Neutron dose rate for ^{252}Cf AT source in medical applications

L. PAREDES* †‡, J. AZORINŦ, M. BALCAZAR†, J.L. FRANÇOIS¥

† National Institute of Nuclear Research, Mexico
‡ Medicine Faculty, Autonomous University of Mexico State, Mexico
Ŧ Basic Sciences Division, Autonomous Metropolitan University, Mexico
¥ Engineering Faculty, Autonomous National University of Mexico, Mexico

Abstract

The AAPM TG-43 modified protocol was used for the calculation of the neutron dose rate of ^{252}Cf sources for two tissue substitute materials, five normal tissues and six tumours. The ^{252}Cf AT source model was simulated using the Monte Carlo MCNPX code in spherical geometry for the following factors: a) neutron air kerma strength conversion factor, b) dose rate constant, c) radial dose function, d) geometry factor, e) anisotropy function and f) neutron dose rate. The calculated dose rate in water at 1 cm and 90º from the source long axis, using the Watt fission spectrum, was $\dot{D}_n(r_0,\theta_0)$ =1.9160 cGy/h-µg. When this value is compared with Rivard *et al*. calculation using MCNP4B code, 1.8730 cGy/h-µg, a difference of 2.30% is obtained. The results for the reference neutron dose rate in other media show how small variations in the elemental composition between the tissues and malignant tumours, produce variations in the neutron dose rate up to 12.25%.

Keywords: Californium, Brachytherapy, Monte Carlo.

1. Introduction

The ^{252}Cf is a neutron emitting radioisotope with potential for both clinical brachytherapy and neutron capture therapy applications. Due to its high yield of neutron emission and relatively long half-life of 2.645 y, it is the most useful neutron emitter with 3.768 neutrons per spontaneous fission, 3.1% decay probability and a total neutron yield of 2.314E12 neutrons/g s [1].

The ^{252}Cf AT source has an active length of 15 mm. It is doubly encapsulated in Pt/ Ir 10% tubes. It is 23 mm long, 2.8 mm in diameter and 0.07 mm thick [1].

2. Methods

According to the AAPM TG-43 modified protocol [1,2] the general equation for the neutron dose rate is presented in equation (1), where the reference neutron dose rate $\dot{D}_n(r_0,\theta_0)$ for any material is defined at a radius of 1 cm and angle of 90°, equation (2).

* Corresponding autor, *e-mail address:* lpg@nuclear.inin.mx

$$\frac{\dot{D}_n(r,\theta)}{\mu g} = \frac{S_{kn}}{\mu g}\Lambda_n\, g_n(r)\left[\frac{G(r,\theta)}{G(r_0,\theta_0)}\right]F_n(r,\theta) \tag{1}$$

The mathematical expressions for each parameter are the following:

$$\frac{\dot{D}_n(r_0,\theta_0)}{\mu g} = \frac{S_{kn}}{\mu g}\Lambda_n \tag{2}$$

$$\frac{S_{kn}}{\mu g} = \frac{\dot{K}_n(d)}{\mu g}d^2 \tag{3}$$

$$\Lambda_n = \dot{D}_n(r_o,\theta_o)/S_{kn} \tag{4}$$

$$g_n(r) = \frac{\dot{D}_n(r,\theta_0)\,G_n(r_0,\theta_0)}{\dot{D}_n(r_0,\theta_0)\,G_n(r,\theta_0)} \tag{5}$$

$$G_n(r,\theta) = \frac{\arctan(L/(2r\sin\theta)+\cot\theta)+\arctan(L/(2r\sin\theta)-\cot\theta)}{Lr\sin\theta} \tag{6}$$

$$G_n(r_0,\theta_0) = \frac{2}{L}\arctan(L/2) \quad \ni \; d \ll 1 \tag{7}$$

$$G_n(r,\theta_0) = \frac{2\arctan(L/2r)}{Lr} \tag{8}$$

$$F_n(r,\theta) = \frac{\dot{D}_n(r,\theta)\,G_n(r,\theta_0)}{\dot{D}_n(r,\theta_0)\,G_n(r,\theta)} \tag{9}$$

where, $\dot{D}_n(r,\theta)$ is the neutron dose rate [cGy h^{-1} μg^{-1}]; $\dot{D}_n(r_0,\theta_0)$ is the reference neutron dose rate [cGy h^{-1} μg^{-1}]; S_{kn} is the neutron air kerma strength conversion factor [cGy-cm^2 h^{-1} μg^{-1}]; Λ_n is the neutron dose rate constant [cm^{-2}]; $g_n(r)$ is the neutron radial dose function [dimensionless]; $G_n(r,\theta)$ is the geometry factor [cm^{-2}]; $G_n(r_0,\theta_0)$ is the geometry factor at r_0= 1 cm, and θ_0=90° [cm^{-2}]; $F_n(r,\theta)$ is the neutron anisotropy function [dimensionless]; $\dot{K}_n(d)$ is the neutron air kerma rate [cGy h^{-1} μg^{-1}]; r is the radial distance from source centre to the point of interest [cm]; θ is the angle from source long axis to point of interest [radians]; d is the calibration reference distance, d_0=100 cm.

