A CONCEPTUAL DESIGN OF A NOVEL HEXAGONAL BETA APPLICATOR INTENDED TO BE USED IN THE TREATMENT OF NON-MELANOMA SKIN CANCERS

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Abstract. Radiation from beta particles can be used to treat various types of tumors. To handle with beta emitter radioisotopes, applicators/plaques play an important role, first allowing to give the radiation dose to the target area; second, to prevent the staff to receive an unwanted amount of radiation. In this work a conceptual novel hexagonal beta applicator is proposed, and a first estimation of dose rates around it using the beta-point source formalism is presented for the Yttrium-90 radionuclide. Initial results show that over 90% of the beta radiation energy from the hexagonal applicator is absorbed in the first layers of the skin tissue. These findings suggest that the applicator may be used in the treatment of non-melanoma skin lesions.

Keywords: Beta radiation, Yttrium-90, Conformal applicators, Hexagonal applicator, Brachytherapy

Introduction

Of the several types of cancers skin cancer is the most common type all over the world. Only in the USA over 3 million new cases of skin cancer are diagnosed each year [1]. Skin cancers can basically be grouped into melanomas and non-melanomas. Non-melanoma skin cancers usually develop in the most external layers of the skin and include a variety of types of cutaneous tumors, and the most common are basal cell carcinoma and cutaneous squamous cell carcinoma. Depending on its location, type and size the non-melanoma skin cancer may be treated by means of various techniques, and therapeutic modalities may include chemotherapy, radiation therapy, cryotherapy and photodynamic therapy. However, the most common kind of treatment is by means of surgery, where the cancerous tumor and a part of the surrounding tissue are removed.

In cases where surgery is not possible or is contraindicated or the tumor is located at a difficult site to treat by surgery, radiotherapy, alone or combined with other techniques, may be used to treat the lesion. External beam radiation therapy using high energy photons or particles may be used to treat non-melanoma skin cancers. Another possibility is by means of the brachytherapy treatment technique where the radiation source is placed near or in contact with the tumor. Whatever the technique used the success of therapy depends on delivering a conformal dose to the target volume while preserving the healthy surrounding tissues.

The energy of beta particles emitted from certain unstable nuclides may be used to treat several types of diseases [2-16]. Their short range in tissue make them convenient to be used in the brachytherapy treatment of small and superficial skin lesions, since that the healthy structures beyond the lesion can be spared [1, 9-16]. In addition, the relatively simple radiation protection procedures on handling the beta sources are another interesting feature of the use of beta particles in radiation therapy. Beta radiation doses are administered by means of plaques or applicators. They are made in different geometrical shapes aiming to optimize the treatment according to the location and type of tumor. As an example, there are concave ophthalmic applicators due to the spherical surface of the eye [4], and there are also planar applicators to be used in treatment of certain kind of skin lesions [9, 12-16].

Whenever skin lesions are small and of regular shape, superficial brachytherapy using planar (square, rectangular, or circular) plaques loaded with an appropriate radionuclide is the prescribed choice of treatment. However, lesions of irregular shape and/or located at sites such as nose, eyes and lips require more complex approaches and an accurate experimental determination of dose distribution around the beta sources may be a difficult and challenging task. In this case, the current trend is the use of conformal plaques, which allows to match the tumor shape [10, 11, 14-16], and theoretical calculations of radiation doses around them described by simple expressions play an important role [12, 15].

In this short study we propose a novel hexagonal shaped beta applicator designed and intended to be used in the treatment of non-melanoma skin cancers, as depicted in Figure 1. Its hexagonal shape can aid to deliver conformal radiation dose distributions for a non-melanoma skin tumor. In a certain extent it can be thought of as an intermediate case between a circular and square applicator. A first insight into the depth-dose distribution based on an analytical/numerical method is presented for a hexagonal applicator loaded with the Yttrium-90 radioisotope.

