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Analysis and characterization of neutron scattering of a Linear Accelerator (LINAC) on medical applications.

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Abstract In several theoretical and experimental studies, the topic of the undesirable generation of photoneutrons in rooms where a linear accelerator (LINAC) operates has been discussed. When energies above 10 MeV are used to produce X-rays and give radiotherapy treatment to patients resulting in additional radiation to patients. Accordingly, an analysis and characterization of the neutron scattering distribution on different zones in a treatment room contributes to evaluate the radiological health risk to patients, technical and other workers involved in treatment. For the evaluation, a device developed at the PAD-IFUNAM formed by a CR-39 detector enclosed by two 3mm thick acrylic plates was employed. To avoid environmental contamination, the CR-39 and the acrylics plates are enclosed in a round plastic box. Sixteen of these devices were settled in different places inside the treatment room, where a linear accelerator is used. The results show a significant concentration of neutron scattering in areas near the head of irradiation. The recommendation will be to evaluate the neutron scattering concentration in all rooms that's operates a LINAC in order to verify the radiological health risk and to mitigate

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the neutron scattering when concentration levels are to high like those in our case, in order to avoid unnecessary exposition to patients and personnel in general.

Keywords: Neutron Scattering, Linear Accelerator (LINAC), Nuclear Track Methodology

1. INTRODUCTION

Nowadays, there is a great interest in both the basic science and medical community worldwide to study the undesirable production of photoneutrons in medical linear accelerators (LINAC), normally used to fight cancer in patients, to asses the negative effects that these photoneutrons produce in the environment, such as the generation of scattered neutrons [1, 15, 16, 22, 23]. This increasing interest has been motivated, among other reasons, since the medical-physicists community have consolidated the opinion that neutron irradiation in the peripheral organs during radiotherapy sessions is significantly related to the occurrence of secondary cancers [10, 13, 14].

A LINAC uses high frequency electromagnetic waves to accelerate electrons up to high energies (4-25 MeV) through a linear accelerator waveguide. Electrons are produced from an electron gun, which is formed at its end by an anode (normally a tungsten filament) and a cathode. When a high voltage is applied between the cathode and the anode, the electrons emitted from the tungsten filament are emitted in the direction of the anode. The generated electrons are then directed to a device known as the Accelerator Waveguide where the electrons are accelerated to relativistic speeds by means of the transfer of energy from an electromagnetic field in the form of microwave radiation [21]. The uniform electron beam produced is then passed to the treatment head of the linear accelerator, where it is collided with an X-ray target, conventionally made of tungsten (being a material with high atomic number and high melting point) converting the energy of the electrons in a controlled X-ray energy spectrum. The X-rays are immediately collimated by a primary collimator, then the beam is modified by flattening filters and finally passed to a secondary collimator before being applied to the patient [19]. Photoneutrons are generated mainly in the X-ray target when the electron beam is converted to X-rays [2]. However, the possibility of other areas inside the irradiation head where neutrons can be generated, cannot be ruled out.

Photoneutrons can be produced in two ways: photo-disintegration reactions that occur when a nucleus absorbs a high energy photon, causing the ejection of one or more subatomic particles (protons, neutrons or alpha particles) [19], and by direct emission, that occurs when a high energy particle (such as an X-ray photon) interacts directly with one or more individual nucleons (neutrons) within a nucleus [9]. For 15-30 MeV X-rays interacting with heavier nuclei, neutron production is $\sim$ 10-20% [17]. Most neutrons, when traveling through matter do not interact with it. If a neutron is able to interact with matter it will do so with the nuclei of the atoms, resulting in different processes that, in general, can be classified into absorption and scattering. The generation of neutron scattering depends on the materials found in the close proximity of the photon-neutrons source emission and the separation distance between them.

In this present work we analyze and characterize different density zones of neutron scattering in a therapy room equipped has a linear accelerator (LINAC) that is used to treat cancer patients, with the first objective of determining the zones with greater concentration of neutron scattering. Secondly, to analyze the importance of the room dimensions, the medical devices and furniture inside of the room, as well as the materials used to manufacture the treatment room, as determinant factors for neutron scattering concentration patterns. To measure the concentration of neutron scattering, Nuclear Track Methodology was chosen, because of its high efficiency and mainly because of its characteristics do not interfere with the usual treatments that are provided to patients inside the room. As detector, the CR-39 polymer attached to a pair of acrylic sheets, was employed. Prior to the actual measurements, our detector was calibrated with an ^{241}Am-Be source.

