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Calculation of beta radiation dose of a circular Y-90 skin patch: Analytical and simulation methods

Ali Pashazadeh[a,*], Eduardo de Paiva[b], Naghmeh Mahmoodian[a], Michael Friebe[a]

[a] Chair for Intelligent Catheter and Image Guided Procedures, Otto-von-Guericke University, Magdeburg, Germany
[b] Medical Physics Division, Institute of Radioprotection and Dosimetry, Brazil

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ABSTRACT

Beta radiation therapy of superficial skin tumors using a radioactive patch can be an interesting treatment, mainly when the lesion is near sensitive targets, for example, close to the eye or bone. Due to their short range and rapid dose fall-off, beta radiation from a skin patch deposits its energy within the first layers of the skin. This property may lead to the protection of sensitive structures located right beneath the skin lesion during the radiation therapy procedure. To create and use individual and personalized radiation patches the distribution of the beta radiation dose needs to be known. An accurate and realistic calculation is needed to determine the amount of radioisotope required and the duration of the radiation therapy procedure to deliver the prescribed dose in a certain depth from the surface. In this paper, the theoretical model for a dose distribution calculation from a radioactive skin patch loaded with Yttrium-90 (Y-90) in different depths of skin tissue is presented. The calculation was based on the Loevinger beta-point source dose function, which is a numerical method for dosimetry of beta-emitting isotopes. Results of the calculation were also compared with that of Monte Carlo simulation methods to assess the reliability of the application of the Loevinger method in dosimetry of a beta-emitting radioactive patch.

1. Introduction

Radiation therapy of skin tumors is an effective technique to manage skin cancer patients. There are several methods whereby the radiation dose can be delivered to the skin lesion and kill cancer cells. Beta radiation therapy using the skin patches loaded with beta-emitting isotopes is a method that can be used in cases where the lesion is very thin (Chung et al., 2000; Sedda et al., 2008; Pandey et al., 2008). Beta particles of isotopes have a short penetration range in tissue, typically less than 10 mm, and present a rapid dose fall-off. Therefore, beta radiation therapy of thin skin tumors can lead to the protection of sensitive structures such as the bone located right beneath the lesion.

We have recently proposed a method for fabrication of a beta-emitting patch for use in skin cancer therapy (Pashazadeh et al., 2019). It is a circular skin patch which is loaded with yttrium-90 (Y-90) radioisotope. Y-90 has a physical half-life of 64 h and emits beta particles with a maximum energy of 2.28 MeV. These energetic particles make Y-90 a suitable beta-emitter to produce radioactive skin patches. Radioactive skin patches containing Y-90 have shown to be efficient in controlling the tumor growth. These patches were used both in single-session and fractionated radiation therapy regimen to suppress tumor growth in fibrosarcoma-bearing mice (Mukherjee et al., 2002). For single dose delivery, patches of 37–74 MBq activity was applied to the mice for one to 3 h. For the fractionated dose delivery, patches impregnated with 92.5 MBq activity was used to irradiate the tumor mass three times at weekly intervals. Both regimens showed that the beta particles could effectively kill cancer cells.

Before the Y-90 containing radioactive patch is applied as a therapeutic option, it is needed to determine its dose pattern in tissue. There are three methods for dosimetry of beta particles: experimental methods, simulation methods, and analytical methods. Experimental dosimetry is based upon the use of dosimeters to measure the radiation dose of beta particles. Because of the short range of beta particles in tissue and their high dose gradient, it is necessary to do dosimetry at sub-millimeter resolution and in very small steps from the source (Chiu-Tsao et al., 2007). Beta radiation dose can be measured practically through the use of radiochromic film (Soares et al., 1998), small-volume scintillators (Bambynek et al., 2000), or ultra-thin TLDs (Schaart et al., 2002). The near-filed dosimetry considerations of beta sources make it challenging to measure their radiation doses in practice. In this framework, calculation methods are of special importance, and there are two general approaches to estimate doses around beta-emitting

* Corresponding author. Room 122, Building 53, Rotgerstrasse 9, 39104, Magdeburg, Germany.
E-mail address: ali.pashazadeh@ovgu.de (A. Pashazadeh).

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sources, including Monte Carlo simulation and analytical/numerical methods.

