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Investigation of Gamma Radiation Shielding in NiMnGa-Doped Multifunctional Smart Polymer Composites Using Geant4 and WinXCOM

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Abstract − This study assesses the gamma radiation shielding efficiency of polymer composites doped with varying amounts of alloy, using software to demonstrate the potential application of innovative materials in radiation protection. Specifically, Poly Lactic Acid (PLA) and Poly Ethylene Glycol (PEG) composites doped with NiMnGa at concentrations of 2, 6, 10, and 15% were analyzed across an energy range of 0.0595 to 1.41 MeV using Geant4 and WinXCOM software. The radiation protection ability of the composites and the pure alloy were assessed by calculating key parameters, including the mass attenuation coefficient (μm), linear attenuation coefficient (μ), half value layer (HVL), tenth value layer (TVL), and mean free path (MFP). The analyses indicated strong agreement between the results obtained from Geant4 and WinXCOM, demonstrating the performance of the software in investigating the radiation shielding characteristics of polymer-based materials. It was investigated that increasing the amount of NiMnGa in the composite structure significantly enhanced its radiation shielding capabilities. Notably, composites with 15% NiMnGa exhibited superior performance, comparable to traditional heavy metals, while maintaining the lightweight and flexible nature of polymer-based materials. The strong agreement between Geant4 and WinXCOM results further validates the computational approach. These findings highlight the potential of NiMnGa-doped polymer composites as eco-friendly, cost-effective alternatives to lead-based shields for medical and industrial applications, offering enhanced protection with reduced toxicity and environmental impact.

Keywords − *Alloy, composites, polyethylene glycol (PEG), polylactic acid (PLA), gamma rays*

1. Introduction

Radiation is an energy form in matter and space classified into ionizing and non-ionizing types. Ionizing radiation, such as high-energy X-rays, alpha, beta, and gamma rays, are biologically hazardous, necessitating effective shielding to minimize exposure [1]. Ionizing radiation, such as gamma and high-energy ultraviolet rays, can cause significant biological damage to tissues by damaging DNA. This damage can lead to mutations in the genetic code and cause cancer. Moreover, other tissues and organs can be harmed, resulting in burns and erythema[2]. Non-ionizing radiation, conversely, has lower energy and poses minimal biological risk. Developing protective materials with specific shielding properties is essential to mitigate the effects of radiation from various sources. The radiation shielding capability of the materials varies according to the

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radiation types [3]. In radiation protection, photon energy diminishes as photons interact with the atoms in the material, which strongly depends on its density and atomic number [4]. The preferred materials for radiation protection are alloys, glasses, ceramics, high-density building materials, and composites [5]. Moreover, due to their intelligent properties, research focused on improving radiation shielding materials based on shape-memory alloys (SMAs) and shape-memory polymers (SMPs).

Shape Memory Alloys (SMAs) are an innovative class of materials with the remarkable ability to recover their original shape when exposed to specific stimuli, such as heat or magnetic fields. This shape memory effect, driven by reversible phase transformations between austenite and martensite phases, allows SMAs to combine high strength, flexibility, and adaptability. SMAs like NiMnGa have gained attention for their magnetic shape memory properties, enabling actuation without direct thermal input. Their excellent fatigue resistance, energy-damping capacity, and ability to sustain large strains make them ideal for dynamic and high-performance environments, including aerospace, robotics, and biomedical applications.

Shape Memory Polymers (SMPs), on the other hand, are exceptional materials offering lightweight, flexible, and durable solutions for various industrial applications compared to metal, glass, and concrete. Unlike SMAs, SMPs are primarily valued for returning to a predetermined shape upon exposure to stimuli like heat, light, or electricity[6]. This property simplifies design and reduces the need for complex mechanical systems. SMPs also exhibit superior chemical resistance, durability against UV radiation, and adaptability to extreme environmental conditions. Their moldability and energy efficiency further enhance their appeal, making them an ideal choice for medical, construction, and aerospace applications[7].

NiMnGa is one of the SMAs becoming prominent in healthcare, dental implants, energy generation, smart batteries, sensors, and actuators due to its magnetic shape memory feature [8]. Polylactic acid (PLA) and polyethylene glycol (PEG) are commonly used SMPs that are preferred for their rigid physical structure and biocompatibility, respectively [9]. Using PLA/PEG blends with NiMnGa enhances the implementation of the alloy in various fields with its shaping capability through heat transfer and low cost [10]. Radiation oncologists, nuclear power plant workers, and military personnel widely utilize lead-containing protective gears to protect against radiation. However, lead aprons have significant drawbacks, including environmental pollution, soil degradation, and potential harm to human tissues due to toxic waste release [11]. These disadvantages necessitate the development of alternative radiation-shielding materials [12]. Polymers alone can be insufficient for radiation protection due to their atomic numbers [13], which can be improved by adding alloys with high atomic numbers [14,15]. Recent studies have demonstrated that blending PLA/PEG films with alloys at varying ratios significantly improves radiation protection [16]. Despite the high cost of producing NiMnGa alloy, combining it with PLA/PEG smart polymers in different proportions has shown promising results in cost-effectiveness and material performance [9, 17, 18]. Due to the great importance of the uniform distribution of metallic alloy fillers for the stability and reliability of shielding materials, a composite shielding material can be formed by mixing NiMnGa alloy with a polymer. This process ensures that the internal structure of the polymer is not damaged and the alloy filler is uniformly dispersed. Additionally, for the alloy's uniform compatibility, the material's performance can be improved by increasing the interface compatibility with polymers.