Figure 1: Photograph taken by us. LINAC used at treatment room.

2. METHODOLOGY

The treatment room has a volume approximately of 224.54 m^3, inside it operates a linear accelerator (LINAC), (**Figure 1**). This linear accelerator emits two different types of energies: photon radiation energies (6 and 18 MeV), and electronic energies (4, 6, 9, 12 and 16 MeV). The linear accelerator operates 5 days a week: from 6 a.m. to 2 p.m. and from 2:30 p.m. to 9:30 p.m., a total 15 hours of working time. In this working time a total of approximately 220 treatments are performed to different patients, where different types of photon and electron energies are used at different operating times, ranging from 30 seconds to 2 minutes maximum, depending on the type of treatment.

To measure neutron scattering concentration levels in the treatment room [3, 5, 8] a device developed at the PAD-IFUNAM was employed. This device is constituted by a radiation sensitive detector, a moderator material, a plastic round box, where the detector and the moderator are placed, and foam to hold the materials inside the plastic box. As a radiation detector plastic polymer CR-39 (allyl diglycol carbonate), was chosen because of its high sensitivity [6, 20, 24]. This polymer is 750 thick, cut into 1.8 $\times$ 0.9 pieces. Acrylic glass (Poly (methyl 2-methylpropenoate)) was used as a moderator material. The acrylic was attached to each face of the surface of the CR-39, creating a sandwich system (acrylic / CR-39 / acrylic). The acrylic moderators are 3 mm thick sheets, cut to the same dimensions of the polymer and attached to it with diurex tape. The objective of the moderator is to produce collisions

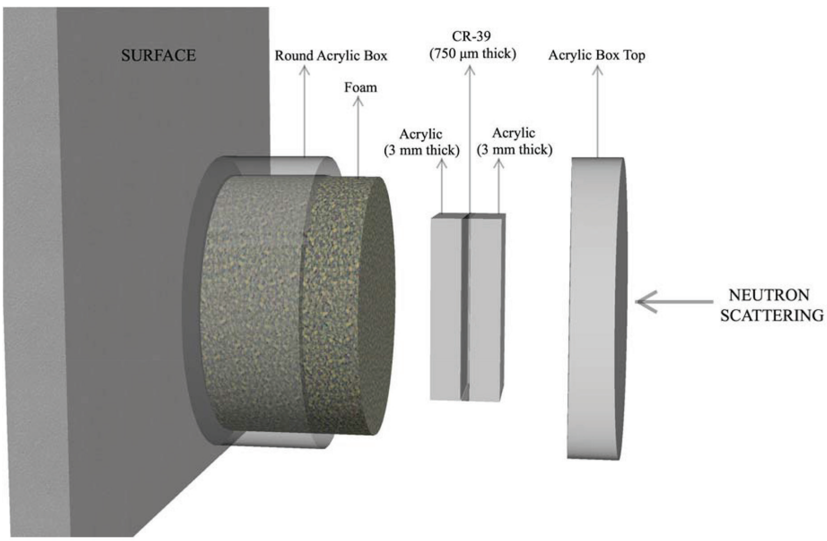

Figure 2: Scheme of the device developed at the PAD-IFUNAM.

(n, p) with the hydrogen atoms of the moderator material and to have thus recoil protons that interact with the CR-39 detector. The function of the plastic box is to prevent contamination of the detector with other radioactive particles in the environment, such as radon gas. The round plastic box is also made of acrylic material and has dimensions of 3.0 cm in diameter by 1.6 cm height. Finally, to attach the plastic box to any surface within the treatment room double-sided tape was used. **Figure 2** shows a scheme of the device used for the measurements.

