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Investigation of Neutron Interaction Parameters of NiTi and CuNiTi Dental Wire and Screw Materials Using Experimental and Simulation Techniques

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Anahtar Kelimeler

Nötron, GEANT4, Diş Teli, NiTi Alaşımı, CuNiTi Alaşımı.

Graphical/Tabular Abstract (Grafik Özet)

Neutron interaction parameters of NiTi and CuNiTi dental alloys were investigated using GEANT4 simulations and experimental measurements. / NiTi ve CuNiTi diş alaşımlarının nötron etkileşim parametreleri GEANT4 simülasyonları ve deneysel ölçümler ile incelenmiştir.

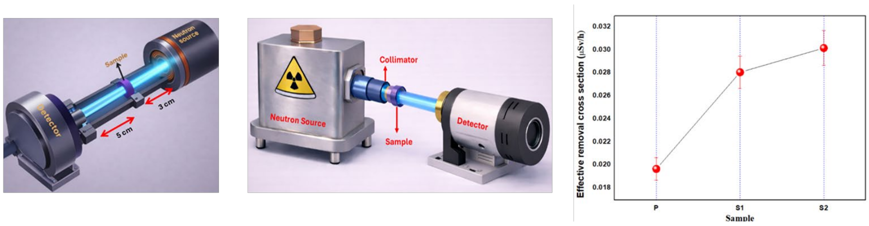

Figure A: *Geant4 simulation and experimental dose measurement geometry and neutron shielding parameters /* ***Şekil A:*** *Geant4 simülasyon ve deneysel doz ölçüm geometrisi ile nötron zırhlama parametresi*

Highlights (Önemli noktalar)

- *CuNiTi alloy exhibited the highest fast neutron attenuation performance. / CuNiTi alaşımı en yüksek hızlı nötron zayıflatma performansını göstermiştir.*
- *Paraffin showed superior epithermal neutron attenuation. / Parafin epitermal nötronlarda daha üstün performans göstermiştir.*
- *Higher density and Cu addition increased neutron interaction probability. / Yüksek yoğunluk ve Cu katkısı nötron etkileşim olasılığını artırmıştır.*
- *Experimental dose measurements validated the simulation results. / Deneysel doz ölçümleri simülasyon sonuçlarını doğrulamıştır.*
- *NiTi and CuNiTi alloys demonstrated suitability for radiotherapy applications. / NiTi ve CuNiTi alaşımları radyoterapi uygulamaları için uygunluk göstermiştir.*

Aim (Amaç): *The aim of this study is to evaluate the neutron interaction, attenuation behavior, and shielding performance of NiTi and CuNiTi dental alloys by combining experimental measurements with GEANT4 simulations. / Bu çalışmanın amacı, deneysel ölçümleri GEANT4 simülasyonlarıyla birleştirerek NiTi ve CuNiTi diş alaşımlarının nötron etkileşimini, zayıflama davranışını ve koruma performansını değerlendirmektir.*
Originality (Özgünlük): *This study offers a combined experimental and Monte Carlo simulation approach to evaluate the neutron shielding performance of commonly used orthodontic alloys. / Bu çalışma, ortodontide yaygın olarak kullanılan alaşımların nötron zayıflatma performansını değerlendirmek için deneysel ve Monte Carlo simülasyonunu birlikte kullanan güçlü bir yaklaşım sunmaktadır.*
Results (Bulgular): *The findings of this study show that NiTi and CuNiTi orthodontic alloys can be safely used during radiotherapy. / Bu çalışmanın bulguları, NiTi ve CuNiTi ortodontik alaşımlarının radyoterapi sırasında güvenle kullanılabileceğini göstermektedir.*
Conclusion (Sonuç): *It was determined that CuNiTi exhibited better fast neutron attenuation performance (S2 > S1) and that both alloys possess attenuation capability against fast and epithermal neutrons. These findings suggest that NiTi and CuNiTi orthodontic alloys may contribute to neutron attenuation in radiotherapy environments. / CuNiTi'nin hızlı nötron zayıflatmada daha iyi performans gösterdiği (S2 > S1) ve her iki alaşımın da hızlı ve epitermal nötronlara karşı zayıflatma kabiliyetine sahip olduğu belirlenmiştir. Bu bulgular, NiTi ve CuNiTi ortodontik alaşımlarının radyoterapi ortamlarında nötron zayıflatmaya katkı sağlayabileceğini göstermektedir.*

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Abstract

This study investigates the interactions that may occur when NiTi and CuNiTi dental orthodontic wire and screw materials, which are widely used in dentistry, are exposed to neutron radiation. A comprehensive analysis was carried out using both experimental and simulation approaches, and the results are presented. Monte Carlo simulations performed using the GEANT4 code were employed to calculate key neutron attenuation parameters, including the effective removal cross-section, half-value layer, mean free path, and radiation shielding efficiency for both epithermal and fast neutrons. In addition, dose measurement experiments were conducted for all materials using an Am–Be fast neutron source and a portable BF_3 neutron detector to determine their fast neutron absorption capacities. The obtained results were also compared with those of paraffin, a reference material commonly used for neutron shielding. Overall, the findings indicate that both NiTi and CuNiTi alloys exhibit notable absorption capacities for fast and epithermal neutrons.

