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Estimation of Dose Deposition by 198-AuNPs in the Prostate with MCNP in Simplified Geometry

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1. Introduction

Cancer is a major public health challenge not only at a national level, but also globally. In Brazil, the National Cancer Institute (INCA) estimates that there will be around 704 thousand new cases a year between 2023 and 2025. Prostate cancer is the second most common cancer among men in the country [3]. It affects the prostate gland of the male reproductive system and is located below the bladder and in front of the rectum. It can be divided into distinct zones - central, transitional, peripheral and fibromuscular - each characterized by its embryological origin, histology and susceptibility to pathological disorders. The origin of 70% of prostate tumors is concentrated in the peripheral zone, which is derived from the urogenital sinus. The transitional zone has a similar origin to the peripheral zone and is also prone to the appearance of a tumor, but in the order of 25%, this difference is due to the different concentration of the stromal component of these zones [4, 5].

Radiotherapy is a technique available for treating cancer, which consists of using ionizing radiation to destroy cancer cells and reduce the size of the tumor. There are two types of radiotherapy treatment: teletherapy, in which the radiation source is positioned far away from the patient, and brachytherapy, in which the radiation source is placed close to the tumor [6]. A crucial aspect for the effectiveness of radiotherapy treatment and the protection of healthy tissues is the selective delivery of radiation to tumor tissues and cells. In this context, the application of nanotechnology has been studied as a strategy to achieve precise delivery of therapeutic doses. This is due to the unique physical, chemical and biological properties that atoms and molecules have on a nanometric scale [7, 8].

Recent research has explored the use of radioactive nanoparticles as an alternative to traditional seeds in brachytherapy. Scientific evidence indicates that brachytherapy with nanoparticles is effective in controlling and inhibiting tumor growth, enabling more effective and targeted treatment, with less impact on healthy cells [1, 10]. The tumor's disordered vascularization results in prolonged retention of the radiopharmaceutical in the tumor microenvironment. Furthermore, due to the small size of the particles, they are able to diffuse homogeneously in the tumor, providing a distribution of radiation that contributes to the effectiveness of the treatment. In this way, their application allows for a controlled release of radiation at the site of the tumor, increasing selectivity and minimizing damage to healthy cells. In addition to the therapeutic advantages, the use of nanoparticles offers a less invasive and more comfortable treatment for patients. 198-Au nanoparticles (198-AuNPs) stand out for having good properties for therapeutic purposes, such as biocompatibility, low toxicity, good optical and electronic properties [9].

In addition, the radiological properties of Au-198 are suitable for use in brachytherapy. Its disintegration process occurs mainly through the emission of β- particles 0.315 *MeV* (98.99%) and γ photons of 0.412 *MeV* (95.62%) and has a half-life of 2.7 days [6]. The β- particles range (up to 4 *mm* in water) allows it to cause damage to tumor cells and reduce the exposure of healthy tissues adjacent to the tumor. In addition, the neutron cross section of natural gold, 98.65 *barns*, is favorable to produce 198-Au in nuclear reactors [2].

Thus, in order to evaluate the potential of 198-AuNPs as a new therapeutic approach in the treatment of prostate cancer, computer simulations focused on dosimetry are needed to evaluate the distribution of absorbed dose in the tumor and adjacent tissues. The aim of this work is to estimate the dose deposition resulting from the emissions of 198-AuNPs in the tumor, as well as in the healthy tissues of the prostate and the organs at risk: bladder and rectum, using the Monte Carlo N-Particle 6.2 (MCNP 6.2) code with a simplified geometry of these structures.

2. Methodology

In the literature, there are few studies that use Monte Carlo simulation with simple geometric models of the tumor and organs to estimate the dose distribution deposited by radioactive nanoparticles. To portray the treatment of prostate cancer, a geometric model of the prostate with a tumor and the organs at risk, the bladder and rectum, was developed. The dimensions of the structures were determined based on data obtained from the literature [1, 5]. The prostate was modeled as an ellipsoid with axes lengths of 2, 3 and 4 *cm* in the anteroposterior, craniocaudal and horizontal axes, respectively. The bladder was considered as a sphere of radius 5 *cm*, assumed according to its average capacity of 500 *ml*. The rectum was represented as a cylinder 13 *cm* long with a radius of 1,5 *cm*, positioned posterior to the bladder and prostate. The tumor was simulated as a sphere with a radius of 0,4 *cm* positioned on the periphery of the ellipsoid, since most prostate tumors originate in the peripheral zone. Figure 1 shows the geometry used in the computer simulations. The prostate, bladder, rectum and tumor were assumed to be composed exclusively of water. For the simulations, the organs were inserted into an infinite water medium.