3. EXPERIMENTATION

A total of sixteen strategic points were placed within the whole room as shown in the drawing of **Figure 3**. Eight devices were placed on each of the four walls, at a height of 1 m from the ground. Six devices were placed on the sides of the stretcher where the patient, who receives the irradiation, is placed, to evaluate in general how exposed are the body parts to the neutron scattering. Two devices were positioned on the head of the LINAC where the radiation energies are emitted. Finally, it is important to mention that the stretcher moves on two of its axes with different objectives such as placing the patient in a certain position and the head of the LINAC rotates 360º, depending on the need of the treatment.

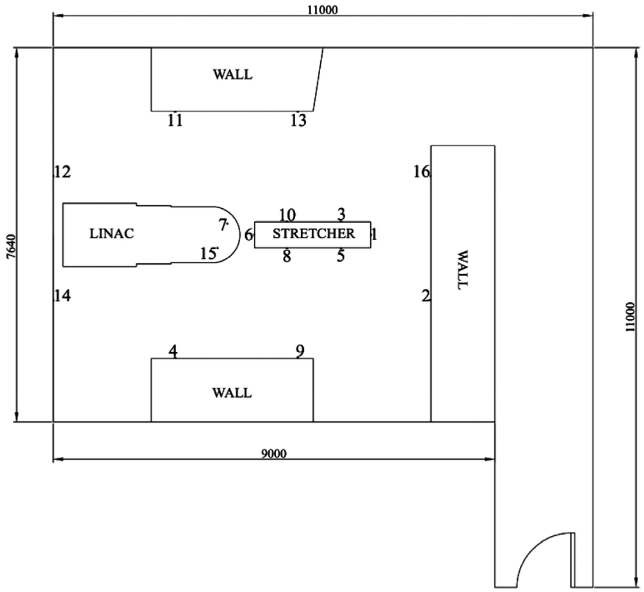

Figure 3: Schematic drawing of the dimensions of the treatment room and the position of the sixteen devices. The dimensions are in millimeters.

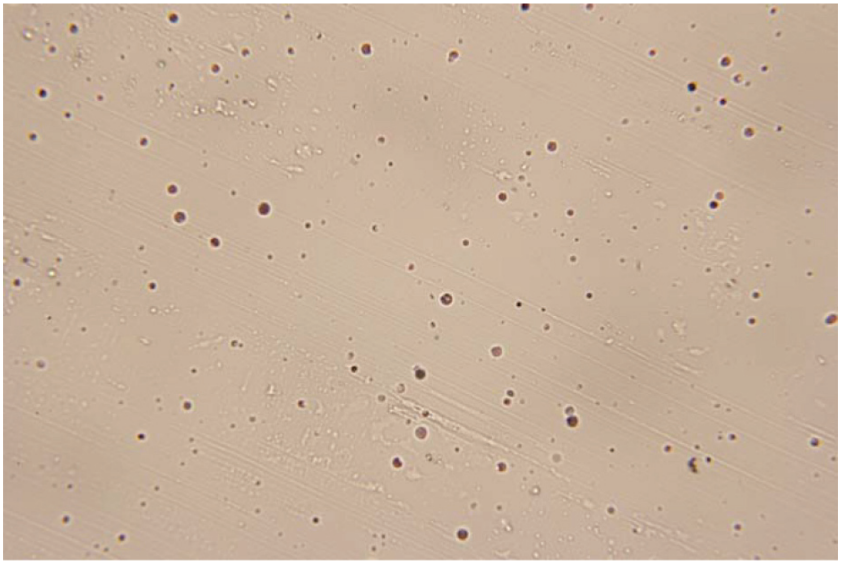

Figure 4: Typical micrograph showing the tracks that are formed by the interaction of protons with the CR-39 detector. 20x magnification.

Because the Nuclear Track Methodology is a passive method of integration, we decided to measure the neutron scattering concentration over one month, enough time to observe sufficient tracks in the polymer. A total of 1,031 patients were treated during this period. After the period of measurement, the sixteen devices were removed from the treatment room and the CR-39 detectors were chemically etched simultaneously for 18 h in a 6.25M KOH solution to 60°C ± 2°C. After the chemical treatment, the etched CR-39 track detectors were washed in distilled water and dried, following a well-established protocol [4]. The chemical etched reveals the interactions made by protons from the acrylic moderator with the CR-39 detector. When the detector is observed in an optical microscope, these interactions appear as small voids as shown in the micrograph of **Figure 4**. Afterwards, the readings of each CR-39 detector were done with the Counting Analysis Digital Imaging System (CADIS) [11].

