Original Article

Development of a Relative Dosimetric System for Calibration of ^{32}P Eye Applicators Using Radiochromic Films

Alireza Nazempoor, Hosein Poorbaygi[1], Seyed Mahmud Reza Aghamiri, Mohammad Reza Javanshir[1], Shahab Sheibani[1], Reza Naghdi[1], Somayeh Moradi[1], Ali Habibpanah[1]

Departments of Medical Radiation Engineering, Shahid Beheshti University, [1]Radiation Application Research School, Nuclear Science and Technology Research Institute, Tehran, Iran

Abstract

Introduction: Beta irradiation after bare scleral surgery of primary pterygium is an effective and safe treatment, which reduces the risk of local recurrence. **Purpose:** Obtaining the reference dose rate for a radioactive applicator consisting of a plate as a 32P absorber, a steel window and a steel capsule. **Methods:** Relative dosimetry and dose profile were measured using two types of radiochromic films, HD-810 and EBT1, for the ^{32}P applicator and were compared with Monte Carlo simulation data. Dose uniformity in the ^{32}P applicator was obtained with radiochromic HD-810 film. **Results:** The measurement depth dose distribution data at distances up to 3.8 mm were compared with calculation data, and the values were not found to differ statistically. Depth dose distribution with a large dose gradient was determined and the dose rate data obtained 0.0053 ± 9.9% in unit of Gy/s.mCi at a 0.1 mm depth distance. Practical results indicated that the dose nonuniformity and the maximum symmetrical for the ^{32}P applicator were 11.5% and 9.2%, respectively. **Conclusions:** Our experiments show that the use of the radiochromic film to perform the relative dosimetric checks is feasible and the activity value with acceptable error can be determined through this indirect method.

Keywords: ^{32}P eye applicator, calibration, dosimetry, radiochromic film

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INTRODUCTION

Postoperative brachytherapy has been extensively investigated using different radioactive sources, such as ^{90}Sr, ^{106}Ru, and ^{32}P for preventing pterygium recurrence.[1-3] Using a ^{90}Sr ophthalmic applicator with an active diameter of 12 or 15 mm, a single dose of 2500 cGy was administered to the surface of the conjunctiva at a dose rate of between 200 and 250 cGy/min.[1,4] However, ^{90}Sr/Y pair requires heavy radiochemical processing for its production from the fission fragments of a nuclear reactor. This pair is classified as highly hazardous radioactive material due to its long half-life (28.8 y); in addition, its production and application require great precautions.[4] As an alternative to ^{90}Sr irradiation, Choi *et al*. proposed that a pure β-emitter of ^{32}P could be an alternative source.[3] Phosphorus-32 is produced by fast neutron activation of sulfur-32 (^{32}S) and decays by beta decay (E_{max} = 1.71 MeV and $<E_{\beta}>$695 keV) with a half-life of 14.3 d. It has a short half-life (14.3 days), which makes a less radio-hazardous material from the viewpoint of transportation, storage, and deposal.[3,4]

For the dosimetry of ophthalmic applicators, three procedures are of interest: (1) calibration of the source, i.e. the determination of the absolute value of the dose rate to tissue (or water) at the surface of the applicator or at a certain reference depth along the central axis of the source perpendicular to the surface; (2) determination of the relative dose distribution close to the source in tissue (or water) along the central axis of the source; and (3) determination of the relative dose distribution as a function of position off of the central axis.[5,6] These sources were calibrated by the manufacturer or by the primary standard dosimetry laboratory of the National Institute of Standards and Technology (NIST), but not by both laboratories.[7] There are many techniques to calibrate clinical applicators, such as the use of extrapolation chambers,[8,9] radiochromic

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Address for correspondence: Dr. Hosein Poorbaygi,
Radiation Applications Research School, Nuclear Science and
Technology Research Institute, End of North Karegar Ave, Tehran, Iran.
E-mail: hpoorbaygi@gmail.com

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films,[6,8] and thermoluminescent dosimeters.[8,10,11] Soares found differences of approximately 20% between the two calibration procedures.[12] Therefore, it would be important that the calibration of the applicators could be done at the same place where they are used, i.e. at the clinics and hospitals (with brachytherapy services). Another reason for this kind of calibration is that not always the applicators can be sent to the NIST, as some clinics and hospitals are located far from the calibration laboratory. Since the sending of a ^{32}P applicator to the calibration laboratory may result in decays in activity, the calibration at the place of their use is a relevant alternative.

