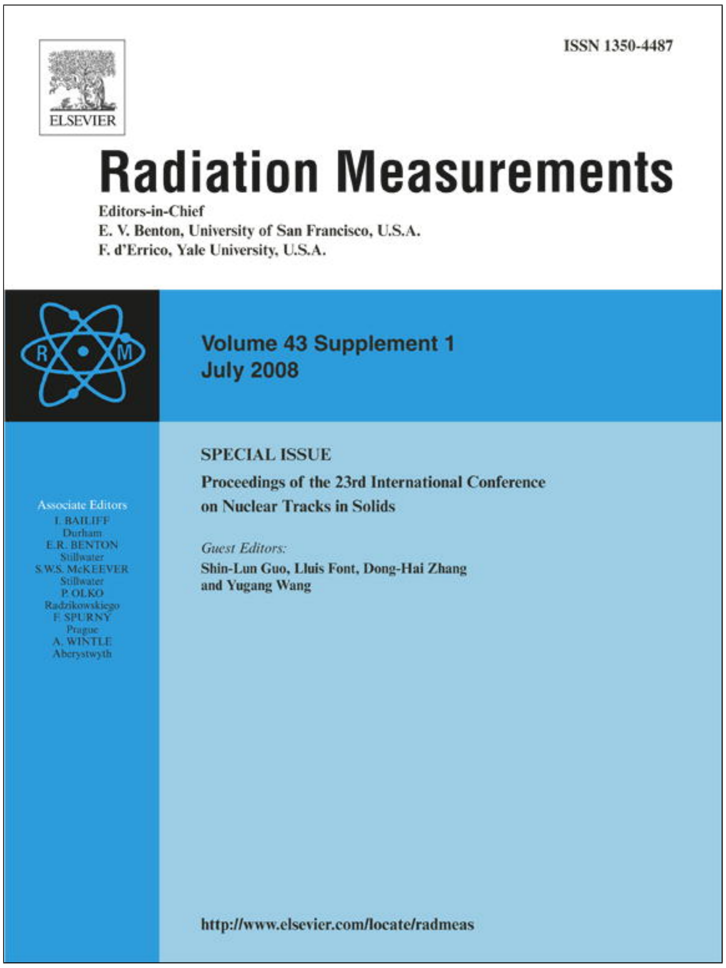
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Photoneutron intensity variation with field size around radiotherapy linear accelerator 18-MeV X-ray beam

H. Al-Ghamdi, Fazal-ur-Rehman, M.I. Al-Jarallah*, N. Maalej

Physics Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Abstract

In X-ray radiotherapy accelerators, neutrons are produced mainly by (γ, n) reaction when high energy X-rays interact with high Z materials of the linear accelerator head. These materials include the lead (Pb) used as shielding in the collimator, tungsten (W) target used for the production of X-rays and iron (Fe) in the accelerator head. These unwanted neutrons contaminate the therapeutic beam and contribute to the patient dose during the treatment of a cancer patient. Knowing the neutron distribution around the radiotherapy accelerator is therefore desired. CR-39 nuclear track detectors (NTDs) were used to study the variation of fast and thermal neutron relative intensities around an 18 MeV linear accelerator X-ray beam with the field sizes of 0, 10×10, 20×20, 30×30 and $40 \times 40\,\text{cm}^2$. For fast neutron detection, bare NTDs were used. For thermal neutron detection, NTDs were covered with lithium tetra borate ($Li_2B_4O_7$) converters. The NTDs were placed at different locations in the direction perpendicular to the treatment couch (transversal) and in the direction parallel to the treatment couch (longitudinal) with respect to the isocenter of the accelerator. The fast neutron relative intensity is symmetrical about the beam axis and exhibits an exponential-like drop with distance from the isocenter of the accelerator for all the field sizes. At the primary beam (isocenter), the relative fast neutron intensity is highest for $40 \times 40\,\text{cm}^2$ field size and decreases linearly with the decrease in the field size. However, fast neutron intensities do not change significantly with beam size for the measurements outside the primary beam. The fast neutron intensity in the longitudinal direction outside the primary beam decreases linearly with the field size. The thermal neutron intensity, at any location, was found to be almost independent of the field size.

Keywords: Neutron dosimetry; Radiotherapy accelerator; Nuclear track detectors; NTD; Fast and thermal neutron; Photoneutrons; High energy X-ray

1. Introduction

Nuclear track detectors (NTDs) are widely used for radiation dosimetry. For fast neutron dosimetry, bare polyallyl diglycol carbonate (PADC) NTDs are used to register fast neutrons through recoils of protons in the detector material. For thermal neutron dosimetry, the NTD is covered with a converter material. The thermal neutrons' nuclear reaction with the converter material produces charged particles, like alpha, which can produce tracks on the NTD.

