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Dose rate distribution around an irridium-192 brachytherapy source: from modeling point of view

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ABSTRACT

Efforts to minimize dose delivered to critical organs of cancer patients and also to improve local tumour control have led to the development of High Dose Rate (HDR) brachytherapy procedures. The associated risks in HDR brachytherapy are relatively high, hence strict quality assurance requirements are needed. In this study, mathematical model has been used to compute the dose rate distributions around an Ir-192 HDR brachytherapy source. The calculations were based on separation of dose rates around the sources into transverse axis component and an anisotropy function. The two dimensional coordinate system for anisotropy functions was then transformed into a one dimensional system with radial distances from the centre of the source as constraints. The maximum average fit uncertainty was found to be 0.35% for the anisotropy functions. The maximum uncertainty in the calculated dose rate distribution around the source was 14.31%, which is less than the uncertainty quoted in published reports for other methods. The model is therefore an improvement over existing recommended systems for dose calculations and the results can be used as quality control tool to improve dose delivery to cancer patients undergoing brachytherapy.

Introduction

Brachytherapy is a term used to describe the short distance treatment of cancers with radiations coming from encapsulated radionuclide sources. Most of the brachytherapy sources usually emit photons however, in few specialized situations beta or neutron emitting sources are used. Brachytherapy treatments can either be a permanent or temporary implant. The physical advantage of brachytherapy treatment compared to external beam radiotherapy is the improved localized delivery of dose to the target tumour volume of interest[1].

The most important aspects which are common to any brachytherapy treatment are the use of a suitable model for the treatment time, dose calculation formalism and the use of calibrated sources. A treatment does not reach its goal if the source misses its aimed positions. Owing to the steep dose gradient that characterizes brachytherapy; such source misses may be seriously detrimental to the intended treatment [2].

Dose delivery in brachytherapy procedures can be achieved by simple or complex mathematical models or computer codes. Mathematical methods of evaluating dose rate distributions around brachytherapy sources include the Sievert Integral algorithm, Monte Carlo simulations and the Modular dose calculation formalisms.[3,4,5]

The Sievert integral is simple and easy to use but its accuracy in calculating dose rate distributions around low energy brachytherapy sources such as Iridium-192 have been repeatedly put to question[6]. The most accurate method of calculating dose rate distributions around brachytherapy is by the Monte Carlo simulations but the input dosimetric parameters for patient dose rate distributions are many; making it user unfriendly and cumbersome in clinical applications. Nevertheless, it can be used as independent verification of dose delivery and calculations in regions of steep dose gradients[4,7].

The modular dose calculation formalism was developed by the Radiation Committee of American Association of Physics in Medicine, Task Group number 43{AAPM(TG-43)} for the calculation of dose rate distributions around brachytherapy sources in two dimensions(2-D). This can be applied to determine the dose rate distribution around a brachytherapy source at any point and it is based on measurable quantities in water equivalent medium. Its uncertainty in the determination of the dose rate distribution around brachytherapy sources is relatively high, of the order of 17%[8].

The aforementioned problems of accuracy in the Sievert algorithms and AAPM(TG43) as well as the cost and complications involved in Monte Carlo simulations necessitates the introduction of a simple but faster, more accurate and cost effective method for calculating the dose rate distributions around a High Dose rate(HDR) brachytherapy source. HDR brachytherapy offers a lot of practical advantages as compared to Low Dose Rate(LDR) brachytherapy. The quality control aspects involved in HDR brachytherapy is quite high and enormous [9,10]

In this study, a mathematical model is presented to account for anisotropy in the dose distribution functions presented by AAPM (TG-43) mathematical formalism. The study covers the mathematical modelling of the dose rate distributions around an Iridium-192 High Dose Rate (HDR) brachytherapy source based on AAPM(TG43) modular dose calculation formalism**.** In this modelling, the AAPM(TG-43) calculation formalisms around the brachytherapy source were modified. The modification was done by separating the AAPM(TG43) formalism into two components. These are the dose rates along the transverse axis of the source and anisotropy functions using one dimensional (1-D) functions. The results obtained from the studies were compared with existing methods.

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Method of analysis

In this modeling, consideration is given to cylindrically symmetric brachytherapy source. For such sources the dose distribution is two-dimensional (2-D) and can be described in terms of the polar coordinate system with its origin at the source centre as shown in Figure 1.

