



RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

## Quantitative Assessment of Dose Enhancement Ratio of Platinum Nanoparticles Using keV X-rays: A Monte Carlo Simulation Study

### keV X-ışınları Kullanılarak Platin Nanopartiküllerin Doz Artırma Oranının Nicel Değerlendirmesi: Bir Monte Carlo Simülasyon Çalışması

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#### Abstract

Low-energy X-rays are widely used in treating skin cancers and dermatological disorders due to their effectiveness in targeting superficial lesions with minimal damage to healthy tissues. The introduction of nanoparticles in radiotherapy has gained attention for enhancing dose delivery through increased free radical production and secondary electron generation. In this study, platinum nanoparticles at concentrations of 6 mg/g and 18 mg/g were incorporated into a soft tissue phantom to evaluate the dose enhancement ratio (DER) at various keV energy levels. Monte Carlo simulations were conducted using the Geant4-DNA code with the TOPAS interface, employing the track structure (TS) algorithm for high-accuracy modeling of low-energy electron interactions. Results showed a clear increase in DER with higher NP concentrations and lower photon energies. The highest DER (2.66703) was obtained with 80 keV X-rays at 18 mg/g platinum concentration, while the lowest DER (1.01222) was observed with 550 keV X-rays at 6 mg/g concentration. The findings indicate that platinum nanoparticles significantly enhance the absorbed dose in the medium, particularly at low energy levels where the photoelectric effect is dominant. This study suggests that using platinum nanoparticles with low-energy X-rays may improve the efficacy of surface tumor treatments. Further studies with different nanoparticle types, concentrations, and radiation energies are recommended to improve treatment strategies and enhance therapeutic outcomes.

**Keywords:** Platinum Nanoparticle, X-Rays, Dose Enhancement Ratio

#### Öz

Düşük enerjili X-ışınları, sağlıklı dokulara en az zarar vererek yüzeysel lezyonları hedeflemedeki etkinlikleri nedeniyle cilt kanserleri ve dermatolojik bozuklukların tedavisinde yaygın olarak kullanılmaktadır. Radyoterapide nanopartiküllerin kullanılması, serbest radikal üretimini ve ikincil elektron üretimini artırarak doz iletimini geliştirmesi açısından dikkat çekmiştir. Bu çalışmada, 6 mg/g ve 18 mg/g konsantrasyonlarındaki platin nanopartiküller, çeşitli keV enerji seviyelerinde doz artırma oranını (DER) değerlendirmek için yumuşak doku fantomuna dahil edilmiştir. Monte Carlo simülasyonları, düşük enerjili elektron etkileşimlerinin yüksek doğrulukta modellenmesi için iz yapısı (TS) algoritmasını kullanan TOPAS arayüzlü Geant4-DNA kodu kullanılarak gerçekleştirilmiştir. Sonuçlar, daha yüksek NP konsantrasyonları ve daha düşük foton enerjileri ile DER'de belirgin bir artış olduğunu göstermiştir. En yüksek DER (2,66703) 18 mg/g platin konsantrasyonunda 80 keV X-ışınları ile elde edilirken, en düşük DER (1,01222) 6 mg/g konsantrasyonunda 550 keV X-ışınları ile gözlenmiştir. Bulgular, platin nanopartiküllerin, özellikle fotoelektrik etkinin baskın olduğu düşük enerji seviyelerinde, ortamda absorbe edilen dozu önemli ölçüde artırdığını göstermektedir. Bu çalışma, platin nanopartiküllerin düşük enerjili X ışınlarıyla birlikte kullanılmasının yüzey tümör tedavilerinin etkinliğini artırabileceğini göstermektedir. Farklı nanoparçacık türleri, konsantrasyonları ve radyasyon enerjileriyle yapılacak daha ileri çalışmalar, tedavi stratejilerini iyileştirmek ve daha iyi sonuçlar elde etmek için önerilmektedir.

**Anahtar Kelimeler:** Platinum Nanopartikülü, X-Rays, Doz Arttırma Oranı

#### 1. Introduction

Low energy X-rays are used to treat skin cancers and some dermatological disorders. This treatment method aims to treat the cancerous area with minimal damage to healthy tissues [1-3]. Since high doses of radiation are absorbed on the skin surface in the use of X-rays at the keV level, the use of low energy X-rays has become an effective option in the treatment of superficial areas. Studies have also proven that the use of low energy X-rays is a valid and safe treatment [4,5].

Free radicals contribute significantly to cell death. The presence of nanoparticles (NP) in the environment increases the presence of free radicals, making NPs important in radiation therapy [6,7]. Studies on the effects of NPs on the use of low-energy X-rays are currently being conducted [8,-11].

NPs added to the tumor medium increase the absorbed dose in the medium. The dose increase in the medium caused by the addition of NPs is related to the photoelectric effect cross section [1,12,13]. Auger electrons formed in the presence of NPs in the medium as a result of irradiation also contribute to the dose increase [14-16].