The objective of this work was to develop a relative dosimetric system using radiochromic film for calibration of the ^{32}P applicator, to be sent to clinics and to radiotherapy services in hospitals as an alternative method, to be used when the clinical applicators cannot be sent to the calibration laboratory. In this study, dosimetry components including reference dose rate, relative central axis depth dose, and dose profile are measured using two types of radiochromic films, HD-810 and EBT1, for the ^{32}P applicator. Then, the results are compared with the Monte Carlo (MC) simulation, and finally, the results are compared with the dosimetry data of the ^{32}P applicator reported by the literature.

METHODS

Radiation device

The radioactive solution of ^{32}P is available as phosphoric acid $H_3{}^{32}PO_4$ after preparation by fast neutron activation. The beta activity of the sample was measured using a dose calibrator, namely ISOMED1010 (Elimpex-Medizintechnik, Austria). A prototype of a ^{32}P applicator was fabricated with a nominal activity of 3.8 mCi (0.22GBq) at the time of delivery. This applicator included various compartments: a stainless steel window (thickness of 0.1 mm), ceramic plate as ^{32}P absorbent (zirconia material with a diameter of 10 mm and a thickness of 0.6 mm), alumina layer with a thickness of 1.3 mm, tungsten alloy as shielding material with a thickness of 3 mm, and capsule head as a part of the grip with Stainless steel (STS) which were covered body steel with an external diameter of 15 mm [Figure 1a-c]. The liquid containing ^{32}P was dropped onto the absorbent disk and then the liquid evaporated, leaving ^{32}P. A laser welding system was used for welding of the stainless steel window, and a TIG system was used for welding the cap. The stainless steel window layer will actually contact the surface of the eyeball. The surface of the window was smooth enough to protect the eye.

Calibration of beta-ray plaque sources

The source strength of the ophthalmic source is defined as the absorbed dose rate D (r_0) = z_0 in water at a point on the source axis (r_0, Z_0) at a distance of z_0 = 2 mm. The r- and z-axis of a planar source is defined in Figure 1d. The average radius of an ophthalmic source is defined as the (mean) radius of the 50% isodose contour.[11]

The nonuniformity is defined as flatness (U_F) according to Equation 1. In this case, the reference dose D_{ref} is the dose rate on the source axis.

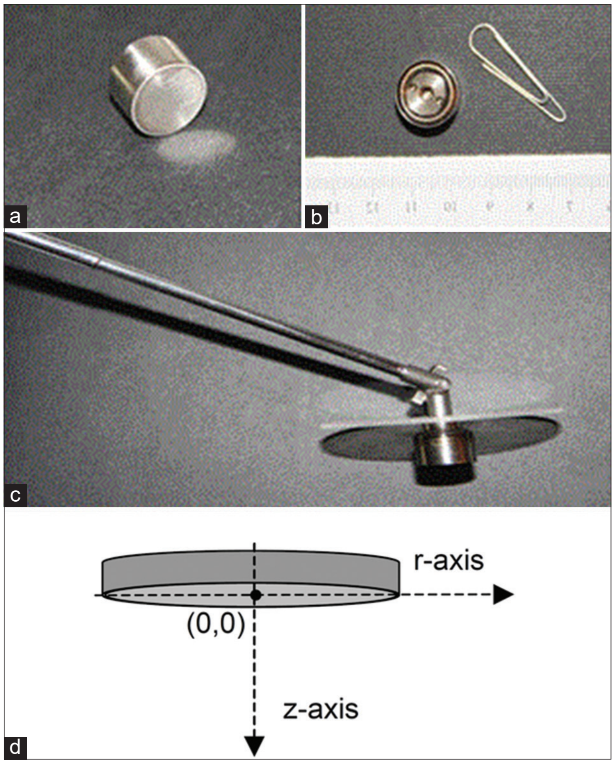

Figure 1: A prototype of ^{32}P applicator. (a) Eye-contact surface, (b) A part of the grip, (c) Applicator capsule and holder, (d) Coordinate systems for a planar ophthalmic source

$$U_F = \max\left(|\dot{D}_{min}-\dot{D}_{ref}|, |\dot{D}_{max}-\dot{D}_{ref}|\right)/\dot{D}_{ref} \times 100\%, \quad (1)$$