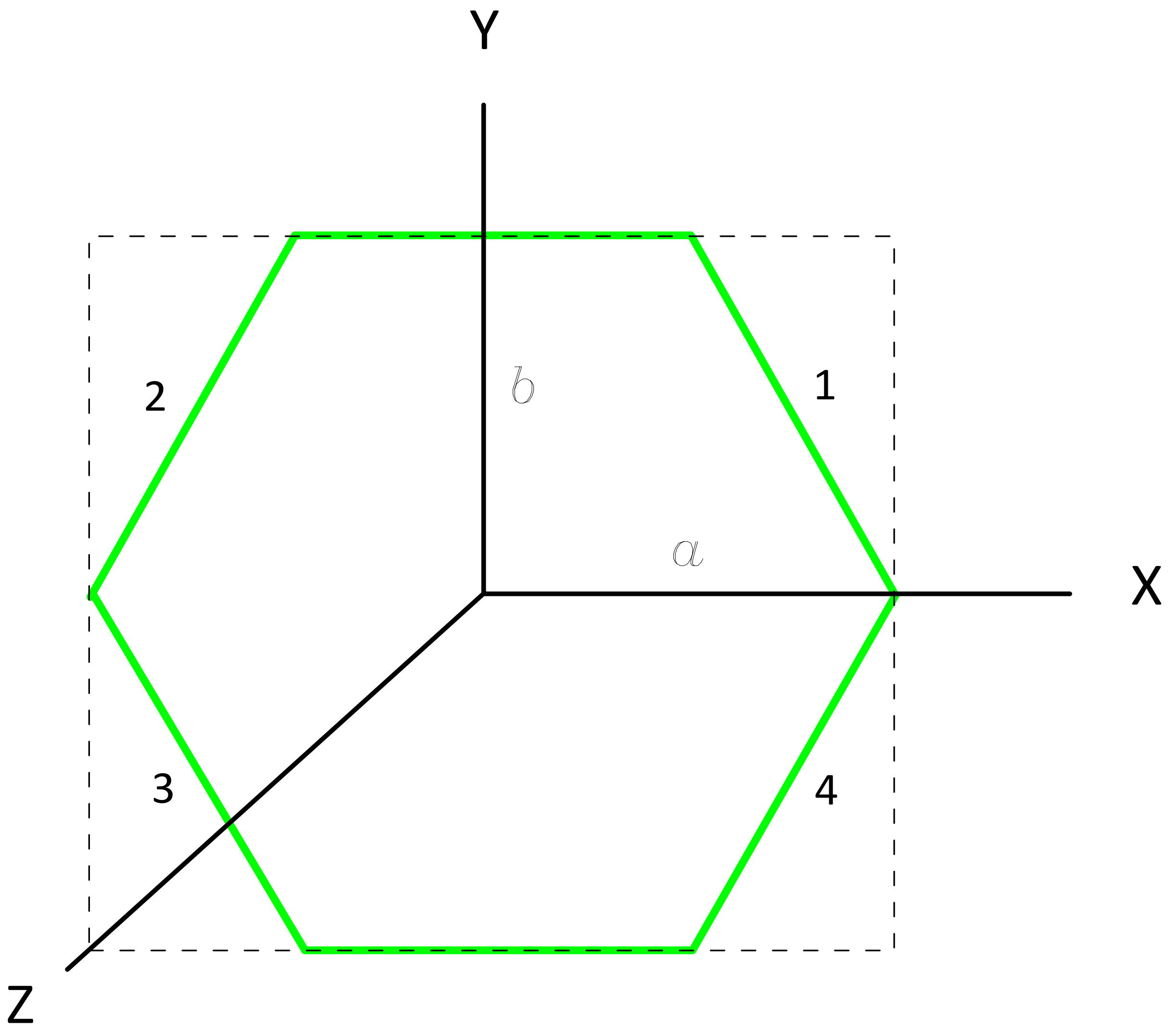

Figure 1. The conceptual design of a hexagonal shaped beta plaque. The hexagon has sides a of 1 cm. The dashed lines represent a rectangle of sides $2a$ and $2b$ ($b = \frac{a}{2}\sqrt{3}$). Regions defined by numbers 1 to 4 are explained in the text.

Methods

In a first approach the beta radiation doses around the hexagonal applicator can be estimated by numerical integration of the beta-point source dose function [12, 15]. In this method the dose around an extended source is calculated from a point-source of beta radiation integrated over the total area or volume of the source [12, 15, 17]. In this approach some simplifying assumptions are considered. The radioisotope is uniformly distributed on the surface of the plaque; the plaque is flat and of negligible thickness; the medium is water-equivalent (ρ = 1 g/cm^3).