The chief advantage of the Monte Carlo simulation method, particularly in dosimetry of beta particles, is the possibility to calculate the radiation dose at high spatial resolution. Additionally, using Monte Carlo simulation allows to handle with complex geometries and various kind of media to obtain results with high accuracy. There are several Monte Carlo codes available and used for this purpose including but not limited to MCNPX (Waters et al., 2007), PENELOPE (Issy-les-Moulineaux, 2003), GEANT4 (Agostinelli et al., 2003), EGS4 (Nelson et al., 1985), and EGSnrc (Kawrakow and Rogers, 2000). Although simulating the dose transport in tissue yields accurate results, however, it may need a considerable time of computation and may not be possible to implement it in a daily clinical routine.

Analytical/numerical methods are another approach for determining the radiation dose of beta-emitting sources. These methods apply only to homogeneous medium (water) and a simple geometry but require a negligible time of computation as compared with Monte Carlo calculations. The basis of these methods is the Loevinger beta-point source dose function. It is an empirically-developed method for estimating the radiation dose of beta particles. Later, the function was modified by several researchers to improve the accuracy of beta dose calculations. Analytical methods may not function well in challenging geometries and large distances; however, they can be applied as a simple method in short distances and geometries that are not complex.

The calculation of the relative dose rates based on the integration of the modified beta-point source dose function has been applied to estimate the dose rate along the central axis of spherical applicators containing the beta-emitters Ru-106/Rh-106 and Sr-90/Y-90, and results were in a fairly accordance with Monte Carlo calculations (Hokkanen et al., 1997; De Paiva, 2015). The use of the point-source dose function was possible because of the spherical symmetry of the applicators and short distances from the point source to the calculation point. The simple geometrical conditions are again reached in this work, ensuring the reliable use of Loevinger function to calculate the dose of our proposed Y-90 patch in tissue.

Therefore, in this work, we used the calculation approach to present estimates of relative dose rate along the central axis of a circular Y-90 patch designed and intended to be used in superficial skin cancer therapy. The simulation study of the dose distribution using EGSnrc code was also done to provide a basis for verification of the calculated values based on Loevinger function.

2. Material and methods

The Loevinger beta-point source dose function, introduced in 1956, is an empirical method to calculate the dose from a point source of beta radiation (Vynckier and Wambersie, 1982). He measured beta transmission through sheets of polystyrene, based on which, developed an empirical function for dosimetry of beta particles. This function is used to calculate the radiation dose near the beta-emitting isotopes in distances that are relevant in clinical applications. Since the first introduction of the function, there have been several other analytical functions and modifications to estimate dose distribution from a point source of beta radiation. One of the successful refinements on the Loevinger function was proposed by Vynckier and Wambersie, which made it better fit the experimental and theoretical data (Vynckier and Wambersie, 1982). The resultant function can define the theoretical point kernels within ± 5% out to 70% of the maximum range of the beta particles (Appendix, 2004). However, as the significant part of the beta energy is absorbed within this range, it is usually of insignificant practical concern.

This refined version of the Loevinger function was the basis of our calculations and is expressed as follows:

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

where ξ is the distance of calculation point from the point source, ρ is the medium density, ν is the absorption coefficient, c and f are dimensionless parameters.

The above expression of the beta-point source dose function was obtained empirically but on a physical basis. The first term (within the bracket) can be thought as accounting for the energy absorbed from the un-scattered component of the beta particles and is zero at distances equal to or greater than $c/\rho\nu$; the second term accounts for the energy absorbed from the scattered component of the beta particles, and the inverse square attenuation law is contemplated by the term ξ^2 at the denominator of the expression.

Vynckier and Wambersie function introduced the third term in (1) with the dimensionless parameter f in order to encompass a set of theoretical and experimental data not used by Loevinger, where $f/\rho\nu$ represents the distance from which the dose due to beta particles is required to be zero due to its range. So, we have

$$\left[1-\frac{\rho\nu\xi}{c}\exp\left(1-\frac{\rho\nu\xi}{c}\right)\right]\equiv 0 \quad \text{for} \quad \rho\nu\xi \geq c \quad (2)$$

and

$$J(\xi)\equiv 0 \quad for \quad \rho\nu\xi \geq f \quad (3)$$

The quantity B is a normalization constant obtained by the requirement that the total energy per disintegration, absorbed in a very large sphere, is equal to the energy emitted. The parameter B is then

$$B = \frac{0.046\rho^2\nu^3\bar{E}_\beta}{3c^2-(c^2-1)\exp(1)+(3+f)\exp(1-f)-4\exp\left(1-\frac{f}{2}\right)} \quad (4)$$

where $\bar{E}_\beta$ is the mean kinetic energy of the beta particles. Although it is out of the scope of this work, we think a complete revision of the expression of the beta-point dose function as well as the parameters c and f should be done for the pure beta-emitters used to or with potential to be used in brachytherapy treatments.