The field of radiation shielding has advanced by focusing on developing effective materials such as dense substances, glass systems, and innovative compositions. The selection of suitable radiation shielding materials has required careful consideration of various factors, including the weight, space requirements, and cost of these materials. Considering these factors, polymers have been widely adopted as gamma radiation shielding materials due to their advantages, such as ease of formability, convenient handling, affordability, and lower maintenance requirements. These polymer composites offer numerous advantages over traditional shielding materials like lead, especially in applications where the shield's weight is critical. At the same time, conventional lead shields provide adequate protection due to their high density but pose significant challenges during transportation and usage. Heavy shields can be cumbersome for users and equipment, particularly in applications requiring portability and flexibility. In contrast, polymer composites are lightweight due to their low density and are easier to shape. For this purpose, this study investigated the radiation shielding properties of PLA/PEG polymers doped with NiMnGa alloy at various concentrations. The radiation protection capabilities of these composites were analyzed over a wide energy range (59.5 to 1400 keV) using the Monte Carlo simulation toolkit Genat4 [19] and the WinXCOM software [20]. The selection of Geant4 and WinXCOM for this study is motivated by their well-documented accuracy, reliability, and widespread use in radiation physics research. Geant4, a Monte Carlo simulation toolkit, is extensively used in high-energy physics, medical physics, and radiation protection due to its ability to simulate complex particle interactions with matter, including gamma radiation shielding, with high precision [20]. Its flexibility in defining material properties and geometry makes it suitable for modeling composites with varying compositions, such as the PLA/PEG-NiMnGa systems studied in this work.

Furthermore, Geant4 has demonstrated excellent agreement with experimental data, showing deviations within acceptable limits for mass attenuation coefficients [21].On the other hand, WinXCOM is a widely used tool for calculating photon cross-sections and attenuation coefficients of elements, compounds, and mixtures. Its simplicity, computational efficiency, and ability to provide accurate theoretical results make it a reliable reference for benchmarking simulation data [20]. Studies consistently report strong agreement between WinXCOM calculations and experimental results, further supporting its reliability [3]. While other tools like FLUKA and Phy-X/PSD are also used in gamma shielding studies, FLUKA requires more computational resources, which is not necessary for the corresponding research, and Phy-X/PSD, though effective, is less extensively validated compared to Geant4 and WinXCOM [22]. The complementary nature of Geant4 for detailed simulations and WinXCOM for theoretical benchmarking ensures a comprehensive and reliable analysis of the shielding properties of NiMnGa-doped polymer composites. The simulations effectively calculate the radiation interaction parameters of different composites, providing valuable insights into their shielding effectiveness for gamma radiation.

2. Materials and Methods

2.1. Materials

In the study, the PLA and PEG polymer films were supplied by ABG Filament Company and Sigma Aldrich. The Ni49.5Mn29Ga21 alloy was produced using a vacuum arc melting method, employing high-purity Nickel (99.8%), Manganese (99.9%), and Gallium (99.9%) in a water-cooled copper crucible [7]. The NiMnGa alloy ingot was ground in a high-speed grinding machine to obtain nano-sized NiMnGa alloy powder [7]. After grounding it to nano size, NiMnGa was added to the PLA/PEG films in varying proportions. For this purpose, NiMnGa was powdered to 0.01 g and mixed with 0.25 g of PLA and 0.25 g of PEG. The resulting mixture containing 2% NiMnGa was poured into a petri dish using the solvent casting [7] and dried in an oven. The same procedure was followed for the preparation of composites, including 6% (0.03 g), 10% (0.05 g), and 15% (0.075 g) concentrations of NiMnGa [7]. The gamma attenuation coefficients were calculated based on the chemical compositions of the polymer composites summarized in Table 1 with corresponding elemental explanations and theoretical densities. The table presents the progressive incorporation of NiMnGa into the PLA/PEG matrix, demonstrating modification of the elemental compositions and theoretical densities with increasing amounts of NiMnGa.

Table 1. Elemental compositions and densities for composites containing PLA/PEG and NiMnGa

Sample	Ni	Mn	Ga	H	C	O	Theoretical density (g cm^{-3})
NiMnGa	49.5	29.5	21	-	-	-	8.35
NiMnGaPLAPEG2	0.9702	0.5782	0.4116	7.2265	51.2407	39.5680	0.6884
NiMnGaPLAPEG6	2.8017	1.6697	1.1186	6.9538	49.3069	38.0751	0.7132
NiMnGaPLAPEG10	4.5040	2.6815	1.9089	6.7001	47.5089	36.6886	0.7378
NiMnGaPLAPEG15	6.4554	3.8468	2.7390	6.4097	45.4497	35.0966	0.7681

2.2. Materials

The attenuation coefficient is critical in determining the materials' radiation shielding properties. The photon mass attenuation coefficients of the samples were calculated using Beer-Lambert's law [23].

$$I = I_0 e^{-\mu x}$$

Where x (cm), μ, I0, and I represent the sample thickness, the linear attenuation coefficient (LAC), the initial intensity of photons passing through a sample of thickness xx, and the attenuated intensity, respectively.

The mass attenuation coefficient (MAC) (μ_m) defines radiation absorption of the material per unit mass that is computed as:

$$\mu_m (cm^2 g^{-1}) = \frac{\mu}{\rho}$$

Where ρ is the density of the sample, the mass attenuation coefficient, described as μ/ρ, is influenced by the atomic numbers of the constituent elements and the photon energy [23]. For a chemical compound or an alloy mixture, μ_m is calculated using the mixture rule:

$$\mu_m = \sum_i w_i (\mu_m)$$

where $\boldsymbol{w_i}$ represents the weight fraction of each element. The thickness per unit mass affects the material's attenuation properties, investigated using the LAC, Half Value Layer (HVL), and Tenth Value Layer (TVL) parameters. The LAC value represents the material's photon absorption ability calculated as:

$$\mu = \mu_m \rho$$

Depending on its thickness, the radiation shielding property of a material can be defined using the HVL that quantifies the required thickness of the material to absorb half of the incident radiation. The following equation calculates the HVL:

$$\text{HVL} = \frac{\ln 2}{\mu}$$

Similarly, the TVL represents the thickness that reduces radiation to 10% of its initial value, which is expressed as:

$$\text{TVL} = \frac{\ln 10}{\mu}$$

The mean free path (MFP) indicates the average distance that photons travel through the material before interacting, which is defined as:

$$\text{MFP} = \frac{1}{\mu}$$

2.3. Computational Methods

The radiation shielding parameters of the alloy and NiMnGa added composites were computed using Geant4 and WinXCOM software for the energy range from 0.0595 to 1.41 MeV. WinXCOM is a widely used software program for calculating various materials' photon cross-sections and attenuation coefficients, such as compounds and mixtures [21]. It is preferred because of its accuracy and reliability in calculating radiation shielding parameters by utilizing input data containing the elemental compositions of the corresponding materials [24].