The Monte Carlo MNCPX code was used for characterize neutron dosimetry in the vicinity of ^{252}Cf AT source. For calculations the Watt fission neutron energy spectrum was used. The neutron air kerma rate was obtained with the +F6 heating tally for estimate the total energy deposition for mass unit of all particles for spherical geometry of 200 cm in radius. Each set of calculations required transport of 10^8 particle histories to attain relative standard uncertainties <0.1%.

The neutron dose was calculated in a variety of clinically relevant media for medical applications; a) Tissue substitute materials: water, A-150 plastic; b) normal tissue: muscle (skeletal), brain, lung, gastrointestinal tract, breast; c) Malignant tumours: sarcoma, carcinoma, squamous cell lung carcinoma, rectal adenocarcinoma, adenocystic carcinoma, melanoma.

3. Results and discussion

First the source was simulated with the MCNPX into a spherical geometry of 200 cm to obtain the neutron air kerma rate $\dot{K}_n(d)$ and the neutron air kerma strength S_{kn} at a distance of 100 cm along the transverse axis. The result is 0.33499±3E-4 cGy-cm^2/h µg. If this value is compared with Rivard *et al* value, 0.3300 cGy-cm^2/h µg, a difference of 1.49% is obtained.

In table 2 is presented a comparison of the reference neutron dose rate $\dot{D}_n(r_0,\theta_0)$ in water for some authors; Colvett, Krishnaswamy, Yanch and Zamenhof, Wierzbicki, Rivard and this study [3-6,1], using the Watt fission neutron spectrum. The difference between this study and Rivard is 2.30% and between this study and Colvett (experimental) is -8.46%.

In table 3 are shown the reference neutron dose rate $\dot{D}_n(r_0,\theta_0)$ and the neutron dose rate constant Λ_n for two tissue substitute materials, five normal tissues and six malignant tumours [7-9]. Therefore, when the reference media is water, $\dot{D}_n(medium)/\dot{D}_n(water)$, there is a variation in the reference neutron dose rate up to 12.25%. When muscle is the reference medium $\dot{D}_n(medium)/\dot{D}_n(muscle)$, the range difference is from -5.66% to 5.00%. So, it indicates that the muscle could be recommended for reference medium in clinical calculations [7-9]. The difference between the muscle and water is about 6%.

The results for the anisotropy function $F_n(r,\theta)$ are presented in table 4. They confirm the $F_n(r,\theta)\approx 1$ approximation. The neutron radial dose function for water, A-150, muscle and brain is shown in figure 1 and the geometry factor in figure 2.

Finally, the neutron dose rate $\dot{D}_n(r,\theta)$ for θ_0=90° constant vs. r for different media is shown in figures 3-4. Similarly $\dot{D}_n(r,\theta)$ for r_0=1 cm constant vs. angle for different media are shown in figures 5-6. This results show how a small difference in the elemental composition, produce variation in the neutron dose rate [7-9].

The elemental composition is of particular importance in neutron radiation therapy where the kerma is mainly determined by the hydrogen and oxygen contents in tissue. The adipose tissue with 11.4% hydrogen and 27.8% oxygen contents may receive approximately 9% more dose than soft tissue with 10.5% hydrogen and 60.2% oxygen contents [7-9].

Table 1. The neutron air kerma rate $\dot{K}_n(d)$ and the neutron air kerma strength S_{kn} at a distance of 100 cm along the transverse axis for ^{252}Cf AT source.

Reference	$K_n(d)$ (MeV/g-n)	$K_n(d)$ (cGy/n)	$K_n(d)$ (cGy/h-μg)	S_{kn} (cGy-cm^2/h-μg)
Rivard	2.4722E-07	3.9614E-15	3.3000E-05	0.33000
This study	2.5095E-07 ± 2E-10	4.0213E-15 ± 4E-18	3.3499E-05 ± 3E-8	0.33499 ± 3E-4
Difference (%)	1.49	1.49	1.49	1.49

Table 2. Comparison of the reference neutron dose rate $\dot{D}_n(r_0,\theta_0)$ in water in a point at *r*=1 cm and 90° along the transverse axis, for ^{252}Cf AT source model by different authors.

