Received:
22 September 2015

Revised:
18 February 2016

Accepted:
31 March 2016

<http://dx.doi.org/10.1259/bjr.20150783>

Cite this article as:

Wu J, Huang J, Long F, Wang C, Wu Z, Gou C. Monte Carlo dosimetric parameter study of a new ^{32}P brachytherapy source. *Br J Radiol* 2016; **89**: 20150783.

FULL PAPER

Monte Carlo dosimetric parameter study of a new ^{32}P brachytherapy source

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Objective: Recently, a new catheter-based ^{32}P brachytherapy source has been developed (College of Chemistry, Sichuan University) for use in high-dose-rate afterloader. This study presents the results of the dosimetric data of the Geant4 Monte Carlo (MC) simulation toolkit for this new ^{32}P brachytherapy source.

Methods: The new ^{32}P source had dimensions of 0.50-cm length and 0.08-cm diameter and was encapsulated in teflon. In this study, we attempted to obtain dosimetric data for this new source, as required by the formalism proposed by the American Association of Physicists in Medicine reports TG60 and TG149. The source was located in a 30-cm radius theoretical sphere water phantom, and the absorbed dose of the source was calculated using MC code.

Results: The dosimetric data included the reference absorbed dose rate, the radial dose function in the range of 0.10–0.50 cm at a longitudinal axis, the polynomial

function for the radial dose function and the anisotropy function with a θ value of 0–90° in 5° intervals and an r of 0.10–0.35 cm in 0.01-cm intervals. The radial and axial dose profiles and away-along quality assurance table are also calculated for the unsheathed ^{32}P source. The dose rate $D(r_0, \theta_0)$ at the reference point for the unsheathed ^{32}P source is determined to be equal to $1.2660 \pm 0.0006 \text{ cGy s}^{-1} \text{ mCi}$. The radial dose function of the new ^{32}P source shows good agreement with the other ^{32}P source presented in this work with an average difference of 1.78%.

Conclusion: Dosimetric data are provided for the new ^{32}P source. These data could be used in treatment-planning systems in clinical practice.

Advances in knowledge: Provided a new beta-emitting brachytherapy source that is intended for treatment of liver cancer. A dosimetric study of the unsheathed ^{32}P source for which no published dosimetric data existed was performed.

INTRODUCTION

At present, more and more beta-emitting sources are utilized in brachytherapy fields, and many new types of brachytherapy sources are available. Two applications of beta-emitting brachytherapy sources have been proposed: (a) in intravascular brachytherapy—the dosimetric parameters of a $^{90}\text{Sr}/^{90}\text{Y}$ source were calculated by Holmes et al¹ using an experimental method. Soares et al² obtained a radial dose function and an anisotropy function from their measurements of an old $^{90}\text{Sr}/^{90}\text{Y}$ source in A150 plastic, and these authors also presented the Monte Carlo (MC) results of these dosimetric parameters. (b) In radiotherapy for localized tumours—the ^{32}P source model RIC-100 (developed by RI consultant) has been used for temporary radiation therapy of the spinal dura and other localized tumours, and dosimetric evaluations have been applied to the source with an MCNP5 (Monte Carlo

N-particle code 5) MC code by Cohen et al.³ ^{90}Y microspheres have recently been used to treat unresectable hepatocellular cancer by Nelson et al.⁴

According to a lot of pre-clinical experiments for the new ^{32}P source, this new source is well suited for liver cancer. So, we intended to use our new ^{32}P brachytherapy source for liver cancer. The ^{32}P source is a pure beta emitter with a 14.3-day half-life, maximum beta energy of 1.71 MeV and average beta energy of 0.695 MeV.^{5,6} According to the American Association of Physicists in Medicine (AAPM) TG60/TG149 report recommendations,^{7,8} dosimetry at distances in the order of 1 mm from the beta-emitting sources are poorly understood, and a better understanding of dosimetry in the millimetre range will help these sources in the development of clinical practice. In addition, TG60 and TG149 are reports that provide the dose parameter

Table 1. Composition of the different materials used in the Monte Carlo simulations in this work

Elements	Teflon (%)	Nylon-12 (%)	Liquid ^{32}P (%)	Air (%)
H		0.1175		
C	0.2402	0.7305		0.0001
N		0.071		0.7553
O		0.081		0.2318
F	0.7598			
Ar				0.0128
H ₂ O			0.999	
^{32}P			0.001	
Density (g cm^{-3})	2.2	1.2	1.0	0.0012048

formalism for a beta-emitting source, and the reference distance is defined to be 0.20 cm.

