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Mean Energy of Neutrons from an Electron Linear Accelerator for Radiation Therapy

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Abstract

Mean energy of neutrons from an electron linear accelerator (LINAC) was experimentally estimated. The LINAC is used for radiation treatments at the Hiroshima Prefectural College of Health Sciences. The thermal neutron fluence rate was determined measuring the gamma rays from ^{116m1}In (half-life of 54.29 min) induced in indium foil exposed to 10 MV X-rays. The mean energy of the neutrons was estimated from the attenuation coefficient of the thermal neutron fluence rates in a polyethylene block, the surface of which was located at the isocenter. The block was surrounded by 10 cm of boric acid layers, except for the upper surface. In the estimations, it was assumed that all thermal neutrons in the block came from the head of the LINAC. Gamma rays from ^{116m1}In were measured by a Ge semiconductor detector, which was shielded by lead blocks thicker than 15 cm. The thermal neutron fluence rate was $(7.1 \pm 0.4) \times 10^8$ $m^{-2}s^{-1}$at a 2 cm depth of the polyethylene block, when the X-ray dose rate was 2 Gy/min at the reference depth for radiation therapy and the field size was 10 cm × 10 cm. Under the same condition, the mean energy of the neutrons from the head of the LINAC was estimated to be 1.22 ± 0.02 MeV. The mean energy increased to 1.34 ± 0.03 MeV through the 5 cm boric acid filter, and decreased to 1.00 ± 0.03 MeV through a 3 cm copper filter. This can be explained by the facts that the boric acids absorbed the incident thermal neutrons, and that the copper plate moderated the incident fast neutrons. The mean neutron energies in 5 cm × 5 cm, 10 cm × 10 cm and 15 cm × 15 cm field sizes were approximately coincident to each other.

Key words : LINAC, photonuclear reaction, neutron

1 Introduction

High energy X-rays from an electron linear accelerator (LINAC) are frequently used for external radiation exposure to treat deep malignant neoplasms. Electron energies greater than 10 MeV have recently been preferred to produce X-rays that will increase the ratio of dose at deeper positions to that at the surface. However, the neutrons from the LINAC increase as the beam energy becomes higher. Except for special treatments using neutrons, the neutron doses should be well suppressed for radiation therapy. Neutrons induce various radioactivities which are unfavorable to the patients and medical workers. It is therefore necessary to measure and control the neutrons. However, the intense X-rays hinder the measurement of neutron fluence from the LINAC. Applying several kinds of nuclear reactions, such as $^{10}B(n, \alpha)^7Li$ and $^3He(n, p)^3H$ to neutron detections, relatively large detectors have been developed for measuring fast neutrons. The detector also has a small sensitivity to X-rays. For example, the sensitivity of the neutron REM counter (Nuclear Enterprise, NM2) to ^{137}Cs gamma rays is guaranteed to be less than 1 % of the sensitivity to neutrons1). This guarantee is not sufficient for detecting photonuclear neutrons in LINAC treatment rooms. For example, J.P. Lin, et al. reported that the neutron dose in an isocenter exposed to 15 MV LINAC X-rays was 1843 ± 90 μGy per 1 Gy of X-ray dose2). This is the reason why ordinary detectors for monitoring neutrons are not suitable for the measurement of a LINAC neutron in an exposure field. Activation foils may be available for measuring neutrons in a small cavity. However the cross sections of nuclear reactions in metallic foils are generally small. Only a few kinds of nuclides have large cross sections for thermal neutrons, and they may be available for detecting thermal neutrons. One of them is indium (In) which was previously used by P. D. LaRiviere for estimating the mean energy of LINAC neutrons3). In the estimation, a stack of polyethylene (PE) plates was exposed to LINAC neutrons, and the attenuation of thermal neutron fluence with depth was examined. As shown by P. D. LaRiviere, the mean energy of LINAC neutrons can be estimated using the relationship between the attenuation coefficient and the energy of incident neutrons3). The method was applied to this study on the neutrons from the LINAC at the Hiroshima Prefectural College of Health Sciences. A few previous studies on neutrons of the other LINACs have been performed2-5). The exposure conditions and the kinds of LINACs used in the studies were different from the present one, and hence the mean neutron energies might have been different from that in the present LINAC. Information on the neutron energy will be useful for elucidating how the neutrons are released from the present LINAC.

