MLEM neutron spectra unfolding in a radiotherapy bunker using Bonner Sphere Spectrometer

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The high-energy radiotherapy treatments of a medical Linear Accelerator (LinAc) generate secondary neutrons that can produce health damage on human body as the induction of secondary cancers. The energy spectrum of these neutrons must be determined to estimate the extra dose received by patients inside a radiotherapy room during radiotherapy treatment. To quantify the neutron production, a Ludlum Bonner Sphere Spectrometer (BSS) is used for measurement at different points of a LinAc bunker at the Hospital Universitari i Politècnic La Fe de València. With the neutron measured data and a set of response detector curves obtained by Monte Carlo simulations with MCNP6.1.1, a Maximum-Likelihood Expectation-Maximization (MLEM) unfolding method is used to unfold the energy neutron spectrum. Unfolded neutron spectra at different locations were compared to those obtained by Monte Carlo simulation of the same setup, showing the same energetic behavior. The fluence rate decrease with source distance and the shape changes from a fast neutron peak in the nearest LinAc head location to a prominent thermal neutron peak in the bunker maze region. Moreover, neutron ambient equivalent dose was obtained from the unfolded spectra and compared to the Berthold detector measurements being consistent.

Keywords: BSS; MCNP6; neutrons; dose; radiotherapy

I. INTRODUCTION

A medical Linear Accelerator (LinAc), is a device for external beam radiation treatments for patients with cancer, being one of the most widely used in the radiation therapy departments. LinAcs can operate with different energy beams depending on the planned treatment. Commonly, the device generates a monoenergetic electron beam producing high-energy X-Rays by bremsstrahlung when electrons hit the heavy target material. The generated electrons and photons can be absorbed and interact with the high atomic number material constituting the accelerator head. If these photons have energies above 8 MeV, neutron emission is possible because of photonuclear reactions [1], [2].

Neutrons originated inside the treatment head contribute to the unwanted dose received by patients. In addition, these neutrons can induce activation of different materials inside the treatment room. These facts expose to patients and personnel radiotherapy personnel a carcinogenic risk [3], [4], [5], [6]. According to the ICRP 103 [7], radiation therapy should deliver the required dose to the volume to be treated, avoiding the unnecessary exposure of healthy tissues. Since the carcinogenic risk associated with secondary neutrons is strongly dependent of the energy [8], it requires an accurate determination of the neutron spectrum.

The biological effects of ionizing radiation on the human body are measured with the equivalent dose. The weighting factor w_r for neutrons and alpha particles presents a high value. In the case of neutrons, depending on the energy, w_r includes values in the range from 5 to 20 producing an equivalent dose on the patient or clinical staff until 20 times larger than the absorbed dose. Considering these facts, the exposure to these non-negligible doses produced by the secondary neutrons, could be significant for people health causing a radiological protection issue [9] .

Although the different LinAcs bunker are similar, there are some differences among hospitals such as the exact material compositions of the walls and the primary barriers or the dimensions of the room that affect at the neutron spectrum [5], specially at places far away from the isocenter where these neutrons have been moderated by the elements of the bunker. The main objective of this work is to develop and validate a methodology to unfold the neutron spectrum produced in a LinAc bunker operating at 15 MV.

II. MATERIALS AND METHODS

To perform the described objective, the work is divided into several steps, which are shown in the flowchart of Figure 1. One of the main steps to unfold a neutron spectrum is generating the response function of the multisphere spectrometer. In this work, this matrix was obtained using Monte Carlo simulations [10], and it is used as a fundamental part in the mathematical process implemented to obtain the final neutron spectrum from Ludlum Bonner Sphere Spectrometer (BSS) [11] measurements. According to this, given a set of measures in neutrons per second in a LinAc bunker position with the BSS device, a theoretical response matrix of the BSS, and an unfolding mathematical algorithm, the neutron spectrum generated by a LinAc at the radiotherapy facility can be obtained. Once the energy spectrum is obtained, it can be used to estimate the absorbed dose by patients and staff in the considered points of the room allowing to improve cancer treatments, reducing secondary cancers produced by secondary radiation.