NiTi ve CuNiTi Diş Teli ve Vida Malzemelerinin Nötron Etkileşim Parametrelerinin Deneysel ve Simülasyon Teknikleri Kullanılarak İncelenmesi

Makale Bilgisi

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Öz

Bu çalışma, diş hekimliğinde yaygın olarak kullanılan NiTi ve CuNiTi ortodontik tel ve vida malzemelerinin nötron radyasyonuna maruz kaldığında meydana gelebilecek etkileşimleri araştırmaktadır. Hem deneysel hem de simülasyon yaklaşımları kullanılarak kapsamlı bir analiz yapılmış ve sonuçlar sunulmuştur. GEANT4 kodu kullanılarak gerçekleştirilen Monte Carlo simülasyonları, hem epitermal hem de hızlı nötronlar için etkili uzaklaştırma kesiti, yarı değer tabakası, ortalama serbest yol ve radyasyon kalkanlama verimliliği dahil olmak üzere temel nötron zayıflama parametrelerini hesaplamak için kullanılmıştır. Ek olarak, tüm malzemeler için Am–Be hızlı nötron kaynağı ve taşınabilir bir BF_3 nötron dedektörü kullanılarak doz ölçüm deneyleri yapılmış ve hızlı nötron soğurma kapasiteleri belirlenmiştir. Elde edilen sonuçlar, nötron kalkanlama için yaygın olarak kullanılan bir referans malzeme olan parafinin sonuçlarıyla da karşılaştırılmıştır. Genel olarak, bulgular hem NiTi hem de CuNiTi alaşımlarının hızlı ve epitermal nötronlar için kayda değer soğurma kapasiteleri sergilediğini göstermektedir.

1. INTRODUCTION (GİRİŞ)

NiTi (Nickel–Titanium) and CuNiTi (Copper–Nickel–Titanium) alloys are widely used, particularly in orthodontic dental treatments, for the manufacture of wires and screws. Owing to their high strength and flexibility, these alloys are commonly employed as orthodontic wire materials and are required to remain in the oral environment for extended periods [1]. The addition of copper to NiTi alloys enhances both the mechanical properties and corrosion resistance of the alloy, thereby increasing its potential for use in orthodontic treatment applications [2]. In addition to orthodontic treatments, these alloys are also used in various dental applications such as dental implants, owing to their biocompatibility [3]. Furthermore, as NiTi and CuNiTi alloys do not induce allergic reactions, they exhibit high biocompatibility, and for this reason, they have

