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A multiwell applicator for conformal brachytherapy of superficial skin tumors: A simulation study

Ali Pashazadeh[1] iD | Mostafa Robatjazi[2] | Nathan J. Castro[3] | Michael Friebe[1] iD

[1]Chair for intelligent catheter and image guided procedures, Otto von Guericke University Magdeburg, Magdeburg, Germany

[2]Department of Medical Physics and Radiological Sciences, Sabzevar University of Medical Sciences, Sabzevar, Iran

[3]Joint Quantum Institute and Physical Measurements Laboratory, NIST/University of Maryland, Gaithersburg, MD, USA

Correspondence
Ali Pashazadeh, Chair for intelligent catheter and image guided procedures, Otto von Guericke University Magdeburg, Room 122, INKA, Building 53, Rötgerstraße 9, 39104 Magdeburg, Germany.
Email: ali.pashazadeh@ovgu.de

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Abstract

Background: Brachytherapy of thin skin tumors using beta particles can protect underlying sensitive structures such as the bone because of the rapid dose falloff of this type of radiation in tissue. The current work describes a skin brachytherapy applicator, based on beta radiation, that can provide the needed cell-killing radiation dose matched to the shape of individual skin tumors.

Materials and methods: The applicator and its template were fabricated using 3D printing technology. Any clinically approved beta-emitting isotope in the form of a radioactive gel could theoretically be used in this applicator. Monte Carlo simulations were employed to study the capability of the applicator in conforming dose distribution based on the shape of the tumor. Dose profile in the shallow depth, transverse dose profiles at different depths, and the percent depth dose from this applicator were calculated. The radioisotope of choice for our calculations was Yttrium-90 (Y-90).

Results: Using the proposed applicator, it is possible to create a desired dose profile matching the tumor surface shape.

Conclusion: The short-range of the beta radiation, together with the dose conforming capability of the applicator, may lead to minimal interactions with the healthy tissue around the skin lesion.

KEYWORDS
3D printing technology, beta particles, beta-emitting isotopes, brachytherapy, Monte Carlo methods, skin tumor, Y-90

1 | INTRODUCTION

Nonmelanoma skin cancer (NMSC) is the most commonly diagnosed malignancy in humans. In the United States alone, more than 3 million NMSCs are diagnosed annually.[1] The primary treatment for skin cancer is surgery, which is the physical removal of the lesion from the skin tissue, including safety margins. It can be done either by a standard excision or by the Mohs surgery whereby the skin tumor is removed in a layer-by-layer fashion.[2] Since surgery exhibits an excellent control rate of the skin tumor, it is considered as the standard of care for skin cancer patients.[3] However, this procedure cannot be indicated for all patients, primarily because of post-surgery complications.

In such cases where surgery is not recommended to the skin cancer patients, radiation therapy techniques are used as an efficient alternative.[4] One of the commonly used radiation therapy techniques in dermatology practices is brachytherapy, in which a source of activity is placed in close contact with the target to deposit the prescribed

dose in its volume. Brachytherapy of skin tumors was first reported in 1899 after the discovery of radium.[5] Since then, brachytherapy practices have experienced several technical developments, which have led to the introduction and application of different brachytherapy applicators. Leipzig and Valencia applicators are the two standard brachytherapy devices used to treat skin tumors. They are cup-shaped tungsten shielding with the Ir-192 radiation source. Radioisotope Ir-192 has a half-life of 73.8 days and emits gamma photons of 360 keV, with a half-value layer of 3 mm in the lead.[6] Since these applicators have fixed geometries, it is not possible to shape the dose distribution based on the tumor shape on the skin surface.

To address this need, we describe in this paper a new surface applicator for superficial skin tumors that allows a radiation dose delivery based on the tumor shape on the skin surface. We suggest a 3D-printed multiwell brachytherapy applicator subsequently filled with a radioactive gel to create the source of radiation based on the 2D shape of the skin tumor. The radioisotope of choice for creating a radioactive gel is a beta-emitting isotope. Because of their short-range in tissue (typically <10 mm), beta particles can suitably be used for treating thin skin lesions of around 3-4 mm thickness. It can be specifically advantageous when the thin lesion is located right on top of bony structures or very close to the eye.