Geant4 is a Monte Carlo simulation toolkit used for the modeling penetration of particles through matter [25]. It has been extensively applied in high-energy physics, medical physics, and radiation protection studies since it provides detailed information about interactions between photons and materials, enabling researchers to evaluate the radiation absorption performance of the materials under different conditions[13].

The main aim of the present study is to assess the composite materials' radiation shielding capacity, including different portions of the alloy compared to pure NiMnGa. To investigate the radiation protection ability of the composites and pure NiMnGa, the MAC, LAC, HVL, TVL, and MFP parameters were computed from Geant4 and WinXCOM separately for different photon energies. Moreover, the consistency of the simulation results was examined, using the deviation percentage for the mass attenuation coefficient between WinXCOM and Genat4 [3] defined as follows:

$$\Delta\,\% = \frac{(\mu_m)_{WinXCOM} - (\mu_m)_{Geant4}}{(\mu_m)_{WinXCOM}} 100$$

3. Results and Discussion

3.1. The Mass Attenuation Coefficient (MAC)

The mass attenuation coefficients of NiMnGa and the composites calculated by Geant4 and WinXCOM within the photon energy range of 0.0595 MeV to 1.41 MeV are represented in Figure 1 and summarized in Table 2. The deviations between the MAC values computed from Geant4 and WinXCOM are listed in Table 3. Considering deviations, it is concluded that MAC values computed from Geant4 and WinXCOM are consistent for all materials.

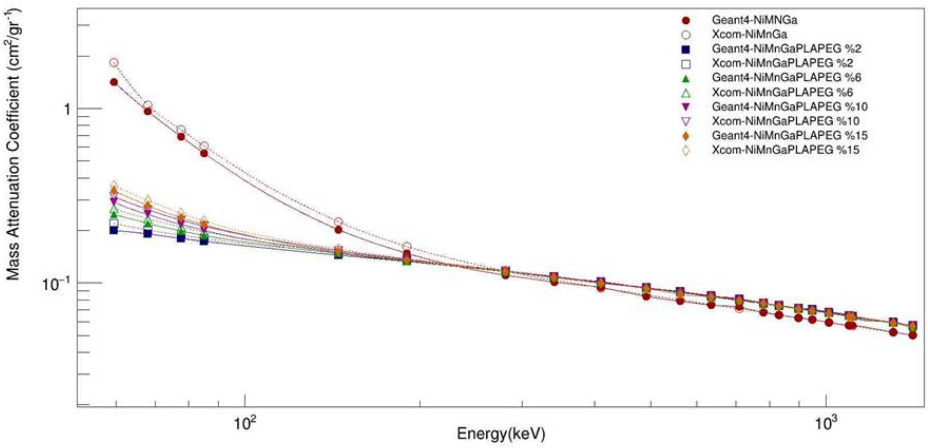

Figure 1. MAC of NiMnGa and the composites computed by Geant4 and WinXCOM

The difference between the MAC values derived from the programs was less than 10%. The results indicate that the mass attenuation coefficients of NiMnGa and the composites decreased exponentially with the increase in photon energy. These changes can result from the increase in the percentage of NiMnGa in the composites. While the mass attenuation coefficients of NiMnGa show a sharp decrease in the low energy region demonstrated in Figure 1, the reduction is more gradual in the composite materials.

The decrease in the mass attenuation coefficients of the alloy and composite materials is lower in the medium and high energy regions, which may result in photon-matter interaction in the energy range [26].

Table 2. List of the MAC values calculated by Geant4 and WinXCOM for the materials

Energy (*keV*)	Mass Attenuation Coefficients (μ_m) (cm^2/g)									
	NiMnGa		NiMnGaPLAPEG2		NiMnGaPLAPEG6		NiMnGaPLAPEG10		NiMnGaPLAPEG15	
	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4
59.5	1.4851	1.4215	0.2186	0.2005	0.2661	0.2480	0.3121	0.2904	0.3618	0.3373
68	1.0501	0.9666	0.2011	0.1909	0.2331	0.2193	0.2637	0.2466	0.2970	0.2779
72.6	0.7566	0.6881	0.1877	0.1798	0.2092	0.1981	0.2297	0.2166	0.2520	0.2365
85	0.6105	0.5526	0.1801	0.1731	0.1963	0.1869	0.2119	0.2007	0.2287	0.2165
145	0.2241	0.2019	0.1479	0.1442	0.1508	0.1473	0.1535	0.1486	0.1565	0.1507
190	0.1614	0.1475	0.1349	0.1327	0.1359	0.1330	0.1368	0.1335	0.1379	0.1343
280.8	0.1171	0.1106	0.1173	0.1159	0.1173	0.1161	0.1177	0.1157	0.1173	0.1156
340	0.1038	0.0961	0.1091	0.1083	0.1089	0.1076	0.1087	0.1076	0.1085	0.1071
410	0.0936	0.0944	0.1013	0.1010	0.1010	0.1004	0.1007	0.1006	0.1004	0.0998
491.3	0.0852	0.0836	0.0940	0.0939	0.0937	0.0936	0.0934	0.0933	0.0930	0.0930
560.7	0.0798	0.0788	0.0888	0.0891	0.0885	0.0887	0.0882	0.0881	0.0878	0.0877
635	0.0750	0.0743	0.0841	0.0843	0.0838	0.0838	0.0834	0.0848	0.0831	0.0833
710	0.0710	0.0705	0.0800	0.0813	0.0797	0.0801	0.0793	0.0796	0.0790	0.0790
780	0.0678	0.0675	0.0766	0.0769	0.0763	0.0766	0.0760	0.0762	0.0756	0.0759
830.3	0.0657	0.0656	0.0744	0.0747	0.0741	0.0743	0.0738	0.0741	0.0734	0.0738
897	0.0632	0.0631	0.0717	0.0720	0.0714	0.0716	0.0711	0.0713	0.0709	0.0709
946.6	0.0615	0.0616	0.0699	0.0705	0.0696	0.0700	0.0693	0.0696	0.0689	0.0692
1012.2	0.0595	0.0594	0.0677	0.0682	0.0674	0.0674	0.0677	0.0676	0.0668	0.0671
1096.2	0.0571	0.0579	0.0651	0.0651	0.0648	0.0650	0.0645	0.0647	0.0642	0.0640
1111.2	0.0567	0.0570	0.0646	0.0646	0.0643	0.0640	0.0640	0.0640	0.0637	0.0636
1305	0.0522	0.0523	0.0595	0.0596	0.0593	0.0592	0.0590	0.0589	0.0587	0.0599
1410	0.0502	0.0502	0.0572	0.0567	0.0569	0.0568	0.0567	0.0568	0.0564	0.0566

