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Dosimetric characterization of ^{192}Ir source-Leipzig applicators sets for surface cancer treatment with Monte Carlo code MCNP4C

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ABSTRACT

Monte Carlo simulations were done to characterize a radioactive Nucletron Classic ^{192}Ir source with 6 Leipzig applicators (3 for the horizontal loading position and 3 for the vertical loading position) used in clinical treatments to irradiate superficial cancerous or non-cancerous lesions. The dosimetric characterization was made for each source-applicator system using the MCNP4C2 code. The percentage depth dose (PDD), the maximum dose rate and the dose profiles expressed as a percentage with respect to the maximum dose and the dose distribution curves were obtained. The maximum dose rate values absorbed in water for a 370 GBq source are: 4.53 cGy/s ± 0.1268, 4.46 cGy/s ± 0.0783, 4.49 cGy/s ± 0.1268 for the 1, 2 and 3 cm diameter applicators and the source with a horizontal position respectively. When the source is in a vertical position, the following was obtained: 2.70 cGy/s ± 0.0393, 2.68 cGy/s ± 0.1226 and 2.65 cGy/s ± 0.1171 for 1, 2 and 3 cm aperture respectively. Characterized the 6 source-applicator systems in the longitudinal, transverse and radial axes, the 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40% and 30% dose distribution curves were built. These distributions were normalized at 0.05 cm depth along the central axis of the applicator. Our surface dose rate values have a maximum relative difference of 2.24% with those of Evans for the horizontal applicator with 3 cm in aperture (experimentally obtained) and 0.67 % with those of Leon (calculated by MC). The PDD values obtained are statistically the same as those of Evans on the surface, but differ by 0.28 % at the depth of 2 mm, 2.46 % at 5 mm and 5.2 % at 10 mm. The surface dose profiles coincide with those of Leon and Evans and differ by 0.53% at 4 mm depth as maximum. Source position is critical since the maximum dose rate values differ considerably between the horizontal source position and the vertical source position, for the same applicator aperture. However, the dose distributions at depths smaller than 2 mm in both cases are similar, showing a maximum difference of 1.5%.

Key words: Leipzig applicators, high dose rate, brachytherapy, dosimetry.

RESUMEN

Se caracterizó dosimétricamente la fuente Nucletron Classic ^{192}Ir junto con 6 aplicadores Leipzig (3 para la carga horizontal de la fuente y 3 para la vertical) realizando simulaciones Monte Carlo. Estos aplicadores son utilizados en tratamientos clínicos para irradiar lesiones superficiales cancerosas y no cancerosas. La caracterización dosimétrica se realizó para cada sistema fuente-aplicador utilizando el código MCNP4C2. Se obtuvieron: la curva del porcentaje de dosis en profundidad, la tasa de dosis máxima y los perfiles de dosis expresados como un porcentaje respecto a la dosis máxima, así como las curvas de distribución de dosis. Las tasas máximas de dosis absorbidas en agua, para una fuente de 370 GBq son: 4.53 cGy/s ± 0.1268, 4.46 cGy/s ± 0.0783, 4.49 cGy/s ± 0.1268 para los aplicadores de 1, 2 y 3 cm de diámetro respectivamente con la fuente en posición horizontal respecto a la superficie de aplicación. Cuando la fuente se encuentra en posición perpendicular respecto a la superficie de aplicación, los valores obtenidos fueron: 2.70 cGy/s ± 0.0393, 2.68 cGy/s ± 0.1226 y 2.65 cGy/s ± 0.1171 para 1, 2 y 3 cm de apertura, respectivamente. Caracterizados los 6 sistemas fuente-aplicador en los ejes longitudinal, transversal y radial, se construyeron las curvas de distribución de dosis de 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40% y 30%. Estas distribuciones se normalizaron a 0.05 cm de profundidad a lo largo del eje central del aplicador. Nuestros valores de tasa de dosis superficial tienen una diferencia relativa máxima de 2.24%, para el aplicador horizontal con 3 cm de apertura, comparados con los de Evans (medidos experimentalmente) y 0.67% con los de León (calculados por MC). Los valores de perfiles de dosis en profundidad, estadísticamente son iguales que los de Evans en la superficie pero difieren en un 0.28% a la profundidad de 2 mm, 2.46% a 5 mm y 5.2% a 10 mm. Los perfiles superficiales de dosis coinciden con los de León y Evans y difieren en un 0.53% a 4 mm de profundidad como máximo. La posición de la fuente es crítica ya que los valores de tasa de dosis máxima difieren considerablemente cuando ésta se encuentra en posición paralela o perpendicular a la superficie de aplicación. Sin embargo, las distribuciones de dosis a profundidades menores que 2 mm en ambos casos, son similares, mostrando una diferencia máxima de 1.5%.