In the current work, the proposed applicator and the workflow of its application to a skin tumor have been illustrated. The capability of the applicator to conform the dose distribution was also studied using Monte Carlo Simulation methods.

2 | METHODS AND MATERIALS

2.1 | Applicator design and fabrication

The applicator was designed using a Computer-Aided Design (CAD) program (SolidWorks 2018, Dassault Systèmes) with a body dimension of (25 × 35 × 10) mm^3. Then, a number of 63 wells of 2 × 2 × 1 mm^3 were cut-extruded in a 7 × 9 array in one face of it. The wells were separated by 1-mm thick walls. The CAD models were then imported into the Slic3r G-code generator to convert it to the printing instruction files. Then, the applicator and its template were fabricated using a 3D printer (Form 2, Formlabs). The printed models of the applicator and its template are given in Figure 1.

2.2 | Implementation of the applicator

The current applicator can produce a planar source of beta radiation with an effective area of about (20 × 25) mm^2. However, for larger tumors, the size of the applicator and its template can be enlarged accordingly. The treatment workflow for skin brachytherapy using the multiwell applicator is given in Figure 2. The process starts with the delineation of the skin tumor and its safety margin. Then, a grid is drawn on the treatment area to determine

the pattern based on which wells of the applicator will contain the beta-emitting gel. The grid also provides a reference for accurately fixing the template on the skin. To prepare the applicator to apply to the patient, the desired wells of the applicator are filled with beta-emitting gel and allowed to harden. A detailed description of the radioactive gel can be found in our previous work.[7] In the end, the applicator is placed into the template, which was previously fixed on the site of the grid.

2.3 | Monte Carlo simulation

For dosimetric studies, the 2D dose profile and the percent depth dose (PDD) from the applicator were determined using Monte Carlo methods. We simulated the applicator and the skin phantom, then filled the wells of the applicator with beta-emitting gel and calculated the absorbed dose in skin issue. First, the capability of the applicator for conforming the dose to a skin tumor of irregular shape was evaluated. To this end, a random shape of radiation source was created by filling specific wells of the applicator with beta-emitting gel. Then, the corresponding 2D dose profile was simulated at the shallow depth of 0.06 mm. After that, all wells of the applicator were filled with a radioactive source to create a uniform distribution of radiation source with a rectangular shape. Then, the dose profiles on the transverse plane perpendicular to the applicator were calculated. It was calculated for five depths from 1 to 5 mm. Then, the PDD alongside the central axis of the applicator was calculated down to 10 mm depth and at the steps of 1 mm.
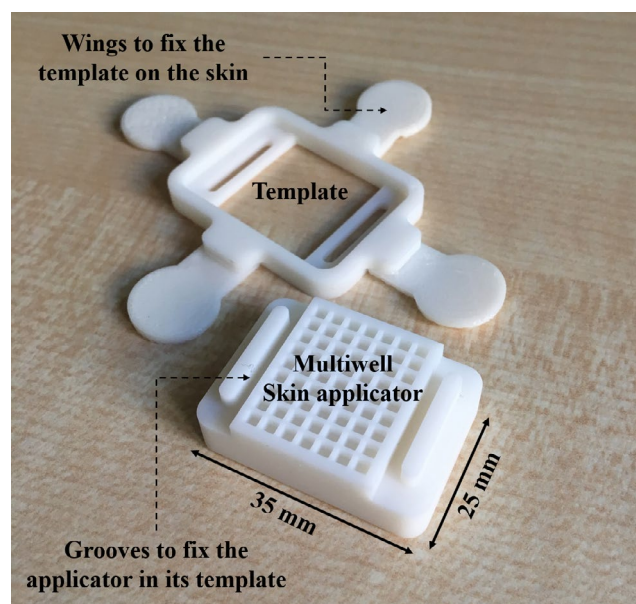