Table 3. Deviations of the MAC values between Geant4 and WinXCOM for the materials

Energy (*keV*)	The Deviations of the MAC Values (%Δ)				
	NiMnGa	NiMnGaPLAPEG2	NiMnGaPLAPEG6	NiMnGaPLAPEG10	NiMnGaPLAPEG15
59.5	4.2825	8.2799	6.8019	6.9528	6.7716
68	7.9516	5.0721	5.9202	6.4846	6.4288
72.6	9.0536	4.2088	5.3059	5.7030	6.1507
85	9.4840	3.8867	4.7885	5.2855	5.3344
145	9.9062	2.5016	2.3209	3.1921	3.7060
190	8.6121	1.6308	2.1339	2.4122	2.6105
280.8	5.5508	1.1935	1.0230	1.6992	1.4492
340	7.4181	0.7332	1.1937	0.0993	1.2903
410	-0.8547	0.2961	0.5940	0.0993	0.5976
491.3	1.8779	0.1063	0.1067	0.1070	0
560.7	1.2531	-0.3378	-0.2259	0.1133	0.1138
635	0.9333	-0.2378	-0.1193	-1.1678	-0.2406
710	0.7042	-1.625	-.0.5018	-0.4065	0
780	0.4225	-0.3916	-0.3931	-0.2812	-0.3968
830.3	0.1522	-0.4032	-0.2699	-0.4329	-0.5449
897	0.1582	-0.4184	-0.2801	0.1477	0
946.6	-0.1626	-0.8583	-0.5747	-0.3100	-0.4354
1012.2	0.1680	-.0.7385	4.1543	0.1477	-0.4491
1096.2	-1.4010	-0.15366	-0.3086	-0.3100	0.3152
1111.2	-0.5291	1.2383	0.4665	0	0.1569
1305	-0.1915	-0.1680	0.1686	0.1694	-2.0442
1410	0	0.8741	0.1757	-0.1763	-0.3546

A high mass attenuation coefficient in the low energy region indicates higher radiation protection efficiency (RPE). According to the results obtained from the software, the deviation percentages between the programs were derived as follows: NiMnGa alloy (10%), NiMnGaPLAPEG2 (9%), NiMnGaPLAPEG6 (7%), NiMnGaPLAPEG10 (7%), and NiMnGaPLAPEG15 (7%). The relatively higher deviations observed in the photon energy range of 59.5 to 340 keV (Table 3) can be attributed to several factors. In this range, the photoelectric effect is the dominant interaction mechanism, and its cross-section is highly sensitive to the material's composition, density, and atomic number. Slight discrepancies in these input parameters between Geant4 and WinXCOM can amplify errors in calculated mass attenuation coefficients, leading to more significant deviations [20].

Furthermore, this energy range marks a transition where the photoelectric effect diminishes, and Compton scattering becomes more significant, introducing complexities in accurately modeling these overlapping interaction mechanisms. Similar discrepancies during this transition have been reported in previous studies comparing Monte Carlo simulations and theoretical methods [3]. Additionally, the NiMnGa-doped composites analyzed here involve complex compositions with varying atomic numbers, which may lead to differences in how Geant4 and WinXCOM handle material heterogeneity [20]. Deviations may also stem from input data limitations, such as assumptions in density or photon cross-sections, which are critical at lower photon energies. Moreover, geometric and boundary conditions in Monte Carlo simulations may introduce minor errors at lower energies that do not affect WinXCOM's analytical calculations, with such discrepancies decreasing at higher energies due to reduced sensitivity to material interfaces [24]. Despite these higher deviations, the overall agreement between Geant4 and WinXCOM remains strong, with deviations within acceptable limits for computational studies of radiation shielding.

3.2. The Linear Attenuation Coefficient (LAC)

The linear attenuation coefficient (LAC) is a gamma radiation shielding parameter defined by the density of the material and the relative mass attenuation coefficient. The LAC of composites with NiMnGa is presented in Figure 2, and the values are listed in Table 4. The polymer composites have lower LAC values due to the elements with low atomic numbers, such as C, H, and O, in the polymer structure. It is concluded that the difference between the μ values of the polymer composite material decreases as the photon energy of the alloy and polymer composite material increases. It explains the photon and matter interaction depending on the increasing percentage of alloy amounts in the polymer composite. There is a significant improvement in the linear attenuation coefficients depending on the amount of gamma energies. NiMnGa alloy shows high gamma radiation at low energy.