The neutron spectrometer used to determine the neutron energy spectrum in different locations of the radiotherapy room was the Ludlum Bonner Sphere Spectrometer (BSS) [11]. The BSS is a device described in 1960 by Brambblett, Ewing and Bonner [12] and it is a system widely used for radiation protection purposes, as LinAc facilities, [13] because it can detect neutrons in a wide energy range from thermal to hundreds of MeV. This is possible due to the set of six polyethylene spheres that act as moderators for different energy neutrons. As the diameter of the sphere increases, higher energy incident neutrons are thermalized and detected by the ^{6}LiI Scintillator Crystal located at the center of the system.

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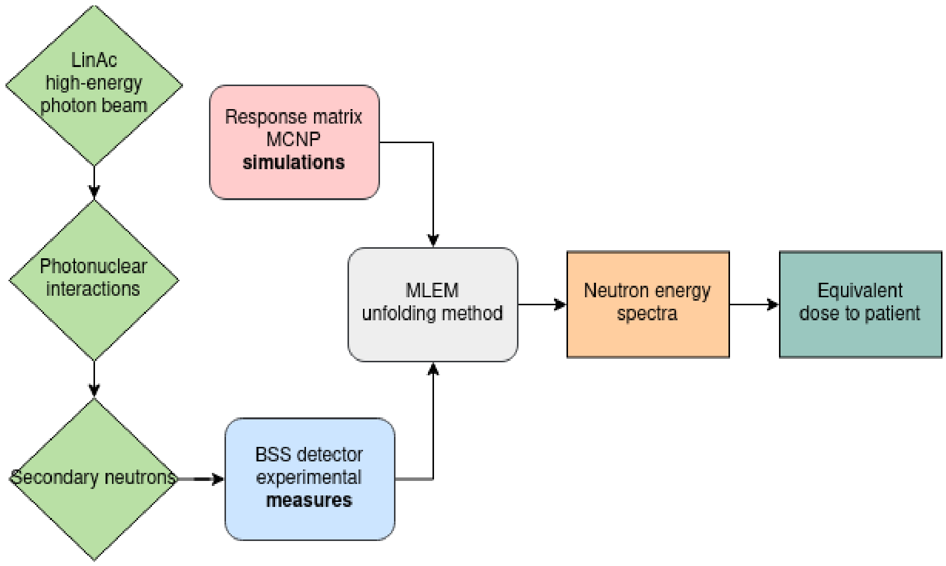


Figure 1. Flowchart to obtain the energy neutron spectrum and equivalent dose to patient using BSS detector.

II.A. Description of the BSS system and measurements in a radiotherapy bunker

The neutron spectrometer used to determine the neutron energy spectrum in different locations of the radiotherapy room was the Ludlum Bonner Sphere Spectrometer (BSS) [11], mentioned above. The BSS is a device described in 1960 by Brambblett, Ewing and Bonner [12] and it is a system widely used for radiation protection purposes, as LinAc facilities, [13] because it can detect neutrons in a wide energy range.

The neutron detector device consists of a central thermal neutron detector and six high-density polyethylene (0.95 g/cm^3) spheres with diameters of 2, 3, 5, 8, 10 and 12 inches. This set of spheres makes possible to obtain spectral information over the neutron energy range from thermal energies to approximately 20 MeV. As the diameter of the spheres increases, higher energy incident neutrons are thermalized and detected by the detector. This cylindrical detector is a scintillator crystal made of lithium iodide (^{6}LiI-Eu) with 4 mm diameter and 4 mm height coupled to a multiplier tube via a Plexiglas light pipe [11].

The BSS system operation methodology is quite simple [14]. Each sphere moderator is inserted in the detector device which is positioned at the center of the sphere being sensitive to different energy neutrons depending on the diameter of the moderator. Moreover, user can leave the bare detector without sphere moderator. With the measurements of this set of spheres, and the bare case, the detector registers neutrons in different energy range giving information about the neutron spectrum which can be unfolded with a mathematical algorithm.

The6escryibed BSS detector has been used to unfold the neutron spectrum of a Varian Clinac at Hospital Universitari I Politècnic La Fe de València operating at 15 MV. To perform the experimental measures, the BSS system was placed at different points of interest of a radiotherapy facility, to study the effect of neutron moderation in the bunker and the maze attenuation effect. Figure 2 shows the Varian Clinac and the BSS detector at the radiotherapy facility of the hospital.