The dosimetric parameters of the ^{32}P source have created new challenges in the field of brachytherapy dosimetry. The challenges of the ^{32}P source revealed the following: (a) the dosimetric parameters of the ^{32}P source are interest in the spatial scale of a millimetre or submillimetre; and (b) the parameters are difficult to perform accurately in these close distances owing to the extremely large dose gradients. Although the dosimetric parameters of the ^{32}P brachytherapy source are difficult to obtain, the experimental works and simulation codes were both successful when performed.^{9–12} Wang et al¹⁰ derived the dosimetric data from their modified EGS4 MC code of a $^{90}\text{Sr}/^{90}\text{Y}$ source in SS304 stainless steel. Xu et al¹² presented the three-dimensional distribution of a $^{90}\text{Sr}/^{90}\text{Y}$ intravascular brachytherapy seed by experimental measurement. In this work, we employed Geant4 to derive accurate calculations of the dosimetric parameters of the new catheter-based ^{32}P source, following the formalism proposed by AAPM reports TG60 and TG149 and the quality assurance (QA) purpose of the new ^{32}P source. These dose parameters include the dose rate at the reference point, radial dose functions and anisotropy functions. To ensure calculation accuracy, the present calculation was compared with several calculations reported by other authors.

Figure 1. Schematic design and dimensions of the new ^{32}P source (centimetres).

Figure 2. Polar coordinate system for dose calculation.

METHODS AND MATERIALS

Brachytherapy sources

The sizes and materials of the new ^{32}P source were provided by the College of Chemistry, Sichuan University, and the manufacturer tolerances of this new source were ± 0.001 cm. The basic sizes and materials of the core and capsules used in the simulation were taken as follows: the active core is composed of a liquid ^{32}P (99.9% H₂O and 0.1% ^{32}P) with a density of 1.0 g cm^{-3} in Table 1. The radioactive material is uniformly distributed in its core, and the energy spectrum of the ^{32}P source is described by Cross et al.¹³

The active core is encapsulated. The active core of the source is a cylinder with a length of 0.47 cm and a diameter of 0.08 cm. The capsule material is teflon (24% C and 76% F), with an effective density of 2.2 g cm^{-3} , as shown in Table 1. At the centre of the capsule is a cylinder of 0.42-cm length, 0.08-cm outer diameter and 0.05-cm inner diameter and two semi-spherical endings with 0.08-cm external diameter and 0.05-cm inner diameter on the top and bottom of the cylindrical capsule. The new ^{32}P source is centred inside a cylindrical catheter of nylon-12 (11.75% H, 73.05% C, 7.10% N and 8.10% O) of 0.12-cm external diameter, 0.09-cm internal diameter and a density of 1.2 g cm^{-3} . Gaps between catheters and sources were assumed to be filled with air. A schematic diagram of the new ^{32}P source is presented in Figure 1.

Dose calculation formalism

The dose calculation formalism for the beta-emitting source, proposed by the AAPM report TG60 in 1999 and TG149 in 2007,^{7,8} has been followed. This formalism has been described in terms of the polar coordinate system, such as that illustrated in Figure 2.

Table 2. Comparison of the dose rate at the reference point from this work with calculated values of other authors (using different MC simulation codes)

Source	$D(r_0, \theta_0)$ ($\text{cGy s}^{-1} \text{ mCi}$)
This work (Geant4)	1.2660 ± 0.0006
Torres et al ¹⁸ (Geant4)	0.2312 ± 0.0008
Torres et al ¹⁸ (PENELOPE)	0.2150 ± 0.0010
Mourtada et al ¹⁹ (EGSnrc)	0.2185 ± 0.0002
Bohm et al ²⁰ (MCNPv4B2)	0.2320 ± 0.0003