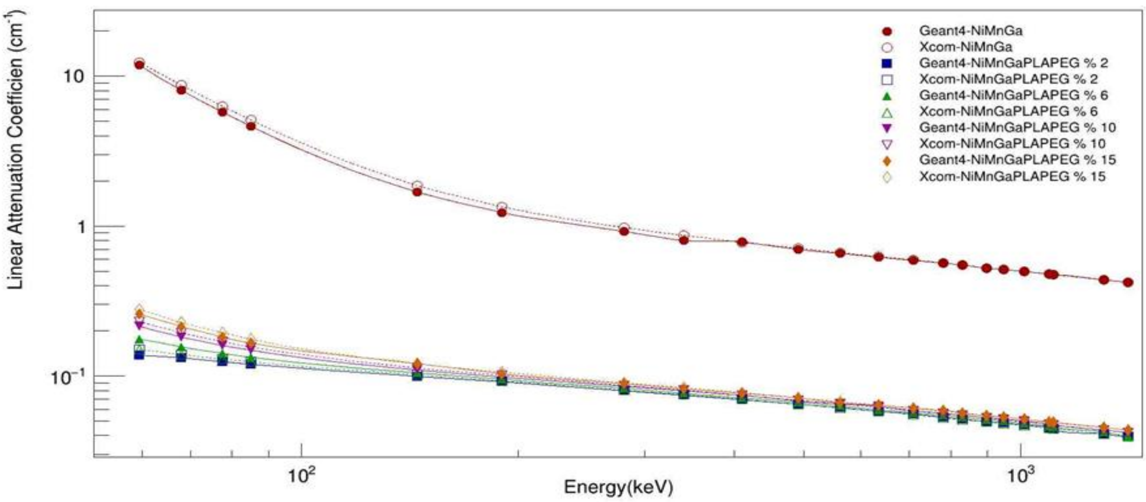

Figure 2. LAC of NiMnGa and the composites computed by Geant4 and WinXCOM

Moreover, PLA/PEG/NiMnGa composite materials provide sound gamma radiation in low-energy regions. It protects against gamma radiation depending on the amount of alloy added to the polymer. The linear attenuation coefficient at low energies shows more significant radiation shielding than higher energies. The fact that the photoelectric cross section is at a low energy level affects its exponential decrease with photon energy [27]. It has been observed that in exponential decay, the absorption ability of photons increases at low energies and decreases with increasing energy. It was concluded that the Compton scattering cross section and absorbing properties are related to the atomic number and energy gaps. An increase in the armoring effect was detected by increasing the alloy contribution. As photon energy increases, pair formation increases. A similar trend is observed between the linear and mass attenuation coefficients.

Table 4. LAC values of NiMnGa and composites computed by Geant4 and WinXCOM

Energy (*keV*)	Linear Attenuation Coefficient (μ) (cm^2/g)									
	NiMnGa		**NiMnGaPLAPEG2**		**NiMnGaPLAPEG6**		**NiMnGaPLAPEG10**		**NiMnGaPLAPEG15**	
	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4
59.5	12.3957	11.8692	0.1505	0.1380	0.1897	0.1768	0.2302	0.2142	0.2778	0.2590
68	8.7675	8.0713	0.1384	0.1314	0.1662	0.1564	0.1945	0.1820	0.2281	0.2135
72.6	6.3176	5.7466	0.1292	0.1238	0.1492	0.1413	0.1694	0.1598	0.1935	0.1816
85	5.0976	4.6171	0.1239	0.1192	0.1400	0.1333	0.1563	0.1481	0.1756	0.1662
145	1.8704	1.6858	0.1018	0.0993	0.1075	0.1050	0.1132	0.1096	0.1202	0.1157
190	1.3404	1.2321	0.0928	0.0913	0.0969	0.0948	0.1009	0.0985	0.1059	0.1032
280.8	0.9769	0.9241	0.0807	0.0798	0.0836	0.0828	0.0865	0.0853	0.0900	0.0888
340	0.8667	0.8024	0.0751	0.0745	0.0776	0.0768	0.0802	0.0794	0.0833	0.0822
410	0.7817	0.7887	0.0697	0.0695	0.0720	0.0716	0.0742	0.0742	0.0771	0.0766
491.3	0.7120	0.6985	0.0647	0.0646	0.0668	0.0668	0.0689	0.0688	0.0714	0.0714
560.7	0.6665	0.6570	0.0611	0.0613	0.0631	0.0633	0.0650	0.0650	0.0674	0.0673
635	0.6268	0.6211	0.0579	0.0580	0.0597	0.0597	0.0615	0.0626	0.0638	0.0640
710	0.5932	0.5890	0.0551	0.0559	0.0568	0.0571	0.0585	0.0587	0.0607	0.0607
780	0.5662	0.5641	0.0527	0.0529	0.0544	0.0546	0.0560	0.0564	0.0581	0.0583
830.3	0.5490	0.5479	0.0512	0.0514	0.0528	0.0530	0.0544	0.0547	0.0564	0.0566
897	0.5281	0.5272	0.0493	0.0495	0.0509	0.0510	0.0524	0.0526	0.0543	0.0544
946.6	0.5141	0.5143	0.0481	0.0485	0.0496	0.0499	0.0511	0.0513	0.0529	0.0531
1012.2	0.4969	0.4963	0.0466	0.0469	0.0480	0.0480	0.0499	0.0499	0.0513	0.0515
1096.2	0.4767	0.4767	0.0448	0.0448	0.0462	0.0464	0.0476	0.0477	0.0493	0.0491
1111.2	0.4735	0.4760	0.0445	0.0444	0.0459	0.0457	0.0472	0.0472	0.0489	0.0488
1305	0.4362	0.4370	0.0410	0.0410	0.0422	0.0422	0.0435	0.0435	0.0451	0.0453
1410	0.4196	0.4198	0.0393	0.0390	0.0406	0.0405	0.0418	0.0419	0.0433	0.0435

3.3. The Half Value Layer (HVL)

TVL has an absorbing effect that reduces the radiation effect by one-tenth, providing information about protecting the material against gamma radiation [29]. The TVL values of the alloy and composites calculated from Geant4 and WinXCOM are represented in Figure 3 and Table 5. The results revealed that adding NiMnGa decreased the TVL of composites, as expected from the HVL calculations. Figures 3 and 4 illustrate that the HVL and TVL results are consistent. In addition, from the figures, it is comprehended that increasing the doping amount of NiMnGa to the polymer-based composites enhances the usability of the materials for gamma radiation protection at low energies. The values from the computation of Geant4 and WinXCOM confirm each other.