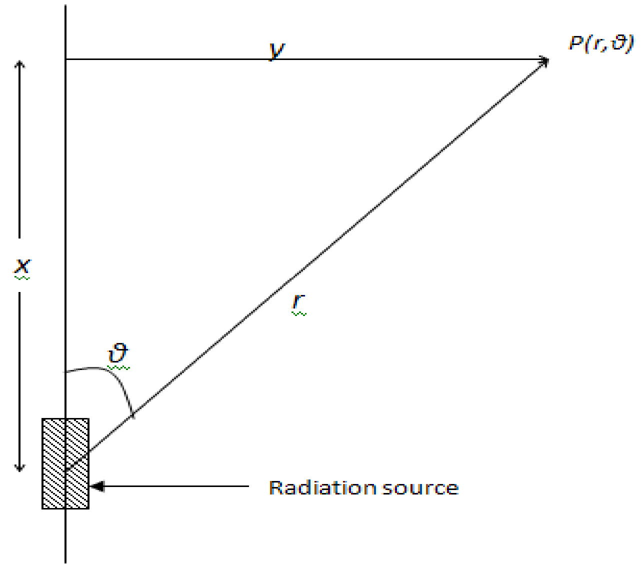

Fig.1. Schematic representation of an HDR brachytherapy source showing the geometric definition of r and θ for a filtered radiation source

The components r and θ are used to specify the calculation point P of interest. The dose rate distributions around the source is 2-D and can be determined using the AAPM (TG43) dose calculation formalism[8] as follows

$$\dot{D}(r,\theta)=S_k\Lambda\left[\frac{G(r,\theta)}{G(r_0,\theta_0)}\right]g(r)F(r,\theta) \quad \textbf{(1)}$$

where

S_k = air Kerma strength of the source.

Λ = dose rate constant

$G(r_0,\theta_0)$ = geometric factor at the reference point.

$G(r,\theta)$ = geometric factor

$g(r)$= radial dose function

$F(r,\theta)$= anisotropy function

From equation (1) expressing the function

$$S_k\Lambda\left[\frac{G(r,\theta)}{G(r_0,\theta_0)}\right]g(r) = kG(r,\theta)g(r) \quad \textbf{(2)}$$

where k, is a constant given by

$$k=\frac{S_k\Lambda}{G(r_0,\theta_0)} \quad \textbf{(3)}$$

At the reference point (r_0,θ_0) the geometric factor is equal to unity and S_k and Λ are constants for a specific brachytherapy source.

The expression in equation (2) is basically a function of r and θ and depicts a 2-D dose rate distribution. This can be further simplified by introducing the function $t(r,\theta)$ as

$$t(r,\theta) = kG(r,\theta)g(r) \quad \textbf{(4)}$$

Equation (1) can therefore be reformulated as

$$\dot{D}(r,\theta)=t(r,\theta)\cdot F(r,\theta) \quad \textbf{(5)}$$

For distances which are equal to 2-3 times the dimension of the characteristic active source, the geometric factor differs from the inverse square law by less than 1% [11]. The purpose of the geometry function is to represent an approximation of particle streaming distribution that is dose distribution in the absence of any absorbing or scattering media. The approximation does not have to be very accurate because the geometry function merely serves as an interpolation function, improving the accuracy of the AAPM(TG43) formalism[12]. Along the transverse axis of the source $\theta=\pi/2$

Therefore

$$t(r,\theta)=t(r) \quad \textbf{(6)}$$

The expression in equation(6) therefore becomes the dose rate along the transverse axis of the source which has been reduced to a one dimensional(1-D) function.

Substituting equation (6) into equation (5), the dose rate distribution at any point of a brachytherapy source can be evaluated by combining the dose rate along the transverse axis of the source and the anisotropy function by the relation