The depth-dose rates (dose rates along z-axis in Figure 1) are described by

$$\dot{D} = a_S \iint J(\xi).dS, \qquad (1)$$

where a_S is the activity per unit area of the source, dS is the area element and $J(\xi)$ is the point-source dose at a point located at a distance ξ on the central *z*-axis [12, 15],

$$J(\xi) = \frac{B}{(\rho\upsilon\xi)^2}\left\{c\left[1 - \frac{\rho\upsilon\xi}{c}\exp\left(1 - \frac{\rho\upsilon\xi}{c}\right)\right] + \rho\upsilon\xi exp(1 - \rho\upsilon\xi) - \rho\upsilon\xi\left(1 - \frac{\rho\upsilon\xi}{2} - \frac{f}{2}\right)\right\}, \qquad (2)$$

where constants c and f are dimensionless parameters, ρ is the density of the medium and υ is the absorption coefficient, with

$$\left[1 - \frac{\rho\upsilon\xi}{c} exp\left(1 - \frac{\rho\upsilon\xi}{c}\right)\right] \equiv 0, \qquad \text{for} \qquad \rho\upsilon\xi \geq c,$$

$$J(\xi) \equiv 0, \qquad \text{for} \qquad \rho\upsilon\xi \geq f.$$

In Expression (2) of the beta-point source dose function the first term within the braces stands for the energy absorbed from the unscattered component of the beta particles and is negligible at distances beyond $c/\rho\upsilon$; the second term accounts for the energy absorbed from the scattered component of the beta particles, and the inverse square attenuation law is given by the term ξ^2; the dimensionless parameter *f* in the third term accounts for a set of theoretical and experimental data not used previously, where $f/\rho\upsilon$ is related to the range of the beta particles, i.e., is the distance from which the dose due to beta radiation is zero.

B is a parameter given by $B = 0.046\,\rho^2\upsilon^3\overline{E}_\beta\alpha$ ($\overline{E}_\beta$ is the mean kinetic energy of beta particle, and the constant α depends on the parameters *c* and f [12, 15, 17]). The distance ξ of a point source on the plaque to a point z_0 on the z-axis where the dose rate is evaluated is given by

$$\xi^2 = z_0^2 + x^2 + y^2. \tag{3}$$

A Fortran program was developed to numerically estimate the double integral of Equation (1). Calculations were performed over the rectangle of width $2a$ and length $2b$ shown in Figure 1. However, inside the program the points above the straight lines 1 and 2,

$$y_1 = -\frac{2b}{a}x + 2b, \tag{4}$$

$$y_2 = \frac{2b}{a}x + 2b, \tag{5}$$

and below the straight lines 3 and 4,

$$y_3 = -\frac{2b}{a}x - 2b, \tag{6}$$

$$y_4 = \frac{2b}{a}x - 2b, \tag{7}$$

are excluded in order to obtain a hexagon (see Figure 1).

Results and Discussion

As a first test we consider a hexagon of side a equal to 1 cm and with the Yttrium-90 radionuclide (half-life equal to 64.1 hours, and maximum kinetic energy of the beta particle equal to 2.28 MeV) uniformly distributed on the surface of the applicator. We also consider the plaque as having an activity of 1 MBq/cm^2. For 90-Y the parameters $\overline{E_\beta}$, υ, c and f are respectively 0.933 MeV, 5.05 cm^2/g, 0.95 and 4.48 [15].

In Figure 2 are displayed the relative dose rates along the depth in tissue (*z*-axis). Results are normalized at 1 mm depth and indicated that dose rate falls off to 50% of the reference value at the 2.1 mm depth; it falls off to just 10% at 4.5 mm depth and is negligible from 7.5 mm on. Results clearly show that a great amount (over 90%) of the beta radiation energy is absorbed in the first layers of the skin tissue. These findings reflect the beta radiation behavior that is its short range and high dose gradient, opening the possibility to use the hexagonal plaque in the treatment of small and superficial skin lesions [12-15].

In Figure 3 is shown the dose profile along the lateral *x*-axis at five depths ranging from 1 mm to 5 mm for the hexagonal Yttrium-90 applicator obtained by the beta-point source dose function approach. We can note that near the surface of the lesion doses diminish strongly as lateral distances increase. As expected, it can be seen that the dose distributions are symmetric in relation to central axis of the applicator, and once again we can notice an abrupt drop of doses after the first layers of tissue making the applicator useful to treat superficial skin tumors.

