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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Investigation of the Dose Distribution of ^{32}P Skin Patch Source by GAMOS Monte Carlo Simulation

^{32}P Cilt Yama Kaynağının Doz Dağılımının GAMOS Monte Carlo Simülasyonu ile İncelenmesi

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Abstract

In recent years, both experimental and theoretical studies on superficial brachytherapy for the treatment of skin cancers have been increasing. The results of experimental and theoretical studies show that the method is promising. The method involves the use of beta-emitting radionuclides. It is crucial to thoroughly understand and investigate the dose characteristics of the radionuclides used for the success of the treatment. In this study, the percent depth dose and transverse dose profiles of the commonly used cancer treatment, the ^{32}P-labeled skin patch source, were examined using the GAMOS Monte Carlo Simulation method. The simulation results obtained are consistent with studies in the literature. The examined 12.5 mm radius skin patch source is suitable for the treatment of skin tumors with sizes ranging from 9.0 to 11.0 mm. By appropriately matching the size of the skin patch source to the size of the skin tumor, both the normal tissue surrounding the tumor and the normal tissue, cartilage, and bone beneath the tumor can be preserved. The ^{32}P skin patch source will be a suitable option for early-stage tumors with a thickness of 1.0-2.0 mm that have not yet reached the deeper layers of the skin tissue. For deeper tumors, radionuclides emitting high-energy beta particles should be utilized.

Keywords: *Phosphorus-32, GAMOS, Superficial Brachytherapy, Skin Patches, Radionuclide*

Öz

Son yıllarda cilt kanserlerinin tedavisinde yüzeysel brakiterapiye yönelik hem deneysel hem de teorik çalışmalar artmaktadır. Deneysel ve teorik çalışmaların sonuçları, yöntemin umut verici olduğunu göstermektedir. Yöntem, beta yayan radyonüklitlerin kullanımını içerir. Tedavinin başarısı için kullanılan radyonüklitlerin doz özelliklerinin iyice anlaşılması ve araştırılması büyük önem taşımaktadır. Bu çalışmada yaygın olarak kanser tedavisinde kullanılan ^{32}P etiketli yama kaynağının yüzde derinlik dozu ve enine doz profilleri GAMOS Monte Carlo Simülasyon yöntemi kullanılarak incelenmiştir. Elde edilen simülasyon sonuçları literatürdeki çalışmalarla tutarlıdır. İncelenen 12,5 mm yarıçaplı cilt yaması kaynağı, boyutları 9,0 ile 11,0 mm arasında değişen cilt tümörlerinin tedavisi için uygundur. Cilt yama kaynağının boyutunun cilt tümörünün boyutuna uygun şekilde eşleştirilmesiyle, hem tümörü çevreleyen normal doku hem de tümörün altındaki normal doku, kıkırdak ve kemik korunabilir. ^{32}P cilt yama kaynağı, henüz cilt dokusunun daha derin katmanlarına ulaşmamış, 1,0-2,0 mm kalınlığındaki erken evre tümörler için uygun bir seçenek olacaktır. Daha derin tümörler için yüksek enerjili beta parçacıkları yayan radyonüklitlerden yararlanılmalıdır.

Anahtar Kelimeler: *Fosfor-32 ,GAMOS , Yüzeysel Brakiterapi, Deri Yamaları, Radyonüklid*

1. Introduction

Skin cancers have been among the most common types of cancer in the last 30 years [1]. There are two main types of skin cancer: melanoma and non-melanoma skin cancer (NMSC). Non-melanoma tumors, including basal cell carcinoma (BCC) and squamous cell carcinoma (SCC), pose the greatest threat to human health despite having a lower probability of occurrence [2, 3]. Various treatment methods, such as surgery, regional treatments, chemotherapy, and radiotherapy, are used in skin cancer treatments based on the type, stage, and location of the skin tumor. Due to the potential for cosmetic complications with surgical methods, radiotherapy stands out as a crucial alternative treatment method. Each method has its own unique advantages and disadvantages. In recent years, alternative superficial brachytherapy methods have been suggested for the treatment of skin cancers, offering the possibility to treat tumors without exposing them to the disadvantages of traditional treatment methods [4]. The superficial brachytherapy method has advantages such as ease of use, simplicity of the treatment procedure, reduction of the dose received through regional dose irradiation, and non-invasiveness. Another benefit is the preservation of healthy tissue and bone underneath the tumor volume by tailoring the size and shape of the patch source used to the size and shape of the skin tumor [5, 6]. In this method, beta (β-) emitting radionuclides with a short penetration depth, such as ^{90}Y, ^{188}Re, ^{166}Ho, and ^{32}P, are preferred.