For evaluation of the asymmetry of ophthalmic sources, the quantity U_{AS} is introduced.

$$U_{AS} = \max\left(\{\dot{D}_{min}(r)-\dot{D}_{max}(r)\}/\dot{D}_{avg}(r)\right) \times 100\%, \quad (2)$$

In this expression, the variation of the dose rate is calculated over a circle with a radius of r. The maximum of this variation for r from 0 to $0.8R_{50}$ gives the value of the asymmetry U_{AS}. U_F and U_{AS} are evaluated within a circle with a radius of $0.8R_{50}$. R_{50}, U_F, and U_{AS} are defined as close to the source surface as possible and parallel to the surface.[11]

Percentage depth dose (PDD) values of the ophthalmic applicator were obtained by the following equation:

$$PDD = (D_d/D_{ref}) \times 100$$

where D_{ref} is the absorbed dose at reference depth, in this study was adjusted to 0.1 mm (surface of applicator).

Calibration of the radiochromic film

To determine the relative dose of the radioactive applicator in Perspex, the two types of radiochromic dosimetry were used, GAFCHROMIC EBT1 and HD-810, manufactured by International Specialty Products, Wayne, NJ.[13]

First, the films were cut into 1.5 cm × 1.5 cm pieces and were placed in prelabeled plastic sleeves. A series of films was placed in a cubic Perspex phantom with a dimension

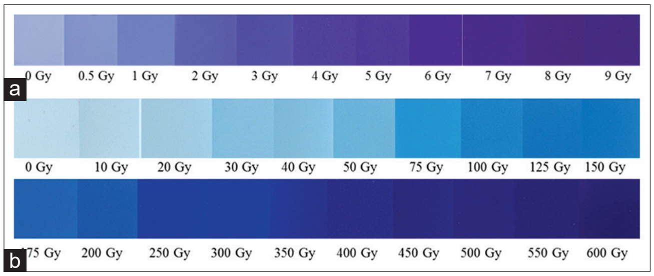

Figure 2: Calibration of films with a cobalt-60 standard source. (a) EBT1 film in the dose range 0.5 Gy–9 Gy, (b) HD-810 film in a dose range 10 Gy–600 Gy

of 30 cm × 30 cm × 15 cm and was irradiated with Co-60 gamma irradiators, namely Picker-V9 at the standard field of Secondary Standard Dosimetry Lab, Karaj, Iran. The dose rate at 80 cm from the source was 195.93 mGy.min − 1. EBT1 film was irradiated and calibrated in the dose range 0.5 - 9 Gy and HD-810 film in a dose range 10 - 600Gy [Figure 2]. The calibration curves were determined using a reflective scanner and Osiris software.

The design of the Plexiglas phantom is shown in Figure 3. To measure the lateral dose profiles, the applicator is placed on the layers of film (EBT1 and HD) with a size of 4 cm × 4 cm in the phantom [Figure 4a]. For depth-dose data, a layer of film was placed perpendicular to the applicator surface between two slabs of Plexiglas. In addition, Plexiglas plates with a thickness of 1 mm were used to measure the absorbed dose at different depth positions. The Plexiglas plates were placed between the ^{32}P applicator surface and the film dosimeters. The film dosimeters were surrounded with 10-cm-thick Plexiglas to ensure full scattering.

Monte Carlo code MCNP5

The MCNP5 code was used to perform the simulations for these investigations.[14] There are several different tally types available in the MCNP5 code for scoring diverse physical characteristics.[15] The *F8 tally (MeV) was used to score the energy deposited in the structure of interest. Simulations were performed to calculate the absorbed dose to water in Plexiglas in order to provide data comparable with the film measurements. For different activity values in mCi, the results should be multiplied by these values, equation (3).

$$\dot{D} = (*F8/M).\ A \qquad (3)$$

where $\dot{D}$ is the dose rate in mGy/min, *F8 is an MCNP5 tally command that provides the deposited energy in MeV, A is the source activity in Bq, and M is the mass in g.

In order to convert the results of the *F8 tally in mGy/min, the results from *F8 tally were divided by the mass (g) of the tally cell, multiplied by the unit conversion factor (9.61×10^{-3} J/kg/min), considering 1 MBq as the source activity.

All inputs were simulated for a total of 8×10^{7} electron histories, resulting in statistical uncertainties generated by the *F8 tally <2%.