3.1 Calibration of the device

For the calibration of the device we use an ^{241}Am-Be source, brand EMA. It presents an activity (φ) of $1.13 \pm 0.03 \times 10^6$ n/s 4π, with uncertainty of $\pm$ 2.5% and has a certification of date 09/11/1978. The source has an active part of 10 mm diameter by 10 mm height, and it is inside a cylinder (whose dimensions are of 18 mm diameter by 18 mm height). This cylinder is in turn inside a container of paraffin whose base is 23.5 cm by 23.5 cm and height of 34 cm. The paraffin container has 3.5 cm diameter holes in its six faces, from where the neutron radiation is emitted. The neutrons flux (φ) of the ^{241}Am-Be source can be calculated from the solid angle (Ω) by the following relation [12]:

$$\Omega = \frac{\pi a^2}{d^2} \quad (1)$$

where a is the radius of the detector (1.75cm) and d the distance from the detector to the neutron source (9.5 cm). By solving equation (1) a solid angle of $\Omega = 0.1066$ is obtained. To calculate the net flow that radiates to the detectors (φ_Ω), we use the following equation:

$$\varphi_\Omega = \Omega\left(\frac{\varphi}{4}\right) \quad (2)$$

The net flux that radiates to the detectors for a solid angle of $\Omega = 0.1066$ and an activity of $= 1.13 \pm 0.03 \times 10^6$ n/s 4π is $\varphi_\Omega = 9.58 \times 10^3$ n-cm^{-2} s^{-1}. Four devices were irradiated at different exposure times: 3, 4.5, 6 and 9 hours. Then, we plot the density of tracks (δ) obtained against the exposure time to the ^{241}Am-Be source for each detector. The track density is equivalent to defining

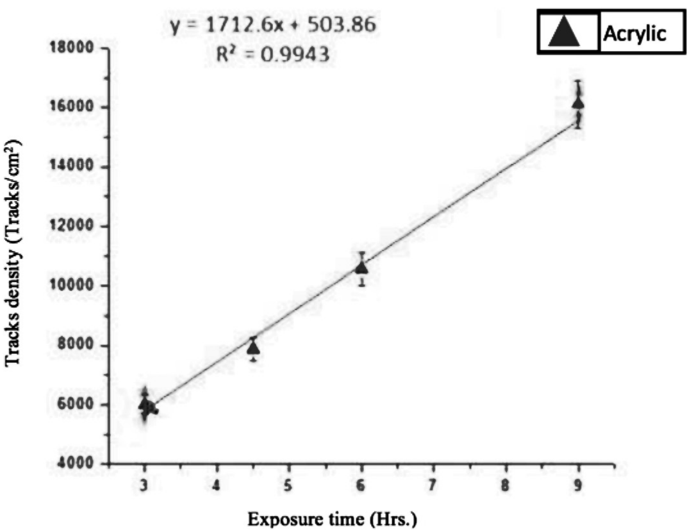

Figure 5: Behavior of the CR-39 as a function of the exposure time to the ^{241}Am-Be source.

it as the flux detected in the CR-39, since the tracks in the material correspond to protons of the reactions (n, p). **Table 1** shows the tracks density obtained in the CR-39 when exposed to the ^{241}Am-Be source. **Figure 5** shows the behavior of the CR-39 as a function of the exposure time to the ^{241}Am-Be source.

Table 1: Tracks density obtained in the CR-39 detector when exposed to the ^{241}Am-Be source.