Measurement of accelerator-based fast and thermal neutron distribution using NTDs was carried out by Al-Jarallah et al. (2000). NTDs have been successfully applied for the fast and thermal neutron relative intensity measurements in prompt gamma ray neutron activation analysis (PGNAA) setup (Al-Jarallah et al., 2002; Naqvi et al., 2003). Assessment of fast and thermal neutron ambient equivalent doses around neutron source storage area using NTDs (CR-39) was carried out by Fazal-ur-Rehman et al. (2005). NTDs were used to study depth dose equivalent and effective energies of photoneutrons generated by 6–18 MeV X-ray beams for radiotherapy (d'Errico et al., 2001). Characterization of neutron fields around high energy X-ray radiotherapy machines was carried out using CR-39 etched-track detectors in Bonner Spheres (Kralik and Turek, 2004). Neutron dose measurements from prostheses material during radiotherapy with protons and photons were performed using etched track detectors (Schneider et al., 2004). Fiechtner and Wernli used a CR-39 as personnel dosimeter.

Active neutron monitor like rem-meter are not recommended inside the radiotherapy accelerator room due to pulse pile-up in the photon dominated radiation field and detection of non-neutron induced pulses generated in the monitor (AAPM Report No. 19, 1986). Instead, NTDs can be utilized as they do

* Corresponding author. Fax: +966 3 860 2293.
E-mail address: mibrahim@kfupm.edu.sa (M.I. Al-Jarallah).

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not require any electronics or power supplies. In radiation therapy, fast and thermal neutrons contaminate the therapeutic beam and contribute to the patient dose during the treatment of cancer (Gudowska et al., 2002). The knowledge of the associated neutron distribution around the radiotherapy accelerator is therefore desired.

The neutrons are produced mainly by (γ, n) reaction when high energy X-rays interact with high Z materials of the linear accelerator head. These materials include the lead (Pb) used as shielding in the collimator, tungsten (W) target used for the production of X-rays and iron (Fe) in the accelerator head. Neutrons are principally produced through giant dipole resonance (GDR) in the nuclear reaction between photons and target nuclei of materials constituting the linear accelerator head and the beam collimation system. A lesser neutron component can also originate from the nuclear reaction between the photon beam and the treatment room walls or the patient body itself (Ongaro et al., 2000). In a previous study, CR-39 NTDs were used for the measurement of fast and thermal neutron distributions around two 18 MeV X-ray beams generated by radiotherapy linear accelerators in a small and large rooms (Fazal-ur-Rehman et al., 2006). In that study, the collimators of the beams of the two accelerators were closed. In the present study, CR-39 NTDs were used to study the variation of fast and thermal neutron relative intensities with the field sizes of 0, 10×10, 20×20, 30×30 and $40\times40\,\text{cm}^2$ around an 18 MeV linear accelerator X-ray beam.

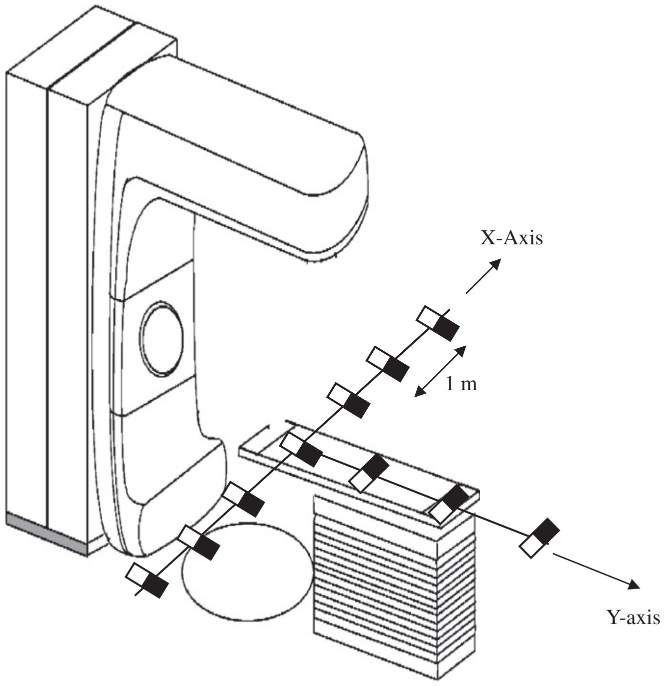

Fig. 1. Experimental arrangement showing the location of CR-39 NTDs around a radiotherapy linear accelerator. The unshaded squares are bare NTDs for fast neutron measurement and the shaded squares are boron converter-based NTDs for thermal neutron measurement.