As the atomic number increases, the secondary electron production due to the photoelectric effect also increases. This increases the radiation absorption. As the X-ray energy increases, the photoelectric effect decreases. The interaction of high atomic number NPs with low energy X-rays results in a higher dose increase in the medium. High atomic number NPs are more effective in radiation therapy compared to megavoltage X-rays [14,17]. This is attributed to their enhanced therapeutic efficacy [18].

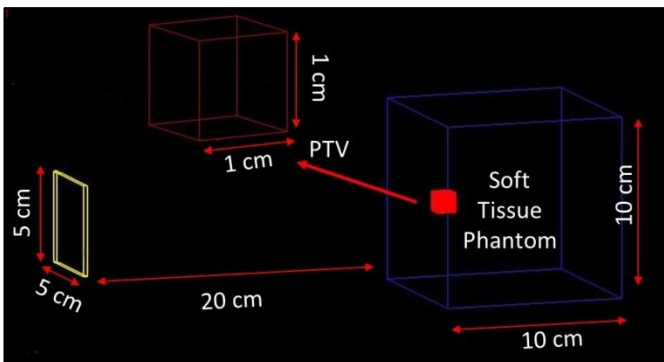
Monte Carlo simulation is widely used in radiation applications with NP addition. The MC method simulates the transport of radiation in the medium using mathematical algorithms and the dose distribution that will occur in the medium is estimated in the most accurate way [1,19,20,21].

In order to accurately estimate the dose distributions at subatomic levels when NP is added, it is recommended to use the trace structure algorithm [22-24]. When evaluating the impact of nanoparticles (NPs) through Monte Carlo (MC) simulations, the dose enhancement ratio (DER) is calculated as the ratio of the dose delivered in the presence of NPs to the dose delivered in their absence [19]. With the help of this ratio, factors such as the appropriate NP, concentration and energy are determined to increase the treatment effect [25].

There are not many studies in the literature on radiation treatments of surface tumors supported by NPs using X-rays at keV energy levels. The aim of this study is to investigate the changes in the dose in the environment in radiation applications at different keV energy levels as a result of the addition of platinum NPs at different concentrations to the environment.

**2. Materials and Methods**

The use of the track structure algorithm at the nanometer scale allows high-accuracy modeling of low-energy electrons produced by NPs. Therefore, the Geant4-DNA code was used for the simulations carried out in this study [14]. The Geant4 code was used with the "Tool for Particle Simulation" (TOPAS) interface in the study. In addition to modeling physical interactions, Geant4-DNA can also model chemical processes such as free radical production, diffusion, and DNA strand breaks. This code can track and model electrons up to the excitation energy of water molecules. In the study, 80 keV, 250 keV, 350 keV, 450 keV, and 550 keV photon beams were generated using the TOPAS interface. The NP to be used in the study was selected as platinum. Platinum concentrations were determined as 6 mg/g and 18 mg/g. A soft tissue phantom of 10x10x10 cm<sup>3</sup> was created. A structure containing 6 mg/g and 18 mg/g platinum with dimensions of 1x1x1 cm<sup>3</sup> was placed at a depth of 1 cm of the phantom. The macroscopic model is an approach used in radiation dose calculations, typically accounting for the average effects of density, atomic composition, and radiation interactions. In this model, the passage of radiation through matter is calculated based on average energy losses and probabilistic interactions. Macroscopic model was used in MC simulations. In the simulation, a phantom was used in which platinum NPs were added to the water medium. The phantom in which NP was added was created from a mixture containing 6 mg/g and 18 mg/g concentrations. The photon beam area was defined as 5x5 cm<sup>2</sup> and simulations were performed with a source-skin distance (SSD) of 20 cm. The created simulation model is shown in Figure 1.