FIGURE 1 The 3D-printed multiwell brachytherapy applicator and its template [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 The workflow of implementation of the multiwell skin brachytherapy applicator; delineation of the treatment area (1), grid-based multiwell array of treatment area (2), mirror image of the array (3), filling the wells of the applicator with beta-emitting gel and based on the pattern of the grid (4), fixation of the template on the tumor site (5), and placement of the applicator into its template (6) [Colour figure can be viewed at wileyonlinelibrary.com]
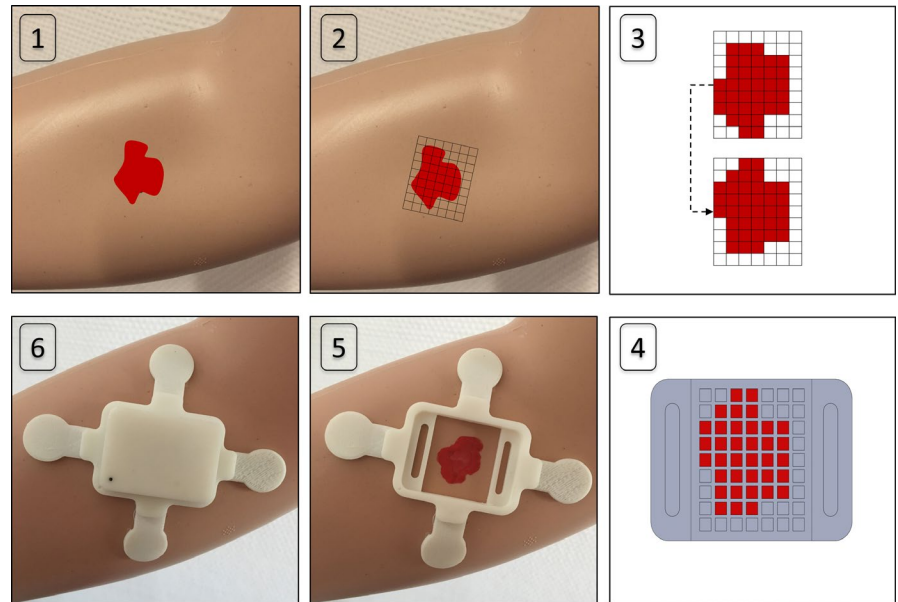
To model the multiwell applicator, the EGSnrc C++ code was used.[8] The size of dose scoring skin phantom was 40 × 40 × 20 mm^3 with a voxel size of 1 × 1 × 1 mm^3. The transport parameters electron cutoff energy (ECUT) and photon cutoff energy (PCUT) were set to 0.521 MeV and 0.01 MeV, respectively. The simulation was run without variance reduction techniques. To satisfy the statistical accuracy in the scored dose, a number of 10^7 histories of the transported particles were considered. The corresponding uncertainty to the scored dose was <1%.

We chose yttrium-90 (Y-90) as the source of beta radiation for this applicator. It has a half-life of 64 hours and emits beta particles with a maximum energy of 2.27 MeV.[9] The spectrum data of Y-90 radionuclide in ENSDF (Evaluated Nuclear Structure Data File) format was used in the EGS_RadionuclideSource class of EGS C++ code. The output of simulations was 3ddose files format that each voxel value was calculated in dose (Gy) per fluence. An in-house MATLAB code was used to read the 3ddose files and plot the dose distribution. It should be mentioned that all of the dose matrices were normalized to the maximum value of the matrix.