Cf-252 AT source reference	$D_n(r_0,\theta_0)_{water}$ (cGy/h-μg)	Method	MCNP/experimental (%)
Colvett	2.0930	Experimental	0.00
Krishnaswamy	1.9290	MCNP	-7.84
Yanch and Zamenhof	1.9000	MCNP	-9.22
Wierzbicki	1.8800	MCNP4B	-10.18
Rivard	1.8730	MCNP4B	-10.51
This study	1.9160 ± 2E-4	MCNPX	-8.46
This study / Rivard	2.30 %		

Table 3. The reference neutron dose rate $\dot{D}_n(r_0,\theta_0)$ and the neutron dose rate constant Λ_n in two tissue substitutes, five normal tissues and six malignant tumours.

Materials	$D_n(r_0,\theta_0)$ (cGy/h-μg)	Λ_n (cm^{-2})	$\Delta D_n(r_0,\theta_0)$ (cGy/h-μg)	$\Delta\Lambda_n$ (cm^{-2})	$D_n/D_{n\ water}$ (%)	$D_n/D_{n\ muscle}$ (%)
Water	1.9160	5.7196	±0.0002	±0.005	**0.00**	6.00
A-150	1.8979	5.6656	±0.0002	±0.005	-0.94	5.00
Muscle	1.8076	5.3958	±0.0002	±0.005	-5.66	**0.00**
Brain	1.8979	5.6656	±0.0002	±0.005	-0.94	5.00
Lung	1.8256	5.4498	±0.0002	±0.005	-4.72	1.00
Gastrointestinal tract	1.8799	5.6117	±0.0002	±0.005	-1.89	4.00
Breast	1.8889	5.6387	±0.0002	±0.005	-1.41	4.50
Sarcoma	1.8074	5.3953	±0.0002	±0.005	-5.67	-0.01
Carcinoma	1.8394	5.4908	±0.0002	±0.005	-4.00	1.76
Squamous cell lung carcinoma	1.7052	5.0904	±0.0002	±0.005	-11.00	-5.66
Rectal adenocarcinoma	1.7052	5.0904	±0.0002	±0.005	-11.00	-5.66
Adenoid cystic carcinoma	1.6483	4.9205	±0.0002	±0.005	-13.97	-8.81
Melanoma	1.6813	5.0190	±0.0002	±0.005	-12.25	-6.98

Table 4. The anisotropy function $F_n(r,\theta)$ for ^{252}Cf AT source.

r (cm)	θ = 0°	θ = 5°	θ = 10°	θ = 20°	θ = 30°	θ = 45°	θ = 60°	θ = 90°
0.25						1.0082	1.0045	1.0000
0.50				1.0235	1.0122	1.0083	1.0068	1.0000
0.75			1.0127	1.0016	1.0014	1.0000	1.0000	1.0000

1.00			0.9856	0.9933	0.9975	1.0012	1.0000	1.0000
1.50	0.9618	0.9688	0.9785	0.9995	0.9954	1.0023	1.0000	1.0000
2.00	0.9489	0.9645	0.9756	0.9954	0.9990	1.0012	0.9999	1.0000
3.00	0.9535	0.9615	0.9769	0.9983	0.9985	1.0000	1.0000	1.0000
5.00	0.9988	0.9838	0.9747	0.9992	0.9986	1.0000	1.0010	1.0000
10.00	1.0088	0.9837	0.9776	0.9957	0.9986	1.0012	1.0000	1.0000

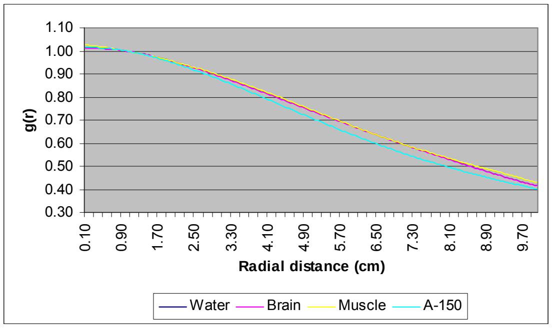

Figure 1. The neutron radial dose function $g_n(r)$ for two tissue substitutes and two tissues.

