Experimental apparatus for measurement of photoneutrons from linear accelerator with energy of 16 MeV

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ABSTRACT

Particle accelerator technology has a deep impact on society. Its applications are well established mainly in the treatment of cancer and other diseases. This work aims to develop an experimental apparatus with $^3$He detectors for 16 MeV photoneutron measurements. The apparatus allows us to obtain multienergetic neutrons with the use of a 22 cm diameter spherical attenuator associated with different shield thicknesses. The microscopic processes of the fast and thermal neutrons in the detector were described by the two energy-group diffusion equation. The Detector Response × Dose Rate results show a directly proportional relationship between these two variables with a degree of reliability attested by the linear correlation coefficient $R^2 \geq 0.999$.

Keywords: Particle accelerator, Experimental apparatus, Neutron detectors.
1. INTRODUCTION

The science of accelerators, as we know, shows profound power of impact on society and this can be seen in the face of their applications that pass both in the midst of science, in general, as well as with regard to the universe of technologies. A good example of this is the significant fraction of radioisotopes manipulated for/in disease treatments, diagnoses and research where so-called accelerators are used. X-ray beams, as well as neutrons, protons and ions derived from particle accelerators, are used for the treatment of cancer and other diseases. In addition, the use of ionizing radiation has been widely used in the medical field, in interventional procedures [1].

Radiotherapy is divided into two modalities: teletherapy and brachytherapy. In brachytherapy, the source of radiation is placed directly in the tumor. The radiation beam is produced by shielded (sealed) radionuclides in order to avoid contamination of the patient with radioactive material [2].

Teletherapy is the use of ionizing radiation, emitted by a device, away from the patient, whose beam is directed to the site to be treated. In this case, $^{60}$Co irradiators or linear accelerators are used. It is important to add to this that being the radiation beam attenuated as it penetrates the body, the radiation dose in organs or tissues near the surface is expressive and should be known. For this reason, single beams of radiation are used only in superficial tumors. In deeper tumors a larger number of bundles is recommended for them to be applied in different directions [3]. This being the case, the radiation beams are focused directly on the tumor and the referred dose will be divided there, thus reducing the amount to be destined to healthy tissues, although there is an increase in the total volume of irradiated tissue [4].

In linear accelerators with energies above 10 MeV neutrons occurs due to the interaction of high-energy particles with the various materials of the radiator and the treatment room. These neutrons, here called photoneutrons appear as a contaminant of the treatment beam.

It is known that the production of these neutrons in the particle accelerator does not occur only in the head, but at several points inside [5]. The particles, in the process of interacting with high atomic number materials present in the accelerator, produce, in addition to restraining X-ray photons, neutrons, mainly through the nuclear reaction of the type ($\gamma$, $n$) [6]. Other reactions occur in accelerators that have large amounts of elastic collisions. However, these collisions do not
represent significant energy losses, since they increase the trajectory traveled by neutrons within the shield, producing reactions (n, 2n) [7].

Neutron detection methods are not trivial due to the lack of charges of these particles, as well as the peculiarity of their interactions with matter [8].

The objective of this research was to develop an experimental device designed to correlate the responses of $^3$He detectors with the measurement of photoneutrons of 16 MeV, as well as the proportionality between them and behavior differences in relation to different moderators of the $^3$He detector with the measurements of multienergetic neutrons. An analytical model, based on the approximation of the diffusion of two energy groups, was constructed in order to better understand the experimental behavior of the device.

2. MATERIALS AND METHOD

Neutron area monitors are built with three fundamental components: moderator, detector, and the electronic component. The physical principle of area monitor with spherical attenuator is based on the moderation of fast neutrons. To obtain the neutron spectrum it is necessary to perform measurements involving the detector with the various moderator plates. This facilitates detection since detectors are typically much more sensitive to thermal neutrons.