Palabras clave: Aplicadores Leipzig, alta tasa de dosis, braquiterapia, dosimetría.

INTRODUCTION

The advances achieved in early cancer diagnosis allow the detection of small tumors confined to only one organ. In those situations, radiation techniques such as brachytherapy are especially suitable.

The technological advances improve brachytherapy sources everyday. They are manufactured in more diverse sizes and forms that can be better adapted to treatment. Also, the use of high dose rate radioactive isotopes has decreased the exposition time for oncological treatments, in the benefit of more cancer patients.

Characterization of high dose rate brachytherapy sources is complicated, mainly due to their size, the type of the radiation emitted and its interaction with the encapsulation and the large dose gradients present[1]. In the past, these characterizations were made exclusively through experimental measurements. More recently, other tools were developed such as Monte Carlo simulation of the radiation interaction with matter. At present, high computing capability has made this tool more accurate and precise. As a consequence, nowadays it's mandatory to carry out Monte Carlo calculations to characterize any new brachytherapy source so that it can be accepted by the scientific community[2,3].

On the other hand, the wide use of brachytherapy has resulted in the appearance of accessories that supplement the treatment of specific pathologies. For example, in 1987 an applicator was developed in the Leipzig University, Germany, that, together with high dose rate sources, proved to be useful in the irradiation of skin cancer and tumors in face, mouth, language, penis, peri-anal and genital regions, Kaposi sarcomas, melanomas, skin manifestations of lymphomas, tumors in solid organs, etc[4].

The Leipzig applicator set is now an accessory for the MicroSelectron ^{192}Ir HDR system[5] for the treatment of superficial lesions. The set is composed by six applicators, three of which are for horizontal source charge and three for vertical source charge. The apertures of the part in contact with the skin or tumor are of 1, 2 and 3 cm.

The dose curves provided by the manufacturer for use in clinical practice are generally originated from measurements carried out with detectors. Their use introduces uncertainties and errors due to detector positioning, angular dependence and alteration of the radiation field. Instead, consent exists in the scientific community to use dosimetric parameters obtained by validated Monte Carlo simulation codes. These calculations have already been useful in finding important practical errors[6].

The Monte Carlo simulation code used in this work is the MCNP4C2[7], a general purpose program that can be used to simulate the transport of neutrons, photons and electrons in almost any medium. It allows the definition of complex geometries by means of mathematical expressions of surfaces and it is possible to declare any source type. Its versatility and solid physical basis allows this program to be applied to a wide range of problems. It contemplates the physical phenomena of coherent and incoherent photon dispersions, fluorescent emission after the photoelectric absorption, pair production with emission of annihilation radiation and bremsstrahlung[6].

MATERIALS AND METHODS

A personal computer with an AMD Turion 64 Mobile 787 MHz processor was used to perform the simulations, with de MCNP4C2 code.

The high dose rate system used for skin surface treatment consists of an encapsulated ^{192}Ir source soldered to a steel cable that allows it to be displaced with the aid of an electric motor controlled by a microprocessor. According to its programming, the source can stop in a series of previously programmed positions inside the applicators. The usual activity of the source varies between 74 and 444 GBq. In this work, the ^{192}Ir MicroSelectron HDR Classic source manufactured by Nucletron Engineering BV, was considered. The source and applicator were modeled as a set.