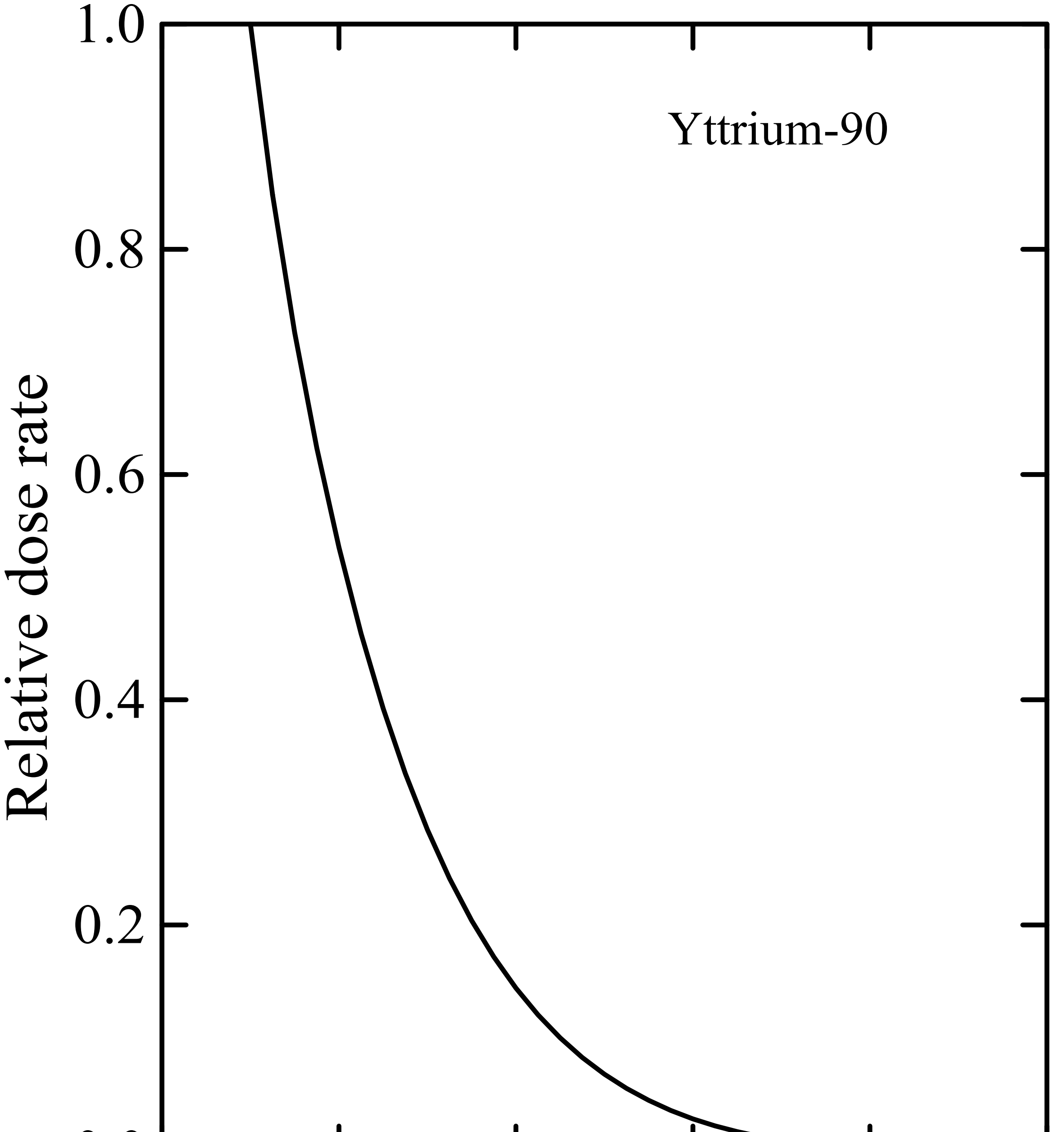

Figure 2. Depth-doses along central axis of the hexagonal Yttrium-90 applicator obtained by the beta-point dose function formalism. Results are normalized at 1 mm depth.