3 | RESULTS

The digital model of the applicator with an arbitrary shape of the Y-90 source distribution and the corresponding dose profile at the shallow depth is presented in Figure 3. As shown, the 2D dose profile
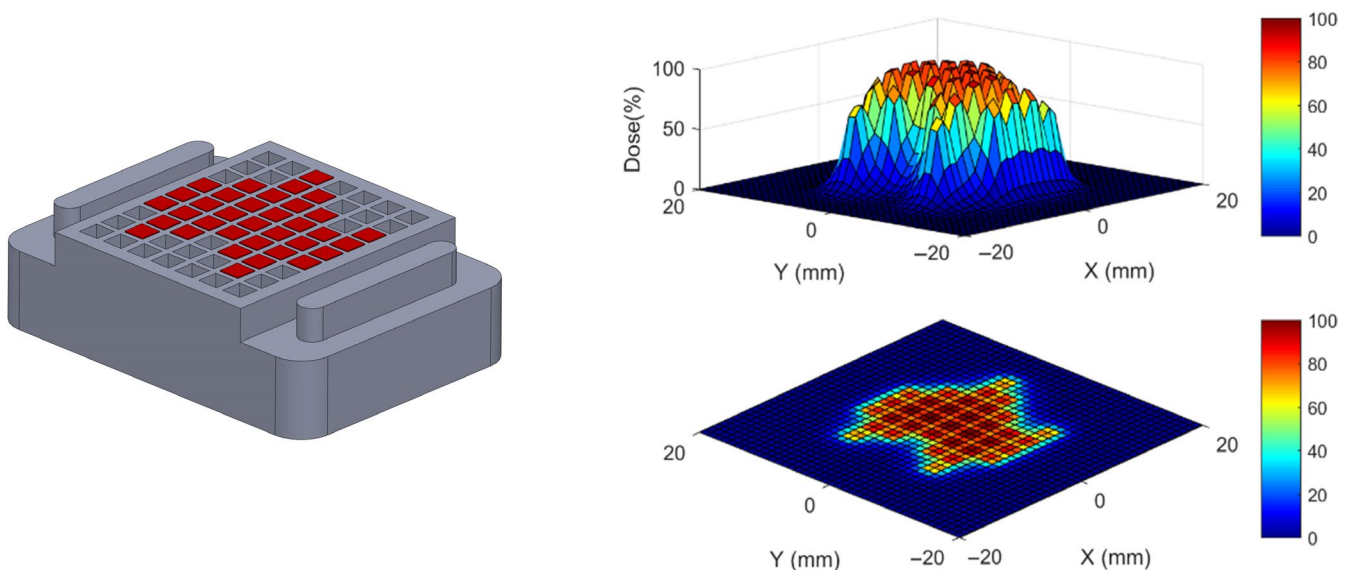

FIGURE 3 The digital model of the multiwell applicator with wells that are randomly filled with Y-90 gel (left image) and the corresponding dose profiles calculated at the shallow depth with 3D and 2D presentation (right image) [Colour figure can be viewed at wileyonlinelibrary.com]
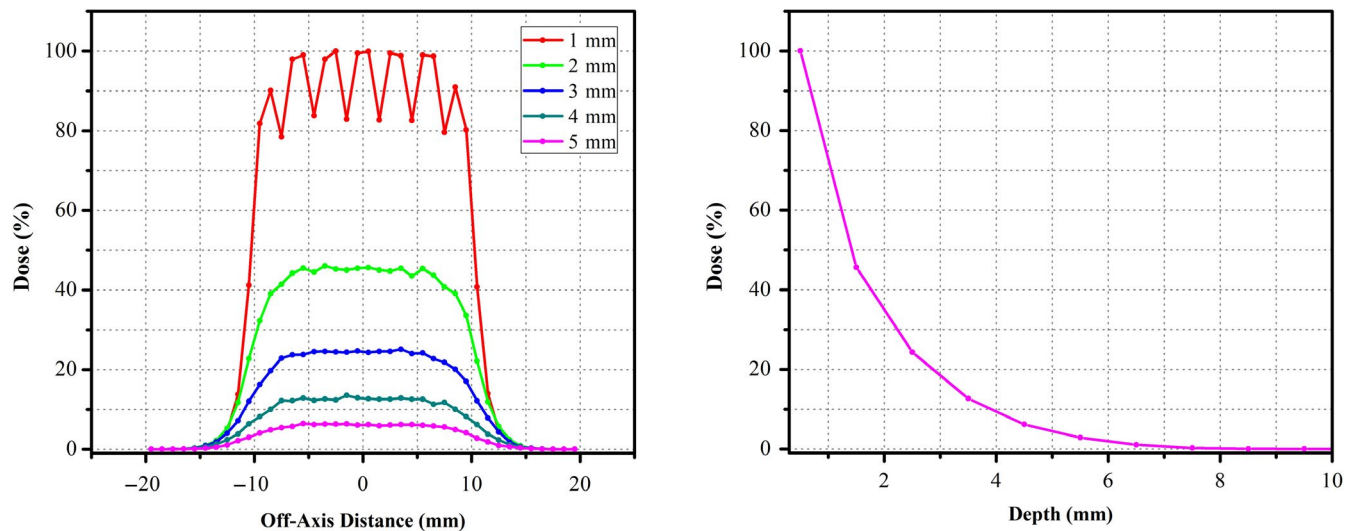
FIGURE 4 Calculated TDP (left image) and PDD (right image) from the multiwell applicator uniformly filled with a source of Y-90 gel [Colour figure can be viewed at wileyonlinelibrary.com]

of the applicator follows the 2D distribution of the beta radiation source. The effect of the 1-mm separation between the wells, where there is no activity in it, on the dose profile is evident in the 2D dose profile at the shallow depth.