2. Experimental method

The variation of fast and thermal neutron relative intensities with the field sizes of 0, 10×10, 20×20, 30×30 and $40\times40\,\text{cm}^2$ around an 18 MeV photon beam generated by a linear accelerator was measured. The linear accelerator (Varian 2300 CD) was located in a room ($7.14\times7.2\times3$ m) at King Fahd Specialist Hospital, Dammam. The volume of the treatment room, excluding the entrance maze, was $154\,\text{m}^3$. The primary shielding wall is composed of standard concrete (density $2.35\,\text{g cm}^{-3}$) with a thickness of 145 cm and a 35 cm thick steel placed at 95 cm from the inner wall surface. The NTDs used for neutron dosimetry were 1.5×1.5 cm in size and were made of PADC ($C_{12}H_{18}O_7$). The NTDs were manufactured by Track Analysis System Limited, University of Bristol, UK.

For fast neutron detection, bare NTDs register fast neutrons through recoils of protons in the detector material. The recoils of oxygen and carbon nuclei cannot be detected due to low energy transferred to these nuclei by fast neutrons. For thermal neutron detection, NTDs were covered with lithium tetra borate ($Li_2B_4O_7$) converter. The measurement of thermal neutrons is through the detection of α-particles from $^{10}B(n,\alpha)^7Li$ and $^6Li(n,\alpha)^3H$ nuclear reactions. Natural lithium consists of 7.4% of ^{6}Li and 92.6% ^{6}Li isotopes, whereas natural boron consists of 19.8% ^{10}B and 80.2% ^{11}B isotopes. The cross-section of thermal neutrons interaction with ^{6}Li and ^{10}B are 940 and 3840 b, respectively. Therefore, the main contribution of (n,α) reactions is mainly due to ^{10}B isotope (96%). Whereas, the contribution from ^{6}Li is only about 4% (Abu-Jarad et al., 2002).

Detectors of fast and thermal neutrons were placed side-by-side at 10 different locations in the linear accelerator room at a height of 1 m from the ground. Fig. 1 shows the locations of NTDs in the accelerator room. The shaded squares, in the figure, indicate the NTDs mounted with boron converter for thermal neutron measurement, while the unshaded squares indicate the bare NTDs for fast neutron measurement. Four sets of NTDs (fast + thermal) were placed in longitudinal direction (y-axis) for each field size. Seven sets of NTDs were placed in the transverse direction (x-axis) for each field size. All the detectors were placed on the top of a 3 m long wooden ruler of 5 mm thickness. The distance between every two consecutive measurement locations was 1 m as shown in Fig. 1. The accelerator was operated at a maximum X-ray energy of 18 MeV with a dose rate of 600 monitoring units (mu's)/min at the isocenter. An exposure time of 13 min was used, giving a total of 7800 mu's of irradiation. This corresponds to a dose of about 78 Gy in a water phantom at the depth of maximum dose.

At the end of each experiment, the NTDs were retrieved and processed for nuclear track measurements. The NTDs for thermal neutron measurement were etched in 30% KOH solution at 70 °C for 3 h. The NTDs for fast neutron measurement were etched for 4 h in 30% KOH solution at 70 °C. The NTDs were then washed with water and dried. The alpha tracks produced by thermal neutrons and proton tracks produced by fast neutrons on NTDs were counted manually under an optical microscope using a magnification of 63. For each measurement, five different areas of the NTD were used to determine the average track density and the standard deviation of the measurement.

Three detectors were used for background track density measurement. The background track density was 24 tracks/cm^2. This track density was subtracted from all the measurements before the determination of neutron distribution.

3. Results and discussion

The proton track densities found in the bare NTDs give the relative intensity of fast neutrons. The alpha track density in the boron covered NTDs give the thermal neutron relative intensity. The linearity of alpha track density from thermal neutrons with irradiation time was demonstrated in a previous study by Abu-Jarad et al. (2002). The linearity of proton track density from fast neutrons in an NTD versus its irradiation time was demonstrated in another investigation by Al-Jarallah et al. (2000).