The source is formed by an iridium metallic core of density 22.42 g/cm^3 in which the radioactive isotope ^{192}Ir is considered to be uniformly distributed. The core is a cylinder of 0.06 cm diameter and 0.35 cm in length. It is covered by an AISI 316L stainless steel capsule of 0.11 cm diameter, with rounded form in one end, as shown in Figure 1. In the other end of the nucleus there is an AISI 304 stainless steel plug, attached to the braided cable. The plug - cable ensemble was modeled as a solid cylinder of 0.3 cm in length[5].

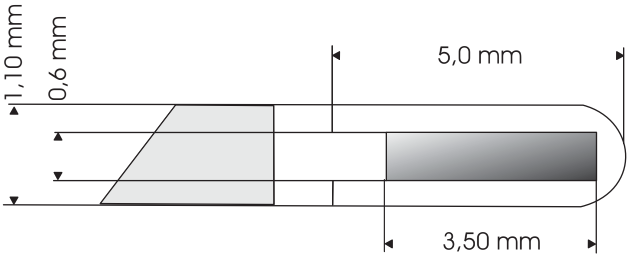

Figure 1. The MicroSelectron ^{192}Ir HDR-Classic encapsulated source, formed by an iridium metallic cylindrical core of 0.06 cm diameter and 0.35 cm length. The core is covered by an AISI 316L stainless steel capsule of 0.11 cm diameter, with rounded form in one end, while in the other end, there is an AISI 304 stainless steel plug, attached to the braided cable.

Figure 2. The six different models of the Leipzig applicators: cone shaped, 92% tungsten and 8% steel alloy devices, with apertures of 1, 2 and 3 cm. Three are for horizontal source loading and three for vertical source loading.

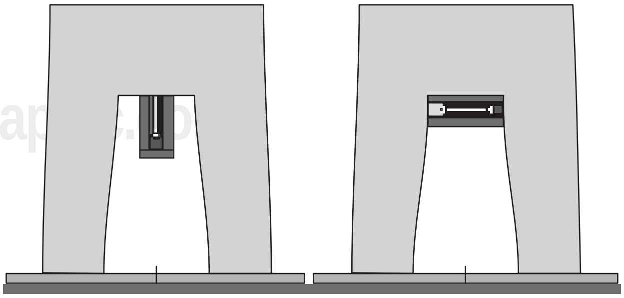

Figure 3. Graphical representation of the Leipzig applicators, modeled with an assembly of mathematical surfaces of cones, cylinders and planes, using the MCNP4C2 code.

Table 1. Chemical composition of materials used in simulations.

Material	Density	Composition [%]									
	g/cm^3	Mn	Si	Cr	Ni	Fe	H	C	O	W	N
AISI 316L	8.20	2	1	17	12	68					
AISI 304	4.81	2	1	19	10	68					
PMMA	1.19						8.0	60.0	32.0		
Tungsten	19.30									100	
Water	1.00						11.2		88.8		
Air	0.001205							0.01	23.2		75.0
Muscle and soft tissue	1.05						10.2	14.3	71.0		3.4
Bone	1.92						3.4	15.5	43.5		4.2

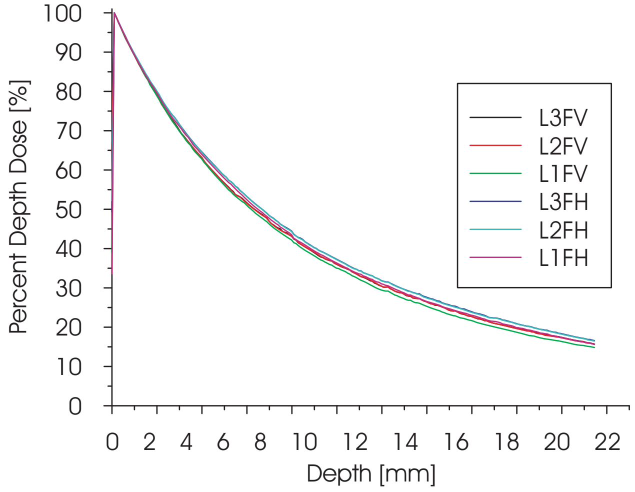

Figure 4. The simulated Percentage Depth Dose (PDD) for all applicators in a water phantom, with respect to the maximum dose at 0.05 cm. L1FH refers to the 1 cm applicator with the source placed in horizontal position, FV with the source placed in vertical position and L2 and L3 refer to the applicators with apertures of 2 and 3 cm.

