

A neutron track etch detector for electron linear accelerators in radiotherapy

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Received 16 September 2009

Accepted 16 November 2009

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Disclosure: No potential conflicts of interest were disclosed.

Background. Electron linear accelerators in medical radiotherapy have replaced cobalt and caesium sources of radiation. However, medical accelerators with photon energies over 10 MeV generate undesired fast neutron contamination in a therapeutic X-ray photon beam. Photons with energies above 10 MeV can interact with the atomic nucleus of a high-Z material, of which the target and the head of an accelerator consist, and lead to the neutron ejection.

Results and conclusions. Our neutron dosimeter, composed of the LR-115 track etch detector and boron foil BN-1 converter, was calibrated on thermal neutrons generated in the nuclear reactor of the Josef Stefan Institute (Slovenia), and applied to dosimetry of undesirable neutrons in photon radiotherapy by the linear accelerator 15 MV Siemens Mevatron. Having considered a high dependence of a cross-section between neutron and boron on neutron energy, and broad neutron spectrum in a photon beam, as well as outside the entrance door to maze of the Mevatron, we developed a method for determining the effective neutron detector response. A neutron dose rate in the photon beam was measured to be 1.96 Sv/h. Outside the Mevatron room the neutron dose rate was 0.62 μ Sv/h. PACS: 87.52. Ga; 87.53.St; 29.40.Wk.

Key words: electron linear accelerator; photoneutron; track etch detector; neutron dose equivalent

Introduction

Nowadays, cobalt and caesium teletherapy machines in medical radiotherapy are being replaced by linear accelerators.¹ The great advantage of this new equipment is that it has no attached radioactive source, which makes them safer from the radiological point of view. However, medical accelerators with photon energies over 10 MeV generate undesired fast neutron contamination in a therapeutic beam. Photons with energies above 10 MeV can interact with the atomic nucleus of a high-Z material, of which the target and the head of the accelerator consist, and lead to the neutron ejection. Consequently, this can increase the patient dose and pose a problem in room shielding dosimetry, which is essential for the quality assurance in radiotherapy.^{2,3}

Neutrons are principally produced through giant dipole resonance in a nuclear reaction (γ, n) between photons and target nuclei.⁴ The giant resonance process produces two groups of neutrons; the first

and the largest group has a spectrum, which can be described by a Maxwellian distribution, with the most probable energy, typically between 0.4 and 1 MeV; the second group of neutrons is produced by direct emission and is somewhat higher in energy (up to 10-20% of the total neutrons in general).⁵ The mean energy of the neutron spectrum generated by the (γ, n) reaction is around a few MeV, but, at the patient plane, neutrons have a more complex distribution and a less mean energy. As beam energies increase (>10 MeV), an undesirable photoneutron dose also increases. Otherwise one can expect, that inside the area treated by linear accelerator, the neutron dose in a tissue will not exceed 1% of the photon dose.⁶

Material and methods

The neutron dosimeter consisted of the LR-115 track detector and boron foil BN-1 (Kodak-Pathe,

France) or ^{10}B converter for reaction (n, α) ; it was calibrated on neutrons generated in the nuclear reactor of the J. Stefan Institute (Slovenia).⁷ Neutron irradiation was carried out in the thermal column of the TRIGA Mark II reactor where the neutron flux was $\Phi = 3.33 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$; for irradiation time, $t = 240 \text{ s}$, we got the fluence, $f = \Phi t = 7.99 \times 10^7 \text{ cm}^{-2}$.

The LR-115 detectors, $2 \times 3 \text{ cm}^2$, were etched in a 10% NaOH aqueous solution at $60 \text{ }^\circ\text{C}$ for 120 min and afterwards counted visually using a microscope of (10×16) magnification.

The irradiated neutron track etch detector had a net track density $D_t = (63394 - B) \cong 63370 \text{ cm}^{-2}$, where the background, B , was 24 cm^{-2} ; the standard deviation of the D_t was $s_{D_t} = 570$. The response, r_t , of the neutron dosimeter for thermal neutrons was:

$$r_t = D_t/f = (7.930 \pm 0.071) \times 10^{-4}, \quad [1]$$

where the error was given as a standard deviation, $s_{r_t} = s_{D_t}/f = 7.1 \times 10^{-6}$.