In the literature, there is an increasing number of both experimental and theoretical studies on patch sources labeled with beta-emitting radionuclides. Pashazadeh et al. presented a patch design loaded with ^{90}Sr radioisotope, which they produced using a 3D printer and medical-grade

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polycaprolactone, tailored to the location and size of the skin tumor [7]. Mukherjee et al, using ^{188}Re-labeled bandages, controlled tumor growth in mice carrying melanoma and found that the tumor size completely regressed at specific radiation doses [8]. Lee et al. treated Bowen's disease and skin cancers using patches impregnated with ^{166}Ho [9]. Salgueiro et al. reported that the design of patches made of silicon or natural rubber labeled with ^{32}P is safe for superficial brachytherapy and achieved complete regression of tumors [10]. Mukherjee et al. tested their ^{90}Y-coated patches to control superficial tumors in mice [11]. Additionally, Saxena and colleagues presented new approaches for preparing ^{90}Y-EGMP patches in superficial brachytherapy [12], and Pashazadeh and colleagues reported the preparation of patches using ^{90}Y microspheres for the treatment of small superficial skin tumors, along with the results of dose calculations [13, 14].

In medical applications, having a good understanding of the dosimetric characteristics of skin patch sources labeled with radionuclides such as ^{90}Y, ^{188}Re, ^{166}Ho, and ^{32}P, which will be used in superficial brachytherapy, is crucial for the success of the treatment. To achieve this goal, in addition to experimental and analytical calculation methods in dose calculations, the Monte Carlo (MC) simulation method based on probability theory is widely used. Obtaining a precise dose distribution with experimental methods is challenging due to the high dose gradient near beta-emitting sources. With MC simulations, these calculations can be performed with high precision. Currently, particle transport codes based on MC such as MCNP [15], EGSnrc [16], PENELOPE [17], FLUKA [18], and GEANT4 [19, 20] are used. In addition to these codes, specifically for users with limited C++ knowledge for special purposes, "Geant4 Application for Tomographic Emission" (GATE) [21] and "GEANT4 based Architecture for Medicine-Oriented Simulations" (GAMOS) [22], which allows users to work with minimal Geant4 knowledge, have been developed.

In this study, the percentage depth dose and transverse dose profiles of a skin patch source labeled with ^{32}P have been investigated using the GAMOS Monte Carlo code.

2. Materials and Methods

In this study, a skin patch source labeled with Phosphorus-32 (^{32}P) radionuclide has been examined. The main physical properties of the ^{32}P radionuclide are presented in Table 1. The spectrum information for the ^{32}P radionuclide is based on RADAR-The Decay Data (2) Figure 1 [23].

Table 1. Physical properties of ^{32}P radionuclide.

Half Life (Day)	E_{max} (MeV)	E_{mean} (MeV)	Range within the tissue (mm)
0.31	0.44	0.97	0.31

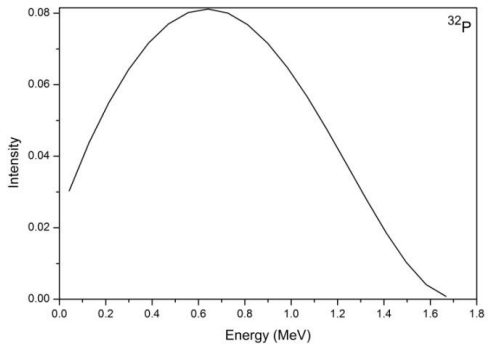

Figure 1. The spectrum of ^{32}P radionuclide.

To simulate the skin patch source labeled with ^{32}P, the GEANT4-based Architecture for Medicine-Oriented Simulations (GAMOS) Monte Carlo code was employed. GAMOS is a Monte Carlo code validated by various researchers and groups, covering applications from radiotherapy to nuclear medicine [22]. The simulation geometry in GAMOS MC was created in ASCII (text) format, as depicted in Figure 2. The patch source has a radius of 12.5 mm and a height of 0.5 mm, protected by an Aluminum shield with a radius of 20.0 mm. To protect the skin, a tissue-equivalent plastic with a thickness of 0.01 mm is present between the generated tissue phantom and the radioactive patch source. The surface where the skin patch source is applied is flat, and there is no air layer between the skin patch source and the skin surface.

The tissue phantom is designed in a rectangular shape with dimensions of 40×40×20 mm^3. To calculate the absorbed dose, the volume of the tissue phantom is filled with voxels of dimensions 0.5×0.5×0.20 mm^3, as shown in Figure 2. The elements and mass fractions of the tissue phantom and tissue-equivalent plastic are provided in Table 2. The densities of the tissue phantom and tissue-equivalent plastic are 1.0 g/cm^3 and 1.127 g/cm^3. When creating the skin patch source, the ^{32}P radionuclide is uniformly distributed throughout the entire volume of the patch source. Beta particles are isotropically emitted from the patch source at an angle of π radians. In MC calculations, the GAMOS electromagnetic physics (GmEMPhysics) package, including low-energy physics, has been employed.