The Leipzig applicator is a cone shaped, 92% tungsten and 8% steel alloy device. There are six different models with apertures of 1, 2 and 3 cm, three are for horizontal source loading and three for vertical source loading, as shown in Figure 2[5]. The superior part of the applicator, where the radioactive source is positioned, is 2 cm in diameter, independently of the load type and the aperture diameter. The distance from the center of the source to the treatment surface is approximately 1.5 cm.

The 2 and 3 cm applicators have a wall thickness of 0.4 cm and those of 1 cm diameter have a wall thickness of 0.5 cm.

The Leipzig applicators using the Monte Carlo code were modeled with an assembly of mathematical surfaces of cones, cylinders and planes, as shown in Figure 3.

The Monte Carlo MCNP4C2 code was validated by carrying out dose rate calculations, percentage depth dose and dose profiles determination, for the 3 cm aperture, horizontal source loading applicator and comparing them with the results of Evans[4] and León[8].

The records of quantities of interest resulting from the simulation are generically known as tallies. The F6 «tally», which provides the average energy deposited by particle emitted by the source, per unit mass (MeV/g per particle) was used.

The interacting materials are defined in the code language introducing their density, their composition by weight or their stoichiometric formula and assigning them to defined geometric cells. The material specifications are shown in Table 1.

In all the simulations, 1E8 particles were followed and the statistical errors of the results were lower than 0.5% in all cases.

The absorbed dose rate in water, the variation of the percentage depth dose and the dose profiles for each source-applicator system were determined. A water phantom of 5 x 5 x 5 cm^3 was simulated. Each applicator was situated on the surface of the phantom and energy accumulation cells of 0.2 x 0.2 x 0.1 mm were defined. Each cell was centered on the symmetry axis of the applicator head.

The dose profiles were obtained at 0.05 cm (maximum dose) and at 0.4 cm depth in the water phantom.

In problems like the one considered here, where particle sampling is scarce due to the size or place