The electron linear accelerator Siemens Mevatron 15 MV has been used as an X-ray radiotherapy source in the Clinical Hospital Osijek. The same accelerator was used to perform experiments for determining a dose equivalent of undesirable photon neutrons by using the neutron track etch detector.

Results and discussion

Linear accelerator neutrons - track detector in the beam

In order to determine a dose equivalent of photon neutrons produced by linear accelerator, operating in a photon production mode at an acceleration potential of 15 MV, we used the LR-114 track etch detector, which was positioned in the beam at 1 m from the accelerator head.

For fast neutrons with higher energy, a detector response should be lower; having considered a total cross-section of neutrons on boron, $^{10}\text{B}(n, \alpha)^7\text{Li}$, depending on neutron energy ($\sigma(E)$, Figure 1)⁸, as well as a neutron fluence spectrum on energies by the linear accelerator (Figure 2)², we divided neutron energy E_a (MeV) in the two areas as follows: the first area, $0 < E_{a1} < 0.5$, and the second one, $0.5 \leq E_{a2} \leq 7.5$.

Afterwards, we estimated the respective mean cross-sections $\sigma_t = 1000 \text{ b}$ (for thermal neutrons), $\sigma_{a1} = 1.33 \text{ b}$ and $\sigma_{a2} = 0.25 \text{ b}$ (for energies E_{a1} and E_{a2} respectively) from the curve $\sigma(E)$ in Figure 1, and

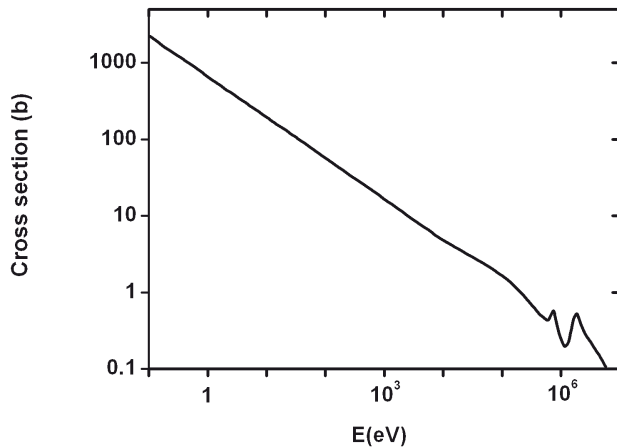


FIGURE 1. The total cross-sections of neutrons on boron (σ/b) versus neutron energy (E/eV).⁸

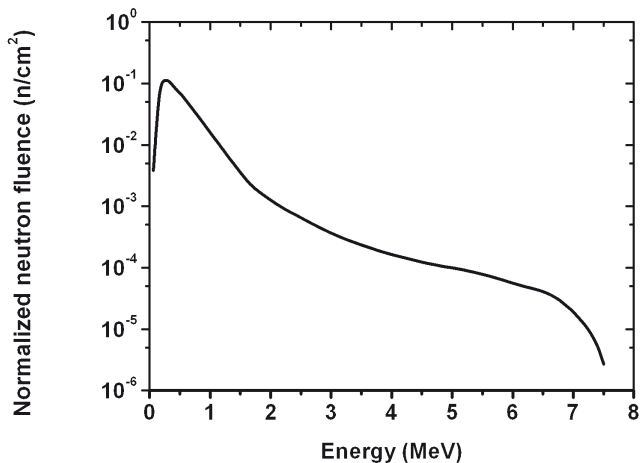


FIGURE 2. Neutron spectrum produced in 15 MV linear accelerator after crossing the tungsten head; fluence ($f/\text{n cm}^{-2}$) versus neutron energy (E/MeV).²