Fig. 2 shows the proton track density produced from fast neutrons in the transverse direction as a function of distance from the isocenter of the linear accelerators for all the field sizes, with the treatment couch in the primary X-ray beam. The fast neutron relative intensity is symmetrical about the beam axis and exhibits almost an exponential-like drop with distance from the isocenter of the accelerator for all the field sizes. Neutron intensities do not change significantly with beam size for the measurements outside the primary beam. However, at the center of the primary beam, the relative fast neutron intensity is highest for $40 \times 40\,\text{cm}^2$ field size and decreases linearly with the decrease in the field size (Fig. 2). This is not in agreement with the reported data of McGinley (1993) who stated that the neutron dose equivalent rate decreased by 15% or less when the collimator was adjusted from minimum to maximum field size.

This lead to the further investigation of the fast neutron intensity in the absence of the treatment couch. The couch is made of 15 mm thick tissue equivalent material and could contribute significantly to the fast neutron intensity. Therefore, the experiment was repeated by removing the treatment couch from the primary X-ray beam. The measurements were carried out at five locations ($x = -0.5, -1, 0, 0.5$ and 1 m) in order to see the drop in intensity with distance from the isocenter. The results showed similar trends (Fig. 3) which confirm the earlier findings shown in Fig. 2. However, the fast neutron intensity at the center of the primary beam was reduced by about 40% compared with that measured with the treatment couch in the primary X-ray beam, as shown in Fig. 4. This reduction is due to the elimination of back-scattered neutrons from the treatment couch.

However, there could be still some contribution of back-scattered neutrons from the wooden ruler holding the detectors. Ipe et al. (2000) reported that high energy photons induce nuclear reactions with the nuclei of the CR-39 detector material ($C_{12}H_{18}O_7$) giving protons and alpha particles. This will enhance the track density in the detector. Moreover, there are two competing effects on the neutron output in the primary beam. First, there is the production of photoneutrons by the interaction of X-rays with the accelerator head. Second, there is the neutron attenuation by the collimator jaws. When the

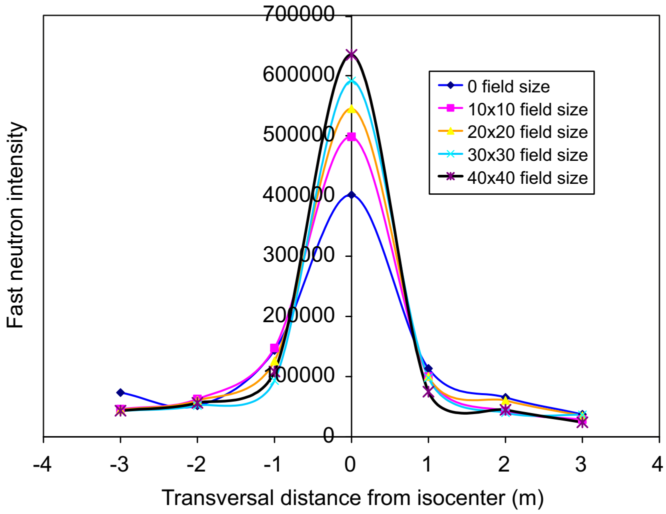

Fig. 2. Proton track density produced from fast neutrons in the transverse direction as a function of distance from the isocenter of the linear accelerators for different field sizes.

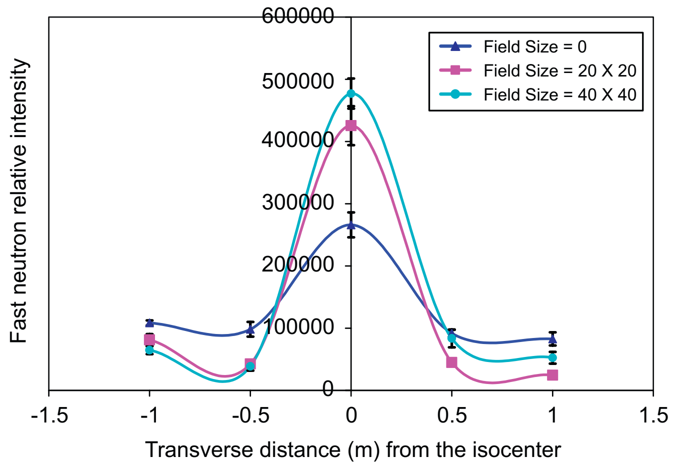

Fig. 3. Proton track density produced from fast neutrons as a function of transversal distance from the isocenter of linear accelerator for the field sizes of 0, 20×20 and $40 \times 40\,\text{cm}^2$ without the treatment couch.