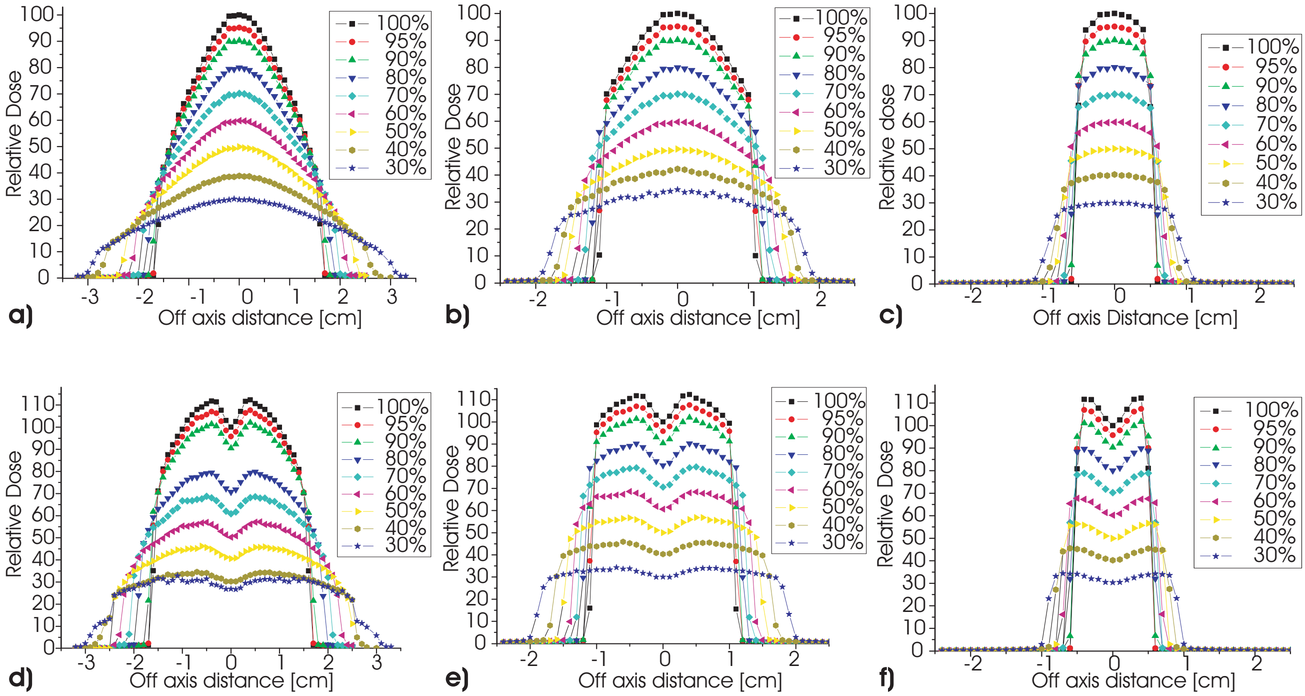

Figure 5. The calculated dose profiles for the Leipzig applicators in water, at 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40% and 30%. (A), (B), (C) are for horizontal source position with 3, 2, 1 cm diameter applicators respectively and (D), (E), (F) are for vertical source position with 3, 2, 1 cm diameter applicators respectively.

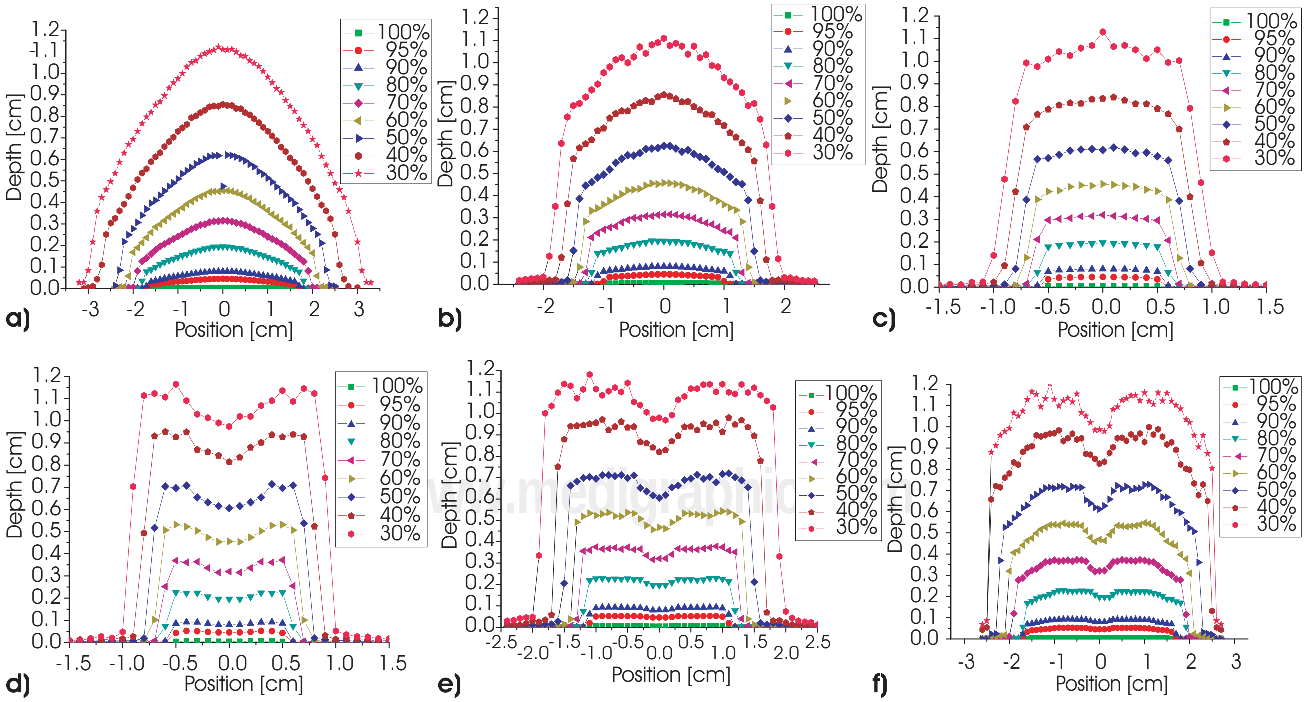

Figure 6. Isodose curves from 100% to 30% for the 6 source-applicator configurations. A, B, C, D, E and F stand for the same sets source-applicator as in figure 5.