For the Y-90 radioisotope, the values of $\bar{E}_\beta$, c ,ν, and f in the refined Loevinger function are 0.933 MeV, 0.95, 5.05 cm^2/g and 4.48, respectively.

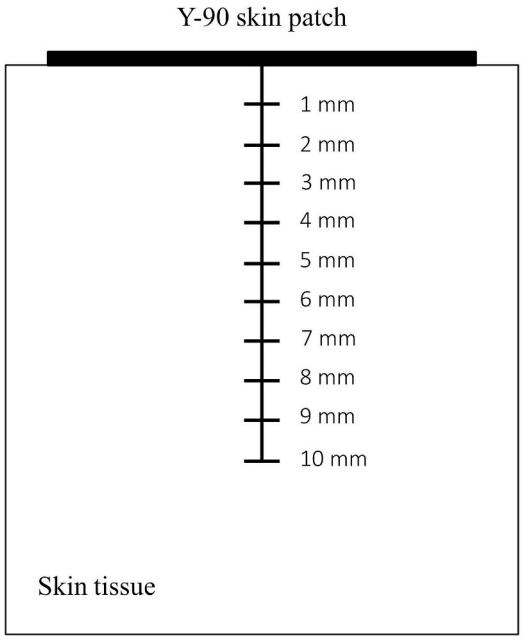
To calculate the beta radiation dose from the Y-90 skin patch, we made some assumptions. We assumed the patch is uniformly loaded with Y-90 and is placed on a flat skin surface. We also assumed that skin tissue is a water-equivalent medium of 1 $g\,cm^{-3}$ density. The patch diameter was 25 mm, and the amount of the radioactivity was considered 60 MBq. Based on these assumptions, we calculated the dose rates in skin tissue from 1 to 10 mm depths in the steps of 1 mm.

A Fortran code was developed to calculate the following numerical integration over the whole area of the circular radioactive patch;

$$D = a_s\int_s J(x)ds, \quad (5)$$

where a_s is the surface activity, which was calculated 12.24 MBq/cm^2 based on the amount of the activity distributed over the patch surface.

The EGSnrc Monte Carlo code used in this study is a code for the simulation of electrons' and photons' transport in a medium. The code can be used for energies in the range of a few keV up to several hundreds of GeV (Kawrakow and Rogers, 2000). The transport parameters, including ECUT and PCUT, which are used to define the global electron and photon cut-off energies, were set to 0.521 MeV and 0.01 MeV, respectively. In all of the simulation process, no variance reduction techniques were used. To satisfy the statistical accuracy in the scored



Depth (mm)	Dose rate (G/h)
1	10.21
2	5.47
3	2.90
4	1.47
5	0.69
6	0.28
7	0.09
8	0.02
9	0.00
10	0.00

Fig. 1. Schematic view of the geometry used in our study (left) and the calculated dose values for the Y-90 patch using the Loevinger function in different layers of the skin (right).