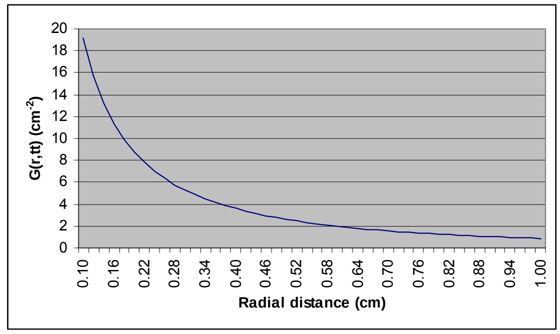

Figure 2. The geometry factor $G_n(r,\theta)$ for the Cf-252 AT source with active length of 1.5 cm

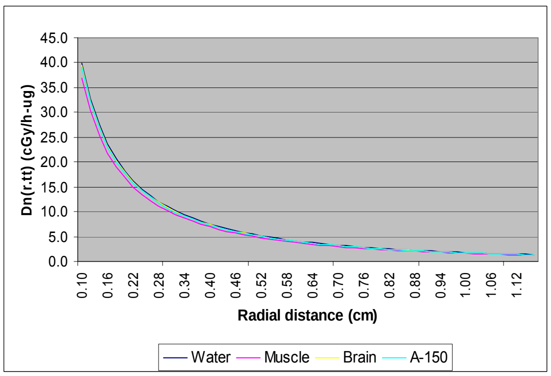

Figure 3. The neutron dose rate $D_n(r,\theta)$ (cGy/h-µg) for Cf-252 AT source for θ_0=90º constant vs. r for two tissue substitutes and two tissues.

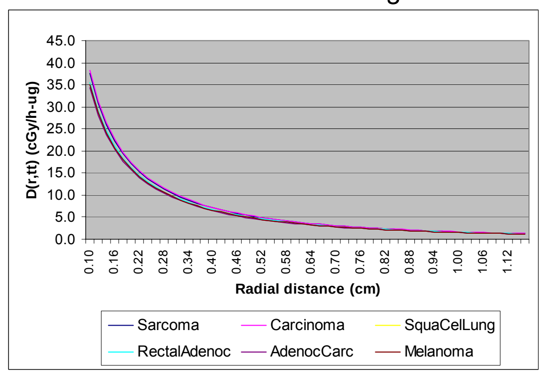

Figure 4. The neutron dose rate $D_n(r,\theta)$ (cGy/h-µg) for Cf-252 AT source for θ_0=90º constant vs. r for six tumours.

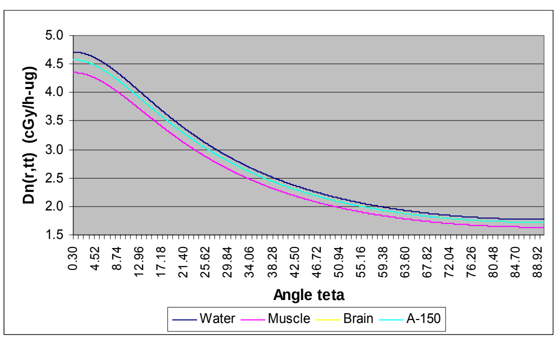

Figure 5. The neutron dose rate $D_n(r,\theta)$ (cGy/h-µg) for Cf-252 AT source for r_0=1 cm constant vs. θ for two tissue substitutes and two tissues.

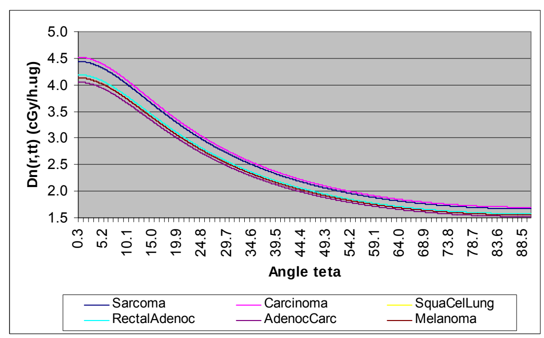

Figure 6. The neutron dose rate $D_n(r,\theta)$ (cGy/h-µg) for Cf-252 AT source for r_0=1 cm constant vs. θ for six tumours.

4. Conclusion

The neutron dosimetry for the ^{252}Cf AT source model has been calculated using the Monte Carlo MCNPX code in some media, using the AAPM TG-43 dosimetry formalism. The difference in the neutron dose rate is attributed to new version of MCNP code, and the using +F6 tally. The results show how small variations in the elemental composition between the normal tissue and malignant tumour, produce variations in the neutron dose rate up to 12.25%.

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