$$\dot{D}(r,\theta)=t(r)\cdot F(r,\theta) \quad \textbf{(7)}$$

The anisotropy function can be reformulated by using the diagram in Figure 2

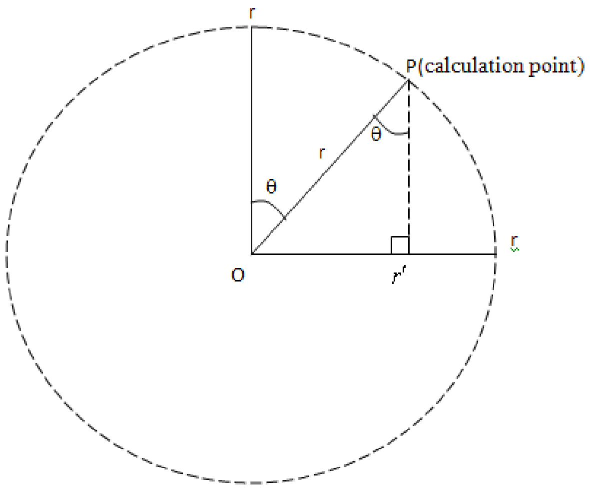

Fig 2. Calculation of radial distances from the centre of the source

The anisotropy is a 2-D function which is based on both r and θ. It is calculated by using a new coordinate system r_1 hence reducing the number of independent variables. From the diagram in figure 2; the point O represents the point source and at the same time the centre of the brachytherapy source. The value of r_1 at any calculation point P was determined using the relation

$$r_1 = rSin\theta \quad \textbf{(8)}$$

The values of r_1 were calculated for the angles ranging from 0^o to 90^0.

Hence the dose rate distribution around the source has been reduced to 1-D and can be determined as follows

$$\dot{D}=t(r)F(r_1) \quad \textbf{(9a)}$$

or

$$\dot{D}(r)=t(r)F(r-r_1) \quad \textbf{(9b)}$$

Some clinical treatment planning systems(TPS) utilize 1-D isoptropic point source model to calculate the dose rate distribution around brachytherapy sources. In this case the dose depends only on the radial distances from the source and the anisotropy function transformed into anisotropy factor $\phi_{an}(r)$

$$\dot{D}(r) = t(r)\phi_{an}(r) \quad \textbf{(10)}$$

The anisotropy factor can be evaluated by using numerical integration as follows

$$\phi_{an}(r) = 0.5\int_0^{\pi} \frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_0)} \sin\theta \, d\theta \quad \textbf{(11)}$$

which finally reduces to

$$\phi_{an}(r) = \int_0^{\pi/2} F(r,\theta)\sin\theta d\theta \quad \textbf{(12)}$$

Equation (12) can be used to evaluate the anisotropy factor in any order of the anisotropy function.

Results and discussions

In this study, the radioisotope used is a high dose rate iridium-192 brachytherapy source. It has an activity of 370 GBq with a total length of 5.0 mm and diameter 1.1 mm (active source length 3.5mm, and active diameter of 0.6 mm). It is encapsulated in a stainless steel. The dose rate distributions along the transverse axis of the source are shown in table **1**. The results of the anisotropy factors for radial distances of r = 2cm and r = 5cm for second order polynomials are presented in tables **2** and **3** respectively. Using regression analysis and the method of least squares to fit the anisotropy factors with radial distances of 2cm and 5cm from the brachytherapy source, the following quadratic equations were obtained.

$F(r_1) = 0.7554+0.2082r_1- 0.0433r_1^2$ *with* $R^2 = 0.9994$ *for* $r = 2cm$ (13)

$F(r_1) = 0.7964+0.0670r_1- 0.0053r_1^2$ *with* $R^2 = 0.9990$ *for* $r = 5cm$ (14)

$F(2-r_1) = 1- 0.0318(2-r_1) - 0.0444(2-r_1)^2$ *with* $R^2 = 0.9991$ *for* $r = 2cm$ (15)

$F(5-r_1) = 1- 0.0149(5-r_1) – 0.0050(5-r_1)^2$ *with* $R^2 = 1.0000$ *for* $r = 5cm$ (16)

A comparison of the dose rate distribution from the AAPM (TG43) and the results from this study is presented in table **4**

It is observed from table**1** that, the dose rate along the transverse axis of the source decreases as the distance from the source increases. A rapid dose falloff is seen between distances 1cm and 3cm, which is due to the effect of the inverse square law. A general increase in anisotropy factor is observed in tables **2** and **3** as the distance away from the source increases. The average fit uncertainty for the anisotropy functions at radial distances of 2cm and 5cm was found to be 0.35%. The calculated anisotropy factors are 0.914 and 0.857 at radial distances of 2cm and 5cm respectively. This is because at distances closer to the source there is less anisotropy, hence there is no significant loss in dose rate distribution around the source.