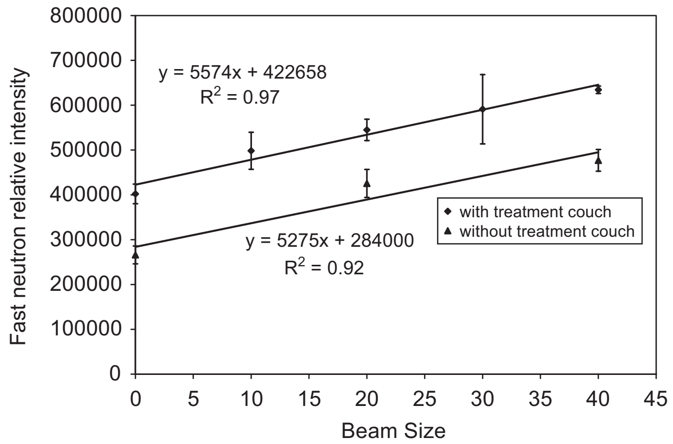

Fig. 4. Proton track density produced from fast neutrons as a function of field size with and without the treatment couch in the primary X-ray beam.

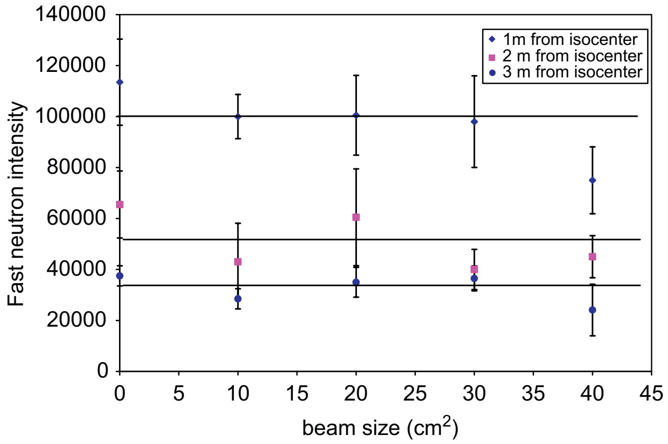

Fig. 5. Proton track density produced from fast neutrons as a function of beam size for the detectors placed outside the primary X-ray beam.

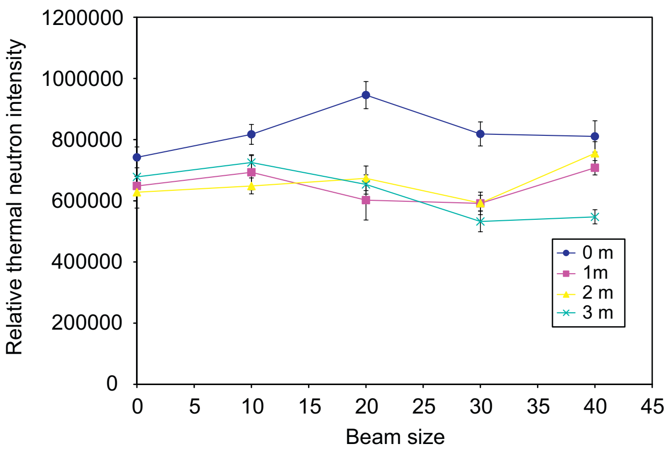

Fig. 6. Alpha track density produced from thermal neutrons as a function of beam size at different distances from the isocenter in the longitudinal direction.

collimator jaws are further apart, there is less attenuation of photoneutrons produced in the linear accelerator head. This could be the reason for the decrease in the relative photoneutron intensity at the center of the primary beam with the decrease in the field size.

Fig. 5 shows the fast neutron relative intensity as a function of beam size, outside the primary beam, at 1–3 m distance from the isocenter along the longitudinal direction. The fast neutron intensity outside the primary beam does not vary significantly with the field size which is in contrast with the case at the center of the primary beam, where the intensity increases linearly with the field size (Fig. 4).

Fig. 6 shows the relative thermal neutron intensity at 0–3 m distance from the isocenter, in the longitudinal direction, as a function of field size. The thermal neutron intensity, outside the primary X-ray beam, is almost constant for all the field sizes. It can be seen, in the figure, that the thermal neutron intensity is highest inside the primary X-ray beam at (0 m). This is in agreement with the published Monte Carlo simulation work (Pena et al., 2005) suggesting that the neutron distribution behaves like that of a gas uniformly distributed inside a room. This is due to neutron scattering from the walls, floor and roof of the linear accelerator room.