The material responsible for braking neutrons is high density polyethylene and has the function of thermalizing the rapid neutrons through the loss of energy by elastic shocks. Its shape can be spherical or cylindrical, depending on the model of the appliance. There are other types of neutron detectors that use gas enriched with high-section shock materials for thermal neutrons [9].

The materials and equipment used in this work were:

1 - Shields composed of five paraffin plates, three paraffin plates and one paraffin plate designated by 5P, 3P and 1P, respectively. Each is 14.5 cm long, 13 cm wide and 3.5 cm thick. Finally, a cadmium plate (1Cd) with 1 mm thickness that serves as shielding (see Figure 3a and 3b);
II - Proportional detection system of type $^3$He that presents discrimination characteristics (neutrons-gammas). The detector has high efficiency of counts for thermal neutrons and low efficiency for fast neutron counts;

III. Spherical attenuator - Diameter (metric) 22 cm;

IV. Varian linear accelerator, Clinacix model, rated accelerator potential of 16 MeV.

The experimental work was divided into four phases:

a) Assembly of the entire experimental arrangement with paraffin plates (P), Cadmium plate (Cd) and spherical attenuator (E) associated with the detector;

b) Measurement of the thermal neutrons arriving at the fixed detector ($^3$He), depending on the composition of the shielding material, according to the sequence of measurements indicated in tables 1 and 2;

c) Data analysis with the aid of MATLAB programming for the preparation of graphs;

d) Formulation of a model describing the behavior of fast and thermal neutrons in the diffusion approach [10]. This physical process can be verified in Figure 1.

Figure 1 shows, in a squematic way, the entry of neutrons by energy group 1 (fast). Through moderation, group 1 neutrons lose energy and add up to group 2 neutrons, already fully thermalized. The arrows (←) to the left of figure 1 represent the rapid and thermal neutron leaks. This scheme is mathematically described by equations (1) and (2) [10].
\begin{align*}
D_1 \frac{d^2 \Phi}{dx^2} + \Sigma_{R1} \Phi &= 0 \\
D_2 \frac{d^2 \chi}{dx^2} + \Sigma_{R2} \chi &= \Sigma_{21} \Phi
\end{align*}

Were,
\(\Phi\) → Rapid neutron flux;
\(\chi\) → Thermal neutron flux;
\(D_1\) → Diffusion coefficient of energy group 1;
\(D_2\) → Diffusion coefficient of energy group 2;
\(\Sigma_{R1}\) → Macroscopic cross section of energy group removal 1 (\(\Sigma_{R1} = \Sigma_{a1} + \Sigma_{21}\));
\(\Sigma_{R2}\) → Macroscopic cross section of energy group 2 removal (\(\Sigma_{R2} = \Sigma_{a2}\));
\(\Sigma_{21}\) → Group 1 macroscopic spreading cross section for group 2.

Equations that fix \(\Phi\) e \(\chi\) are subject to the following boundary conditions:

\[\Phi(0) = 0, \quad J_1^-|_S = J_1\]

and,

\[\chi(0) = 0, \quad J_2^-|_S = 0\]

The reentrant current being \(S\) given by:

\[J_1^-|_S = \frac{\Phi}{4} + \frac{D_1}{2} \left(\frac{d \Phi}{dx}\right)_S\]

Equation (5) is the reentrant partial current that represents the source of fast neutrons on the surface \(S\) of the design. Analogously, you have the following expression for \(\chi\):
\[ J_2^- \Big|_S = \frac{x}{4} + \frac{D_2}{2} \left( \frac{dx}{dx} \right)_S \]  \hspace{1cm} (6)

Figure 2 illustrates the physical principle of validation of the experimental apparatus. In the approximation of diffusion to two energy groups, it results in four constants for each region. Contour and media interface conditions (flux and current continuity) allow the system to be determined. The first group must be without the shielding, as it is possible to check the result in Figure 15, and the second group, in turn, considering the complete attenuation system, according to the result shown in figure 16.