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applications in many medical fields, particularly in orthodontic treatments. For the safe use of these materials in patients undergoing radiotherapy, as well as in individuals working in radiation-related environments, it is essential to understand their interactions with radiation. In this context, resistance to neutron radiation is a particularly desirable property, especially for materials intended for use in cancer patients, such as those undergoing boron neutron capture therapy. Therefore, investigating the interactions of NiTi and CuNiTi alloys with neutron radiation is of critical importance for ensuring the safety of patients receiving radiotherapy. Moreover, as neutrons are employed in various research and medical applications, including radiotherapy for oral, laryngeal, cheek, and gingival cancers, a thorough understanding of the interaction mechanisms between neutron radiation and oral cavity–implanted alloys is required [4]. Therefore, to determine the neutron interaction characteristics of NiTi and CuNiTi alloys, it is essential to calculate key attenuation parameters, including the effective neutron removal cross-section, mean free path and half-value layer to evaluate the alloys based on these parameters [5]. The use of well-established Monte Carlo–based simulation techniques, such as GEANT4, for calculating these parameters provides reliable and robust data. The determination of these attenuation parameters is particularly important for NiTi and CuNiTi alloys, which are widely employed in orthodontic applications. Such simulations enable the assessment of the protective performance of these materials, including their behavior against secondary radiation generated during neutron interactions, thereby contributing to the evaluation of their safety in clinical use [6]. The neutron radiation attenuation parameters of Al–Ni–Cr–W alloys were calculated with the Monte Carlo–based GEANT4 simulation techniques and their neutron absorption capacities were systematically evaluated. It reported that these alloys have low density and good neutron attenuation ability, so these samples can be used in both dental and other radiotherapy applications as protective material [7]. Several studies have investigated the radiation absorption ability and physical properties of NiTi and CuNiTi alloys commonly used in dentistry. Preliminary studies have evaluated the suitability of NiTi alloys, commonly used in medical applications, and Ti-coated stainless steels for radiotherapy by assessing their radiation shielding efficiency and corrosion resistance. The results demonstrate that NiTi alloys provide effective shielding, especially for low-energy neutrons [8]. In orthodontics, the interactions of CuNiTi alloys used in dental treatments with gamma radiation have been investigated both experimentally and theoretically at low and high energies. The results of these studies indicate that CuNiTi alloys have the potential to protect patients during radiotherapy applications [9]. Similarly, the radiological properties of seven different alloys commonly used in medical applications have been examined against both gamma and neutron radiation, and alloys with high zirconium content were reported to exhibit enhanced resistance to corrosion as well as improved attenuation of neutron and gamma radiation. In another study, the neutron radiation attenuation parameters of Cr–Co–Ni alloys, which are widely used in dental therapy applications, particularly in implant manufacturing, were evaluated using the Monte Carlo–based GEANT4 simulation techniques. The findings demonstrated that the use of these alloys in radiological environments may contribute to patient protection. Furthermore, the gamma-ray interaction parameters of dental alloys such as Nitinol, Elgiloy, and beta-titanium have been theoretically determined at both low and high energies using simulation tools including FLUKA, GEANT4, and WinXCOM, highlighting their potential suitability for radiotherapy applications [10,11,12]. These studies have provided clinicians with preliminary information by assessing the safety of dental materials for use in radiotherapy applications. The findings serve as a guide for selecting appropriate treatment methods and application techniques. In addition, other studies have investigated the epithermal and fast neutron absorption capacities of NiTi and CuNiTi alloys commonly used in dentistry, demonstrating that these alloys have the potential to protect patients during neutron radiotherapy.

2.MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Monte Carlo Simulation Geant4 Code (Monte Carlo Simülasyonu Geant4 Kodu)

GEANT4 (GEometry and Tracking) is a simulation toolkit based on Monte Carlo methods. It enables the prediction of particle and radiation interactions with materials, as well as the probabilities of secondary processes. This simulation approach, which has been widely validated and extensively used in high-energy plasma physics, nuclear physics, radiotherapy, and other nuclear applications, offers numerous advantages. GEANT4 is commonly employed in radiation and detector selection, experimental design, and nuclear accelerator development to model radiation–matter interactions. By allowing simulations to be performed in advance, it provides practical guidance for material selection, thereby saving both time and resources. Furthermore, its three-dimensional modeling capabilities enable the accurate prediction of experimental configurations and processes, offering reliable guidance for experimental strategies and for understanding scattering, absorption, and other nuclear interaction phenomena [13]. The physics list QGSP_BIC_HP was used together with high-precision neutron cross-section data from the G4NDL 4.6 library. A monoenergetic neutron source of 4.5 MeV was defined to represent the effective energy of the Am–Be neutron spectrum. The number of simulated events was set to 105 particles to ensure statistical stability. Simulations conforming to the geometry shown in Figure 1 were performed to calculate the shielding plating parameters of the materials.

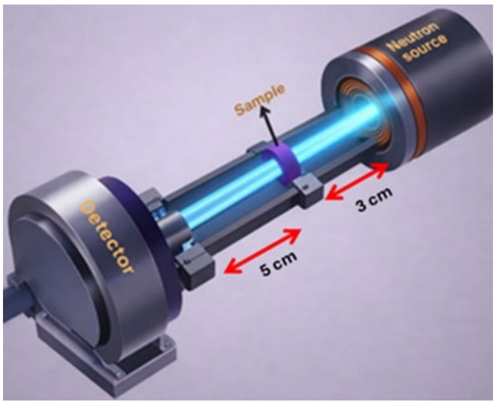

Figure 1. Geant4 simülation geometry (Geant4 simülasyon geometrisi)

2.2. Principles of Neutron Radiation Protection and Interaction Mechanism (Nötron Radyasyonundan Korunma Prensipleri ve Etkileşim Mekanizmaları)