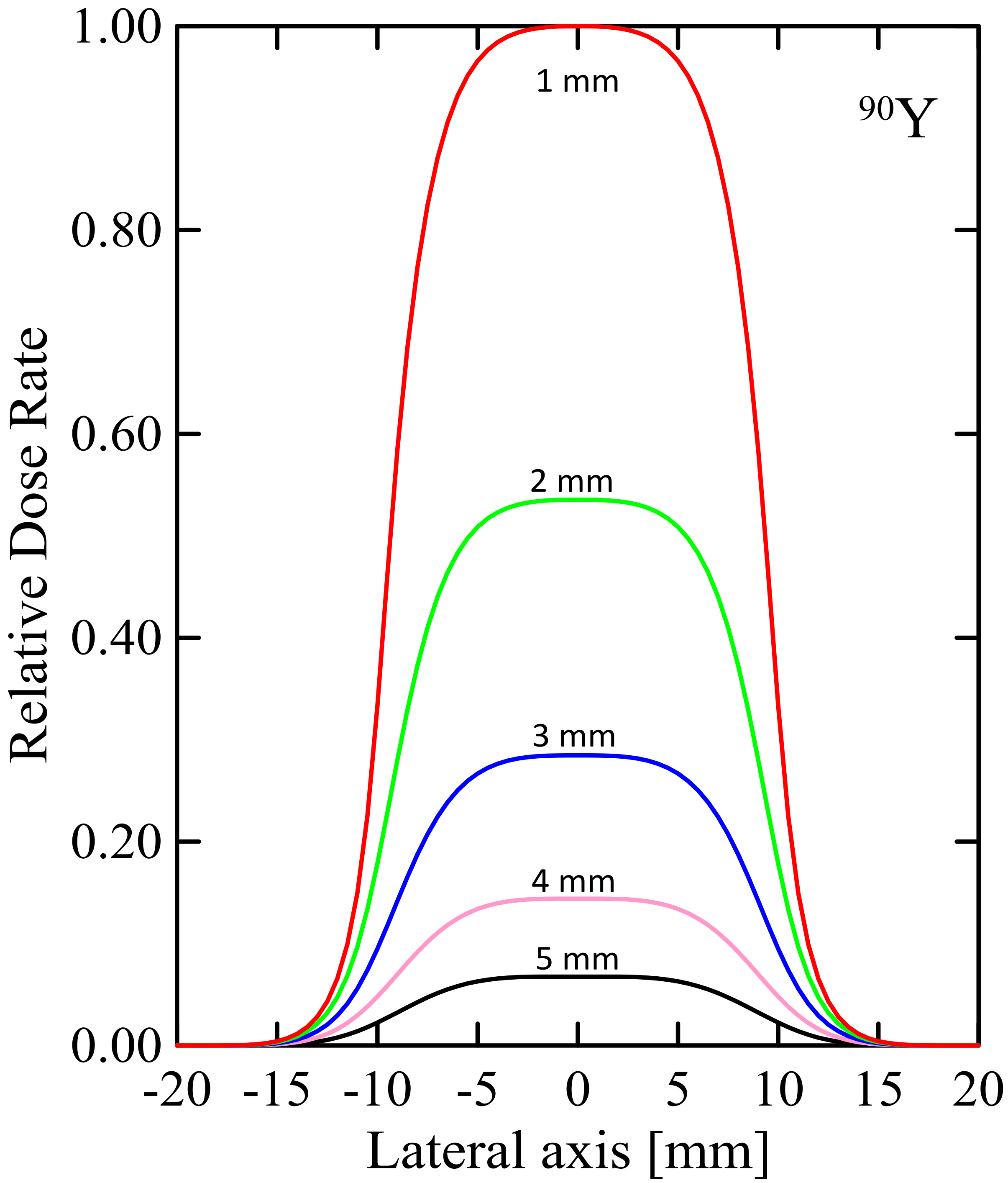

Figure 3. Relative lateral dose rates along *x*-axis for the hexagonal Yttrium-90 applicator at 1-, 2-, 3-, 4- and 5- mm depths.