In recent times, one of the most widely used models in clinical treatment planning systems (TPS) in brachytherapy is the one-dimensional(1-D) isotropic point model. In this case, the dose rate distributions around the source depend on the radial distance from the source when using this model. The two-dimensional(2-D) dose calculation model leads to large dose calculation errors at shorter distances in high dose rate brachytherapy. This is because of its inability to account for the geometric distribution of radioactivity in the source rather than the distance-dependence of the anisotropy function. Even though, anisotropy in reality is 2-D, the 1-D anisotropy function is preferred due to a number of considerations; for example, it is easier to calibrate sources along the transverse axis which makes it more practicable.

In this study, the American Association of Physicist in Medicine Task Group number 43 {AAPM(TG43)} model was modified to determine the dose rate distribution around an iridium-192 high dose rate brachytherapy source using one dimensional(1-D) functions. Comparing the results of this study with that of the AAPM(TG43) as shown in table **4**, it was observed that, the maximum uncertainty in the dose rate distributions calculated using this model was found to be 14.3% in water equivalent tissue for a radial distance of 5cm from the source. This is lower than the maximum uncertainty of 17.0% as recommended by AAPM (TG-43) for the same medium. The results show that incorporating this model into the treatment planning system in brachytherapy dosimetry will not introduce significant errors.

Conclusion

The dose rate distribution around an iridium-192 brachytherapy source has been investigated using theoretical calculations. The results were compared with AAPM(TG43) method and it indicates that, considering accuracy, speed and cost implications this method offers a faster, simpler and cheaper means of determining dose rate distributions around a High Dose Rate(HDR) brachytherapy source such as iridium-192. This method could be used as a quality control tool to improve accuracy in dose calculations in HDR brachytherapy. In this investigation, the anisotropy factor closer to the source is observed to be lower than at a further distance away from the brachytherapy source.

In future, techniques for modeling the dose rate distributions around an iridium-192 HDR brachytherapy source using one dimensional function is recommended.

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Table 1: Dose rate along the transverse axis of the source

Distance y*(cm)*	Dose rate *(cGys^{-1})*
1	12.934 ± 0.26%
2	3.244 ± 0.22%
3	1.444 ± 0.41%
4	0.814 ± 0.00%
5	0.521 ± 0.38%

Table 2: Anisotropy factor at radial distances r = 2cm and 5cm around the source

Degrees (θ)	Radial distance r_1 (for r = 2cm)	Anisotropy factor for r = 2cm	Radial distance r_1 (for r=5cm)	Anisotropy factor for r = 5cm
0	0.000	0.758	0.000	0.799
10	0.347	0.820	0.868	0.848
20	0.684	0.875	1.710	0.893
30	1.000	0.920	2.500	0.930
40	1.286	0.954	3.214	0.959
50	1.532	0.976	3.830	0.978
60	1.732	0.989	4.330	0.990
70	1.880	0.995	4.698	0.995
80	1.970	0.997	4.924	0.997
90	2.000	0.998	5.000	0.997

Table 3: Anisotropy factor at radial distances of (2- r_1) and (5-r_1) for radial distances of r = 2cm and 5cm around the source

Degrees (θ)	Radial distance (2-r_1) (for r=2cm)	Anisotropy factor for r = 2cm	Radial distance (5-r_1) (for r = 5cm)	Anisotropy factor for r = 5cm
0	2.000	0.762	5.000	0.800
10	1.653	0.823	4.132	0.853
20	1.316	0.878	3.290	0.897
30	1.000	0.923	2.500	0.931
40	0.714	0.956	1.786	0.957
50	0.468	0.979	1.170	0.976
60	0.268	0.991	0.670	0.988
70	0.120	0.997	0.302	0.995
80	0.030	1.000	0.076	0.999
90	0.000	1.000	0.000	1.000

Table 4: Comparison of dose rate distributions between AAPM (TG-43) and this work for radial distance of 2cm and 5cm

Distance y (cm)	AAPM (TG-43) dose rate *(cGy/s)*	Dose rate for this work; for r = 2cm *(cGy/s)*	Dose rate for this work; for r = 5cm *(cGy/s)*
1	13.361	12.212	11.450
2	3.340	3.053	2.862
3	1.485	1.357	1.273
4	0.835	0.763	0.716
5	0.534	0.488	0.458

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