2 Materials and Methods

In the LINAC (Mitsubishi, EXL-15DP) used in this study, a copper (Cu) target was used for 10 MV X-rays6). A platinum target was used for 6 MV X-rays6). The filter for flatting X-ray beams was made of stainless steel, and the collimator was made of lead plates6). One gram of grained In (Wako Chemical Co., Ltd) was used to make a foil of 4.1 cm^2 in area. The In foil was sandwiched by two 15 μm aluminum foils and exposed to the LINAC neutrons. The thermal neutron absorption cross section of ^{115}In to induce $^{116m1}In$ or $^{116m2}In$ was determined to be 154 ± 6 b by Jozefowicz E.(1963) (cited on the International Atomic Energy Agency web site)7). The half life of $^{116m2}In$ is 2.18 s, and it decays into $^{116m1}In$, of which the half life is 54.29 ± 0.17 min. Owing to the large cross section and the appropriate half life of $^{116m1}In$, In foil is convenient as a detector for LINAC thermal neutrons. A strong resonance peak at a low energy region from 1 eV to 2 eV is seen in the neutron absorption cross section of ^{115}In8). Because the PE plate is a good moderator for neutrons, neutrons scattered in it are expected to be well thermalized. In this study, the thermal neutron activation cross section mentioned above was assumed to be usable for calculating the thermal neutron fluence rate. The following three experiments were performed. The dose rate was always 200 MU/min, where 100 MU corresponds to 1 Gy at the reference depth for radiation therapy with a 10 cm × 10 cm field size.

Experiment 1

The In foils were located at 0, 2, 5, 10 and 15 cm depths in a PE block along the central axis. The exposures were conducted setting the beam axis on the central axis of the PE block with three field sizes, 15 cm × 15 cm, 10 cm × 10 cm and 5 cm × 5 cm. Each exposure lasted for 1 min. The isocenter was positioned at the center of the upper surface of the PE block. The isocenter was 128.3 cm above the floor. Forty PE plates were used to compose the PE block. Each plate has a dimension of 30 cm × 30 cm × 0.5 cm, and the density was 0.96 g/cm^3. The PE block was surrounded by acrylic-resin boxes containing 10 cm thick boric acid (BA)(H_3BO_3, Kanto Chemical Co., Ltd.) layers.

These were located on a bed for patients under the head of the LINAC. In addition, a box containing 10 cm BA was located under the bed. The upper surface of the PE block was open to the X-ray and neutron beams.

Experiment 2

A BA filter of 30 cm × 30 cm in area was located on the PE block. The field size was maintained at 10 cm × 10 cm. The other conditions were the same as those in Experiment 1. The BA of 5 cm in thickness was contained in a box which was composed of four 0.5 mm aluminum plates for the sides and 0.15 mm paper for the bottom. Then, in place of the BA filter, a Cu filter was mounted on the PE block. The Cu filter was 20 cm × 20 cm in area and 3 cm in thickness.

Experiment 3

The In foils on and in the PE block were exposed to 6 MV X-rays in a 10 cm × 10 cm exposure field. The exposure time was 5 min. The other conditions were the same as those in Experiment 1.

More than 15 min after the exposure, the In foil was put in the bottom of a plastic capsule (4.5 cm in inner diameter and 3 cm in inner height), and was mounted on the window of a Ge-semiconductor detector (OXFORD CPVDS30-0190) in a lead shield which was thicker than 15 cm. The detector is cylindrical and the circular window faces upward. The detector could be used for measuring gamma rays even if the intensities were as low as natural ones. The detection efficiencies were determined using the standard source of ^{152}Eu (Japan Isotope Cooperation, EU-402).

3 Results

Figure 1 shows a spectrum obtained measuring the gamma rays from the In foil which was exposed to X-rays and neutrons on the surface of the polyethylene block. Every measurement was conducted for 10 min. The full energy peaks of gamma rays from ^{116m1}In (54.29 min) and 336 keV-gamma rays from ^{115m}In (4.5 h) were clearly seen. Most of the detected gamma rays were from ^{116m1}In. For example, the 1294 keV gamma-ray peak area decreased with the passing of time, and the decrease corresponded to a half-life of 53.5 ± 5.2 min. The half life was well coincident with 54.29 ± 0.17 min, which was the half life of ^{116m1}In cited in Reference 7. The ^{116m2}In nuclide is also induced by ^{115}In(n, γ)^{116m2}In reaction. This nuclide decays to ^{116m1}In with a short half life (2.12 s)$^{9)}$. The ^{116m1}In isotopes detected were therefore induced by both ^{115}In(n, γ)^{116m1}In and ^{115}In(n, γ)^{116m2}In reactions$^{9)}$. The mean thermal neutron fluence rate in In foil, ϕ was calculated using the following equation:

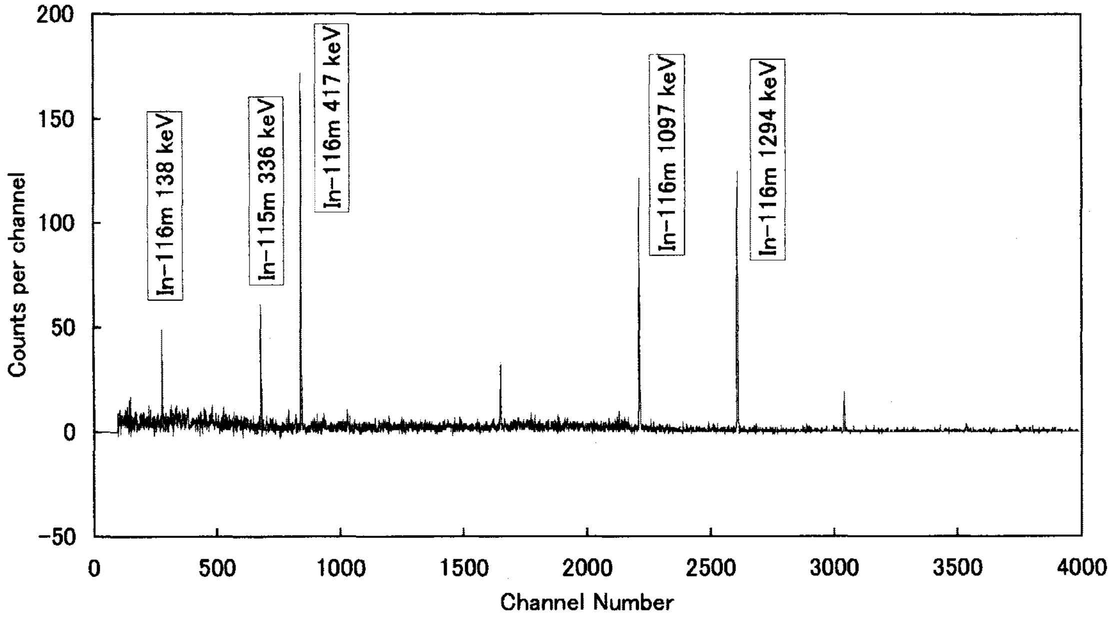

Figure 1 Spectrum of gamma-rays from indium foil exposed to LINAC neutrons.
The Indium foil was exposed to X-rays on the surface of a polyethylene block with the exposure field of 10 cm × 10 cm for 1 min. The measurement started 88 min after the exposure, and lasted for 10 min. The spectrum is indicated after subtraction by a background spectrum, which was also measured for 10 min.

$\phi = \frac{[^{116m}\mathrm{In}/^{115}\mathrm{In}]}{\sigma_r} \cdot \frac{\lambda}{1-e^{-\lambda t}}$, where $[^{116m}\mathrm{In}/^{115}\mathrm{In}]$ is the ratio of ^{116m1}In and ^{116m2}In atoms to the ^{115}In ones immediately after the exposure; σ_r is the thermal neutron cross section of $^{115}\mathrm{In}(n,\gamma)^{116m1+116m2}\mathrm{In}$; λ is the decay constant of ^{116m1}In; and t is the exposure time (60 s). This equation could be approximately used, because the half life of ^{116m1}In, as well as the exposure time, is much longer than the half life of ^{116m2}In. Since the In foil itself absorbed thermal neutrons, the mean fluence in the foil was less than the incident fluence. The correction factor for the decrease was calculated assuming the thermal-neutron angular distribution to be spherically symmetric.

Experiment 1

Figure 2 shows the thermal neutron fluence rates determined in Experiment 1. At every depth, the thermal neutron fluence for 5 cm × 5 cm field size was smaller than that for the 10 cm × 10 cm field size. Few differences could be seen between the depth profiles for the 10 cm × 10 cm and 15 cm × 15 cm field sizes.

The depth profile of ^{116m1}In in a PE block exposed to neutrons was precisely studied by Tochilin and Shumway, and the results were quoted in the report by LaRiviere[3)]. In this study, the ^{116m1}In activity was assumed to be proportional to the thermal neutron fluence (TNF) rate. Moreover, it was assumed that the photonuclear reactions in the block contributed negligibly to the depth profile of ^{116m1}In. Figure 3 shows the depth profiles of the thermal neutron fluence rate from a figure reported by LaRiviere[3)]. Kobayashi also showed depth profiles of thermal neutron fluences in a human body exposed to neutrons with a field of 10 cm in diameter[10)]. The data determined by Kobayashi is also shown in Figure 3[10)]. The depth profiles of the thermal neutron fluence rate obtained in Experiment 1 were very different from those for the incident thermal and epithermal neutrons. The attenuation coefficients for the TNF rate between 5 cm and 15 cm in depth were determined from the data shown in Figure 2. LaRiviere obtained the relationship of the incident neutron energy and attenuation coefficient from the depth profiles of In activation determined by Tochilin and Shumway[3)]. Using the relationship and the attenuation coefficients, the mean incident neutron energy was estimated to be 1.27 ± 0.02 MeV for 15 × 15 cm^2, 1.22 ± 0.02 MeV for 10 × 10 cm^2 and 1.24 ± 0.03 MeV for 5 × 5 cm^2. The uncertainties of the mean energies were evaluated without considering the