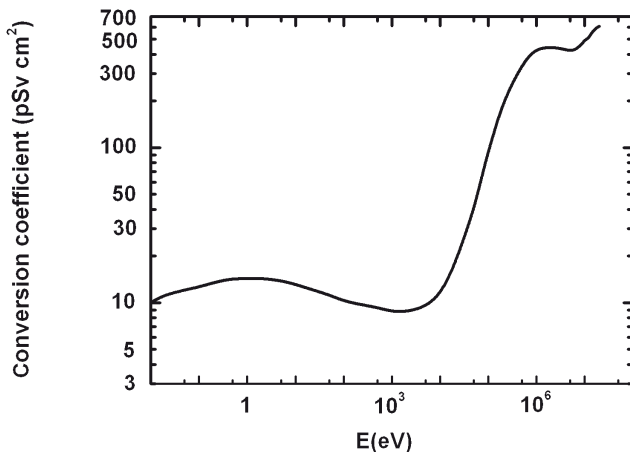


FIGURE 3. Conversion coefficient ($k/\text{pSv cm}^{-2}$) from neutron fluence to personal dose equivalent versus neutron energy (E/eV).

we determined the neutron detector responses for the low energy areas as follows: $\sigma_i/\sigma_{a1} = r_i/r_{a1}$, $\sigma_i/\sigma_{a2} = r_i/r_{a2}$, where the r_i was the response that had already been calculated by using equation [1]. Thus we got $r_{a1} = 1.06 \times 10^{-6}$ and $r_{a2} = 2.00 \times 10^{-7}$, with the standard deviations of 9.1×10^{-9} and 1.8×10^{-9} , respectively, and we were able to determine an average or effective value of the neutron detector response r_{ae} but as a weighted or pondered mean.⁹

Therefore, we took the surfaces under the neutron fluence spectrum curve (Figure 2; $f(E)$) for the two energy areas as above and we got the relative surfaces: $s_{a1} = 0.58$ and $s_{a2} = 0.42$, those had the meaning of the relative frequencies in the calculation of the pondered mean (for instance, s_1 is the ratio of the surface under the curve between 0 and 0.5 MeV to the total surface under the curve between 0 and 7.5 MeV). The mean or effective detector response was: $r_{ae} = r_{a1}s_{a1} + r_{a2}s_{a2} = (6.97 \pm 0.07) \times 10^{-7}$.

For a measured detector density D_a , the respective fluence was (like in equation [1]): $f_{ae} = D_a / r_{ae}$. When the neutron fluence is known, a conversion coefficient (k) from neutron fluence to dose equivalent, depending on neutron energy, gives a personal dose equivalent (H_a), as follows:¹⁰ $H_a = k_{ae} f_{ae}$.

Having considered a great dependence of k on neutron energy (Figure 3), we calculated the average or effective k_{ae} for the two energy areas, like above, and we used the same relative frequencies s_{ai} ($i = 1, 2$); taking the average values of k_a for the neutron energies E_{a1} and E_{a2} as $k_{a1} = 200$ and $k_{a2} = 430$ pSv cm², respectively, we calculated the effective conversion factor as follows:

$$k_{ae} = k_{a1}s_{a1} + k_{a2}s_{a2} = 296.4 \text{ pSv cm}^2.$$

Thus, the measured detector net density $D_a = (383.1 \pm 0.04) \text{ cm}^{-2}$ corresponded to the following dose equivalent:

$$H_a = k_{ae} f_{ae} = k_{ae} / r_{ae} D_a = 425.5 D_a \text{ (}\mu\text{Sv)}, \quad [2]$$

$$H_a = (0.163 \pm 0.002) \text{ Sv}$$

The dose rate was calculated as a ratio of the dose equivalent and exposure time, t , or:

$$\dot{H} = H/t, \text{ and for } t = 5 \text{ min, we got the dose rate } \dot{H} = (1.96 \pm 0.02) \text{ Sv/h.}$$

The measurement errors were determined as variances or standard deviations for track densities in the following way (according to the Poisson distribution):

$$s_D^2 = s_{D_b}^2 + s_B^2 = D_b + B;$$

The dose equivalent variance was calculated as total differential of the function of the form like in equation [2], which led to the following expression:

$$s_H^2 = (kD/r^2)^2 s_r^2 + (k/r)^2 s_D^2.$$

Linear accelerator neutrons - track detector behind the wall

The neutron track etch detector was positioned outside the entrance door to the accelerator maze. The neutron spectrum in the same position was measured by Schraube *et al.*¹¹, hereby presented in Figure 4. We used the given neutron spectrum in the procedure for determining a neutron dose equivalent by the track detector, as above. Otherwise, neutron spectrum can vary depending on the wall construction of a room.