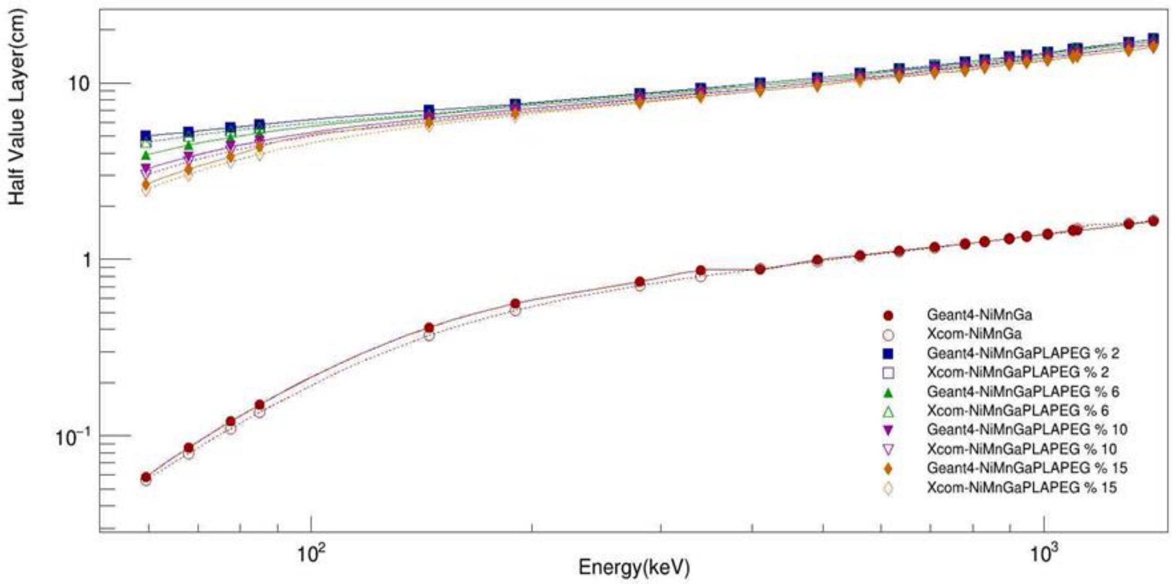

Figure 3. The HVL of NiMnGa and the composites computed by Geant4 and WinXCOM

Table 5. HVL values of NiMnGa and composites computed by Geant4 and WinXCOM

Energy (*keV*)	**Half Value Layer**									
	NiMnGa		**NiMnGaPLAPEG2**		**NiMnGaPLAPEG6**		**NiMnGaPLAPEG10**		**NiMnGaPLAPEG15**	
	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4
59.5	0.0559	0.0583	4.6056	5.0213	3.6535	3.9185	3.0101	3.2359	2.4951	2.6751
68	0.0790	0.0858	5.0064	5.2718	4.1690	4.4299	3.5626	3.8085	3.0387	3.2461
72.6	0.1097	0.1206	5.3640	5.5984	4.6451	4.9043	4.0900	4.3375	3.5810	3.8154
85	0.1359	0.1501	5.5900	5.8145	4.9506	5.1999	4.4335	4.6834	3.9473	4.3391
145	0.3705	0.4111	6.6807	6.9803	6.4442	6.5957	6.1205	6.3202	5.7666	5.9891
190	0.5143	0.5625	7.4636	7.5869	7.1510	7.3070	6.8676	7.0302	6.5452	6.7151
280.8	0.7095	0.7500	8.5838	8.6806	8.2852	8.3703	8.0095	8.1174	7.6939	7.8051
340	0.7997	0.8637	9.2284	9.2965	8.9242	9.0241	6.6427	8.7254	8.3210	8.4271
410	0.8866	0.8788	9.9390	9.9661	9.6216	9.6754	9.3302	9.3390	8.9902	9.0430
491.3	0.9735	0.9922	10.7010	10.7215	10.3702	10.3764	10.0581	10.0748	9.6984	9.7021
560.7	1.0398	1.0549	11.3376	11.2927	10.9762	10.9450	10.6523	10.6539	10.2718	10.2993
635	1.1057	1.1159	11.9714	11.9301	11.5949	11.6105	11.2651	11.0729	10.8643	10.8211
710	1.1683	1.1766	12.5775	12.3997	12.1925	12.1200	11.8486	11.8082	11.4192	11.4117
780	1.2240	1.2286	13.1352	13.0920	12.7323	12.6787	12.3599	12.2854	11.9302	11.8893
830.3	1.2625	1.2650	13.5248	13.4670	13.1128	13.0659	12.7311	12.6509	12.2898	12.2317
897	1.3124	1.3147	14.0341	13.9831	13.6017	13.5687	13.2103	13.1729	12.7651	12.7206
946.6	1.3482	1.3475	14.3955	14.2680	13.9578	13.8768	13.5531	13.4984	13.0955	13.0339
1012.2	1.3947	1.3965	15.8712	14.7540	14.4165	14.4405	13.8741	13.8795	13.5063	13.4510
1096.2	1.4538	1.4540	15.4627	15.4720	14.9934	14.9385	14.5581	14.5100	14.0569	14.0912
1111.2	1.4638	1.4561	15.5627	15.6111	15.0946	15.1673	14.6601	14.6791	14.1516	14.1776
1305	1.5887	1.5860	16.9006	16.9060	16.3903	16.4252	15.9341	15.9270	15.3623	15.2741
1410	1.6516	1.6509	17.6015	17.7730	17.0549	17.1147	16.5468	16.5192	15.9891	15.9192