Figure 1: Three-dimensional representation of the geometry used.

The simulation was conducted using the MCNP 6.2 code. As previously mentioned, Au-198 decays through the emission of β- particles and γ photons. The individual and joint contributions of these emissions to dose deposition in the tumor, prostate, bladder and rectum regions were evaluated using the *F6 *tally*. The *F6 *tally* returns the average energy deposited by a particle in a cell, and its unit of measurement is *GJ/g*. Different simulations were carried out, one considering only the emission of photons, which in the decay of Au-198 is predominantly γ photons, and another simulation considering the source as a β- particle emitter taking into account the energy deposited by secondary photons.

3. Results and Discussion

In the simulation configured for photon emission only, 10^{9} stories were used, while in the β- particle simulations 10^{8} stories were chosen, since the uncertainty calculated for this number of stories is already satisfactory. The results obtained using the *F6 *tally* were converted to *J/kg*, equivalent to *Gy* (1 *Gy* =1 *J/kg*). In the case of the results obtained for photon emission, the dose obtained was multiplied by the average number of photons per decay. It is important to note that in the case of β- particle emission this is not necessary, as each decay only emits one particle. Table I therefore shows the dose deposited (in *pGy*) per decay for each simulation, together with the associated uncertainty.

Table I: Results of the simulations carried out: deposited dose (in *pGy*) per decay, accompanied by the associated uncertainty (%).

Cells	Simulation: Emission of Photons		Simulation: Emission of β- Particles	
	pGy by decay	Uncertainties (%)	*pGy* by decay	Uncertainties (%)
Tumor	1,40	$< 10^{-5}$	$1,11\cdot 10^{2}$	$1\cdot 10^{-2}$
Prostate	$9,54 \cdot 10^{-2}$	$< 10^{-5}$	$3,59\cdot 10^{-1}$	$4\cdot 10^{-2}$
Bladder	$2,90 \cdot 10^{-3}$	$1\cdot 10^{-2}$	$1,02\cdot 10^{-5}$	$4,4\cdot 10^{-1}$
Rectum	$1,87 \cdot 10^{-3}$	$1\cdot 10^{-2}$	$5,77\cdot 10^{-6}$	1,11

By analyzing the individual contributions of the 198-Au emissions, it can be seen that most of the deposited dose is attributed to the β- particles. In the tumor region, the energy deposited by the particles is around 100 times greater than the energy deposited by the photons. In both simulations the energy is deposited predominantly in the tumor. It is interesting to note that in the β- particle simulation, the difference between the absorbed dose in the tumor and the absorbed doses in other regions is considerably greater than the difference observed in the results obtained for photon emission. This highlights the characteristic of β- radiation of concentrating the greatest dose deposition locally, due to its short penetration range. This characteristic is relevant for the application of therapeutic sources aimed at localized dose delivery and the protection of healthy tissues adjacent to the tumor. Evaluating the results of the simulation in which the source is configured to emit β- particles, it can be observed that the dose deposited in the tumor is $1,11\cdot 10^{2}$ *pGy* per decay. In the prostate, this dose decreases around 300 times to $3,59\cdot 10^{-1}$ *pGy* per decay. In areas further away from the source, the absorbed dose is even lower, in the bladder the average is $1,02\cdot 10^{-5}$ *pGy* per decay and in the rectum it is $5,77\cdot 10^{-6}$ *pGy* per decay. These values, which are 7 to 8 orders of magnitude lower than the absorbed dose in the tumor, are favorable for the application of radioactive nanoparticles in brachytherapy, highlighting a favorable dose distribution profile capable of minimizing damage to healthy tissues. Therefore, the results indicate a promising therapeutic potential of 198-AuNPs, since the application of nanoparticles in brachytherapy aims to concentrate a high dose in the tumor to destroy the cancer cells, while minimizing the dose absorbed by the surrounding healthy tissues.

4. Conclusions

The simulations carried out with MCNP 6.2 showed that the 198-AuNPs deposit most of their energy inside the tumor, while very small amounts of energy are recorded in the regions furthest from the source in the bladder and rectum. This reinforces the importance and potential of radioactive gold nanoparticles as an innovative therapeutic approach in the fight against cancer, highlighting their ability to provide localized and minimally invasive therapy aimed at significantly improving clinical outcomes and patients' quality of life.

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