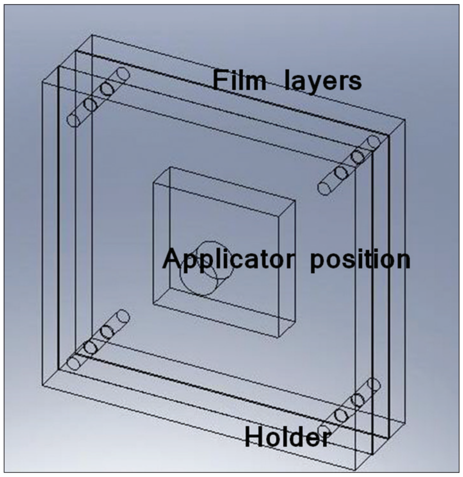

Figure 3: Phantom design for film dosimetry: The ^{32}P applicator is placed on the film layer and then placed inside the Plexiglas that it is also considered as a holder

The ^{32}P beta spectrum in this simulation was extracted from ICRU 72 report.[16]

^{32}P decays to 32S with a half-life of 14.26 days and emit beta particles with a maximum energy of 1.17 MeV [Figure 5].

The structure and material of the applicator such as ceramic plate and steel window were modeled. In order to calculate dose distribution over depth in Perspex, spherical cells were positioned according to depth. The geometry of the applicator is presented in Figures 1 and 3.

The phantom size in this simulation was comparable with the experimental setup (i.e. 20 cm × 20 cm × 5 cm) which is shown in Figure 3. The composition of the Plexiglas was H: 8%; C: 60%; and O: 32%, with a mass density of 1.19 g/cm^3.[15]

To calculate its dose rate, the radioactive applicator was simulated in the center of the phantom [Figure 4b and c] and the simulations were performed at different distances away from the source. We assumed that the source activity was uniformly distributed in the entire volume of the absorbent disk.

PDD was calculated in spherical cells (diameter of 0.4 mm) located along the central axis of the applicator and also a mesh tally was used for calculating the dose profile.

Results

The irradiated radiochromic films for EBT1 and HD-810 film are shown in Figure 6a and b, respectively. Furthermore, the intensity gradient in the films was obtained by Osiris software, as shown in Figure 6a and b for EBT1 and HD-810 film, respectively.

On the other hand, the irradiated films for different depth distances from the applicator surface are shown in Figure 7a and b for EBT1 and HD-810 films, respectively.

Intensity profile in the surface of ^{32}P eye applicator was obtained by ImageJ software that is shown in Figure 8a, and

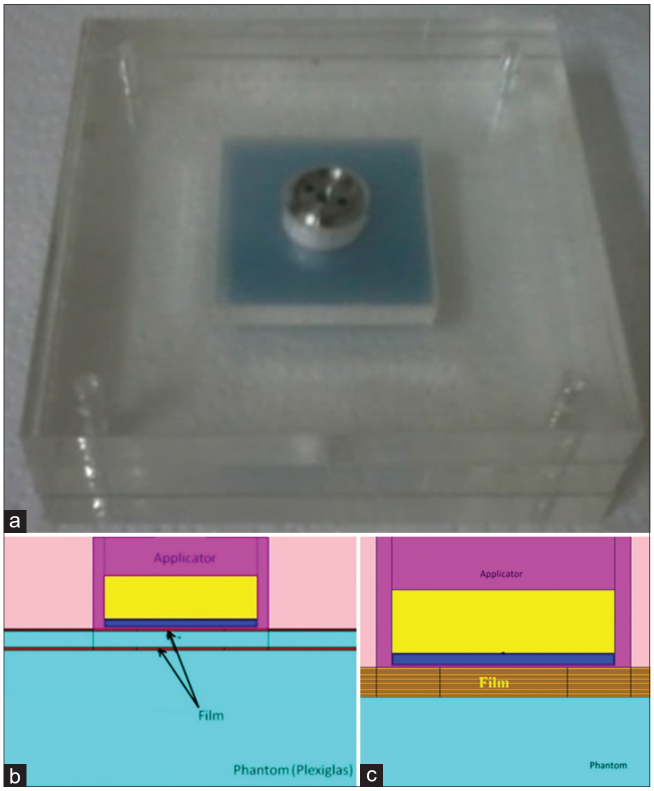

Figure 4: Layout of the film, phantom, and ^{32}P applicator. (a) Experimental setup for films into Plexiglas phantom, (b) Monte Carlo modeling of EBT1 films at the depth distances of 0.1 mm and 1.4 mm in Plexiglas phantom, (c) Monte Carlo modeling of EBT1 films at the depth distances of 0.1 mm to 1.4 mm in Plexiglas phantom by 14 films placed on top of each other

then, normalized dose profile (%) on X-axis and Y-axis was obtained, as shown in Figure 8b.