Figure 2. BSS detector at the radiotherapy bunker and the Varian Clinac at the "Hospital Universitari I Politècnic La Fe de València".

Measurements with each moderator sphere were done with the LinAc operating with a rate of 600 MU per minute and each measurement was carried out for 2 minutes, measuring also the neutron background of the room to subtract these counts from the measures with the spheres. The LinAc was operated at 15 MV and the gantry positioned at 0º. The jaws collimators were positioned with a field size of $0.5 \times 0.5\ cm^2$, in a closed position, and the multileaf collimator remained open. Figure 3 shows the LinAc room facility where measurements were done, and the points A, B and C correspond to the BSS location.

Figure 3. Measurement location points at the radiotherapy facility of a Varian Clinac at the "Hospital Universitari I Politècnic La Fe de València".

II.B. Monte Carlo Simulations

The Varian Clinac of the Hospital Universitari I Politècnic La Fe de València has been accurately modelled, including all the head accelerator components. This detailed geometry has been created using blueprints transferred by Varian to the research group under a confidential agreement with the company for research purposes. Figure 4 shows the LinAc geometry with the jaws closed and the MLC opened. Moreover, a detailed detector model and the six different spheres, were created according to the detector layout and manufacturer's information Figure 5, and the walls, ceiling and floor of the bunker have been also modelled. The geometries have been generated using the 3D Modeling Software for Engineering ANSYS SpaceClaim, and the solid models have been meshed with Abaqus/CAE [15]. The geometry model of the LinAc and the BSS detector geometry have been previously validated with experimental results in previous works [16], [17].

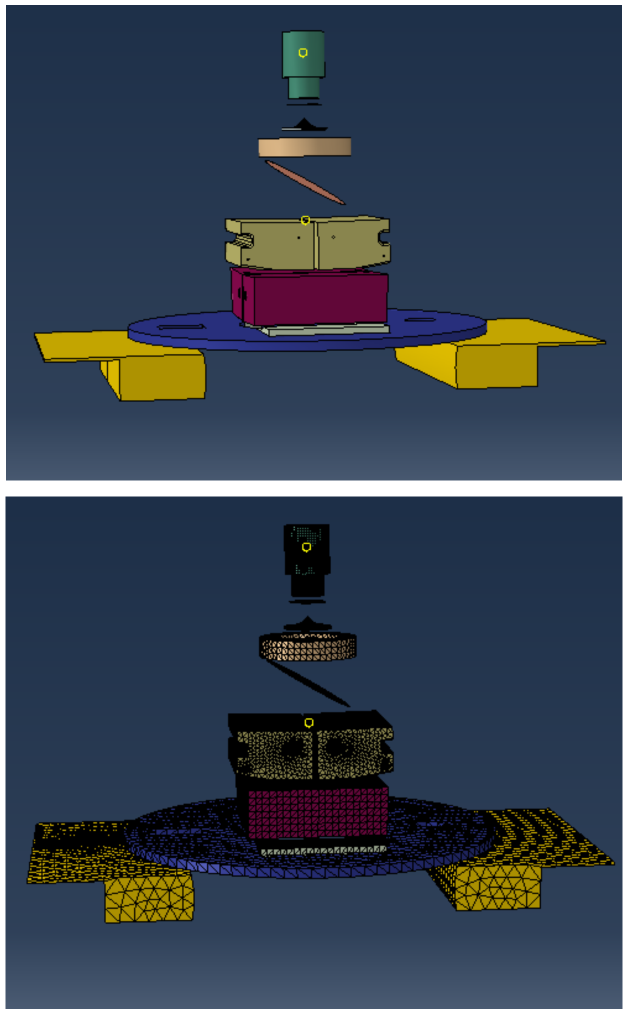


Figure 4. LinAc geometry with jaws closed and MLC opened used to perform described Monte-Carlo simulations, material composition (top), and meshed geometry (bottom).