Neutrons carry no electrical charge; therefore, they can penetrate matter and interact directly with atomic nuclei without undergoing Coulomb interactions with surrounding electrons. Neutrons incident on a nucleus can induce nuclear reactions such as fission and fusion. The likelihood of these interactions depends on the energy of the incoming neutron radiation and the atomic properties of the target absorption material. Neutrons exhibit particularly effective absorption and scattering, especially in materials with high hydrogen content. Consequently, determining the nature and probability of neutron–matter interactions in candidate shielding materials is critical for the success of neutron-related applications. This behavior primarily arises from the close similarity between the neutron mass and that of the hydrogen nucleus, enabling efficient energy transfer even in a single elastic scattering event. Oxygen, as another light element, also contributes to neutron moderation by promoting energy loss through scattering processes. Consequently, hydrogen- and oxygen-containing materials, including water, concrete, and paraffin-based polymer composites, are widely used for neutron moderation and shielding applications. In addition, neutrons can interact with high-atomic-number materials through absorption, elastic and inelastic scattering, energy transfer, and fission. The likelihood of these interactions can be quantified using the total macroscopic cross section, as expressed below.

$$\sigma_{T}=\sigma_{elastic\ scattering}+\sigma_{inelastic\ scattering}+\sigma_{proton}+\sigma_{alpha}+\sigma_{2neutron}+\sigma_{neutron+proton}+\sigma_{gamma}+\sigma_{fission} \quad (1)$$

where σ represents the microscopic cross-section, which the probability of interactions between a neutron radiation striking a target absorption material and the nuclei of the atoms that make up that material.

$$N_A=\frac{\rho}{A}N_0 \quad (2)$$

N_A is the number of atoms of the target sample nuclide per (atom/cm^3), N_0 is the Avogadro's number (6.02.10^{23}), ρi is the density of the i-th target material density, A is the atomic (or molar) mass of the target material (g/mol).

, μ is the mass attenuation coefficient, and σ_A is the atomic cross-section (cm^2/atom).

$$\mu=N_A\sigma_A \quad (3)$$

$$\mu=\frac{\rho i}{A}N_0\sigma_A \quad (4)$$

$$\sigma_A={}^{\mu}/_{\rho i}\left(\frac{A}{N_0}\right) \quad (5)$$

The potential interactions that neutrons can have with materials such as alloys, high-density composites, or heavy concrete are indicated by macroscopic cross-sections (∑) .

$$\sum\nolimits_{Total}=\sum\nolimits_{coherent\ scattering}+\sum\nolimits_{incoherent\ scattering}+\sum\nolimits_{absorption\ cross\ section}+\sum\nolimits_{captureabsorption\ cross\ section}+\sum\nolimits_{fission\ absorption\ cross\ section}+\cdots \quad (6)$$

The removal cross section (ΣR), similar to the macroscopic cross section, is used to describe the neutron attenuation properties of materials; however, it does not directly represent the probabilities of neutron–nucleus interactions. Instead, this parameter reflects the overall effectiveness of a material in removing fast neutrons from the incident beam through processes such as energy loss, scattering, and capture during collisions. The probability values associated with the removal cross section are generally lower than those of the macroscopic cross section [14]. Nevertheless, ΣR is a crucial parameter for the choice and design of neutron moderator materials, including composites, alloys, and mixtures, and can be calculated as follows…

$$\Sigma_R = \sum(\Sigma_{R/\rho})_i \quad (7)$$

$$\rho_i = w_i\rho \quad (8)$$

w_i is the weight percentage and ρ_i is the density of protective target material i.

The thickness of a material required to attenuate 50% of the incident neutrons is defined as the half-value layer (HVL). This attenuation parameter is commonly used in the evaluation, choice, and development of neutron attenuation shielding materials and can be found as follows:

$$HVL = ln2/\Sigma R \quad (9)$$

The average free path (mean free path) represents the average distance a neutron travels within a material between successive collisions with the atoms of the moderator material. This parameter can be found as follows:

$$\lambda = {}^{1}/_{\Sigma_R} \quad (10)$$

Neutron radiation are a form of particulate type radiation and can be quantified. When neutrons interact with a shielding material, they may undergo elastic or inelastic scattering or be captured by the nuclei of the material. Neutrons that are not captured or significantly scattered may traverse the material with reduced energy. The ratio (I/I_0) = transmitted / incident) of the number of incident neutrons (I_0) to the number of transmitted neutrons (I) provides information about the neutron attenuation and stopping capability of the material, and this parameter is widely used in shielding studies.

2.2 Dose Measurement Experimental Design and Sample Preparation (Doz Ölçümü Deney Tasarımı ve Numune Hazırlama)

Commercially available nickel–titanium (NiTi) and nickel–titanium–copper (NiTiCu) orthodontic wires, widely used in dentistry, were prepared as test specimens for neutron attenuation measurements. The wires were cut into predetermined lengths and cold-pressed into pellet form with a diameter of 0.5 cm and a thickness of 1 mm. The elemental compositions and mass densities of the prepared specimens are presented in Table 1.