Table 3. Comparison of the radial dose function [$g_L(r)$] of this work with the calculated values of other authors

r (cm)	$g_L(r)$ (this work)	$g_L(r)$ (Torres et al ¹⁸)	% difference
0.10	1.4020	1.4280	1.82
0.11	1.3554		
0.12	1.3217		
0.13	1.2887		
0.14	1.2528		
0.15	1.2132	1.2260	1.04
0.16	1.1729		
0.17	1.1319		
0.18	1.0888		
0.19	1.0441		
0.20	1.0000	1.0000	0.00
0.21	0.9552		
0.22	0.9110		
0.23	0.8657		
0.24	0.8206		
0.25	0.7767	0.7800	0.42
0.26	0.7338		
0.27	0.6925		
0.28	0.6515		
0.29	0.6122		
0.30	0.5740	0.5860	2.05
0.35	0.4033	0.4120	2.11
0.40	0.2665	0.2700	1.30
0.45	0.1656	0.1670	0.84
0.50	0.0948	0.0900	5.33

$g_L(r)$, radial dose function; r , radial distances from 0.10 to 0.50 cm.

where r denotes the distances from the centre of the active source to the point of interest, r_0 is the reference distance, which is defined to be 0.20 cm in this protocol. θ denotes the polar angle of the point of interest, and the reference angle, θ_0 , is specified to be $\pi/2$. β is the angle subtended by the active source with respect to the point of interest $P(r, \theta)$. The reference point is represented by $P(r_0, \theta_0)$ in Figure 2. L is the active length of the source ($L = 0.47$ cm). $GL(r, \theta)$ is the geometry factor, $g_L(r)$ is the radial dose function and $F(r, \theta)$ is the dose anisotropy function. The dose at any point around the source can be expressed as:

$$\dot{D}(r, \theta) = D(r_0, \theta_0) \cdot \frac{G_L(r, \theta)}{G_L(r_0, \theta_0)} \cdot g_L(r) \cdot F(r, \theta) \quad (1)$$

For a beta particle-emitting source, the formalism is a little different from that of a photon-emitting source; the air kerma strength S_k and dose rate constant in water λ were replaced by the dose rate $D(r_0, \theta_0)$ at the reference point, which has units of centigray per millicurie. This is because air kerma is applied to

only photon-emitting sources and does not exist for beta-emitting sources.

Monte Carlo simulation code

MC particle transport methods are increasingly used in medical physics, in particular for the development of brachytherapy. Popular MC methods in this field are Geant4,¹⁴ FLUKA (fluctuating cascade),¹⁵ EGS (electron gamma shower),¹⁶ MCNP (Monte Carlo N-particle code)¹⁷ and PENELOPE (penetration and energy loss of positrons and electrons in matter).^{9,18} In this article, Geant4 was used to derive all necessary dosimetric data for the new ^{32}P source. The Geant4 code has been developed and successfully applied in both high- and low-energy ranges. In addition, Geant4 allows for the simulation of the passage of primary particles and the produced secondary particles through matter. It can be applied to energies ranging from a few hundred electron volts to up to 1 GeV and with arbitrary materials.

Figure 3. Radial dose functions calculated for the new ^{32}P source without catheter and the old ^{32}P source. The line is the polynomial fit of order 5 for the new ^{32}P source. cm, centimetre.

Geant4 (Geant4.9.6.P02 development version, European Organization for Nuclear Research) was developed by the European Organization for Nuclear Research and is based on the C++ language. It requires the user to write each particle and physics model to be included in the simulation. It also provides interaction models for all electromagnetic and nuclear processes relevant for the transport of brachytherapy. The Geant4 physics model selected in this work was a standard electromagnetic interaction model and used the function GetTotalEnergyDeposit, to obtain the dosimetric data. The number of electrons N_e generated in each simulation was $N_e = 3 \times 10^8$. The electron and the photon cut-off energy were set to 1 keV.

In this study, we assumed that the ^{32}P source was positioned at the centre of a spherical liquid water phantom of 30-cm

Figure 4. Radial dose profiles $D(y,z)$ with a different radial position z for the unsheathed ^{32}P source in water. cm, centimetre.