![Model used to represent experimental apparatus](image)

**Figures 2:** Model used to represent experimental apparatus [11].

In the experimental procedure, mobilized here, the energy of 16 MeV was adopted for neutrons of the reentrant partial current \( J_1^- \), in order to measure the leakage current and the beginning of the production of photonèutrons. According to the literature, the production of photoneutrons occurs for photon energies greater than 8 MeV [12]. Then the detector and accelerator reference system, called gantry, initially positioned at angle 0º (see figure 3a). Then the gantry was changed to 270º angle (see figure 3b).
3. RESULTS AND DISCUSSIONS

In this section will be presented the results collected in the activities mentioned in the previous section.

Considering table 1, energy of 16 MeV of the linear accelerator, as well as the fields y = 25.2 cm and x = 5 cm, the results presented in figures 4 to 7 that are below were obtained. Similarly, table 2 shows the fields y = 0.4 cm and x = 5 cm, the results of which are shown in figures 8 - 11 and can be observed later.

The correlation index of 0.999 attests to the linearity between the detector response and the efficiency in figures 4 - 11. This experimental response is in full agreement with the predictions of the diffusion model to two energy groups, that is, the increase in the dose rate tends to increase the probability of shock interaction in the head, resulting in the production of photon neutrons.

In addition to linearity, there was an increase in detector count. It is noteworthy that when removing the paraffins plates, there was a decrease in the measurement of thermalized neutrons. This suggests that the neutron flux generated in the head has different energies. The measurements performed directly next to the spherical attenuator indicate that the flux of higher intensity neutrons occurs due to the lower energy photoneutrons produced in the head.

Figures 3: Illustration of the reference system [11].
Table 1: Linear Accelerator 16 MeV photon energy (fields y = 25.2 cm and x = 5 cm).

| Energy 16 MeV | Gantry 270° | Monitor | Gantry 270° | Monitor | Gantry 270° | Monitor | Gantry 270° | Monitor |
|---------------|-------------|---------|-------------|---------|-------------|---------|-------------|---------|
| Dose (cGy/min) | 5P+1Cd+E   | Average | 3P+1Cd+E   | Average | 1P+1Cd+E   | Average | E           | Average |
| 100           |             |         |             |         |             |         |             |         |
| 200           |             |         |             |         |             |         |             |         |
| 300           |             |         |             |         |             |         |             |         |
| 400           |             |         |             |         |             |         |             |         |
| 500           |             |         |             |         |             |         |             |         |
| 600           |             |         |             |         |             |         |             |         |

Figure 4: Shielding with energy beam 16 MeV: 5 paraffins, 1 Cadmium, the Sphere.
Figure 5: Shielding with energy beam 16 MeV: 3 paraffins, 1 Cadmium, and the Sphere.

Figure 6: Shielding with energy beam 16 MeV: 1 paraffin, 1 Cadmium and the Sphere.
Figure 7: Shielding with energy beam 16 MeV: Sphere.

Table 2: Linear accelerator 16 MeV photon energy (fields y = 0.4 cm and x = 5 cm).