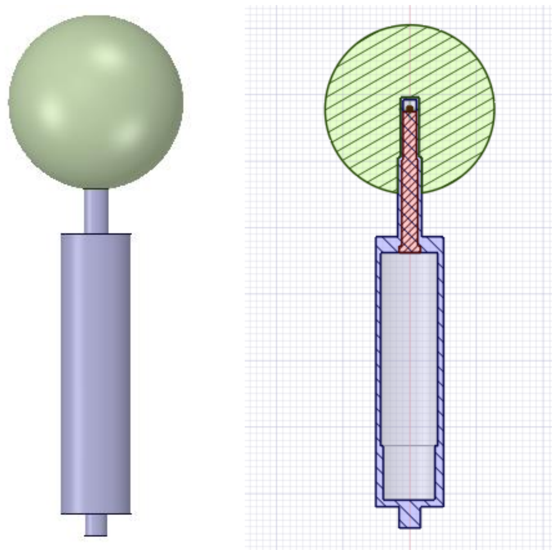


Figure 5. BSS detector and sphere of 5 in modeled according to manufacturer's information.

The meshed geometries have been used to perform the simulations with MCNP6.1.1 version [11]. For each point of the radiotherapy room showed in Figure 3, six simulations have been carried out, one for each sphere of the BSS system. The primary particles in these simulations were an spectrum corresponding to a 15 MeV photon beam placed at the target exit of a Varian Clinac head, which was extracted from *Rogers and Bagheri* works [18]. The other geometry characteristics such as the field size setting or the exact measuring location points, have been set to the same values of the experimental set up described.

II.C. Maximum-Likelihood Expectation-Maximization (MLEM) Unfolding Method

To obtain the neutron spectrum, we must unfold the raw data measured with the BSS, using the response function matrix of the sphere system. The response function of each BSS moderator is a continuous function of the neutron energy with a characteristic shape depending on the neutrons energy that are preferably thermalized by the sphere. For this reason, the response function is unique for each detector and sphere moderator related to its diameter. The MLEM neutron unfolding method used in this work relies on the BSS theoretical response obtained in previous works [17] by Monte Carlo simulations using MCNP6.1.1. This BSS response function for each sphere was validated with others published response functions [19], [20], [21], [22] founding that they fit precisely with an error lower than the 3%.

Each sphere-detector combination i, has a unique response function denoted by $R_i\ (E)$ depending on the neutron energy E. The counts recorded experimentally or simulated for each moderator, are denoted by m_i. Finally, the $n(E)$ is the unknown energy neutron spectrum to be found through the unfolding method. The relation between the neutron spectrum and the response function is given by the Fredholm integral equation of the first kind as is shown in (1).

$$m_i = \int_{E}^{E+\Delta E} R_i(E) n(E) dE \tag{1}$$

The integral can be written in a matrix form: $m = R \cdot n$, where m is an array of i dimension being i the measured data for each sphere moderator, R is the linear operator corresponding to the rectangular response matrix with dimension $i\ \times j$, that represents the response for each i sphere and for each j energy neutron beam; finally, n corresponds to the solution of the problem: the unfolded energy spectrum, an array with dimension j.

The problem of the unfolding method is that the number of measurements for each sphere, 6, is smaller than the number of energy bins of the unknown spectrum. In these BSS response function [17], 29 energy bins have been used for each sphere. This kind of problems has an infinite number of mathematical solutions, many of them without a physical sense. In this case, one of the possibilities to unfold the neutron spectra is the MLEM method [23], [24], an iterative process that maximizes the likelihood of obtaining the measured data when convergence is achieve, providing an accurate neutron spectrum. The iterative form of the MLEM method is described in equation (2), where the summation limits, N and J, correspond to the total number of moderators and the total number of energy bins, respectively.

$$n_j^{k+1} = \frac{n_j^k}{\sum_{i=1}^{N} r_{ij}} \sum_{i=1}^{N} r_{ij} \frac{m_i}{\sum_{b=1}^{J} r_{ib}\, n_b^k} \tag{2}$$

In this equation, n_b^k is the initial spectra, used at the first iteration and uploaded until the k-th iteration; n_j^k is the current spectrum uploaded in each iteration; r_{ij} is each element of the previously calculated response matrix, i.e., the response function of the detector; and m_i are the experimental measurements, in counts, one by each sphere moderator of the detector device. The MLEM method, starts with an initial spectrum, usually a uniform spectrum or a step function, and iterates obtaining a calculated m, that it is the solution of the product, which in the matrix form refers to $R \cdot n$, named the reconvolved spectrum. If the ratio between m, and the deconvolved spectrum is lower than a minimum value established by the user, the iteration method stops, otherwise, the method starts a new iteration. Each step provides a new neutron spectrum uploading the previous one. Finally, when the stop criteria are accomplished, the MLEM gives the unfolded neutron spectrum over a wide energy range. In this work, the stop criteria is selected with an error constraint of 0.01 between the experimentally measured data and those calculated with MLEM algorithm, and the initial spectra is a uniform spectrum.