The depth dose rate obtained from experimental results using HD-810 and EBT film dosimetry and also MC result are shown in Figure 9. The dose rate data are normalized in 0.1 mm distance from the applicator surface. The measurement depth dose distribution data at distances up to 4 mm were compared with calculation data, and the values were not found to differ statistically up to 1.5 mm [Figure 9]. The PDD decreased very rapidly (more than exponentially) with increasing depths [see curve related to HD film and MC dosimetry results in Figure 9]. However, the EBT1 film values at longer distances are 10% different from the HD-810 film.

The PDD by film dosimetry was measured at two depth distances, surface and 1.4 mm (center of the circular surface) in phantom which is shown in Figure 10, respectively.

The dose rate data obtained 0.0053 ± 9.9% (Gy/s.mCi) using EBT1 film and 0.0046 ± 5.5% (Gy/s.mCi) using MCNP5 simulation at 0.1 mm depth distance (at the front surface). There is a relative error of about 11.5% between EBT1 film dosimetry and MCNP5 calculation.

Typical isodose curves at two planes, z = 0.1 mm and z = 1 mm away from perpendicular to the applicator axis, are shown in Figure 11. For color contours, isodose levels were 100%, 80%, 60%, 40%, and 20%. The X- and Y-axes in the contour plot are length and width of the film (2 cm × 2 cm), and we will have a two-dimensional dosimetry.

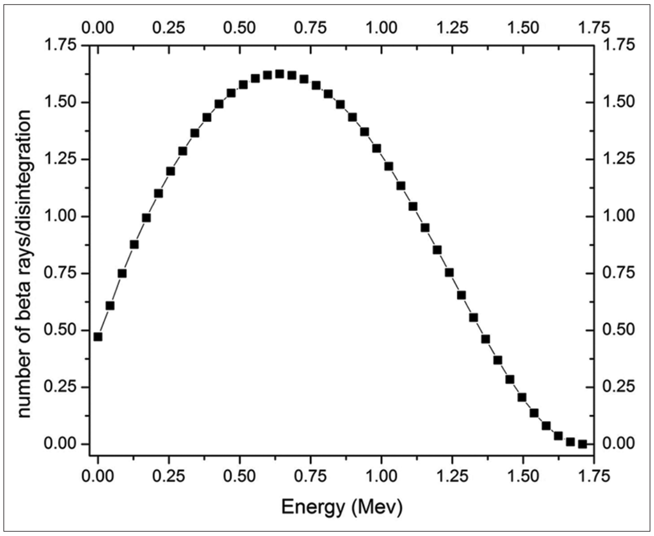

Figure 5: Spectrum of ^{32}P source from ICRU 72[16]

Relative depth dose and lateral dose profiles were tallied along the symmetry axes of the applicators, extending from the inner flat surface into the Plexiglas slab. The isodose in slices perpendicular to the central axis, such as the applicator surface and at a depth of 1 mm, was calculated with MCNP5*F8 tally, which can be seen in Figure 11a and b, respectively. In addition, the experimental isodoses obtained from the radiochromic film corresponding to the two mentioned slices are shown in Figure 11c and d. The comparison results in Figure 11 indicate that the experimental results confirm the MC results. Furthermore, the results showed an appropriate uniformity for the isodose in the mentioned slices.

To determine nonuniformity and asymmetry of ophthalmic source, amounts of $\dot{D}_{min}$, $\dot{D}_{ref}$, $\dot{D}_{max}$, and $\dot{D}_{avg}$ were obtained from the dose profile in Figure 8a.