The default production cut-off value in GAMOS is 100 μm for all processes on all materials. The energy threshold value in the tissue phantom is 1.06 keV for gammas and 84.66 keV for electrons. Variance reduction techniques were not used in the calculations. 10^9 particles were used to keep the statistical error below 1.0 %. The dosimetric data within the tissue phantom has been obtained at increments of 0.20 mm from the surface to a depth of 10 mm. Simulation results are in the form of a 3D dose file in the DOSXYZnrc format. The outcomes have been evaluated using a custom code written in MATLAB R2023b (MathWorks, Natick, Massachusetts, USA).

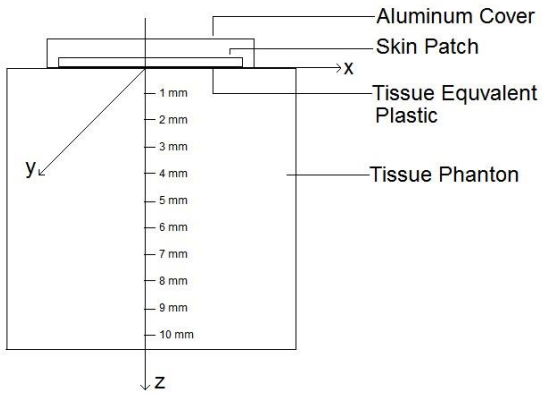

Figure 2. Simulation geometry.

3. Results and Dicussion

The percentage depth dose and normalized dose profiles for 1 mm of the ^{32}P skin patch source are given in Figure 3 [24]. As seen in Figure 3a, there is a sharp decrease in dose with increasing depth. The dose decreases to 90 %, 80 %, and 50 % at depths of R_{90}=0.31 mm, R_{80}=0.44 mm, and R_{50}=0.97 mm, respectively Table 3. This sharp decrease in dose is a desired

feature in superficial brachytherapy to preserve normal tissue, bone, and cartilage beneath the target tumor volume.

Table 2. The elements of tissue phantom and tissue equivalent plastic and their mass fractions.

Elements	Tissue Phantom	Tissue Equivalent Plastic
C	0.23219	0.77550
Ca	0.00023	0.01838
H	0.10447	0.10133
N	0.02488	0.03506
O	0.63024	0.05232
F	-	0.01742
Cl	0.00134	
Fe	0.00005	
K	0.00199	
Mg	0.00013	
Na	0.00113	
P	0.00133	

Table 3. Dosimetric parameters of the percent deep dose curve of the ^{32}P patch source.

R_{90} (mm)	R_{80} (mm)	R_{50} (mm)
0.31	0.44	0.97

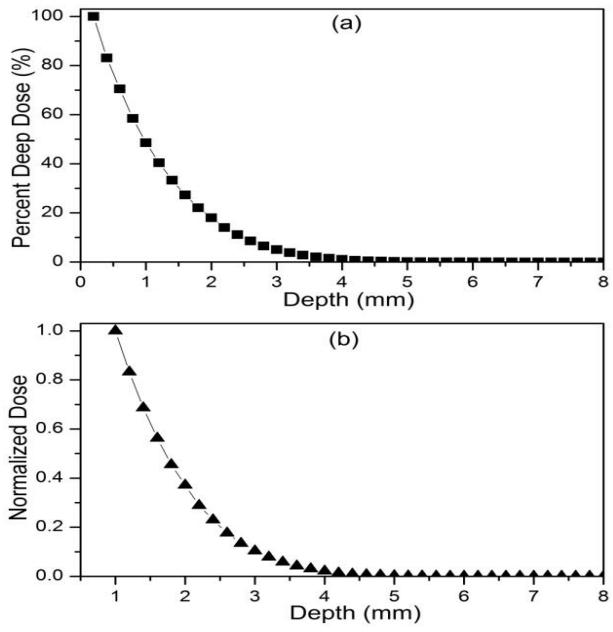

Figure 3. a) Percent deep dose curve of ^{32}P skin patch source, b) Normalized dose curve according to 1.0 mm.

This study's obtained data has been compared with the study conducted by Eduardo et al. Eduardo and colleagues utilized an analytical method and the EGSnrc Monte Carlo code to calculate the dose distributions of ^{32}P and ^{90}Y multichannel skin applicators [25]. The results of Monte Carlo calculations for both studies are presented in Figure 4 and Table 4.