4. Conclusion

CR-39 nuclear track detectors (NTDs) were used to study the variation of fast and thermal neutron relative intensities around an 18 MeV linear accelerator X-ray beam with the field sizes of 0, 10×10, 20×20, 30×30 and $40 \times 40\,\text{cm}^2$. The fast neutron relative intensity was found to be symmetrical about the beam axis and exhibits an exponential-like drop with distance from the isocenter of the accelerator for all the field sizes. At the primary beam (isocenter), the relative fast neutron intensity is highest for $40 \times 40\,\text{cm}^2$ field size and decreases linearly with the decrease in the field size. However, outside the primary beam, the fast neutron intensity does not change significantly with the field size. The thermal neutron intensity at any location was found to be almost independent of the field size.

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References

AAPM Report No. 19 (1986). Neutron measurements around high energy X-ray Radiotherapy Machines.

Abu-Jarad, F., Fazal-ur-Rehman, Al-Haddad, M.N., Al-Jarallah, M.I., 2002. Thermal neutron equivalent dose assessment around the KFUPM neutron source storage area using NTDs. Radiat. Prot. Dosim. 102 (4), 349–354.

Al-Jarallah, M.I., Abu-Jarad, F., Fazal-ur-Rehman, Khiari, F.Z., Aksoy, A., Nassar, R., 2000. Measurement of accelerator-based neutron distributions using nuclear track detectors. Nucl. Instrum. Methods B 171, 584–588.

Al-Jarallah, M.I., Naqvi, A.A., Fazal-ur-Rehman, Abu-Jarad, F., 2002. Fast and thermal neutron intensity measurements at the KFUPM PGNAA setup. Nucl. Instrum. Methods B 195, 435–441.

Ongaro, C., Zanini, A., Nastasiand, U., Rodenas, J., 2000. Analysis of photoneutron spectra produced in medical accelerators. Phys. Med. Biol. 45, L55–L61.

d'Errico, F., Luszik-Bhadra, M., Nath, R., Siebert, R.L.B., Wolf, U., 2001. Depth dose-equivalent and effective energies of photoneutrons generated by 6–18 mV X-ray beams for radiotherapy. Health Phys. 80 (1), 4–11.

Fazal-ur-Rehman, Al-Ghamdi, H., Al-Jarallah M.I., Maalej, N., 2006. "Photoneutron distributions around 18 mV X-ray radiotherapy accelerators using nuclear track detectors", submitted for publication.

Fazal-ur-Rehman, Al-Jarallah, M.I., Abu-Jarad, F., Qureshi, M., 2005. Assessment of fast and thermal neutron ambient equivalent doses around KFUPM neutron source storage area using CR-39 nuclear track detectors. Radiat. Meas. 40 (2–6), 595–600.

Fiechtner, A., Wernli, C., Radiation protection for particle accelerator facilities, National Council on Radiation Protection and Measurements NCRP Report No. 144.

Gudowska, I., Gudowski, W., Kopec, M., 2002. Monte Carlo evaluation of neutron contamination in high energy photon therapy beams.

In: Proceedings of the 12th Biennial RPSD Topical Meeting, Santa Fe, NM, United States, Radiation Protection and Shielding Division of American Nuclear Society, April 14–18, pp. 652–658.

Ipe, N.E., Roesler, S., Jiang, S.B., et al. 2000. Neutron measurements for intensity modulated radiation therapy. Proceedings of the 22nd Annual International Conference of the IEEE Engineering In Medicine and Biology Society, July 23–28, pp. 3234–3237.

Kralik, M., Turek, K., 2004. Characterisation of neutron fields around high-energy X-ray radiotherapy machines. Radiat. Prot. Dosim. 110 (1–4), 503–507.

McGinley, P.H., 1993. Design of therapy facilities. In: Proceedings of the Health Physics Society Summer School, Hospital Health Physics. pp. 53–67.

Naqvi, A.A., Fazal-ur-Rehman, Al-Jarallah, M.I., Abu-Jarad, F., 2003. Performance tests of external moderators of a PGNAA setup. Appl. Radiat. Isot. 58 (1), 27–38.

Pena, J., Franco, L., Gomez, F., Iglesias, A., Pardo, J., Pombar, M., 2005. Monte Carlo study of Siemens PRIMUS photoneutron production. Phys. Med. Biol. 50, 5921–5933.

Schneider, U., Fiechtner, A., Besser, J., 2004. Neutron dose from prostheses material during radiotherapy with protons and photons. Phys. Med. Biol. 49, N119–N124.