We divided neutron energy, E_{ν} , in two areas as follows: the first area, $0 < E_{b1} < 100$ eV, and the second one, $100 \text{ eV} \leq E_{b2} \leq 3750$ eV. Because the E_{b1} was the area of thermal neutrons, we estimated the respective mean cross-sections $\sigma_i = \sigma_{b1} = 120$ b and $\sigma_{b2} = 14.75$ b (for energies E_{b1} and E_{b2} , respectively) from the curve $\sigma(E)$ in Figure 1, and we determined the neutron detector responses for the low energy areas as follows: $\sigma_{b1}/\sigma_{b2} = r_{b1}/r_{b2}$, where $r_{b1} = r_i$ was already assessed response by using equation [1]. Thus we got $r_{b1} = 7.94 \times 10^{-4}$ and $r_{b2} = 9.75 \times 10^{-5}$, and were able to determine the average or effective value of the neutron detector response r_{be} for neutrons in the energy area E_b .

As in the previous case, we took the surfaces under the neutron fluence spectrum curve (Figure 4; $f(E)$) for the two energy areas and we got the relative surfaces: $s_{b1} = 0.18$ and $s_{b2} = 0.82$, those had the meaning of the relative frequencies in the calculation of the pondered mean. The mean or effective detector response was: $r_{be} = r_{b1}s_{b1} + r_{b2}s_{b2} = 2.2 \times 10^{-4}$.

For the measured detector density D_{ν} , the respective fluence is (like in equation [1]): $f_{be} = D_{\nu} / r_{be}$. When the neutron fluence is known, a conversion coefficient (k) from neutron fluence to dose equivalent, depending on neutron energy, gives a personal dose equivalent (H_{ν}), as follows: $H_{\nu} = k_{be} f_{be}$.

Having considered a great depending k on neutron energy (Figure 3), we calculated the average or effective k_{be} for the two energy regions, like above, and we used the same relative frequencies s_{bi} ($i = 1, 2$); taking the average values of k_b for the neutron energies E_{b1} and E_{b2} as $k_{b1} = 11.58$ and $k_{b2} = 9$ pSv

cm², respectively, we calculated the effective conversion factor as follows:

$$k_{be} = k_{b1}S_{b1} + k_{b2}S_{b2} = 9.45 \text{ pSv cm}^2.$$

Thus, the measured detector net density $D_b = 1.2 \pm 0.01 \text{ cm}^{-2}$ corresponded to the following dose equivalent:

$$H_b = k_{be}f_{be} = k_{be}/r_{be} D_b = 42.9 \times 10^{-3} D_b (\mu\text{Sv}),$$

$$H_b = (0.050 \pm 0.0006) \mu\text{Sv}.$$

The dose rate was calculated as a ratio of the dose equivalent and exposure time of 5 min, and we got the neutron dose rate outside the entrance door to the maze of the 15 MV Mevatron, $\dot{H}_b = (0.62 \pm 0.007) \mu\text{Sv/h}$. The linac room 1.7 m walls were constructed of barite concrete, with density of 3200 kg/m³.

Although the obtained neutron dose rate outside the accelerator room was 3165 times smaller than the neutron dose rate in the photon beam, the measured dose rate \dot{H}_b was not negligible from the aspect of personal dosimetry.

Some considerations of neutron energy attenuation after crossing the treatment room walls were performed for different concrete barrier thickness and materials. A neutron spectrum attenuation from the 15 MV linear accelerator, after passing a conventional 1 m concrete barrier, with density of 2260 kg/m³, was measured by Facure *et al.*, hereby presented in Figure 5.²

Observing the neutron spectra in Figure 5 and Figure 4, one can notice a broad neutron energy area in Figure 5 (from 0.1 eV to 10 MeV), that contributes to the neutron dose outside the Mevatron treatment room; neutrons that crossed the 1 m concrete barrier had higher energies than those behind the 1.7 m concrete wall (with energy below 1 keV).

In order to compare the neutron detection parameters r_e and k_e , we divided neutron energy E_c (MeV) of the spectrum (Figure 5) in the two areas as follows: first area $E_{c1} < 2 \text{ MeV}$, and the second one $2 \text{ MeV} \leq E_{c2} \leq 7.5 \text{ MeV}$.