Device Code	Exposure time to radiation (Hrs.)	Tracks density δ (Tracks/cm²)
01	3	4907 ± 743
02	4.5	7879 ± 962
03	6	9722 ± 1363
04	9	16113 ± 1166

To calculate the total flux of neutrons (φ_T) received by the device during the time that is subjected to the irradiation, we use the following equation:

$$\varphi_T = \varphi_\Omega t \tag{3}$$

where is the total exposure time of the device to the radioactive source. Finally, we calculate the average value of the efficiency (ε) from the tracks density (δ) recorded in the CR-39 and the total neutron flux (φ_T) emitted by the ^{241}Am-Be source in a certain time by means of the equation:

$$\mu = \frac{\delta}{\varphi_T} \tag{4}$$

The average efficiency obtained was $4.91 \times 10^{-5} \pm 2.53 \times 10^{-6}$ tracks / neutron. The efficiency values of the detection device can be compared with the reports of other authors [18].

4. RESULTS AND DISCUSSION

The sixteen devices placed at the treatment room presented a considerable amount of neutron scattering. This confirms, once again, that linear accelerators used to give medical treatments produce undesirable neutrons. **Figure 6** shows an image with the concentrations of neutron scattering recorded by each of the sixteen devices placed in the treatment room. These concentrations are represented by colored circles, where each color corresponds to a certain number of tracks. The image also shows a color scale, where the dark blue

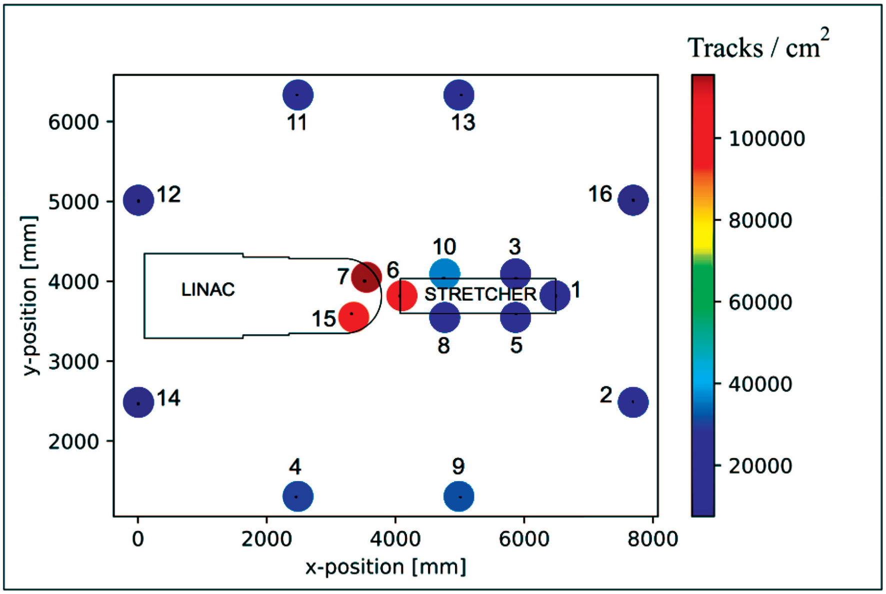

Figure 6: Image with the concentrations of neutron scattering recorded by each of the sixteen devices.

color represents the lowest number of tracks recorded in the device and the dark red color represents the largest number of recorded tracks. The diameter of the circles does not represent the area of measurement of neutron scattering.

As shown in **Figure 6**, the zone with the highest concentration of neutron scattering is located at the head of the LINAC. In this area, device 7 recorded more than 110,000 tracks / cm^2, the highest neutron scattering concentration level in the room. While the device 15 also had a high level of concentration close to 90,000 tracks / cm^2. On the other hand, the zone with the lowest neutron scattering concentration was located at the back to the LINAC´s head, as demonstrated by the devices 12 and 14 that recorded between 7,000 and 8,000 tracks / cm^2. The zone in front of the head of the LINAC (devices 2 and 16) had a concentration level range around 15,000 to 20,000 tracks / cm^2, a concentration higher than the zone at the back of the accelerator (device 12 and 14) despite being located almost at the same distance; this would mean that the way in which the neutron scattering are distributed within the room will also depend on the position of the LINAC with respect to the walls of the place. The zone where the devices 11 and 13 were placed recorded a concentration level around 25,000 tracks / cm^2, while the zone where devices 4 and 9 were placed had a concentration level around 30,000 tracks / cm^2. Both zones have a greater concentration with respect to the zones located in front of and behind