3.4. The Tenth Value Layer (TVL)

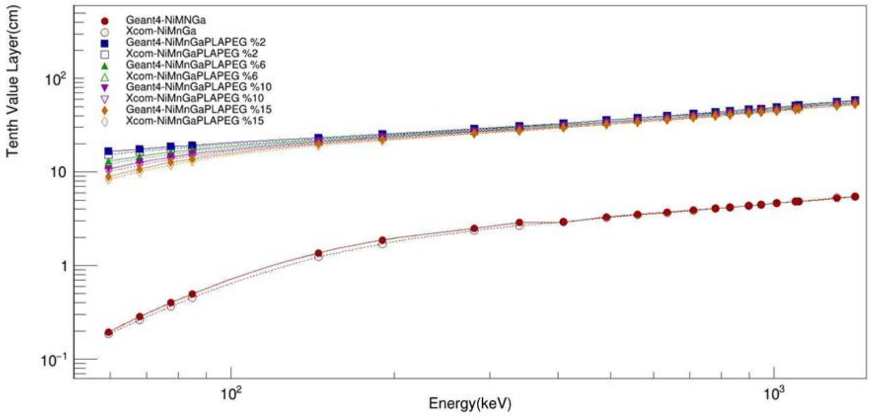

Figure 4. The TVL of NiMnGa and the composites computed by Geant4 and WinXCOM

TVL has an absorbing effect that reduces the radiation effect by one-tenth, providing information about protecting the material against gamma radiation [29]. The TVL values of the alloy and composites calculated from Geant4 and WinXCOM are represented in Figure 4 and Table 6. The results revealed that adding NiMnGa decreased the TVL of composites, as expected from the HVL calculations. Figures 3 and 4 illustrate that the HVL and TVL results are consistent. In addition, from the figures, it is comprehended that increasing the doping amount of NiMnGa to the polymer-based composites enhances the usability of the materials for gamma radiation protection at low energies. The values from the computation of Geant4 and WinXCOM confirm each other.

Table 6. The TVL values of NiMnGa and composites computed by Geant4 and WinXCOM

Energy (keV)	Tenth Value Layer (TVL)									
	NiMnGa		NiMnGaPLAPEG2		NiMnGaPLAPEG6		NiMnGaPLAPEG10		NiMnGaPLAPEG15	
	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4
59.5	0.1857	0.1939	15.2995	16.6805	12.1367	13.0170	9.9991	10.7496	8.2886	8.8875
68	0.2626	0.2852	16.6316	17.5128	13.8493	14.7158	11.8341	12.6515	10.0946	10.7839
72.6	0.3644	0.4006	17.8190	18.5977	15.4308	16.2917	13.5861	14.4091	11.8959	12.6741
85	0.4516	0.4986	18.5696	19.3153	16.4458	17.2737	14.7281	15.5475	13.1126	13.8543
145	1.2310	1.3657	22.6142	23.1881	21.4072	21.9106	20.3318	20.9955	19.1562	19.8841
190	1.7085	1.8687	24.7936	25.2034	23.7551	24.2735	22.8136	23.3646	21.7430	22.3091
280.8	2.3569	2.4915	28.5149	28.8219	27.5231	27.8056	26.6071	26.9655	25.5581	25.9301
340	2.6566	2.8687	30.6561	30.8823	29.6457	29.9776	28.7105	28.9852	27.6421	27.9911
410	2.9455	2.9193	33.0167	33.1069	31.9625	32.1410	30.9941	31.0237	29.8641	30.0401
491.3	3.2339	3.2961	35.5666	35.6161	34.4492	34.4698	33.4143	33.8525	32.2175	32.3670
560.7	3.4543	3.5043	37.6855	37.5136	36.4621	36.3585	35.3861	35.4243	34.1224	34.2137
635	3.6733	3.7069	39.7683	39.6997	38.5176	38.5692	37.4221	36.7641	36.0906	35.9491
710	3.8812	3.9088	41.7811	41.1911	40.5028	42.2620	39.3601	39.1729	37.9938	37.9081
780	4.0660	4.0814	43.6343	43.4909	42.2958	42.1178	41.0581	40.8115	39.6314	39.4954
830.3	4.1940	4.2024	44.9284	44.7364	43.5600	43.4040	42.2881	42.0256	40.8259	40.6338
897	4.3598	4.3674	46.6204	46.4511	45.1842	45.0744	43.8831	43.7595	42.4048	42.2570
946.6	4.4788	4.4766	47.8210	47.3977	46.3669	46.0977	45.0251	44.8409	43.5024	43.2979
1012.2	4.6332	4.6393	49.4010	49.0120	47.8907	47.9705	46.0881	46.1070	44.8672	44.6841
1096.2	4.8294	4.8302	51.3660	51.3969	49.8071	49.7318	48.3631	48.2014	46.6961	46.8100
1111.2	4.8626	4.8373	51.7155	51.8600	50.1434	50.4952	48.7011	48.6804	47.0107	47.0972
1305	5.2777	5.2687	56.1428	56.1606	54.4475	54.5636	52.9321	52.9086	51.0324	50.7401
1410	5.4866	5.4844	58.4709	58.2932	56.6553	56.8539	54.9674	54.8757	53.1161	52.8841

3.5. The Mean Free Path (MFP)

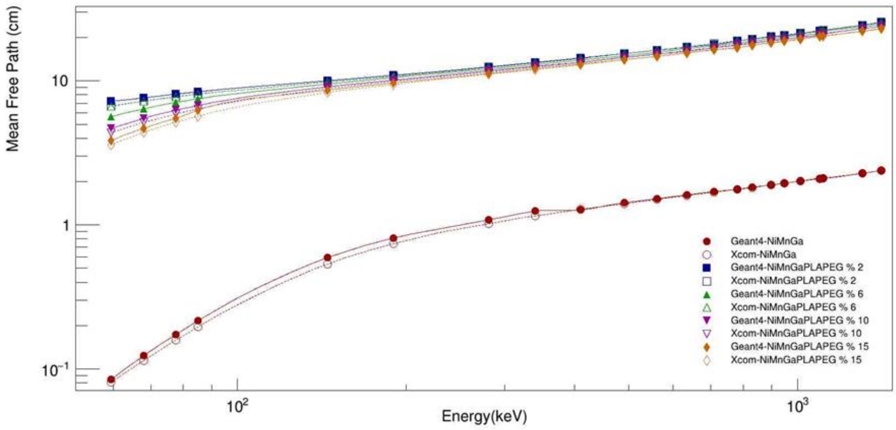

Figure 5. MFP of NiMnGa and the composites computed by Geant4 and WinXCOM

The Mean free path (MFP) values of the alloy and composites calculated by Geant4 and WinXCOM are represented in Figure 5 and Table 7. From the figure, it is concluded that the MFP increases from lower to higher energy regions for all materials. We increase the photon energy depending on the amount of the alloy in the values. Since the PLA and PEG polymers have low density, the MFP values change concerning the amount of the doped alloy in the composites [22]. An increase in the alloy amount in the composites decreases the MFP, consistent with the HVL and TVL results. Both computations exhibited similar results for each material.