Figure 5. Axial dose profiles $D(y,z)$ with a different radial position y for the unsheathed ^{32}P source in water. cm, centimetre.

radius, to provide dose data to water and simulate infinite phantom conditions for $r < 1.0$ cm. In this way, the phantom was divided into a large number of cells to reduce calculation error, and all dosimetric data in this study were obtained with respect to only the coordinates of r (ranging from 0.10 to 0.35 cm).

The absorbed dose that was used to calculate the radial dose function and anisotropy function was obtained simultaneously in cylindrical (y, z) and spherical (r, θ) coordinates, and the source axis was along the z -axis of the coordinate system, as shown in Figure 2. In cylindrical coordinates, y and z are representatives of the radial and axial coordinates, respectively. In spherical coordinates, r is defined as the distance from the centre of the active region of the source. When $z = 0.0$, we set up cells at y in the range of 0.10–0.35 cm with increments of 0.01 cm to obtain the absorbed dose $D(y,z)$; subsequently, we used these absorbed doses to obtain the radial dose function. In the spherical coordinate system, we set up cells at the same distances as those used in the cylindrical coordinate system. At the same time, θ ranged from 0° to 90° (angular sampling was taken every 5°) while obtaining the absorbed dose $D(r,\theta)$, and then we used the anisotropy function equation to calculate the anisotropy function.

For the new ^{32}P source, the statistical uncertainty of the MC dose $D(y,z)$ depended on the axial position z and the radial position y . When $z \leq 0.25$ cm, the statistical uncertainty was within 0.20% for $y \leq 0.40$ cm. With increases in the position z , the statistical uncertainty was within 0.31% for $y \leq 0.40$ cm.

RESULTS

Unsheathed source

Reference absorbed dose rate

The dose rate at the reference point for the unsheathed source was obtained by using the Geant4 code and it was found to be equal to 3.4216×10^{-10} Gy per electron. The dose rate $D(r_0, \theta_0)$ at the reference point of the unsheathed ^{32}P source in water

Angle (°)	Radial distance (cm)																										
	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	
0																	1.332	1.454	1.547	1.627	1.699	1.745	1.819	1.881	1.960	2.049	
5																	1.414	1.481	1.551	1.615	1.671	1.729	1.784	1.841	1.902	1.989	
10																1.491	1.495	1.524	1.573	1.623	1.676	1.730	1.778	1.839	1.899	1.985	
15																	1.468	1.496	1.536	1.578	1.622	1.666	1.713	1.758	1.815	1.867	1.950
20																	1.476	1.502	1.537	1.572	1.610	1.648	1.689	1.728	1.772	1.821	1.900
25	1.100	1.105	1.118	1.124	1.143	1.165	1.190	1.218	1.248	1.276	1.308	1.336	1.364	1.391	1.421	1.453	1.479	1.512	1.545	1.577	1.607	1.644	1.677	1.719	1.758	1.831	
30	1.071	1.076	1.087	1.103	1.124	1.145	1.170	1.195	1.222	1.246	1.276	1.301	1.328	1.355	1.384	1.410	1.435	1.462	1.495	1.526	1.551	1.584	1.611	1.648	1.686	1.750	
35	1.050	1.059	1.071	1.086	1.104	1.121	1.143	1.164	1.187	1.210	1.235	1.256	1.281	1.302	1.328	1.352	1.373	1.396	1.424	1.450	1.471	1.497	1.523	1.553	1.586	1.645	
40	1.041	1.049	1.061	1.072	1.088	1.105	1.122	1.140	1.161	1.179	1.199	1.219	1.239	1.258	1.280	1.299	1.318	1.339	1.357	1.380	1.398	1.421	1.443	1.469	1.495	1.549	
45	1.036	1.038	1.047	1.057	1.069	1.082	1.096	1.112	1.128	1.141	1.160	1.176	1.193	1.210	1.226	1.241	1.256	1.272	1.288	1.305	1.319	1.338	1.354	1.376	1.397	1.449	
50	1.033	1.029	1.035	1.042	1.052	1.061	1.073	1.084	1.096	1.108	1.121	1.134	1.147	1.158	1.171	1.186	1.195	1.208	1.223	1.236	1.249	1.261	1.271	1.292	1.307	1.356	
55	1.027	1.021	1.024	1.027	1.031	1.033	1.035	1.049	1.142	1.125	1.134	1.144	1.157	1.168	1.182	1.194	1.203	1.216	1.229	1.242	1.253	1.266	1.279	1.299	1.323	1.398	
60	1.020	1.019	1.019	1.018	1.018	1.018	1.018	1.106	1.099	1.103	1.113	1.122	1.133	1.142	1.154	1.164	1.172	1.182	1.193	1.205	1.213	1.225	1.235	1.254	1.277	1.347	
65	0.991	0.983	1.003	0.998	0.998	1.007	1.076	1.057	1.060	1.065	1.073	1.081	1.089	1.097	1.105	1.113	1.119	1.128	1.138	1.146	1.153	1.163	1.173	1.190	1.211	1.291	
70	1.013	0.995	0.990	0.986	0.992	1.057	1.032	1.031	1.035	1.039	1.047	1.053	1.059	1.065	1.073	1.080	1.084	1.091	1.100	1.108	1.114	1.123	1.132	1.151	1.175	1.265	
75	1.015	0.995	0.988	0.985	0.984	1.055	1.022	1.019	1.022	1.023	1.028	1.032	1.038	1.042	1.048	1.053	1.056	1.062	1.069	1.076	1.080						