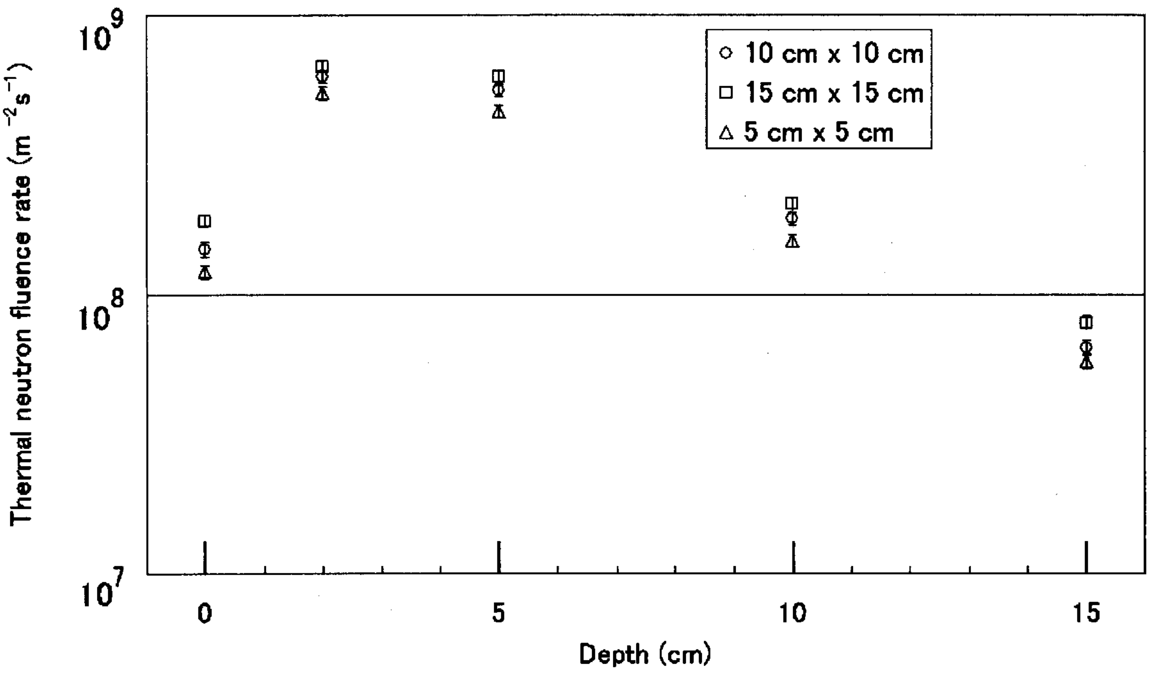

Figure 2 Thermal neutron fluence rate in the polyethylene block.
The thermal neutron fluence rates were estimated from the isotope ratios of $^{116m1}\mathrm{In}/^{115}\mathrm{In}$ immediately after the exposures. The exposures were conducted with the field sizes 15 × 15 cm^2 (□), 10 × 10 cm^2 (○), and 5 × 5 cm^2 (△).