| Energy 16 MeV | Gantry 270° | Monitor | Gantry 270° | Monitor | Gantry 270° | Monitor | Gantry 270° | Monitor |
|--------------|-------------|---------|-------------|---------|-------------|---------|-------------|---------|
| **Dose (cGy/min)** | **5P+1Cd+E Average** | **3P+1Cd+E Average** | **1P+1Cd+E Average** | **E Average** | **E Average** | **E Average** | **E Average** |
| 100 | 1911 | 1908 | 1917 | 1916 | 1913 | 1944 | 1950 | 1941 | 1936 | 1942.75 | 2136 | 2095 | 2096 | 2097 | 2106 | 2311 | 2309 | 2311 | 2322 | 2313.25 |
| 200 | 3791 | 3809 | 3836 | 3788 | 3806 | 3914 | 3859 | 3850 | 3953 | 3894 | 4274 | 4223 | 4012 | 4081 | 4147.5 | 4711 | 4714 | 4721 | 4675 | 4705.25 |
| 300 | 5776 | 5741 | 5730 | 5736 | 5745.75 | 5838 | 5878 | 5874 | 5841 | 5857.75 | 6403 | 6334 | 6314 | 6349 | 6350 | 7070 | 7103 | 7057 | 7125 | 7088.75 |
| 400 | 7760 | 7800 | 7714 | 7732 | 7751.50 | 7959 | 7939 | 7937 | 7987 | 7955.50 | 8492 | 8529 | 8536 | 8536 | 8523.25 | 9638 | 9630 | 9568 | 9571 | 9601.75 |
| 500 | 9800 | 9814 | 9809 | 9851 | 9818.50 | 9968 | 9973 | 9938 | 9971 | 9962.50 | 10800 | 10700 | 10750 | 12100 | 12200 | 12150 |
| 600 | 11900 | 11800 | 11850 | 12000 | 12050 | 1100 | 13100 | 14600 | 14800 | 14700 |
**Figure 8:** Shielding with energy beam 16 MeV: 5 paraffins, 1 Cadmium and the Sphere.

**Figure 9:** Energy beam shield16 MeV:3 paraffins, 1 Cadmium, and the Sphere.
As can be seen, the correlation coefficient showed to be 0.999 in figures ranging from 4 to 11, with variations only in the fourth decimal place. This proves the related relationship between x and y, within the required precisions. Figures 12 and 13 show a growth behavior in the response due to the different neutron attenuations for different dose rates.
Figure 12: Different dose rates with different neutron attenuator thicknesses.

Figure 13: Different dose rates with different neutron attenuator thicknesses.
Figure 14 presents different detector responses for different dose rates and different neutron attenuator thicknesses. It is noteworthy that the standard behavior of radiation attenuation, in this case, neutrons, follows the exponential law.

![Attenuation of Neutrons - Beam 16 MeV](image)

In order to validate the methodology under discussion, the experimental results were compared with the theoretical model in the approximation of diffusion. A figura 15 mostra o que acontece com os fluxos $\Phi$ e $\chi$ na ausência de placas de parafina, ou seja, pouca termalização dos nêutrons. Em contraste, a figura 16 mostra um cenário bem diferente quando se adicionam as placas de parafina. Grande parte dos nêutrons são termalizados aumentando, consideravelmente, o fluxo térmico $\chi$. Apesar de qualitativo o modelo explica, de forma simples, a razão das variações de $\chi$. 

**Figure 14:** Shields with different fields.
Figure 15: Graphs of the rapid and thermal flux distribution without the thicknesses of paraffins.

Figure 16: Graphs of the rapid and thermal flux distribution with the complete thicknesses of paraffins.
4. CONCLUSIONS

A single series of measurements was performed on the linear accelerator. This machine only offers the rated potential of 16 MeV. The results showed a proportional correlation between the detector response caused by photoneutrons and the dose rate with correlation coefficient $R^2 \geq 0.999$. In addition, the results show that the influence of photon measurement on the neutron detector (gamma radiation) should be better investigated.

A proposal to evaluate the influence of gamma radiation would be:

1- Redo the measurements with the accelerator at 16 MeV energy, threshold energy for photogeneration of photons whose same photon intensity of 16 MeV was used in this work;

2- Irradiate the equipment to evaluate the gamma field, in order to verify the discrimination of the neutron detector.

This experimental apparatus allowed the obtaining of a multi-energy neutron measurement procedure using the same detector and changing the different thicknesses (attenuators) of paraffin shielding for different rates of radiation doses. It was also observed that the tungsten collimators used in the accelerator did not serve as shielding for neutrons. Due to this presence of neutrons, healthy organs are also irradiated, and may generate some kind of damage in the patient undergoing treatment. This fact evidenced in Thalhofer's dissertation [13]. We also understand that this finding points to a right in the proposal of the methodology under development.
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