Figure 6. Anisotropy function calculated for the unsheathed ^{32}P source for selected distances.

was $1.2660 \pm 0.0006 \text{ cGys}^{-1} \text{ mCi}$, as shown in Table 2, along with the corresponding values calculated by other authors.^{18–20}

The dose rate at the reference point for the 2.70-cm ^{32}P source was calculated to be 0.2312 ± 0.0008 and $0.2150 \pm 0.0010 \text{ cGys}^{-1} \text{ mCi}$ for Geant4 and PENELOPE by Torres et al.¹⁸ The dose at the reference point $0.2185 \pm 0.0002 \text{ cGys}^{-1} \text{ mCi}$ was calculated by Mourtada et al.¹⁹ using an EGSnrc code, and the dose rate at the reference point $0.2320 \pm 0.0003 \text{ cGys}^{-1} \text{ mCi}$ was calculated by Bohm et al.²⁰ using an MCNPv4B2 MC code. The value of the dose rate at the reference point for the new ^{32}P source (the length of the active source was 0.47 cm) in this work is higher than that calculated for the old ^{32}P source. These percentage differences were nearly equal to the percentage differences observed for the sizes and materials of the sources.

Radial dose functions

The calculations of the radial dose functions $g(r)$ of the unsheathed ^{32}P source for radial distances from 0.10 to 0.50 cm are presented in Table 3. It must be noted here that at radial distances far from the source ($r > 0.35 \text{ cm}$), the radial dose functions have fewer values. When the results of our calculations were compared with those of Torres et al.¹⁸ for the 2.0-cm-long ^{32}P source in NiTi tubes, differences of 5.33% were observed between radial dose function values only at $r = 0.50 \text{ cm}$ and they were $< 2.11\%$ for all other radial distances.

The radial dose function, $g_L(r)$, also fit over the range of $0.10 \leq r \leq 0.50 \text{ cm}$ using a fifth-order polynomial function, as presented in Figure 3. The polynomial function is shown in Equation (2). The values of the fitted parameters in Equation 2 were as follows: $R^2 = 1$, $a_0 = 0.01771$, $a_1 = -0.44983$, $a_2 = 5.68668$, $a_3 = -11.82432$, $a_4 = 2.79516$, $a_5 = 5.56452$ and $a_6 = 2.56705$. The overall accuracies of the fits were excellent, and the fits were based on the polynomial exhibited maximum of $< 0.20\%$.

$$g(r) = (a_0 r^{-2} + a_1 r^{-1} + a_2 + a_3 r + a_4 r^2 + a_5 r^3) e^{-a_6 r} \quad (2)$$