Table1. Samples properties (Örneklerin özellikleri)

S:Sample

Sample	Density (g/cm^3)	Ni	Ti	Cu
S1	6.89	54.52	45.48	0
S2	7.03	50.7	42.4	6.9

Experimental dose measurements were obtained using a 4.5 MeV Am–Be fast neutron source, the specifications of which are given Table 2, together with a portable BF_3 gas neutron detector manufactured by Canberra. The source–sample distance was 10 cm and the sample–detector distance was 5 cm. To minimize environmental scattering, shielding blocks made of lead and paraffin were placed around the setup. The initial dose (D_0) was determined from a 20-minute blank measurement. Following the experimental geometry shown in Figure 2, all samples were positioned between the neutron source and the detector, and the transmitted dose through each sample (D_D) was measured. The dose absorbed by the samples (D_S) was then found using the relation $D_S = D_0 - D_D$.

Table 2. Nuclear structure characteristics of the ^{241}Am-Be neutron source (^{241}Am-Be nötron kaynağının nükleer yapı özellikleri)

Physical half-life: 432.2 years Specific activity: 127GBq/g			
Principle Emissions	Energy (MeV)	Effective energy (MeV)	Dose rate (Sv/h / GBqat1m)
Gamma	0.0139 (42.7%) 0.0595 (35.9%)	-	85
Alpha	5.4430 (12.8%) 5.4860 (85.2%)	-	-
Neutron	-	4.5	0.6

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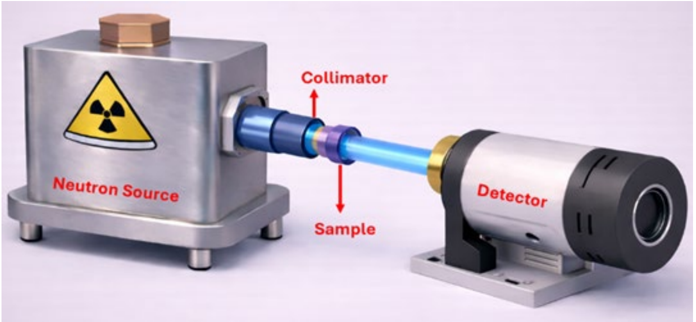

Figure 2. Experimental design (Deneysel tasarım)

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

The neutron interaction properties of NiTi and CuNiTi alloys, which are commonly used in dental therapy applications, were investigated using Monte Carlo simulations and experimental measurements. To evaluate epithermal and fast neutron interactions, key shielding parameters including effective removal cross-section, transmission number half-value layer, and mean free pathwere determined using the GEANT4 techniques based on the simulation geometry shown in Figure 1 for the alloys listed in Table 1. The calculated results are presented in Tables 3 and 4 and Figures 3–6. Additionally, dose measurements were performed to quantify the absorbed dose rates of the samples.

3.1. Neutron Interaction Properties (Nötron Etkileşim Özellikleri)

The ERCS values for 4.5 MeV fast neutrons were determined for all samples, as shown in Table 3 and Figure 3. As clearly observed from both the table and the figure, all samples exhibit non-zero effective removal cross-section values, indicating that they are capable of interacting with fast neutrons and attenuating the incident neutron flux. Among the investigated materials, the ERCS values increase in the order P < S1 < S2. Accordingly, sample S2 exhibits the highest fast neutron removal capability, followed by S1, while sample P (paraffin) shows the lowest shielding performance. The superior neutron attenuation performance of S2 can be attributed to its higher density and the presence of Cu in its alloy composition compared to S1 and P, which increases the probability of neutron with matter interactions

Table 3. Comparison of shielding parameters in 1 mm thick samples for 10^5 incident fast neutrons (4.5 MeV) (1 mm kalınlığındaki numunelerde 105 adet hızlı nötron (4,5 MeV) için koruma parametrelerinin karşılaştırılması)

Sample Code	Half value layer (mm)	Mean free path λ (mm)	Neutron transmission factor (I/I_0)	Fast Neutron ERCS (cm^{-1})
P	350.05±0.355	50.58±0.580	0.98042	0.0197
S1	246.61±0.2556	35.58±0.3610	0.97229	0.0281
S2	229.47±0.2210	33.11±0.3401	0.97021	0.0302

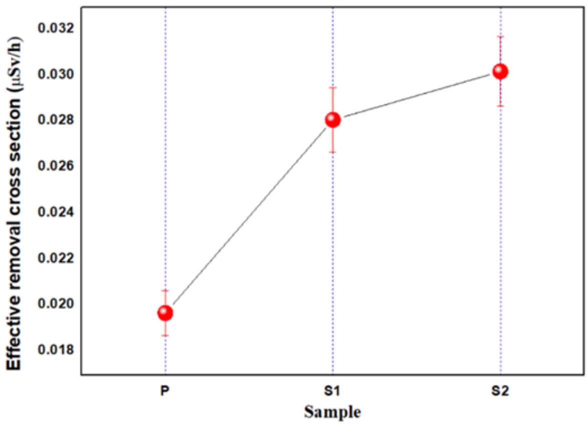

Figure 3. Comparison of the fast neutron effective removal cross-sections of the samples (Numunelerin hızlı nötron etkili uzaklaştırma kesitlerinin karşılaştırılması)

The HVL values given in Table 3 and Figure 4 are ranked as P > S1 > S2 (350.05 mm, 246.61 mm, and 229.47 mm, respectively).