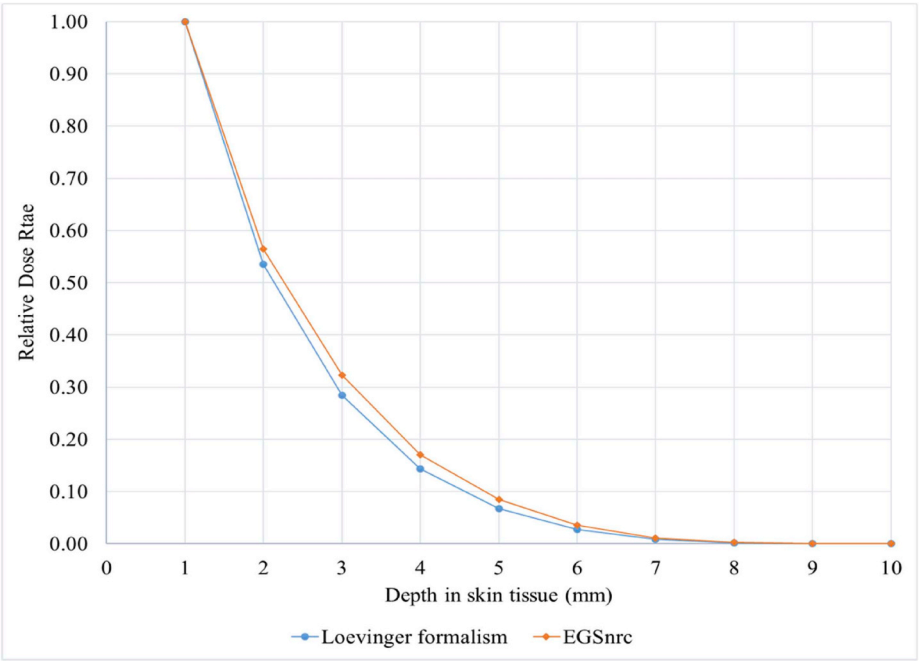


Fig. 2. Relative dose rates from the circular radioactive patch of Y-90 alongside the central axis in the skin tissue – calculated results of Loevinger function (in blue) and simulated results of EGSnrc Monte Carlo method (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dose, the number of histories of transported particle considered as 10^7 in the simulation process and associated uncertainty to the scored dose was less than 1%. The voxel sizes were $0.2 \times 0.2 \times 0.2\,mm^3$.

3. Results

The geometry used in our calculations and resulted values from the Loevinger function is given in Fig. 1. The results show that after a depth of 4–5 mm the dose is less than 10% of the dose at a depth of 1 mm indicating that, with a sharp gradient, a significant part of the radiation dose has been delivered within the first few millimeters of the skin tissue.

The calculated values using the Loevinger function were then normalized to the dose rate at 1 mm depth and compared with that of obtained using the EGSnrc simulation. We observed a very good agreement between the normalized values of calculation and simulation methods (Fig. 2). The maximum relative difference observed between the two value sets was less than 4%. This agreement is in line with a similar study performed to calculate the dose values from an ophthalmic applicator of beta-emitting isotope ^{106}Ru (De Paiva, 2015).

4. Discussion

Application of skin patch of beta-emitting isotopes is an interesting treatment for superficial skin tumors located close to sensitive structures such as the bone or eye. Because of their short range in tissue, beta particles deliver radiation dose within the first few millimeters of skin tissue where the thin lesion is extended. To apply the radioactive patch

on the skin, it is essential to have the pattern of beta dose distribution in tissue. The Loevinger point-source dose function can be successfully used for this purpose. This function has long been the basis for beta dosimetry because of its simplicity and fewer parameters involved in comparison to other functions.

Based on our observation, the pattern of dose distribution obtained by the Loevinger function, refined by Vynckier and Wambersie, showed a very good agreement with that of obtained by EGSnrc code. This observation can be partly explained by the short distances used for calculation of the beta radiation dose. A short distance in this context is the one that is comparable with the mean range of beta particles.

The Y-90 patch is intended to be used for those superficial skin tumors that are thin, typically less than 3–4 mm thickness, and located in flat surfaces. Therefore, in such an application, the short-distance and simple-geometry criteria are satisfied, and the Loevinger function can be readily used for dose calculation. It should be noted that in complex anatomies and large distances, the calculation method will be associated with significant error.

In summary, the dosimetry of beta applicators used in brachytherapy is very difficult to perform mainly because of the challenges in near-field dosimetry. In this regard, a simple calculation via the integration of the modified Loevinger function may be useful. The calculation of the dose rate along the central axis of the beta-emitting applicator investigated in this work can be performed in a typical PC in a few minutes. Thus, even with its limitations, Loevinger function can be suitable to be used in a clinical routine as an auxiliary tool to dose planning as well as a guide for future experimental and theoretical work on these sources.

5. Conclusion

The Loevinger function refined by Vynckier and Wambersie can be used as a quick and reliable method to calculate the dose distribution of a circular patch of Y-90 when applied as a radiotherapeutic option to thin skin tissue in flat surfaces.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radphyschem.2019.108491.

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