Conclusion

Brachytherapy using radiation from beta particles plays an important role in the treatment of superficial skin tumors since that beta particles deliver most of their energies at the first layers of the skin sparing the healthy tissues underneath the tumor. In this sense there are various kinds of beta applicators intended to be used in brachytherapy treatments of skin lesions. In this work a novel beta applicator of hexagonal shape loaded with Yttrium-90 isotope is proposed. It has the advantage of having a relatively simple geometry, which allows to carry out analytical estimations of dose rates along central and lateral axes in a fast and simple way. Despite the limitations of the analytical method, it may be served as a reference and as a guide for future more detailed calculations.

Initial results of dose rates around the hexagonal Yttrium-90 plaque obtained by means of the beta-point source dose function formalism is presented. The depth-dose curves indicated that the hexagonal Yttrium applicator may have the potential to be used to treat non-melanoma skin tumors.

References

[1] Yosefof E, Kurman N, and Yaniv D. The role of radiation therapy in the treatment of non-melanoma skin cancer. Cancers 2023; 15: 2408.

[2] Radhoe SP, Schuurman AS, Ligthart JM, et al. Two decades after coronary radiation therapy: A single center longitudinal clinical study. Catheterization and Cardiovascular Interventions 2020; 96(3): E204-E212.

[3] McMahon JM. The long-term effect of experimental beta-radiation therapy on the human cornea. Contact Lens and Anterior Eye 2017; 30(4): 249-253.

[4] De Paiva E. Estimates of relative beta radiation doses on central and lateral axes of ruthenium/rhodium COB-type plaque used in eye brachytherapy. Applied Radiation and Isotopes 2020; 156(2): 108991.

[5] Arora S, Stea BD, Hamilton RJ, Chhablani J. Brachytherapy for Central Serous Chorioretinopathy. Ophthalmology and Therapy 2022; 5: 1611-1616.

[6] Diaz MJ, Kwak SH, Root KT, et al. Current Approaches to Craniopharyngioma Management. Frontiers in Bioscience 2022; 27(12): 328.

[7] Kunikowska J, Morgenstern A, Pełka K, et al. Targeted alpha therapy for glioblastoma. Frontiers in Medicine 2022; 9: 1085245.

[8] Klaassen NJM, Arntz MJ, Arranja AG, et al. The various therapeutic applications of the medical isotope holmium-166: a narrative review. EJNMMI Radiopharmacy and Chemistry 2019; 4: 19.

[9] Pashazadeh A, Castro N, Morganti E, et al. Conceptual design of a personalized radiation therapy patch for skin cancer. Current Directions in Biomedical Engineering 2018; 4(1): 607-610.

[10] Chmura J, Erdman A, Ehler E, et al. Novel design and development of a 3D printed conformal superficial brachytherapy device for the treatment of non-melanoma skin cancer and keloids. 3D Printing in Medicine 2019; 5: 1-6.

[11] Rogers B, Lawrence J, Chmra J, et al. Dosimetric characterization of a novel ^{90}Y source for use in the conformal superficial brachytherapy device. Physica Medica 2020; 72: 52-59.

[12] Pashazadeh A, De Paiva E, Mahmoodian N, Friebe M. Calculation of beta radiation dose of a circular Y-90 skin patch: Analytical and simulation methods. Radiation Physics and Chemistry 2020; 166: 108491.

[13] Pashazadeh A, Landes R, Boese A, et al. Superficial skin cancer therapy with Y-90 microspheres: A feasibility study on patch preparation. Skin Research and Technology 2020; 26(1): 25-29.

[14] Pashazadeh A, Robatjazi M, Castro NJ, Friebe M. A multiwell applicator for conformal brachytherapy of superficial skin tumors: A simulation study. Skin Research and Technology 2020; 26(4): 537-541.

[15] De Paiva E, Pashazadeh A, Robatjazi M. Calculations of beta radiation doses from multiwell Phosphorus-32 and Yttrium-90 applicators designed to be used in the treatment of superficial skin tumors: comparison of Monte Carlo and analytical methods. The European Physical Journal Plus 2022; 137: 916.

[16] De Paiva E. Role of the use of conformal beta applicators in the radiation treatment of small skin lesions. Radiology and Imaging Journal 2023; 2: 1-3.

[17] Wambersie A, Vynckier S. Dosimetry of beta sources in radiotherapy - the beta point source dose function. Physics in Medicine and Biology 1982: 27: 1339-1347.