According to these results, sample S2 exhibits the lowest HVL value, followed by S1, while sample P has the highest HVL. This ranking clearly indicates that S2 and S1 demonstrate superior fast neutron shielding performance compared to P, since a lower HVL value means that the material can reduce the incident neutron flux by half with a smaller thickness. Consequently, materials with lower HVL values possess higher neutron attenuation capability.

Similarly, the mean free path (MFP, λ) values presented in Table 3 decrease in the order of P > S1 > S2 (50.58 mm, 35.58 mm, and 33.11 mm, respectively). A lower MFP value implies that neutrons interact with the material atoms over a shorter distance, leading to earlier energy loss and more effective attenuation. Accordingly, neutrons interacting with S2 and S1 experience more frequent collisions compared to P, which enhances their neutron shielding effectiveness. Among all samples, S2 exhibits the best shielding performance based on its minimum MFP value.

Furthermore, the neutron transmission factor (I/I_0) values listed in Table 3 follow the same trend, decreasing in the order of P > S1 > S2 (approximately 0.98042, 0.97229, and 0.97021, respectively). The lower transmission factor of S2 indicates a reduced neutron penetration rate, confirming that this sample provides the highest neutron shielding capacity among the investigated materials. In general, a material characterized by low HVL and MFP values along with a low neutron transmission factor is considered highly effective for fast neutron attenuation. Based on all evaluated theoretical shielding parameters, sample S2 demonstrates the highest neutron shielding capability, followed by S1, whereas sample P exhibits the weakest shielding performance. These differences in neutron shielding behavior can be attributed to variations in the Ni, Ti, and Cu ratios within the material composition, which influence neutron–matter interaction probabilities. Determining the epithermal neutron shielding properties of stainless steel wire materials commonly used in dentistry is important for both patient safety and the evaluation of radiation–biomaterial interactions. These materials, which remain in the oral cavity for extended periods during orthodontic treatments, may be exposed to neutron radiation originating from radiotherapy procedures, laboratory research, or environmental sources. Neutrons in the epithermal energy range interact strongly with material composition and microstructure through scattering and absorption processes. Therefore, calculating epithermal neutron absorption cross-sections and key shielding parameters—such as the half-value layer (HVL), mean free path (MFP), effective removal cross-section, and neutron transmission factor provides valuable insights into the long-term biocompatibility and radiation safety of dental steel wires. The obtained results were also compared with those of paraffin, a reference material widely used in neutron shielding applications.

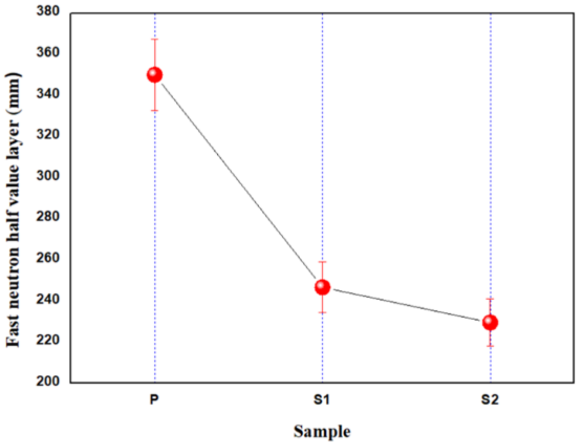

Figure 4. Comparison of the fast neutron half value layer of the samples (Numunelerin hızlı nötron yarı değer katmanlarının karşılaştırılması)

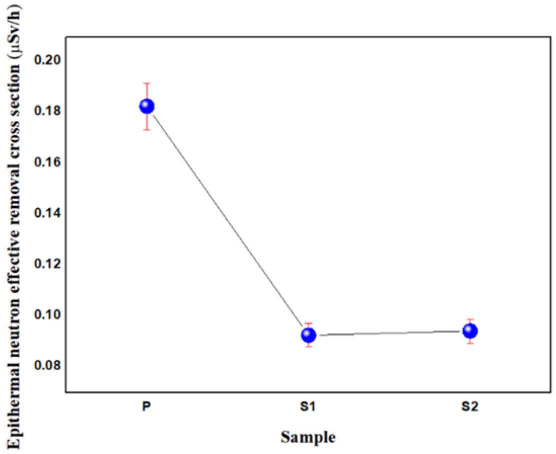

Figure 5. Comparison of the epithermal neutron effective removal cross-sections of the samples (Numunelerin epitermal nötron etkin uzaklaştırma kesitlerinin karşılaştırılması)