Dose profiles

The following is the two-dimensional dose profiles $D(y, z)$ of the unsheathed ^{32}P source in water. Figure 4 shows the radial dose profiles $D(y, z)$ for selected axial distances of $z = 0.0, 0.10, 0.25, 0.40$ and 0.50 cm . It can be observed that for $0 < z < L/2$ ($L = 0.47 \text{ cm}$, which is the active length of the source), the radial dose values are higher than those for $z > L/2$. Furthermore, the radial dose decreases more sharply than for other regions; for $y > 0.25 \text{ cm}$, as y increases, the dose fall-off becomes shallower. The axial dose profiles $D(y, z)$ of the ^{32}P source at radial distances $y = 0.0, 0.10, 0.15, 0.25, 0.40$ and 0.50 cm are presented in Figure 5. The results show that the axial doses at $y = 0.10$ and 0.15 cm are higher and sharper than for other positions. Beyond this region, the dose declines in an approximately exponential way. In addition, for $z > L/2$, the decline of doses is smoother than for other positions. The dose distributions were normalized by the maximum dose of the axial and radial distances at 0.20 cm , respectively.

Anisotropy functions

In Table 4 and Figure 6, full data for the anisotropy functions $F(r, \theta)$ are presented for radial distances $r = 0.10\text{--}0.35 \text{ cm}$ and polar angles $\theta = 0^\circ\text{--}90^\circ$. Anisotropy function values were not calculated for points located inside the source volume. A feature of the anisotropy functions is that $F(r, \theta)$ of a beta-emitting source has more points, > 1.0 . Thus, we can observe that the effective distance of the ^{32}P source is less than 0.35 cm ; beyond this distance, we can ignore the absorbed dose.

An along-away table for QA purposes is presented in Table 5. For this table, the longitudinal direction is equal to the y -axis (cm) and the transverse direction is equal to the z -axis (cm), as we can see in Figure 2. The new ^{32}P source is symmetric about the transverse and vertical axes; therefore, the QA values were tabulated over the range of $0.10 \leq y \leq 0.4$ and $0.0 \leq z \leq 0.40 \text{ cm}$.

Sheathed source

Here, we show the effect of the catheter on the dosimetric data. Table 6 shows the comparison of depth doses for the sources sheathed and unsheathed by the catheter. As we can see, our calculated depth dose rate values for the sheathed source $\dot{D}_{\text{cath}}(r, z_0)$ agreed with the calculated depth dose rate values for the unsheathed source $\dot{D}(r, z_0)$. However, the source sheathed by the catheter shows an increase in the depth dose rate on the longitudinal axis.

Figure 7 shows the relative difference between the depth dose rate value for the source sheathed $\dot{D}_{\text{cath}}(r, z_0)$ and unsheathed $\dot{D}(r, z_0)$ in this work using Equation 3. The study shows that an unsheathed source produces a slightly smaller modification of the dose in water than a sheathed source. When $r \leq 0.23 \text{ cm}$, the relative difference is always within 2.0% and is 2.0–3.2% for the positions of $0.30 < r \leq 0.50 \text{ cm}$.

$$\frac{\dot{D}_{\text{cath}}(r, z_0) - \dot{D}(r, z_0)}{\dot{D}(r, z_0)} \quad (3)$$

Table 5. Quality assurance away-along data (gray per minute millicurie) for the unsheathed ^{32}P sources