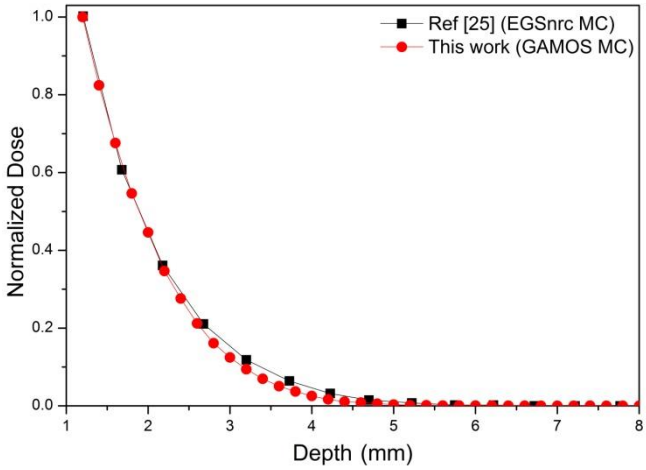

Figure 4. The comparison of the PDD dose distribution. (Curves are normalized to 1.25 mm).

Table 4. Dosimetric parameters of this study and Ref [25].

Depth (mm)	This Study	Ref. [25]
R_{90}	1.32	1.32
R_{80}	1.43	1.44
R_{50}	1.89	1.89

As seen in Figure 4, the results of the two studies are consistent. Beyond 2.2 mm, the maximum difference between the two curves is 2 %. The difference is within reasonable limits. The reasons for this difference lie in the modeling of the tissue phantom in this study and the smaller voxel size of the tissue phantom. Transverse dose profiles of the ^{32}P skin patch source for depths of z=0.2-5.0 mm within the tissue phantom are given in Figure 5.

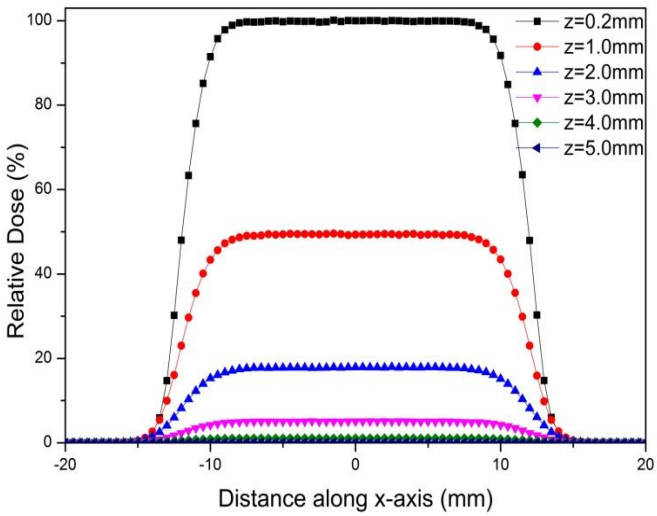

Figure 5. Transverse dose profile of the ^{32}P skin patch source.

The transverse dose profile obtained for a depth of 0.2 mm has symmetry and flatness, which can increase the uniformity of the dose within the target tumor area. The dose value decreases to 40 % at 1.0 mm depth, 17.6 % at 2.0 mm depth and 5.05 % at 3.0 mm depth and after 3.0 mm the dose decrease below 5.0 %. The transverse dose profile of the ^{32}P skin patch source with a

radius of 12.5 mm showed that the patch source is suitable for the treatment of skin tumors with a size of 9.0-10.0 mm. Dosimetric parameters of the transverse dose profile are given in Table 5.

Table 5. Dosimetric parameters of the transverse dose profile.

Depth (mm)	Central axis dose value (%)	R_{90} (mm)	R_{80} (mm)	R_{50} (mm)
0.2	100	10.1	10.8	12.0
1.0	49.0	9.79	10.6	11.8
2.0	17.6	9.84	10.5	11.9
3.0	5.05	9.28	10.3	11.7

4. Conclusions

The importance of using skin patch sources labeled with beta-emitting radionuclides in the treatment of superficial skin tumors is clearly evident, especially if there is a bone or cartilage just below the target tumor volume (nose, ear,..). As a result;

- The transverse dose profile of the 12.5 mm radius ^{32}P skin patch source under investigation showed that the patch source is suitable for the treatment of skin tumors with a size of 9.0-11.0 mm. By matching the size and shape of the patch source to the size and shape of the skin tumor, normal tissue surrounding the tumor and normal tissue, bone and cartilage under the tumor volume can be preserved.
- In the treatment of skin tumors with an early stage and a thickness of 1.0-2.0 mm that have not yet spread to the deep layers of the skin tissue, the use of ^{32}P skin patch sources will be a good option for the superficial brachytherapy method.
- In the treatment of deeper-seated skin tumors, it would be appropriate to use skin patch sources labeled with ^{90}Y (2.28 MeV), ^{188}Re (2.12 MeV) radionuclides, which have higher beta energy.

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