Table 7. MFP values of NiMnGa and composites computed by Geant4 and WinXCOM

Energy (keV)	Mean Free Path (MFP)									
	NiMnGa		NiMnGaPLAPEG2		NiMnGaPLAPEG6		NiMnGaPLAPEG10		NiMnGaPLAPEG15	
	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4	WinXcom	Geant4
59.5	0.0806	0.0842	6.6445	7.2463	5.2714	5.6561	4.3440	4.6685	3.5997	3.8610
68	0.1140	0.1238	7.2254	7.6103	6.0168	6.3938	5.1413	5.4945	4.3840	4.6838
72.6	0.1582	0.1740	7.7399	8.0775	6.7024	7.0771	5.9031	6.2578	5.1679	5.5066
85	0.1961	0.2165	8.0710	8.3892	7.1428	7.5018	6.3979	6.7521	5.6947	6.2617
145	0.5346	0.5931	9.8231	10.0704	9.3023	9.5238	8.8339	9.1240	8.3194	8.6430
190	0.7420	0.8116	10.7758	10.9529	10.3199	10.5485	9.9108	10.1522	9.4428	9.6899
280.8	1.0236	1.0821	12.3915	12.5313	11.9617	12.0772	11.5606	11.7233	11.1111	11.2612
340	1.1538	1.2462	13.3155	13.4228	12.8865	13.0208	12.4688	12.5944	12.0048	12.1654
410	1.2792	1.2679	14.3472	14.3884	13.8888	13.9664	13.4770	13.4770	12.9701	13.0548
491.3	1.4044	1.4316	15.4559	15.4798	14.9700	14.9700	14.5137	14.5348	14.0056	14.0056
560.7	1.5003	1.5220	16.3666	16.3132	15.8478	15.7977	15.3846	15.3846	14.8367	14.8588
635	1.5954	1.6100	17.2711	17.2117	16.7504	16.7504	16.2601	15.9744	15.6739	15.6250
710	1.6857	1.6977	18.1488	17.8890	17.6056	17.5131	17.0940	17.0357	16.4744	16.4744
780	1.7661	1.7727	18.9753	18.9035	18.3823	18.3150	17.8571	17.7304	17.2117	17.1526
830.3	1.8214	1.8251	19.5312	19.4552	18.9393	18.8679	18.3823	18.2815	17.7304	17.6678
897	1.8935	1.8968	20.2839	20.2020	19.6463	19.6078	19.0839	19.0114	18.4162	18.3823
946.6	1.9451	1.9443	20.7900	20.6185	20.1612	20.0400	19.5694	19.4931	18.9035	18.8323
1012.2	2.0124	2.0149	21.4592	21.3219	20.8333	20.8333	20.0400	20.0400	19.4931	19.4174
1096.2	2.0977	2.0977	22.3214	22.3214	21.6450	21.5517	21.0084	20.9643	20.2839	20.3665
1111.2	2.1119	2.1008	22.4719	22.5225	21.7864	21.8818	21.1864	21.1864	20.4498	20.4918
1305	2.2925	2.2883	24.3902	24.3902	23.6966	23.6966	22.9885	22.9885	22.1729	22.0750
1410	2.3832	2.3820	25.4452	25.6410	24.6305	24.6913	23.9234	23.8663	23.0946	22.9885

4. Conclusion

Alloys containing high atomic number (Z) elements, such as lead or tungsten, exhibit exceptional gamma radiation shielding properties compared to polymers. However, polymers, primarily composed of low-Z elements like carbon, oxygen, and hydrogen, are inherently less effective in attenuating gamma rays. Incorporating high Z elements into polymers, such as composite materials, significantly enhances their radiation shielding capabilities. This study evaluates the gamma radiation protection efficiency of NiMnGa doped PLA/PEG-based composites, demonstrating the potential of smart materials in radiation shielding applications. By varying the concentration of NiMnGa in these composites, the research highlights how tailored, smart materials can meet specific shielding requirements, offering a flexible, lightweight, and efficient solution for radiation protection. The study calculated critical shielding parameters MAC, LAC, HVL, TVL, and MFP for pure NiMnGa alloy and composites containing 2, 6, 10, and 15% NiMnGa, across an energy range of 0.0595 to 1.41 MeV. The results indicate that increasing the alloy concentration significantly enhances the gamma radiation protection of the composites at low photon energy levels. For instance, the MAC of the 15% NiMnGa composite at 59.5 keV reached 0.3618 cm^2/g, outperforming the 2% composite (0.2186 cm^2/g) and approaching the performance of pure NiMnGa alloy. Comparisons with existing literature confirm that these composites provide comparable or superior shielding efficiency to materials like Pb-doped PLA/PEG or tungsten trioxide (WO_3) composites while maintaining the advantages of reduced toxicity, lower weight, and higher flexibility.

Furthermore, NiMnGa-doped composites exhibited decreasing radiation protection efficiency at higher photon energies due to the transition from photoelectric dominance at low energies to Compton scattering and pair production at higher energies. This behavior aligns with previously reported trends in NiMnGa-based and other SMA composites, further validating the computational methodologies employed in this study using Geant4 and WinXCOM. The computational results from both tools demonstrated consistency, reinforcing their reliability for assessing gamma radiation shielding properties. The findings underscore the potential of NiMnGa-doped polymers as a lightweight, non-toxic alternative to traditional shielding materials like lead, making them ideal for wearable and portable applications. Future work should focus on experimental validation of the findings, particularly to resolve discrepancies observed in the intermediate energy range (59.5–340 keV). Optimizing material compositions for targeted applications and conducting detailed cost analyses will further establish commercial feasibility. Exploring the incorporation of other high-Z elements or nanoparticles could enhance shielding performance at higher photon energies, broadening the applicability of these materials.

Author Contributions

All the authors equally contributed to this work.

Conflicts of Interest

All the authors declare no conflict of interest.

Ethical Review and Approval

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