In Figure 4, the calculated transverse dose profile (TDP) at different depths from this applicator, as well as the PDD, is presented. Comparing the dose profile at different depths shows that the effect of the walls between wells on the dose nonhomogeneity decreases as we go deeper into the skin layers. In the PDD curve, the pattern of dose deposition clearly shows how the significant part of beta radiation is absorbed within the first layers of the skin tissue. Based on this curve, the beta radiation dose from the applicator beyond the 4 mm depth drops to less than 10% of the shallow dose. The PPD becomes almost zero beyond the depth of 7 mm.

4 | DISCUSSION

In the current study, a new multiwell skin brachytherapy applicator with beta-emitting sources has been introduced. Results of the simulation study showed the dose distribution from this applicator can be conformed to the shape of a tumor in the skin entry by adjusting the pattern of the source distribution in the applicator. Because of the rapid dose falloff of beta radiation in tissue, the use of this applicator can be advantageous when a skin lesion is located right on top of a sensitive structure such as bone or very close to the eye.

Beta-emitting isotopes have successfully been used in several nuclear medicine and brachytherapy practices. A traditional and well-established procedure using a beta-emitting isotope is the treating of hyperthyroidism using Iodine-131 (I-131) radioisotope.[10] Another promising application of beta radiation has been the treatment of inoperable liver tumors using Y-90 microspheres.[11] Intracoronary radiation therapy using Phosphorus-32 (P-32) stent for the prevention of restenosis is another therapeutic use of

beta-emitting isotopes.[12] Radiation therapy of eye tumors using a hand-held Strontium-90 (Sr-90) applicator or eye brachytherapy plaques containing Ruthenium-106 (Ru-106) is another successful use of beta-emitting isotopes to manage disease.[13]

The use of beta-emitting isotopes for brachytherapy of skin tumors is not an established method. However, there are several studies that assessed and showed its effectiveness in treating thin skin malignancies.[14-17] There are also some works aiming at developing methods for creating therapeutic models based on beta-emitting isotopes for skin cancer.[18-23] They are mainly focused on creating planar sources of beta radiation applicable to skin tumors, with very few studies focusing on conforming the dose to the skin tumor shape.[7,24] The current multiwell brachytherapy applicator presents a simple method to conform the dose of beta radiation to the superficial skin tumors. As the applicator is fabricated using 3D printing technology and with plastic materials, the manufacturing process of the applicator body is quick and inexpensive. In addition to that, once the radioactive source is provided, the radioactive gel can be prepared, added, and hardened in the applicator in <1 hour. The applicator body, with a wall thickness of about 5 mm, can absorb a significant part of the beta radiation in unwanted directions and provide shielding for that.

Unlike the conventional skin brachytherapy applicators, the proposed applicator and its template can be fixed on the patient's skin without a supporting arm. A direct result of the in-situ fixation of the applicator will be the reduced setup error during the treatment delivery. A comfortable situation for the patient, where they do not have to be immobilized, is another feature of this light-weight applicator.

Besides the features that this applicator may offer for skin cancer patients, its limitations should not be ignored. Firstly, this applicator is only suitable for thin skin tumors of around 3-4 mm in thickness. In addition, as the radiation source of this applicator is unsealed, special radiation safety considerations are needed to be satisfied when handling the applicator.

5 | CONCLUSION

In the current work, a multiwell skin brachytherapy applicator that can be loaded with a beta-emitting isotope, such as Y-90, was described. A dosimetry study using Monte Carlo simulation methods showed the capability of this skin brachytherapy applicator in conforming the beta radiation dose to the tumor shape on the skin surface. The beta-emitting source used in this applicator not only can lead to sparing sensitive structures beneath the tumor but makes the shielding of the source easier, compared with the gamma-emitting sources.

CONFLICT OF INTEREST

The authors report no conflict of interest.

ORCID

Ali Pashazadeh https://orcid.org/0000-0002-7916-9604
Michael Friebe https://orcid.org/0000-0002-8624-0800

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