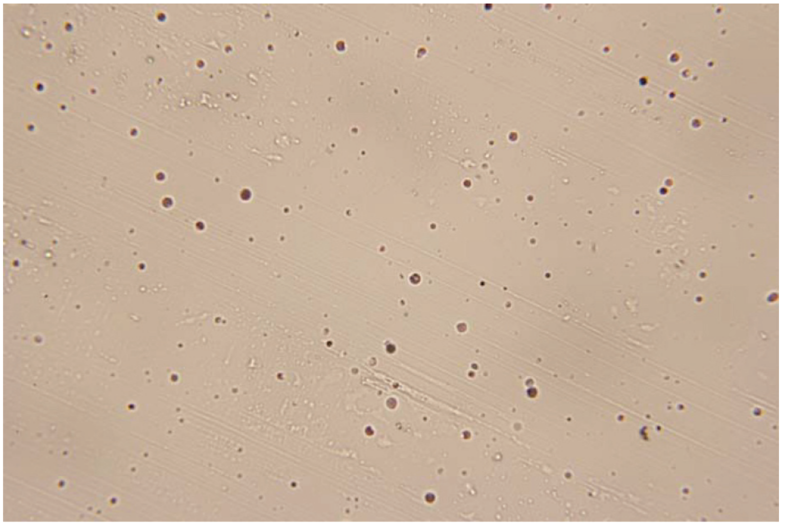

Figure 7: Micrograph of device 10. 20x magnification.

the accelerator. This result is so because these walls are closer to the LINAC's head. But the difference of concentration that these two zones has, in spite of being located to distances very close with respect to the LINAC´s head, is possibly due to the influence that acquire all the furniture and materials that are inside the room. The stretcher also had very varied levels of neutron scattering concentration. The place where the patients put the head presented a high level of neutron scattering concentration of around of 100,000 tracks / cm^2 (device 6), by situate near the head of the LINAC. The concentration in the place where the patients put their left arm (device 10) was more than 35, 000 tracks / cm^2, smaller than the registered in the head but higher than the one on the walls, whereas the place where the right arm is put (device 8) was near of 20,000 tracks / cm^2, very similar with respect to the walls. Finally, the zone near the location where patients place their legs and feet (devices 3, 5 and 1) had a concentration around also 20,000 tracks / cm^2. Therefore, it is observed that the concentration of neutron scattering in the area where patients place the upper part of their body is very high, while the area where they place their lower part is similar to that of the fourth in general. The patient is therefore exposed to undesirable additional radiation. **Figure 7** shows a micrograph belongs to the detector of device 10 with a magnification of 20x.

There are several practical and theoretical reports on the production of photoneutrons in linear accelerators used for medical applications, but this present one is the first to characterize a treatment room by measuring different density zones of neutron scattering within the room, in addition to identify the zones with the highest concentration. This work allows to understand that radiological risk should not only be considered in patients, but also in technicians and local workers. Finally, the factors involved in the way in which neutron scattering are concentrated within the room are better understood.

CONCLUSION AND RECOMMENDATIONS

The linear accelerator produces a considerable amount of photoneutrons, which in turn interacts with materials found in the vicinity, producing scattered neutrons. The sixteen devices placed in a treatment room for a month showed a considerable concentration of neutron scattering. In the room evaluated, the zone with the highest levels of concentration of neutron scattering are located at the head of the lineal accelerator and at the top of the stretcher, while the zone with the lowest concentration is located at the back of the LINAC. These results show that the distribution of the neutron scattering concentration will depend on the dimensions and geometry of the room, the materials in which the room is made, the position of the linear accelerator within the room and the furniture and materials that are inside the room. These results are a reference to recommend their mitigation to avoid that patients, physicians, technicians and other workers are unnecessarily irradiated by these particles. Also, these results invite us to recommend similar measurements in all treatment rooms equipped a linear accelerator for medical applications, to analyze the results and mitigate the neutron scattering. Finally, we observe the need to carry out more studies to understand the degree of interaction that these neutron scattering have with patients [7], but especially with the personnel working inside the room.

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