DISCUSSION

Several problems arise in the dosimetry of pure beta sources, especially for medical purposes. These sources have a relatively steep dose gradient and a short penetration depth (1 cm in water). This gradient is also present in the detection volume and small disturbances in source or detector positioning (about 0.1 mm) may result in large changes in the signal by 10%. On the other hand, there is little standardization in the dosimetry of sealed beta sources. Although several detectors are available for the dosimetry of beta sources, it is difficult to find detectors calibrated and traceable to the primary standard for these sources.[16] In this study, we aimed to develop a relative dosimetric system using radiochromic film for calibration of the ^{32}P eye applicator.

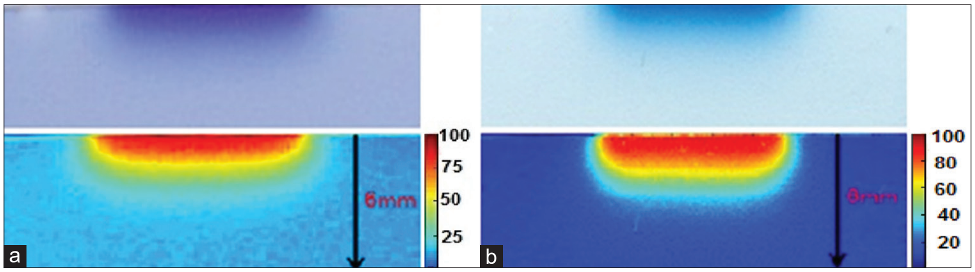

Figure 6: Irradiated radiochromic films (up) and the resulting intensity gradient as the color images (down), (a) EBT1 film and its intensity gradient, (b) HD-810 film and its intensity gradient

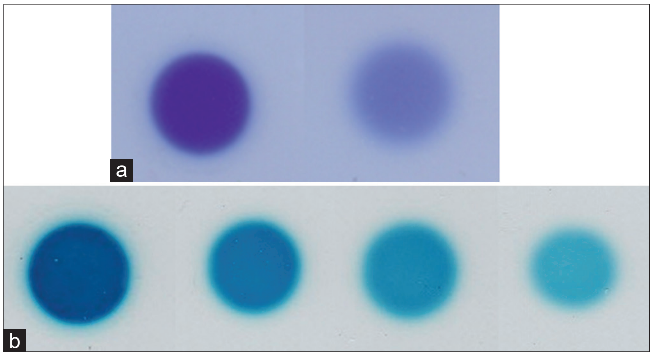

Figure 7: Optical density (OD) pattern of the films at the depth distances. (a) Irradiated HD-810 films at the depth distances 0.1 mm, 0.5 mm, 1 mm, and 1.4 mm shown from left to right and dose corresponding of 349.0 Gy, 245.0 Gy, 162.0 Gy, and 97 Gy, respectively, (b) Irradiated EBT1 films at the depth distances 0.1 mm and 1.4 mm and dose corresponding of 339.0 Gy and 113.0 Gy, respectively

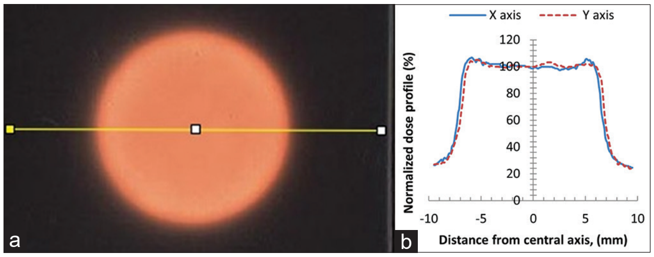

Figure 8: Lateral dose profile in the surface of ^{32}P eye applicator that normalized in central axis. (a) Film intensity profile by ImageJ software, (b) Normalized dose profile (%) in X-axis and Y-axis

Choi *et al*. reported that, due to the possibility of nonuniform distributions of ^{32}P in an absorbent disk, measuring dose profiles as well as the reference dose rate for every new applicator would be recommended.[3] As can be seen in Figure 7, for the HD film, a higher resolution is observed in the gradient intensity. In addition, the intensity in the lateral profile, which indicates the uniformity of the activity at the surface of the source, as well as the uniformity of the applicator window foil, was determined by ImageJ software for the surface film (type HD-810), as shown in Figure 8a. This profile is drawn in two directions x and y, which are compared in Figure 8b. There is slight nonuniformity in the edge of the applicator which can be ignored. This change may be due to small changes in the edge thickness of the steel plate. The radiochromic films were also used to assess dose uniformity on the flat source, and the result indicated that phosphorus is absorbed uniformly in the plate and comparable with the data referred by the literature.[3] This claim can be obtained in Figure 11c by a qualitative comparison between the dose profiles of this study and Choi *et al*.[3] In addition, using equation 1 and equation 2, the nonuniformity and the maximum asymmetry were determined 25.1% and 9.7%, respectively, that they are acceptable amounts for ophthalmic applicator.[15]