Afterwards, we estimated the respective mean cross-sections $\sigma_t = \sigma_{c1} = 0.619 \text{ b}$ (for thermal neutrons, like above), $\sigma_{c2} = 0.203 \text{ b}$ (for energies E_{c1} , E_{c2} , respectively) from the curve $\sigma(E)$ in Figure 1, and we determined the neutron detector responses for the three energy areas as follows: $\sigma_{c1}/\sigma_{c2} = r_{c1}/r_{c2}$ where $r_{c1} = r_t = 7.94 \times 10^{-4}$ was the response that had already been calculated by using the equation [1]. Thus we got $r_{c2} = 2.6 \times 10^{-4}$ and we were able

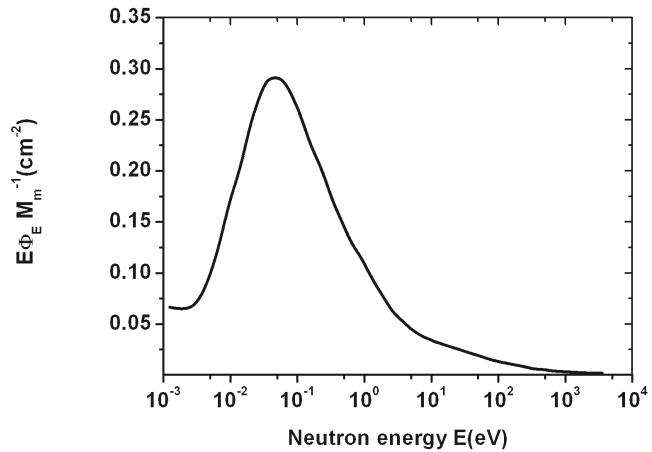


FIGURE 4. Neutron spectrum measured at position outside the entrance door to the maze of the 15 MV Mevatron.¹¹

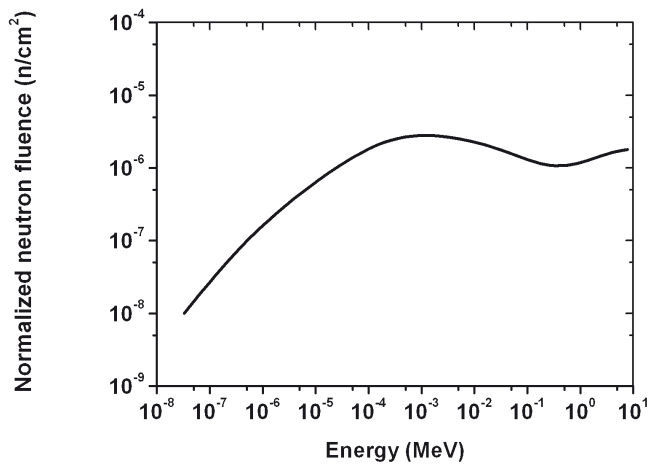


FIGURE 5. Neutron spectrum attenuation from a 15 MV linear accelerator, after concrete barrier of 1 m.

to determine the average or effective value of the neutron detector response r_{ce} but as a weighted or pondered mean.

Therefore, we took the surfaces under the neutron fluence spectrum curve (Figure 5; $f(E)$) for the two energy regions, like above, and we got the relative surfaces: $s_{c1} = 0.22$, $s_{c2} = 0.78$, which had the meaning of the relative frequencies in the calculation of the pondered mean. The mean or effective detector response was: $r_{ce} = r_{c1}s_{c1} + r_{c2}s_{c2} = (3.78 \pm 0.03) \times 10^{-4}$.

Having considered a great depending k on neutron energy (Figure 3), we calculated the average or effective k_{ce} for the three energy areas, and we used the same relative frequencies s_{ci} ($i = 1, 2, 3$); taking the average values of k_c for the neutron energies E_{c1} and E_{c2} as $k_{c1} = 366$, $k_{c2} = 433 \text{ pSv cm}^2$, respectively,

we calculated the effective conversion factor as follows:

$$k_{ce} = k_{c1}S_{c1} + k_{c2}S_{c2} = 418 \text{ pSv cm}^2.$$

Thus, since $k_v/r_c = 25,75 k_v/r_b$, and according to equation [2], one can see that neutrons of the given distribution in Figure 5 (behind the 1 m concrete barrier) contribute to a neutron dose 26 times more than neutrons from the distribution in Figure 4 (behind the 1.7 m concrete wall).

