18869/acadpub.ijrr.14.4.305

[6] Venning, A., Healy, B., Nitschke, K. and Baldock, C. (2005) Investigation of the MAGAS Normoxic Polymer Gel Dosimeter with Pyrex Glass Walls for Clinical Radiotherapy Dosimetry. *Nuclear Instruments and Methods in Physics Research Section A*: *Accelerators*, *Spectrometers*, *Detectors and Associated Equipment*, **555**, 396-402. https://doi.org/10.1016/j.nima.2005.09.002

[7] Aljamal, M., Zakaria, A. and Shamsuddin, S. (2013) Radiological Properties of MAGIC Normoxic Polymer Gel Dosimetry. *Journal of Physics*: *Conference Series*, **423**, Article 012016. https://doi.org/10.1088/1742-6596/423/1/012016

[8] Venning, A.J., Hill, B., Brindha, S., Healy, B.J. and Baldock, C. (2005) Investigation of the PAGAT Polymer Gel Dosimeter Using Magnetic Resonance Imaging. *Physics in Medicine and Biology*, **50**, 3875-3888. https://doi.org/10.1088/0031-9155/50/16/015

[9] Brown, S., Venning, A., De Deene, Y., Vial, P., Oliver, L., Adamovics, J., *et al.* (2008) Radiological Properties of the PRESAGE and PAGAT Polymer Dosimeters. *Applied Radiation and Isotopes*, **66**, 1970-1974. https://doi.org/10.1016/j.apradiso.2008.06.005

[10] Gorjiara, T., Kuncic, Z., Doran, S., Adamovics, J. and Baldock, C. (2012) Water and Tissue Equivalence of a New PRESAGE® Formulation for 3D Proton Beam Dosimetry: A Monte Carlo Study. *Medical Physics*, **39**, 7071-7079. https://doi.org/10.1118/1.4757922

[11] Deene, Y.D. (2004) Essential Characteristics of Polymer Gel Dosimeters. *Journal of Physics*: *Conference Series*, **3**, 34-57. https://doi.org/10.1088/1742-6596/3/1/006

[12] Sagsoz, M.E., Korkut, O. and Gallo, S. (2025) Advancements in Tissue-Equivalent Gel Dosimeters. *Gels*, **11**, Article 81. https://doi.org/10.3390/gels11020081

[13] Salvat, F. (2019) PENELOPE-2018: A Code System for Monte Carlo Simulation of Electron and Photon Transport. In: *Workshop Proceedings*, Barcelona, Spain, 28 January-1 February 2019.

[14] Townson, R., Tessier, E., Mainegra, E. and Walters, B. (2020) Getting Started with EGSnrc. Ionizing Radiation Standards. National Research Council of Canada.