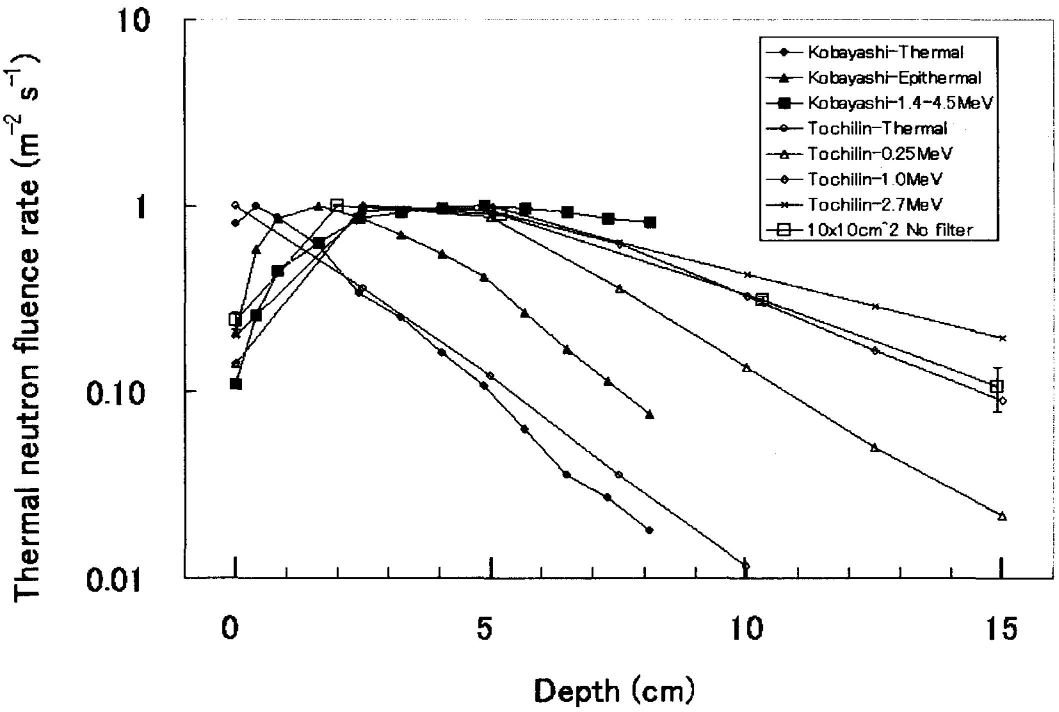

Figure 3 Thermal neutron fluence rate in the polyethylene block [3,10].

The depth for the fluence rates determined by Kobayashi in human tissue was converted to the depth in a polyethylene block equivalent to human tissue in hydrogen atom density. (Kobayashi-Thermal, Epithermal and 1.4-4.5 MeV)[10]. The density of hydrogen in human tissue was assumed to be $0.11g/cm^3$. The fluence rates of Tochilin-Thermal, -0.25MeV, -1.0MeV, -2.7MeV were reported by Tochilin and Shumway,1960 and quoted by LaRiviere[3]. Each fluence curve was normalized to be one at the maximum. The present fluence rates for the field size of 10 × 10 cm^2 are indicated by open squares.

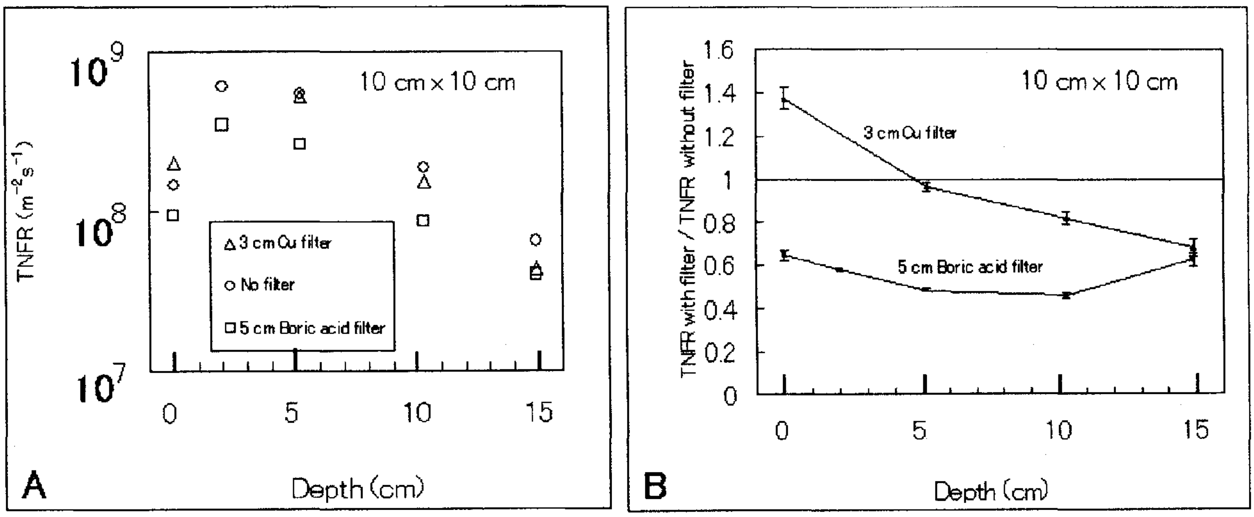

Figure 4 Thermal neutron fluence rate (TNFR) in the polyethylene block under filter.

The filters were 5 cm boric acid and 3 cm copper plate. The field size was 10 cm × 10 cm. Panel (B) shows the fluence rates divided by those without any filter (See the results of Figure 2).

uncertainty of the relationship between the attenuation coefficient and the incident neutron energy.

Experiment 2

The full energy peaks of 138 keV, 417 keV, 1097 keV and 1294 keV gamma rays from ^{116m}In were analyzed to determine the TNF rates at 0 cm, 5 cm, 10 cm and 15 cm depths in the PE block. The rates were compared with those obtained in Experiment 1. The results are shown in Figure 4. A large difference was seen on the surface of the PE block. The estimated mean energy of neutrons were 1.34 ± 0.03 MeV under a 5 cm BA filter and 1.00 ± 0.03 MeV under a 3 cm Cu filter.