Table 2. Percentage depth dose for the 3 cm Leipzig applicator with horizontal source position compared with those of Leon and Evans.

Depth (cm)	MCNP4C2	León	Evans	Difference MCNP4C2-León	Difference MCNP4C2-Evans
0.05	100%	100%	100%	0%	0%
0.2	79.77%	79.94%	80%	0.21%	0.28%
0.5	58.52%	58.17%	60%	0.59%	2.46%
1.0	37.92%	37.24%	40%	1.79%	5.20%

Table 3. Maximum dose rates for 3 cm Leipzig applicator with horizontal source position obtained by Monte Carlo and relative percentage difference with other studies.

	Maximum dose rate (cGy/s)	Δ (%)[a]
Manufacturer Value	4.45	
MCNP4C2	4.49 ± 0.1268	0.89 %
León	4.42	0.67 %
Evans	4.35	2.24 %

[a] The relative percentage difference has been calculated as: $\Delta = 100 \cdot$ (simulation value-Manufacturer Value)/Manufacturer Value.

of the simulated region, it is convenient to use variance reduction techniques that make the computation time short enough to obtain sufficiently precise results and good statistics.

In this work two variance reduction methods were used. In the first one, unimportant geometry sections or particles that leave the geometry were not taken into account; in the second, cut-off energies of 0.02 MeV for electrons and 0.01 MeV for photons were established. The history of a particle concludes automatically when its energy falls below that value.

RESULTS

Regarding the code validation, in Tables 2, 3 and 4 results for the percentage depth dose, maximum dose rate and dose profiles are shown and compared with those of Evans *et al*[4] and León[8]. The results obtained in this work are in better agreement with those of León than those obtained experimentally by Evans.

The dose variation in depth presented as a percentage with respect to the maximum dose at 0.05 cm is shown in Figure 4. L1FH refers to the 1 cm applicator with the source placed in horizontal position, FV with the source placed in vertical position and L2 and L3 refer to the applicators with apertures of 2 and 3 cm. The error bars obtained in the calculation are negligible in the graph since they are covered by the points that indicate the values. The relative statistical uncertainties of the values obtained by simulation have been systematically around 1%.

Table 5 shows the quantitative variations of the percentage depth dose obtained for the 6 applicators taking as a reference the 3 cm applicator in the horizontal source position.

The maximum dose rate values for the 6 source-applicator systems, calculated with MCNP4C2 are shown in Table 6. The maximum uncertainty ó in the values calculated by the simulations was 0.1268 cGy/s for the L3FH applicator.

Nine dose profile curves were obtained for each applicator, at 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40% and 30% and presented in Figure 5. The calculations for less than 30% were not carried out since they do not have clinical relevance.

Using the previous results, the isodose curves from 100% to 30% were calculated for the 6 source-applicator configurations and are presented in Figure 6.

DISCUSSION

As shown in Table 2, for depths shallower than 0.5 cm, the percentage depth dose values for the 3 cm applicator with horizontal source loading, obtained in this work are in good agreement with those of León and Evans. For greater depths, the results are in better agreement with those of León than with the experimental results from Evans. The differences are of 2.46% and 5.2% at 0.5 cm and 1.0 cm depths, respectively.

Table 3 shows the results for the maximum dose rate obtained at 0.05 cm depth. A smaller relative difference with León[8] than with Evans[4] can be observed. A larger error could be associated to the Evans' measurements due to the use of detectors.

Table 4. Dose profiles for 3 cm Leipzig applicator with horizontal source position compared with those of Leon and Evans.

Depth (cm)	MCNP4C2	León	Evans	Difference MCNP4C2-León	Difference MCNP4C2-Evans
0.05	100%	100%	100%	0%	0%
0.40	62.33%	61.95%	62%	0.60%	0.53%

Table 5. The Percentage Depth Dose (PDD) for Leipzig applicators with 1, 2 and 3 cm in diameter and source in vertical (FV) and horizontal position (FH) in a water phantom.