The measured data from the EBT1 film and HD-810 film were found not to differ between radiochromic films up to 2 mm, but a small deviation was observed for depth distances between 2 mm and 5 mm [Figure 9], attributed in part to its high spatial resolution. The results indicated that HD-810 film is the more accurate dosimeter for high gradient dose application than EBT1 film. In addition, comparison of depth dose distribution from MC data with the experimental result (HD-810 film) in Figure 9 shows the acceptable validation for MC data. As can be seen from Figure 6, the ^{32}P applicator has a large dose gradient. Radiochromic film dosimetry is suitable for beta dosimetry because its high spatial resolution permits easy replacement near the applicator surface and can be used to measure dose at millimeter intervals,[18] but the main disadvantage of this technique is the reduced reproducibility owing to the scanner type. At depth distances close to the surface of the applicator, the dose rate from ^{32}P betas is reduced to approximately one-tenth at a distance of 2 mm. Being considered very high dose gradient and measurement setup uncertainties, measured data sets in depths of surface to 1.5 mm agreed with MC data, so that the average error of experimental and simulation was 7%.

The eye dose required for the post-operative radiation in each therapeutic fraction is approximately 10 Gy and the obtained dose rate (9.9% ± 0.0053 Gy.s-1.mCi-1) makes a practical treatment time. As well as, it is comparable to the data presented (0.0064 Gy. s-1. mCi-1) by Choi *et al*.[3,17]

The results of the measured dose rates and the PDD in Figure 10 showed that at a distance of 1.4 mm in comparison with the surface of the applicator, dose decline begins sooner and dose gradient is less with increasing distance from the applicator, therefore delivering a lower dose to healthy tissue in the lateral distance from the center.

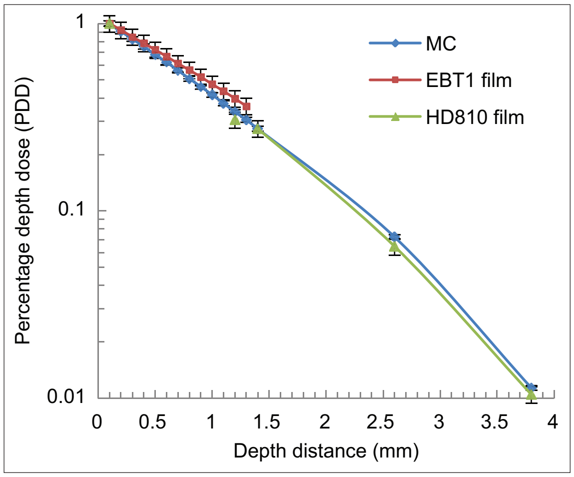

Figure 9: Comparison of percentage depth dose obtained from experimental results (using HD-810 and EBT film dosimetry) with Monte Carlo result up to a depth distance of 3.8 mm from the ^{32}P applicator surface, which the data normalized in 0.1 mm distance from the applicator surface

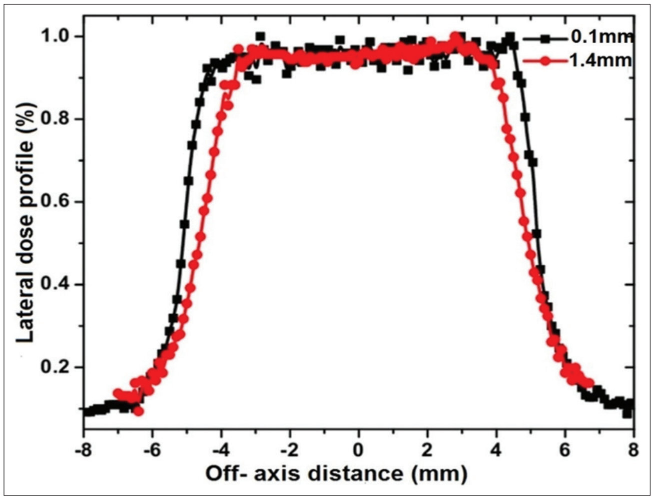

Figure 10: Lateral dose profile by film dosimetry (type EBT1) at depth distances of 0.1 mm and 1.4 mm