The 336 keV gamma-ray full energy peaks from ^{115m}In were also analyzed, and the activities were determined, as shown in Figure 5. The 5 cm BA filter increased the activity on the surface, and little influence from the filter was seen at the deeper positions. On the other hand, the 3 cm Cu filter decreased the activity in every position. This implies that the ^{115m}In activity has a relationship with the X-ray fluence in the PE box.

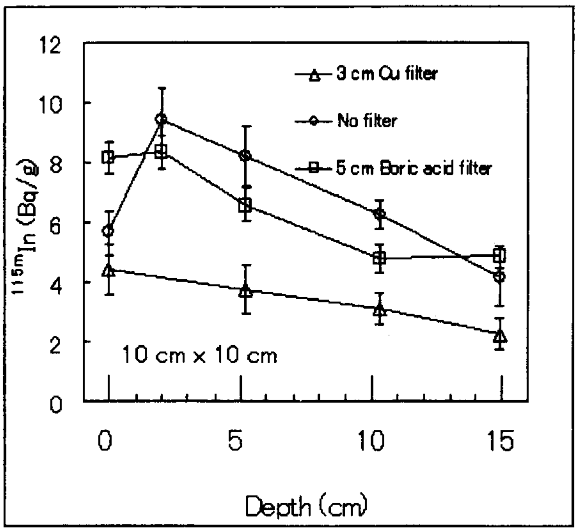

Figure 5 ^{115m}In activities.
The field size was 10 cm × 10 cm. The polyethylene block was exposed through a 3 cm Cu filter (△) or 5 cm boric acid filter (□). The activities induced without a filter are also marked (○). The ^{115m}In activities per 1 g of In indicated are those immediately after the exposure.

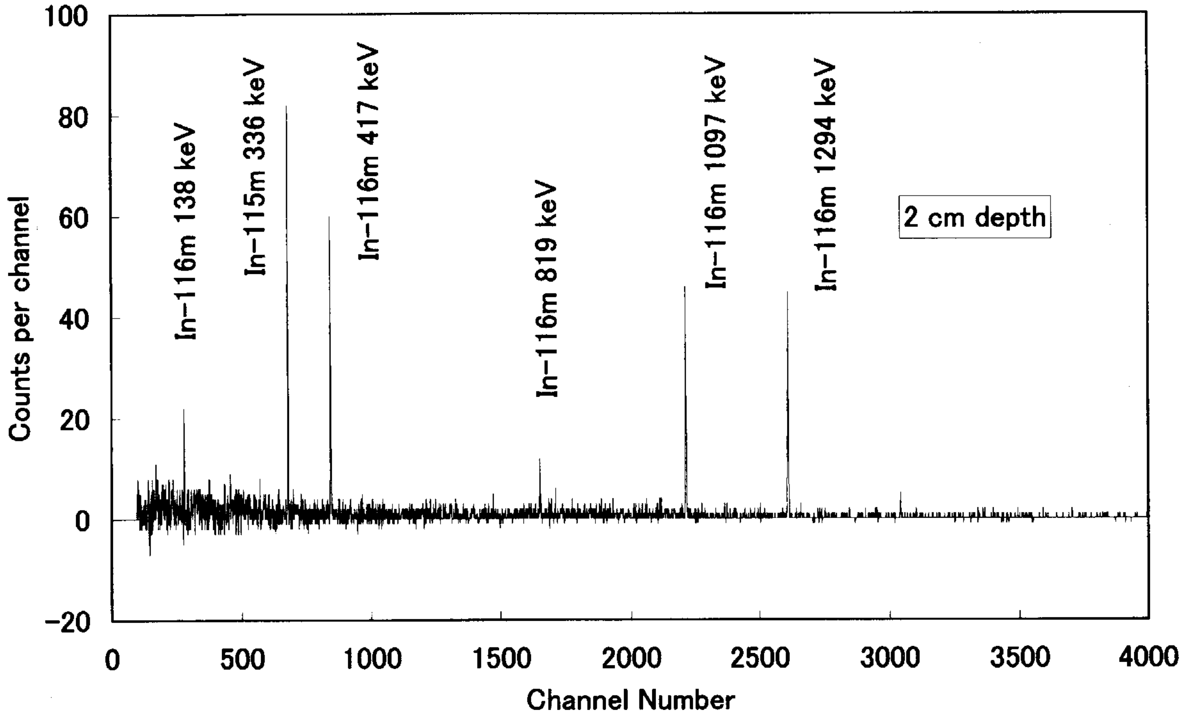

Figure 6 Gamma-ray spectrum for indium foil exposed to 6 MV X-rays.
The foil was located at a 2 cm depth in the polyethylene block with a 10 Gy treatment dose (5 min) and 10 cm × 10 cm field size. Measurement started 36 min after the end of exposure, and lasted for 10 min. The spectrum is indicated after the background subtraction. The background gamma rays were also measured for 10 min.