Depth (cm)	L3FH %	L2FH %	L1FH %	L3FV %	L2FV %	L1FV %	Δ (%)[a] L3FH - L2FH	Δ (%)[a] L3FH - L1FH	Δ (%)[a] L3FH - L3FH	Δ (%)[a] L3FH - L2FH	Δ (%)[a] L3FH - L1FH
0.05	100	100	100	100	100	100	0	0	0	0	0
0.20	79.77	79.68	79.53	79.18	79.23	78.74	0.11	0.30	0.73	0.67	1.24
0.50	58.52	58.12	57.42	56.12	56.08	55.59	0.68	1.87	4.1	4.1	5
1.00	37.92	37.01	36.93	35.74	35.76	34.92	2.39	2.61	5.74	5.69	7.90

[a] The relative percentage difference has been calculated as: Δ = 100 • (PDD value of each applicator – PDD value of L3FH)/PDD value of L3FH.

Table 6. Maximum dose rate values at 0.05 cm depth, for the 6 Leipzig applicators.

Applicator	Maximum dose rate (cGy/s)	Standard deviation
L1FH	4.53	± 0.1268
L2FH	4.46	± 0.0783
L3FH	4.49	± 0.1268
L1FV	2.70	± 0.0393
L2FV	2.68	± 0.1226
L3FV	2.65	± 0.1171

With respect to the dose profiles, as shown in Table 4, very good agreement can be observed with both the results of León[8] and Evans[4], in the range from 5 to 40 mm.

The percentage depth dose curves presented in Figure 4, show similar behavior in all applicators independently of their diameter and source position. The quantitative variations of the percentage depth dose obtained for the 6 applicator-source configurations taking as a reference the 3 cm applicator in the horizontal source position are shown in Table 5.

The maximum dose rate values calculated with MCNP for the 6 source-applicator systems are shown in Table 6. These values are up to 40% greater when the source is in horizontal position than when it is in vertical position. Consequently, when a treatment is done with the source in vertical position, the treatment time would be longer in order to achieve the same prescribed dose. Due to the latter, the physician and the medical physicist should consider the advantages of placing the source one way or the other, for each particular patient, based on clinical, geometric and other criteria.

The dose distribution curves provided by the manufacturer of Leipzig applicators (Nucletron) were obtained from experimental measurements made with detectors in different positions. Part of the objective of this work was to implement the same analysis by means of simulation using the Monte Carlo MCNP code version 4C2 under standard irradiation conditions. This way it is possible to evaluate a larger number of positions and reduced effective volumes (including detectors) with which positioning errors due to dispersion introduced by the measuring devices are avoided.

After reproducing the geometry in the MCNP4C2 code of source-applicator located on water surface that represents tissue and from the data obtained in the determination of the percentage depth dose and the dose profiles, a calculation of the dose distribution curves was made. In Figure 6 the isodose curves are shown for the 6 applicators.

The dose distribution curves obtained show that the difference between using a horizontal load applicator or a vertical load one, is small near the surface (for the first two millimeters), being smaller than 1.5% for the vertical applicators in relation to the 3 cm horizontal load applicator.

CONCLUSIONS

The absorbed dose rate values were obtained for the 6 Leipzig applicators beginning from a validation of the results obtained from the calculation by other authors under the same geometric and simulation conditions and that have been accepted by the international scientific community. The relative statistical uncertainties of the simulated values have been systematically around 1%. The differences among the values for the cases of horizontal and vertical source with the same aperture are considerable except for near the surface at a distance of less than 2 mm.

A total of nine dose profiles were obtained for each commercially available applicator which will assist medical physicists to obtain the isodose distributions for these applicators. These curves were obtained in the maximum, 95%, 90%, 80%, 70%, 60%, 50%, 40% and 30% of the deposited energy.

The calculation of the dose distribution curves for the 6 applicators was carried out from the data obtained in the percentage depth dose determination and the dose profiles. These distributions can be used as entry data in a planning system.

The dosimetric parameters obtained here by Monte Carlo simulation, help to improve the precision in medical treatments and can increase the rate of success in the applications of this HDR system in superficial cancer diseases.

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