II.D. MLEM validation

To ensure that the MLEM described methodology can be properly used in this unfolding problem, two validations have been carried out. On the one hand, an experimental validation has been done using measurements of a known neutron source to unfold the neutron spectrum. On the other hand, some simulations were performed to validate that the unfolded spectrum with MLEM methodology fits with the simulated neutron spectrum, under the same conditions.

II.D.1. Experimental Validation

To validate the MLEM unfolding method, BSS experimental measurements were performed for an ^{241}*Am-Be* neutron source with an activity of 1.48 GBq from a surface moisture density gauge, (Troxler Model 3430 Plus, Figure 6) of the Universitat Politècnica de València. Once the energy spectrum is obtained for this source, it is compared with the standard ^{241}*Am-Be* spectrum taken from the ISO-8529-1 [25]. As shown in Figure 7 the unfolded ^{241}*Am-Be* spectrum fits with accuracy to the reference spectrum.

Figure 6. ^{241}*Am-Be* neutron source measuring experimental set up with the BSS system

Both spectra show the same shape and the mean intensity in the energy interval from 0.5 to 12 MeV presents a percentage difference of 6% validating the unfolding MLEM algorithm used in this work.

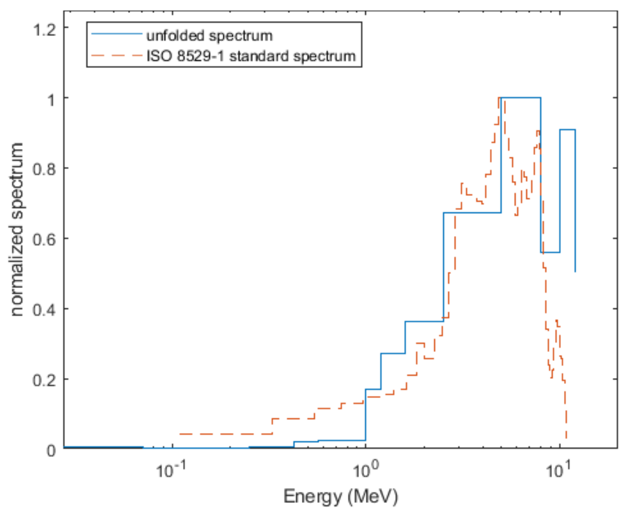


Figure 7. Comparison between normalized unfolded neutron energy spectrum using MLEM (continuous line) for ^{241}*Am-Be* neutron source and the ISO 8527-1 standard ^{241}*Am-Be* spectrum (dashed line). Energy values in a logarithmic scale.

II.D.2. Monte Carlo Simulation Validation

In this case two sets of simulated data have been used to validate the MLEM methodology. First, in the modelled radiotherapy room, the accelerator and the BSS device were simulated with Monte Carlo techniques, using the MCNP6 code. At point A (Fig. 3), the counts per second for each sphere-detector combination, were measured simulating the BSS detector inside the radiotherapy room. Then, using these 6 measures, the spectrum has been unfolded using MLEM methodology, obtaining the solid line shown in Figure 8. In a different MCNP6 simulation, a F5 tally was located at the same point A to obtain directly the neutron spectrum shown in the shaded line of Figure 8. This figure shows the comparison between both described spectrums, providing further validation of the MLEM algorithm for neutron spectrum unfolding.