Experiment 3

One of the gamma-ray spectra for the In foils is shown in Figure 6. The foil was located at a 2 cm depth, and exposed to 6 MV X-rays. The 336 keV gamma-rays from ^{115m}In were detected even when the foil was exposed to 6 MV X-rays. At the 2 cm depth, the activity of ^{115m}In was 11 ± 1 Bq/g, which was approximately the same as that in a foil exposed to 10 MV X-rays for 1 min. On the other hand, the TNF rate estimated from ^{116m}In production rate was (3.6 ± 0.2) × 10^6 m^{-2} s^{-1}, which was less than one percent of the TNF rate in the foil exposed to 10 MV X-rays. These findings also suggest that the ^{115m}In was mainly produced by ^{115}In (γ,γ')^{115m}In reactions.

4 Discussion

Mean neutron energy

The threshold energies for γ-n reaction were calculated for the elements used for the target, filter for flatting X-ray intensity, and collimator. The calculations could be done using the data of experimental nuclear mass by Audi G. and Wapstra A.H., 1995 (cited in the appendix of Reference 9). The results show that 10 MeV X-rays may release neutrons with energy higher than 2 MeV by photonuclear reactions in ^{61}Ni, ^{57}Fe, ^{207}Pb and ^{208}Pb elements. This suggests that the mean energy of 1 MeV is plausible in the present LINAC neutrons. LaRiviere exposed In foil in a PE block to LINAC X-rays, and measured beta-rays from ^{116m1}In in the foil by a Geiger counter[3]. The mean energies of LINAC neutrons measured by LaRiviere were 0.32 MeV for a closed collimator and 0.68 MeV for 20 × 20 cm^2 in the case of 10MV-LINAC X-rays[3]. The mean neutron energy may decrease as the field size decreases. This tendency was not seen in the present study.

The mean neutron energy in the present LINAC was approximately 1 MeV, and was larger than the mean energies measured by LaRiviere [3]. Lin et al revealed that the mean energy of photoneutrons increased as the distance to the isocenter decreased [2]. The mean energy of neutrons at 1 m from the isocenter for 15 MV X-rays from a LINAC was 0.5 MeV[2]. This suggests that the mean energy at the isocenter in the LINAC might have been close to the present mean energy.

As shown in the results of Experiment 2, the mean neutron energy under the Cu filter was lower than that without any filter. On the surface of the PE block under the Cu filter, the TNF rate was much larger than that without any filter. The 5 cm BA filter increased the mean neutron energy. These results suggest that the incident fast neutrons strongly contributed to the TNF rate in the PE block.

Photonuclear reactions in indium foil and polyethylene

Uehara shows an energy distribution of 10 MV LINAC X-rays[11]. Assuming that the X-ray energy distribution was the same as that in the present LINAC, neutron production rate due to ^{115}In(γ, n)^{114}In in In foil was estimated to be less than 5 × 10^6 $m^{-2}s^{-1}$. In the estimation, the cross section of this reaction shown by Dietrich and Berman was also used[12]. Although the full energy peak for 157 keV gamma rays from ^{112}In was small, analysis was possible when the foil was located near the top surface. The results showed that the neutron production rate due to the ^{113}In(γ, n)^{112}In reaction was approximately 1.8 × 10^6 $m^{-2}s^{-1}$ at the top surface of the PE block. This neutron production rate corresponds to the fast neutron fluence, which was only 2 % of the TNF rate at the same location. The threshold energy for this photonuclear reaction was 9.5 MeV, and the natural abundance was only 4.3 %. This is the reason why the reaction rate of ^{113}In(γ ,n)^{112}In was very small. The In foils were small and hence the neutrons produced in the In foils scarcely contributed to the TNF rate to produce ^{116m1}In in the In foil itself.

The PE includes ^{2}H and ^{13}C. The cross section for ^{13}C(γ ,n)^{12}C is less than 1 mb, while X-ray energy is less than 10 MeV[12]. It is well known that the cross section for ^{2}H(γ ,n)^{1}H reaction has been precisely examined, as explained in Reference 13. The photonuclear reaction by ^{2}H is possible even if the X-ray energy is less than 6 MeV. However, the cross section for ^{2}H(γ ,n)^{1}H is 2-3 mb, even at the maximum[13]. The contribution of ^{2}H(γ ,n)^{1}H photonuclear reactions in the PE block to the thermal neutron fluence seems to be small, as suggested by the results of the experiment using 6 MV X-rays. However, this has not been confirmed for the 10 MV X-rays. Further research is necessary to estimate how the photonuclear reactions in the PE block contribute to the production of ^{116m1}In atoms.