Conclusions

The neutron dosimeter, consisting of the LR-115 track etch detector and boron foil BN-1, was calibrated on thermal neutrons generated in the nuclear reactor of the J. Stefan Institute (Slovenia), and was applied to dosimetry of undesirable neutrons in photon radiotherapy with the Siemens Mevatron 15 MV electron linear accelerator.

Having considered a broad neutron spectrum of energies in the photon beam and high dependence of the track detector response on neutron energy, we divided the spectrum in the two energy areas, below and over 2 MeV. Afterwards we determined the detector responses (r) for the energy areas using corresponding cross-sections for neutron and boron, and then we calculated the pondered or effective response depending on surfaces under the respective neutron spectrum areas. Using the empirical curve $k(E)$, we performed the similar procedure for determining an effective conversion coefficient (k) from neutron fluence to dose equivalent, depending on neutron energy (E).

The relative measurement errors made by track etching method with the LR-115 detector were about 1%. It is to mention that we took the data from the empirical curves (e.g. $\sigma(E)$, $k(E)$) as average values without respective experimental errors.

The measurement of the neutron dose equivalent by the track etch detector, positioned outside the Siemens Mevatron 15 MV room (room wall of 1.7 m, density of 3200 kg/m³), gave the dose rate of 0.62 $\mu\text{Sv/h}$.

Observing the neutron spectrum attenuation from 15 MV Mevatron behind the 1m concrete barrier, one was able to notice that the neutrons (Figure 5) had higher energies and contributed to a neutron dose 26 factor times more than neutrons from the distribution in Figure 4 (behind the 1.7 concrete wall).

References

1. Strojnik A. In search of the shortest regimen: fractionation of a fully isoeffective combination of hyperfractionated and hypofractionated treatment. *Radiol Oncol* 2008; **42**: 170-2.
2. Facure A, Falcão RC, Silva AX, Crispim VR, Vitorelli JC. A study of neutron spectra from medical linear accelerators. *Appl Radiat Isotop* 2005; **62**: 69-72.
3. D Ryan C Rivest, Terence A Riarka, Albert D Murtha, B Gino Fallone. Dosimetric implications of two registration based patient positioning methods 203 in prostate image guided radiation therapy (IGRT). *Radiol Oncol* 2009; **43**: 203-12.
4. Ongaro C, Zanini A, Nastasi U, Rodenas J, Ottaviano G, Manfredotti C. Analysis of photoneutron spectra produced in medical accelerators. *Phys Med Biol* 2005; **45**: 55-61.
5. Králík M, Turek K. Characterisation of neutron fields around high-energy x-ray radiotherapy. *Radiat Prot Dosimetry* 2004; **110**: 503-7.
6. Rivera JC, Falcão RC, deAlmeida CE. The measurement of photoneutron dose in the vicinity of clinical linear accelerators. *Radiat Prot Dosimetry* 2008; **130**: 403-9.
7. Izerrouken M, Skvarč J, Ilić R. A wide range personnel neutron dosimeter. *Radiat Meas* 2003; **37**: 21-4.
8. Lilley J. *Nuclear Physics*. Chichester: John Wiley & Sons; 2001. p. 196.
9. Vuković B, Radolić V, Lisjak I, Vekić B, Poje M, Planinić J. Some cosmic radiation dose measurements aboard flights connecting Zagreb Airport. *Appl Radiat Isotop* 2008; **66**: 247-51.
10. Lopez Ponte MA, Castellani CM, Curri van L, et al. A catalogue of dosimeters and dosimetric services within Europe—an update. *Radiat Protec Dosim* 2004; **112**: 45-68.
11. Schraube H, Kneschaurek P, Schraube G, Wagner FM, Weitzenegger E. Neutron spectra around medical treatment facilities. *Nucl Instrum Meth A* 2002; **476**: 463-7.