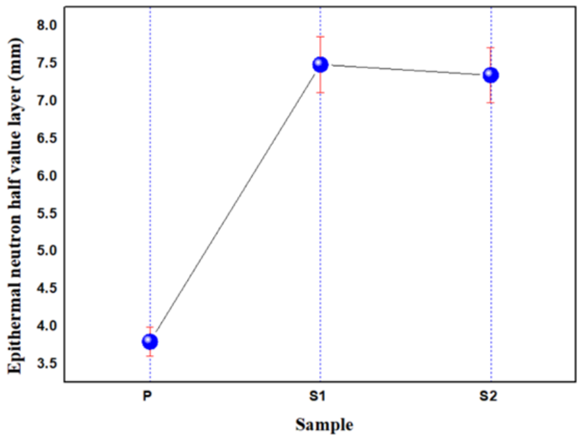

Figure 6. Comparison of the epithermal neutron Half value layer of the samples (Örneklerin epitermal nötron yarı değer tabakasının karşılaştırılması)

Based on the epithermal neutron effective removal cross-section (ERCS) values presented in Table 4 and Figure 5, paraffin (P) exhibits the highest ERCS value (0.1827 cm⁻¹), followed by S2 (0.0943 cm⁻¹) and S1 (0.0926 cm⁻¹). Materials with higher ERCS values possess greater epithermal neutron attenuation capability; therefore, the epithermal neutron attenuation capacity of the materials can be ranked as P > S2 > S1 according to their ERCS magnitudes. This behavior is attributed to the high hydrogen content in paraffin, since hydrogen is highly effective in moderating epithermal neutrons.

Table 4. Comparison of shielding parameters for 1mm thick samples, for 10^5 incident epithermal neutron (0.25 eV) (1 mm kalınlığındaki numuneler için, 105 adet epitermal nötron (0,25 eV) ışınımına karşı koruma parametrelerinin karşılaştırılması

Sample code	Epithermal Neutron Half value layer (cm)	Epithermal Neutron Mean free path λ (mm)	Epithermal Neutron transmission factor (I/I_0)	Epithermal Neutron ERCS (cm^1)
P	3.79±0.37	5.47±0.54	0,83296	0.1827
S1	7.48 ± 0.75	10.79 ± 0.80	0.91147	0.0926
S2	7.34 ± 0.74	10.60 ± 0.10	0.90995	0.0943

P: Paraffin, S: Sample

When the half-value layer (HVL) values given in Table 4 and Figure 6 are examined, it is observed that paraffin, S2, and S1 have HVL values of 3.79 cm, 7.34 cm, and 7.48 cm, respectively. The HVL represents the thickness of a material required to reduce the neutron intensity by half; therefore, materials with lower HVL values exhibit greater epithermal neutron attenuation capability. Accordingly, the epithermal neutron attenuation capacities of the materials can be ranked as P > S2 > S1. Similarly, an examination of the mean free path (MFP) values presented in Table 4 shows that paraffin, S1, and S2 have MFP values of 5.47 mm, 10.79 mm, and 10.60 mm, respectively. A lower MFP value indicates a higher neutron attenuation capability of the material. Based on the MFP values, the ranking can be expressed as S1 > S2 > P, indicating that epithermal neutrons travel the shortest distance within paraffin. This implies that neutrons lose their energy more rapidly through interactions within paraffin and are therefore more effectively attenuated. Consequently, the epithermal neutron attenuation performance of the materials can again be ranked as P > S2 > S1. Furthermore, considering the neutron transmission factors (I/I_0) provided in Table 4, paraffin, S1, and S2 exhibit values of 0.83296, 0.91147, and 0.90995, respectively. A lower transmission factor indicates stronger epithermal neutron attenuation, as this parameter represents the ratio of transmitted neutrons to incident neutrons. Accordingly, a lower value reflects a higher fraction of neutrons absorbed or scattered within the material. Based on these values, the neutron attenuation performance of the materials can be ranked as P > S2 > S1. The higher neutron absorption capability of S2 compared to S1 can be attributed to the presence of copper (Cu) in its composition, as well as its higher density relative to S1.