Dose from thermal neutrons

In a preliminary study, thermal neutron fluence rate was estimated from a measurement of ^{66}Cu activity in a copper (Cu) plate exposed to the LINAC neutrons on the surface of the PE block, when the X-ray dose rate was 2 Gy/min at the reference depth for radiation therapy and the field size was 10 cm × 10 cm. The TNF rate was (1.7 ± 0.3)× 10^8 $m^{-2}s^{-1}$, which was approximately coincident with that for ^{116m1}In, (1.7 ± 0.1) × 10^8 $m^{-2}s^{-1}$. The cross section of ^{65}Cu (n, γ)

^{66}Cu reaction has no resonance in the energy region lower than 100 eV[8)]. This suggests that the present TNF rates are usable for estimating the thermal neutron absorption rates in the other nuclides. The details of the experiments using a Cu foil will be reported in the future.

In the 10 cm × 10 cm exposure field, the maximum TNF rate was $(7.1 \pm 0.4) \times 10^{8}$ m^{-2}s^{-1} at a 2 cm depth. For thermal neutrons, the kerma factor and radiation weighting factor were assumed to be 2.08×10^{-17} [Gy m^2] and 5 [Sv/Gy], respectively[14,15)]. Dose equivalent from thermal neutrons was estimated to be 4.2 ± 0.2 μ Sv/min at a 2 cm depth with a 10 cm × 10 cm field size. The dose from thermal neutrons was approximately 10^{-6} times the X-ray dose in the exposure field. Fast neutrons induce a reaction of ^{115}In(n,n$'$)^{115m}In. The BA filter increased the ^{115m}In activity at the surface of the PE block, and the Cu filter reduced activity in every position, as shown in Figure 5. The Cu filter also reduced the X-ray intensity, and the attenuation was approximately coincident with that shown in ^{115m}In nuclei. This suggests that a considerable part of ^{115m}In nuclei might have been produced by ^{115}In(γ, γ')^{115m}In reactions. The information from the ^{115m}In activity appears to be of no use for the estimation of fast neutron dose. Other experiments will be carried out to estimate the fast neutron doses as soon as possible.

5 Conclusion

The polyethylene attenuation method was used to estimate the mean incident neutron energy at the isocenter of a LINAC at the Hiroshima Prefectural College of Health Sciences. The estimated energies were 1.27 ± 0.02 MeV for the 15×15 cm^2 field size, 1.25 ± 0.04 MeV for the 10×10 cm^2 field size, and 1.24 ± 0.03 MeV for the 5×5 cm^2 field size. The mean energy scarcely varied at all with the field size. The incident neutrons were moderated by a 3 cm copper filter, and the mean energy was 1.00 ± 0.03 MeV. Meanwhile, a boric acid filter of 5 cm hardened the neutrons, and the mean neutron energy was 1.34 ± 0.03 MeV under the filter.

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医療用電子線線形加速器で発生する中性子線の平均エネルギー

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抄　録

放射線治療に用いられる医療用電子線線形加速器を加速エネルギー10 MeVで運転し治療用x線を発生させる時に光核反応によって発生する熱中性子のフルエンス率と全中性子の平均エネルギーを実験的に推定した。熱中性子フルエンス率は中性子を照射したインジウム(In)金属箔の中で生じた^{116m1}In（半減期，54.29 min）からのγ線を測定して推定した。中性子平均エネルギーは熱中性子フルエンス率の20cm厚のポリエチレンブロックにおける熱中性子フルエンス率の減弱係数から推定した。ポリエチレンブロックの表面の中心はアイソセンターに置いた。ポリエチレンブロックは側面と底面（治療台の下）に10 cm厚のホウ酸を置き熱中性子を遮蔽した。中性子平均エネルギーの推定において，ポリエチレンブロックの熱中性子は全て加速器のヘッド部からきたものと仮定した。γ線は15cm厚の鉛ブロックで遮蔽されたGe検出器を用いて測定した。測定した^{116m1}In生成率から推定した熱中性子フルエンス率は，照射野サイズ 10 cm × 10 cm，線量率 2 Gy/minで照射中のポリエチレンブロック表面から2cmの深さで $(7.1 \pm 0.4) \times 10^8\ m^{-2}s^{-1}$ であった。ポリエチレンによる熱中性子フルエンス率の減弱曲線から推定したポリエチレンブロック表面に入射した中性子の平均エネルギーは 照射野 $10 \times 10\ cm^2$ で 1.22 ± 0.02 MeV であった。この中性子平均エネルギーは3cm厚の銅フィルターによって 1.00 ± 0.03 MeVまでに下がった。一方，5cm厚のホウ酸フィルターによって，1.34 ± 0.03 MeV まで上がった。この結果は，銅フィルターによる速中性子の減速，ならびにホウ酸フィルターによる熱中性子の吸収の効果を表していると考えられる。照射野を5 cm × 5 cm, 10 cm × 10 cm ならびに 15 cm × 15 cmに変えて調べた中性子の平均エネルギーはほぼ一致していた。

キーワード：ライナック，光核反応，中性子