y/cm	z/cm																
	0.0	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40
0.10	2.855	2.687	2.590	2.470	2.301	2.101	1.870	1.587	1.311	1.068	0.835	0.655	0.515	0.395	0.307	0.243	0.185
0.12	2.131	1.975	1.893	1.806	1.669	1.528	1.380	1.179	0.995	0.844	0.668	0.536	0.437	0.335	0.263	0.215	0.162
0.14	1.628	1.494	1.431	1.362	1.252	1.148	1.051	0.904	0.776	0.676	0.542	0.443	0.369	0.287	0.229	0.188	0.144
0.16	1.257	1.145	1.094	1.042	0.956	0.879	0.812	0.703	0.610	0.541	0.441	0.365	0.310	0.243	0.196	0.164	0.126
0.18	0.977	0.884	0.842	0.805	0.738	0.682	0.633	0.550	0.482	0.434	0.357	0.299	0.258	0.204	0.167	0.140	0.109
0.20	0.761	0.687	0.654	0.626	0.573	0.532	0.496	0.432	0.382	0.347	0.288	0.244	0.213	0.170	0.140	0.119	0.093
0.22	0.596	0.536	0.510	0.488	0.447	0.416	0.390	0.341	0.303	0.278	0.232	0.198	0.175	0.141	0.116	0.100	0.078
0.24	0.466	0.419	0.399	0.382	0.349	0.326	0.307	0.269	0.240	0.222	0.186	0.161	0.142	0.116	0.096	0.083	0.066
0.26	0.364	0.327	0.312	0.299	0.273	0.256	0.241	0.212	0.190	0.177	0.149	0.129	0.116	0.094	0.079	0.069	0.054
0.28	0.285	0.256	0.244	0.233	0.213	0.200	0.189	0.167	0.151	0.141	0.119	0.103	0.093	0.076	0.064	0.056	0.045
0.30	0.223	0.200	0.190	0.182	0.166	0.157	0.148	0.131	0.118	0.111	0.094	0.082	0.074	0.061	0.052	0.045	0.036
0.32	0.173	0.155	0.148	0.142	0.130	0.122	0.116	0.102	0.093	0.087	0.075	0.066	0.059	0.049	0.042	0.037	0.029
0.34	0.135	0.121	0.115	0.110	0.101	0.095	0.090	0.080	0.073	0.068	0.059	0.052	0.047	0.039	0.033	0.029	0.023
0.36	0.104	0.093	0.089	0.084	0.078	0.074	0.070	0.062	0.057	0.053	0.046	0.040	0.037	0.030	0.026	0.023	0.018
0.38	0.080	0.072	0.069	0.065	0.059	0.057	0.054	0.047	0.044	0.041	0.035	0.032	0.028	0.024	0.020	0.018	0.014
0.40	0.061	0.055	0.052	0.049	0.045	0.043	0.040	0.036	0.033	0.031	0.027	0.024	0.021	0.018	0.016	0.014	0.011

Table 6. Depth dose rates (in centigray per second per millicurie) calculated for the sheathed ^{32}P source, $\dot{D}_{\text{cath}}(r, z_0)$, and unsheathed source, $\dot{D}(r, z_0)$

r (cm)	$\dot{D}(r, z_0)$	$\dot{D}_{\text{cath}}(r, z_0)$
0.10	4.7916	4.8266
0.15	2.3719	2.4013
0.20	1.2660	1.2831
0.25	0.6856	0.6977
0.30	0.3719	0.3786
0.35	0.1993	0.2030
0.40	0.1035	0.1064
0.45	0.0518	0.0534
0.50	0.0244	0.0247

r , radial distance.

CONCLUSION

Many new types of brachytherapy sources are becoming available. Before any of these sources can be used in clinical practice, their dosimetric parameters must be calculated by using the MC code. The main purpose of the present work was to use the MC simulation code Geant4 to derive all the necessary dosimetric parameters (reference absorbed dose rate, radial dose function and anisotropy function) for the new ^{32}P brachytherapy source, based on the dose calculation formalism recommended by AAPM TG60 and TG149. The dose distribution and QA purpose are also calculated for the new ^{32}P source. These parameters are shown in this work in the configuration of both a graph and a table. Furthermore, these dosimetric parameters for the new ^{32}P source did not exist previously. All of the statistical uncertainties at distances of $z \leq 0.40$ cm and $y \leq 0.40$ cm were below 0.31%.

Figure 7. The relative difference between the depth dose rates calculated for the sheathed ^{32}P source, $\dot{D}_{\text{cath}}(r, z_0)$, and the unsheathed source, $\dot{D}(r, z_0)$. cm, centimetre.

The results of this study have been compared with those of several published works. Differences in the sizes and materials of the new ^{32}P source do not seem to affect radial dose function calculations. The decreased length of the new ^{32}P source design (the active length of the new source was 0.47 cm) resulted in increased reference absorbed dose rate compared with the old ^{32}P source (the active length of the old source was 2.70 cm). The presence of the sheathed source produces an increase of within 3.2% in the depth dose rate on the longitudinal axis. These differences could produce non-negligible modifications in the clinical use of the sources. At present, the new ^{32}P brachytherapy source has been applied in the Fonics plan treatment system developed by a Chinese company (Qilin Co., Ltd).

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