The analysis of the uncertainties of the measured doses with GAFCHROMIC film calibrated with ^{60}Co gamma rays was reported by Soares *et al.*[19] Uncertainties are both random, statistical (type A) and nonrandom, systematic (type B). In this study, uncertainty of type B was estimated at 4% which included uncertainty of net film response (2%) and film calibration (2%). Film nonuniformity correction type B was estimated at 2.9%, which included absorbed-dose response, time and temperature corrections, and film nonuniformity correction. However, overall uncertainty for the dose rate in term Gy/s was estimated at 6.9%.

The beta activity of the ^{32}P solution before dropping into the absorbent disk was measured for at least four times using the dose calibrator (ISOMED1010), and the average activity was recorded. The uncertainty associated with the activity measurement was estimated to be about 3%.[20] Therefore, the overall uncertainty can be estimated reported 9.9% for the dose rate in term Gy/s.mCi.

We now have a dose rate in term Gy/s.mCi (with the error of 9.9%) for this eye applicator, so in the hospital, the dose rate amount at the reference depth (such as 0.1 mm) in Plexiglas can be measured by the film in term Gy/s (with the error of 6.9%), and finally, the activity value in term mCi with the acceptable error can be determined through this an indirect method.

The Netherlands Commission on Radiation Dosimetry[15] recommends not to use beta sources with a source strength that deviates more than 10% from the certificate and the dose nonuniformity should be below 30% for ophthalmic sources and a maximum asymmetry below 20%, and with these tolerances, the variation in absorbed dose in the target volume can be kept at an acceptable level.[15] Our results indicated that the dose nonuniformity and the maximum symmetrical for the ^{32}P applicator were 9.7% and 7.8%, respectively. However, during acceptance of a new source, other than purely dosimetric aspects should be considered a QC procedure.

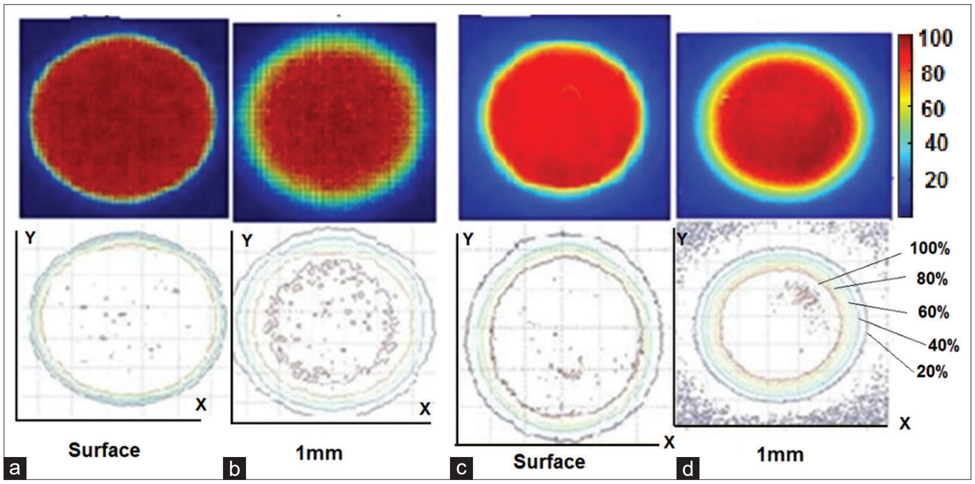

Figure 11: Isodose curves of the ^{32}P applicator obtained using Monte Carlo method and film dosimetry (type HD-810) and for the surface of applicator and depth of 1 mm, (a) Monte Carlo method in surface, (b) Monte Carlo method in 1 mm, (c) Film dosimetry in surface, (d) Film dosimetry in 1 mm. For color contours, isodose levels were 100%, 80%, 60%, 40%, and 20%

CONCLUSIONS

We report the measurements of the dose distribution on the ^{32}P applicator, and the dose distribution is practical for irradiation after pterygium excision. Our experiments showed that the use of a low-cost radiochromic film to perform relative dosimetric checks by the user of the beta ophthalmic applicator is feasible.

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Conflicts of interest

There are no conflicts of interest.

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