3.2. Neutron Dose Measurement Results (Nötron Doz Ölçüm Sonuçları)

Table 5. Absorbed dose results of all samples (Tüm numunelerin absorbe edilen doz sonuçları)

Sample	Absorbed Dose by Samples (µSv/h)	Radiation protection efficiency (%)
Background	1.3905	-
P	0.4516	32.47
S1	0.5206	37.43
S2	0.5318	38.24

P: Paraffin, S: Sample

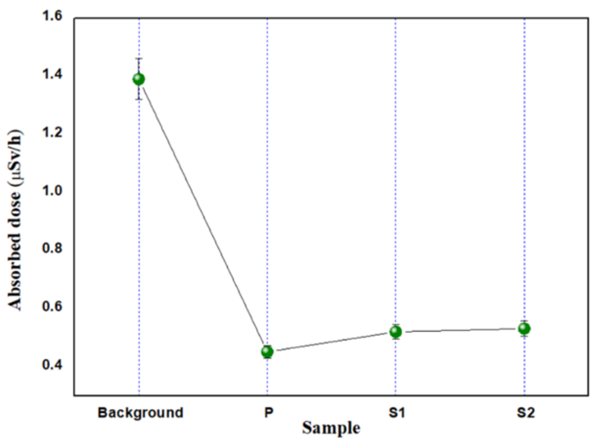

Figure 7. Comparison of the absorbed dose rates of the samples (Numunelerin absorbe edilen doz hızlarının karşılaştırılması)

As shown in Table 5 and Figure 7, the measured absorption values clearly demonstrate the high fast neutron absorption capacities of the investigated materials. While the dose rate emitted by the source was approximately 1.39 µSv h^{-1}, all examined samples significantly reduced the transmitted dose. Among the samples, paraffin (P) absorbed 32.47% (0.4516 µSv h^{-1}) of the emitted dose, whereas S1 and S2 absorbed 37.43% (0.5206 µSv h^{-1}) and 38.24% (0.5318 µSv h^{-1}), respectively, indicating markedly higher absorption compared to paraffin. As observed for other parameters, the hydrogen content plays a significant role in the neutron absorption behavior of paraffin. The superior absorption performance of S2 can be attributed to its higher density (7.03 g cm^{-3}) and the presence of copper (Cu) in its composition, as presented in Table 1. An increase in shielding material density and the incorporation of heavier elements enhance the probability of neutron–matter interactions. Based on these findings, the fast neutron absorption capacity of the materials can be ranked, from highest to lowest, as S2 > S1 > P.

4. CONCLUSIONS (SONUÇLAR)

This paper comprehensively investigates the neutron interaction behavior of S1 (NiTi) and S2 (CuNiTi) alloys, which are commonly used in orthodontic atherapy pplications, under exposure to both fast and epithermal neutrons. The principal neutron attenuation parameters the effective removal cross-section, half-value layer (HVL), neutron transmission factor, and mean free path (MFP) were theoretically calculated using the Geant4 Monte Carlo simulation techniques and compared with paraffin, a widely used neutron moderator. In addition, experimental radiation measurements were performed to evaluate the fast neutron absorption capacities of the materials. Based on the combined theoretical and experimental results, both alloys exhibited notable attenuation capabilities against fast and epithermal neutrons. The fast neutron attenuation performance of the materials followed the order S2 > S1 > P, with the superior attenuation capacity of S2 primarily attributed to the presence of copper (Cu) in its composition and its higher density relative to the other materials. In contrast, the epithermal neutron attenuation performance was ranked as P > S2 > S1, with the high attenuation efficiency of paraffin mainly arising from its high hydrogen content. Orthodontic wires fabricated from these alloys remain in the oral cavity for extended periods, ranging from days to months or even years. Therefore, for patients who may undergo radiotherapy during orthodontic treatment, prior knowledge of the radiation interaction characteristics of these alloys is critically important for ensuring patient safety and treatment efficacy. The findings of this study indicate that orthodontic wires made from NiTi and CuNiTi alloys can be safely used concurrently with radiotherapy, and that these materials may contribute to the protection of oral and dental tissues by attenuating the fast and epithermal neutrons with which they interact.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS’ CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Nurhan BAYINDIR DURNA*:** She provided samples, prepared for experiments, and wrote the article for some sections

Örnekler sağladı, deneyler için hazırlık yaptı ve makalenin bazı bölümlerini yazdı.

Esra CİNAN: She both wrote and participated in the experiments made.

Hem yazdı hem de yapılan deneylere katıldı.

Bünyamin AYGÜN: He both wrote some sections in the article and did the simulation and the experimental parts.

Makalenin bazı bölümlerini kendisi yazdı, ayrıca simülasyon ve deneysel kısımları da kendisi yaptı.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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