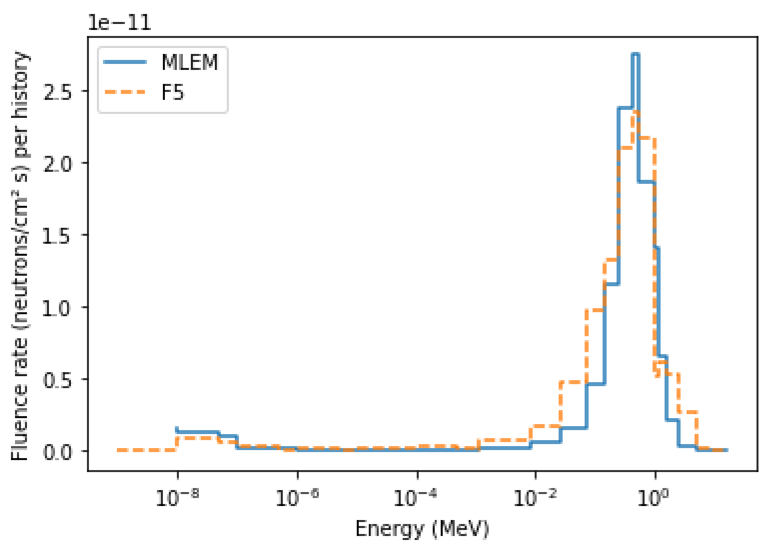


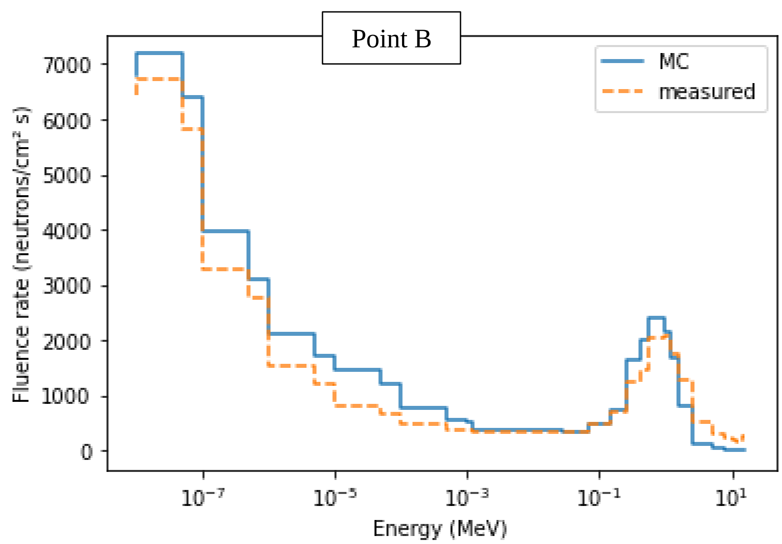
Figure 8. Comparison between unfolded neutron energy spectrum using simulated counts per second and MLEM for point A in the radiotherapy LinAc facility (solid line) and the simulated spectrum with MCNP6.1.1 obtained with F5 tally in the same point (shaded line). Energy values in a logarithmic scale.

III. RESULTS

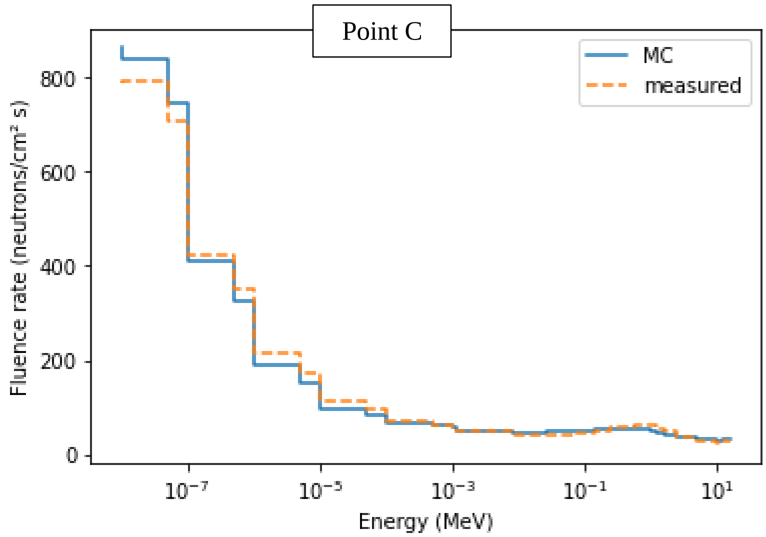
III.A. Spectrum Unfolding

The unfolded neutron spectra have been obtained for both set of data described below, at locations B and C in the bunker for a Varian Clinac. The first set of data consists of the counts per second obtained with MCNP6 simulation of BSS system at these locations. The second set of data is the counts per second experimentally measured at the Hospital Universitari i Politècnic La Fe of València. The neutron spectra unfolded using simulated data is obtained per primary particle, nevertheless a factor between this spectrum and the measured one is obtained minimizing the χ^2 distribution. The initial spectrum used in each case as input for MLEM algorithm is a uniform spectrum.