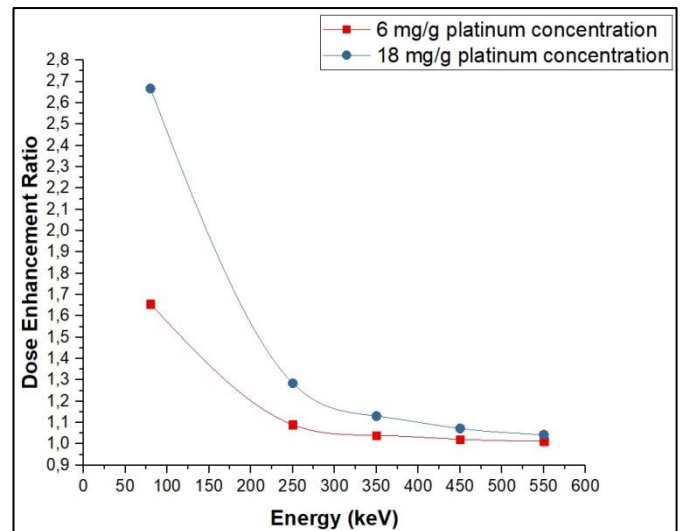


**Figure 1.** Schematic representation of the model created for Monte Carlo simulation.

Two different platinum concentrations were irradiated for the selected 5 photon energies. Since simulations will be performed in the presence and absence of NP, a large number of simulations are needed, which means high calculation times. Powerful workstations are needed to minimize uncertainties and times. To minimize uncertainties, the number of histories was set to 1x10<sup>9</sup>. The materials representing normal tissue in the simulation were composed of 76.2% oxygen, 2.6% nitrogen, 11.1% carbon, and 10.1% hydrogen, as defined by the International Commission on Radiation Units and Measurements (ICRU) [26]. Accurate selection of physics parameters is crucial for properly capturing radiation interactions, particularly in low-energy Monte Carlo (MC) simulations. The g4em-standard\_opt3 module in the Geant4 code was used in the MC simulations. In the physics settings of the MC simulations, fluorescence radiation, Auger effect, particle-induced X-ray emission (PIXE) and Auger cascade interactions were enabled. The DER value is used to investigate the effect of NPs in radiation applications. DER is defined as the ratio of the dose measured with NPs to the dose measured without NPs. This value may vary depending on the location, concentration and properties of NPs [15,27]. All simulations performed with and without NPs in the environment were modeled in a way that the physics parameters and beam geometry were the same.

**3. Results and Discussion**

For 5 different energy values, DER values were calculated for 6 mg/g and 18 mg/g platinum concentrations. Figure 2 shows DER values for 6 mg/g and 18 mg/g concentration values, respectively.



**Figure 2.** DER values obtained for 6 mg/g platinum concentration and 18 mg/g platinum concentration at different energies.

For 6 mg/g platinum concentration, DER values obtained in 80 keV, 250 keV, 350 keV, 450 keV and 550 keV X-rays are 1.65695, 1.09059, 1.04041, 1.02194, 1.01222, respectively. The lowest DER value in the simulations was obtained for 550 keV X-rays at 6 mg/g platinum concentration. For 18 mg/g platinum concentration, DER values obtained in 80 keV, 250 keV, 350 keV, 450 keV and 550 keV X-rays are 2.66703, 1.28455, 1.13085, 1.07254, 1.04377, respectively. As can be seen from the figure 2, the DER value increases for all energies when the concentration

value increases. The highest DER value is 2.66703, measured as a result of 80 keV photon irradiation for 18 mg/g platinum concentration. It is important to see that there is an increase in dose as a result of adding NPs to the 1 cm depth of soft tissue for low energy X-rays because the depth of the lesions that need to be irradiated for treatment is in these ranges [1,9].

It is clearly seen that the DER value decreases as the energy increases for both concentration values. As the photoelectric effect decreases as the energy increases, the dose increase in the environment also decreases accordingly [17]. Platinum nanomaterial is an element with a high atomic number. In the low X-ray range, the photoelectric effect plays a dominant role and the photoelectric effect is directly proportional to the atomic number [14]. This allows more secondary electrons to be formed in the medium. Therefore, the addition of a high atomic number NP to the medium results in an increase in dose. The simulation results showed that platinum NPs caused an increase in dose in the low energy X-ray range, which may be evidence that the NP can perform well for surface treatments. The percentage differences in DER values obtained for different energies are shown in Table 1.

**Table 1.** Percentage differences between DER values obtained for 18 mg/g and 6 mg/g concentrations.

Energy (keV)	18 mg/g	6 mg/g	Percentage Differences (%)
80	2,667	1,657	60,96
250	1,284	1,091	17,78
350	1,130	1,04	8,69
450	1,0725	1,0219	4,95
550	1,04	1,012	3,12

As seen from the results in Table 1, the importance of concentration decreases as the energy increases. The dose occurred in the environment at a concentration of 18 mg/g platinum at a photon energy of 80 keV is 60% higher than that at a concentration of 6 mg/g. In the study conducted by Gebremariam et al. using platinum nanoparticles, it was shown that the DER value increased when the concentration increased. Again, the study conducted by Khairil Anuar et al. showed that platinum is a good radiosensitizer for photon beam radiotherapy [28-29]. We obtained similar results in our study.

#### 4. Conclusions

In the study, the dose enhancement that platinum nanomaterial can create in the environment when used on surface tumors was investigated with the help of Monte Carlo simulation. It was obtained in the study that the dose enhancement is very high in dependence on concentration and energy. The results suggest that using X-rays with energies below 100 keV for treating lesions situated 1 cm beneath the surface in the presence of NPs may offer a more effective therapeutic outcome. The study also found that the platinum NP used in the study was effective in increasing the dose in the soft tissue phantom. To achieve more accurate and effective results, it is recommended to conduct similar studies with a broader range of materials, varying depths, and different energy levels. It is thought that the results obtained in the study will help to accelerate and facilitate other studies to be conducted.

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#### Author Contribution Statement

The conceptualization, experimental design, data collection, analysis, literature review and writing prepared by Taylan Tuğrul.

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