Figure 9 shows the comparison of the fluence rate spectrum in units of neutrons/cm^2 s as a function of energy, between unfolded neutron spectrum obtained from measured data and from simulated Monte Carlo (MC) data, at points B (Figure 9 (a)) and C (Figure 9 (b)) respectively. Both spectra fit precisely with a difference of 5 % at point B and a difference less than 1 % at point C.



(a)



(b)

Figure 9. Comparison between unfolded neutron spectrum obtained from experimental data (dashed lines) and from simulated data (solid lines) at points B (a) and C (b) respectively in the facility room of a Varian Clinac at the "Hospital Universitari i Politècnic La Fe de València".

At point B, located in the maze-room junction, the fast neutron peak can be observed, while a thermal neutron peak appears with higher fluence surpassing that of the fast neutron. In this point the fluence rate has a maximum value of the order of $7 \cdot 10^3$ neutrons per cm^2 and second. At point C, located in the maze of the bunker, the neutron spectrum shows the thermal neutron peak that has been decreased until one order of magnitude compared with the same peak at point B.

Moreover, the spectrum shows a tail of intermediate energy and a very small fast neutron peak. The fluence difference between both thermal peaks is due to the attenuation produced by the maze wall that separates the irradiation zone of the bunker and the security maze region.

III.B. Ambient Dose Equivalent Calculations

Neutron ambient dose equivalent was also calculated. ICRP-74 [26] fluence to dose coefficients were used over the unfolded spectrum obtained with simulated data, to convert the neutron flux spectrum into ambient dose equivalent and integrated over the energy range to obtain the total ambient dose equivalent in each point of measurement. Moreover, the ambient dose equivalent was also measured using a detector LB6411 designed between Berthold and the Karlsruhe Research Center [27]. The results for neutron ambient dose equivalent are shown in Table 1.

	Total fluence (n/cm^2s)	H*(10) (mSv/h) unfolded spectrum	H*(10) (mSv/h) calculated with Berthold
Point B	4.71e4	13.6	13.1
Point C	4.67e4	0.97	0.92

Table 1. Total fluence rate, ambient dose equivalent H*(10) for unfolded spectrum and for measurements using a Berthold detector at different locations in a facility room of a Varian Clinac at Hospital Universitari i Politècnic La Fe de València. Point B and C.

In the same way as the fluence values, the ambient dose equivalent decrease when the point of measurement is moved away from the LinAc isocenter.

III.C. Point A Considerations

Although ^{6}LiI-Eu detectors provide a satisfactory sensitivity to neutrons and excellent properties in terms of photon rejection when the measurements were carried out from a neutron source, the main problem of this detector is the separation of neutron and photon events when photon fluence is extremely high compared with neutron contribution. Its highly sensitive to photons is due to the high density and atomic number of Iodine. In the LinAc bunker facility, photon beams are used so the photon signal is extremely high compared with neutron contribution which can perturb the results obtained with the BSS [28], [29].

This is the reason that for the point A, the values of measured data cannot be directly precisely obtained. The reason is that in this location, due to the short distance to the isocenter, the photon component signal is large compared to the neutron signal, and the counts per second measured with the BSS system are higher than the real ones. According to this, at point A, only simulated data has been considered to unfold the spectrum and to obtain the ambient dose equivalent.

The neutron spectrum obtained at point A shown in Figure 10, has been obtained applying the same conversion factor used in points B and C between simulated and measured data. Using this factor, the spectrum is finally shown in units of neutrons per cm^2 and second.

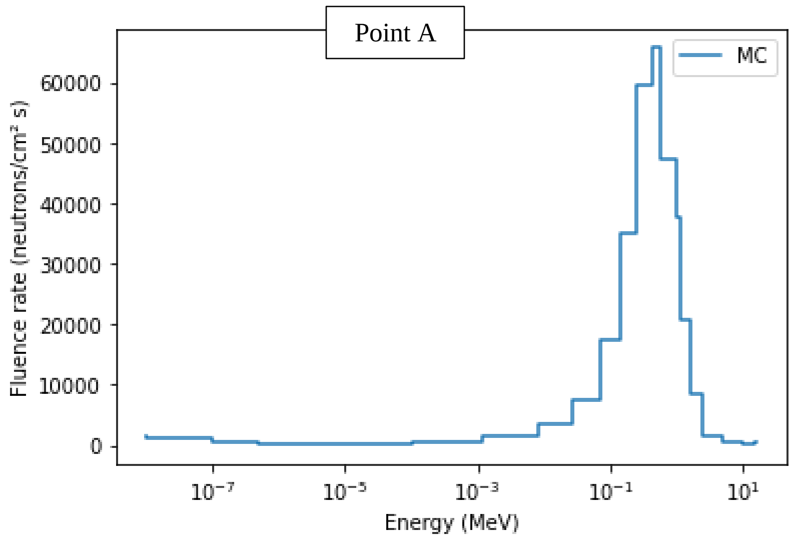


Figure 10. Unfolded neutron spectrum obtained from MC simulated data using LinAc geometry of a Varian Clinac at the "Hospital Universitari i Politècnic La Fe de València".

The unfolded spectrum at point A, which is at 1 m of the LinAc isocenter, was the closest to the LinAc head measured in this work, showing the largest fluence rate values of all bunker measurements locations. The peak corresponding to the fast neutron peak is shown in the point A spectrum with 25 more intensity that the fast neutron peak in the point B.

By the same reasons described above, for the BSS system, with the LB6411 detector, the measurements at point A cannot be used to obtain the ambient dose equivalent, so its value is calculated using the unfolded spectrum as the same way that at points B and C as it is shown in Table 2.

	Total fluence (n/cm^2s)	H*(10) (mSv/h) unfolded spectrum
Point A	3.15e5	357.0

Table 2. Total fluence rate, ambient dose equivalent H*(10) for unfolded spectrum and for measurements using a Berthold detector at different locations in a facility room of a Varian Clinac at Hospital Universitari i Politècnic La Fe de València. Point A.

Comparing values from Table 1 and Table 2, total fluence values have been reduced an 85 % in both points B and C respect to the point A total fluence values, while the total ambient dose equivalent has been reduced 96 % and 99 % at points B and C respectively in comparison with the total ambient dose equivalent at point A.

The developed methodology has been applied in a bunker with a Varian Clinac at the Hospital Universitari i Politècnic La Fe de València, using a neutron spectrometer, but it can be applied in any medical or nuclear facility in which is of interest to know the neutron spectrum to calculate the equivalent neutron dose.

IV. CONCLUSIONS

In this work, the secondary neutron spectrum in different points of a radiotherapy room treatment have been obtained. A realistic simulation of a Varian Clinac emitting a beam of 15 MeV, has been performed, including the BSS system geometry to obtain the counts per second per history for each sphere in a different LinAc bunker points. Moreover, these counts per second have been measured using a BSS system at the Hospital Universitari i Politècnic La Fe de València. Using both data sets, an unfolding methodology has carried out using the MLEM algorithm. This algorithm uses the neutron response curves for each moderator obtained in previous works and has been validated.

After unfolding the spectrum, a decrease of the neutron fluence rate has been observed at higher distances from the source. The shape of the neutron spectrum changed in the different locations showing a prominent fast neutron peak in the nearest LinAc source point to a prominent peak in the thermal neutron region in the maze of the bunker facility. Both spectra obtained for measured and simulated data respectively, agree in the described shape of the spectrum.

For dose values obtained in this work, neutron ambient dose equivalent has been obtained from the unfolded neutron spectrum being consistent with the experimental data measured with the Berthold detector.

With the methodology described and validated in this work, obtaining the dose values in each point of the treatment room is possible just with MC simulations, MLEM algorithm and the neutron responses.

Although in this work, the described methodology has been applied to the medical field and to measure the dose associated to the neutrons in a LinAc treatment, this methodology can be used not only in radiotherapy bunkers, but also in any other radiation facility, like cyclotrons, nuclear power plants, or uranium enrichment factories, to obtain neutron dose contribution in any region of interest.

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