Development of real-time thermal neutron monitor array for boron neutron capture therapy

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Background: We have performed over 500 boron neutron capture therapy (BNCT) clinical studies using a research reactor. Irradiation time is evaluated by the measured neutron flux using gold activation methods at the surface of the affected area. To perform highly accurate BNCT treatment, it is desired to measure thermal neutrons in real time.

Methods: We have developed a real-time thermal neutron detector array using a small scintillator combined with a quartz fiber to fulfill the required characteristics, including count rate, neutron field disturbance, radiation resistance, and gamma ray discrimination. A characteristic test was performed using reactor- and accelerator-based neutron sources.

Results: We present the result of the performance test. One scintillator combined with a quartz fiber can measure the trends of thermal neutron flux up to 10^9 (n/cm^2/s) using an accelerator-based neutron source. The newly developed detector array can also measure the one-dimensional thermal neutron flux up to 10^9 n/cm^2/s. Furthermore, it is confirmed that a two-dimensional thermal neutron distribution can be measured by scanning with our developed detector array.

Conclusions: A real-time neutron detector array was developed. According to the irradiation test using accelerator- and reactor-based neutron sources, it was confirmed that the developed system fulfilled the required characteristics.

Keywords: Boron neutron capture therapy (BNCT); real-time neutron monitor; thermal neutron

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Introduction

The heavy water neutron irradiation facility (HWNIF) of the Kyoto University Research Reactor (KUR) is used for basic clinical research of boron neutron capture therapy (BNCT). Clinical BNCT studies using this equipment began in 1974 for brain cancer and malignant melanoma. More than 550 clinical studies have been performed, of which more than 80% have occurred since 2001. Recently, in addition to brain tumor and malignant melanoma, the adaptation of clinical cases has been expanded to recurrent head and neck tumors, liver tumors (1), mesothelioma (2), etc., and this approach has shown efficacy for each treatment. The main reasons for the increase in the number of cases are the use of epithermal neutrons, ability to irradiate in sitting positions, and a change in the structure of the equipment that allows access to the irradiation room

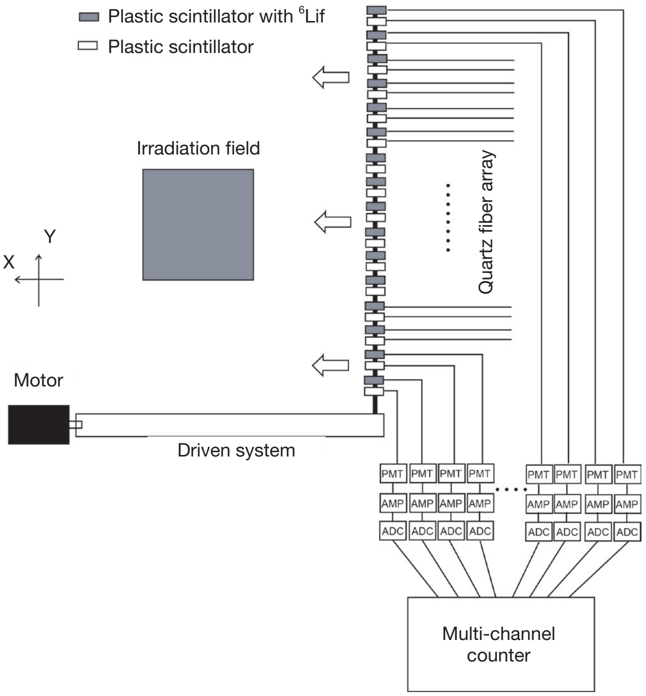

Figure 1 Schematic layout of real-time thermal neutron monitor array.

even during full-power KUR operation. To demonstrate the effectiveness of the BNCT, it is important to evaluate doses more accurately and to increase the number of cases. Accurate dosimetry is also necessary for a basic research performed in this facility, such as mouse and cell irradiation. At present, in clinical and basic research, the neutron dose is evaluated by the gold activation method. Although this method has the advantage of not disturbing the neutron irradiation field, the dose is evaluated after irradiation; thus, if the output of the nuclear reactor fluctuates during irradiation, there is the possibility that the necessary dose will not be accurately determined. In addition, the gold activation method is merely a point evaluation.

Fission chambers are used in reactor-based neutron sources such as Tsing Hua Open-pool Reactor (THOR) (3) and Finnish research reactor FiR 1 (4) with good detector performance by beam intensity monitors. However, it is difficult to introduce the fission chamber in Japan due to difficulties in obtaining permission.

Although two-dimensional evaluations are desired, they have not been performed owing to technical difficulties. In addition, to determine the exact doses to be administered to patients in clinical research and in basic experiments, it is required that the neutron flux be measured in real time during irradiation and that the irradiation can be stopped at the prescribed dose.

The real-time neutron measurement is performed as follows. The neutron field should not be disrupted as that with the gold activation method. The degradation due to irradiation is small. The count rate should measure the flux of the order of 10^9 n/cm^2/s, and show good performance in terms of radiation resistance and gamma-ray discrimination.

In this study, we construct a real-time neutron detector by combining the scintillator and quartz fiber, satisfying the performance parameters described above. Furthermore, it is operated as a line detector. It is possible to measure the two-dimensional neutron flux by the scanning method. We report on the count rate characteristics up to 10^9 n/cm^2/s and the two-dimensional neutron distribution measurements using a nuclear reactor neutron source and an accelerator neutron source.

Methods

Neutron detector

Highly radiation-resistant materials are necessary for the irradiation field of the BNCT. Because a normal quartz fiber has a small bending radius, it is unsuitable for scanning the environment as required by this research. In contrast, a quartz fiber coated with a polyimide (Optical Fiber FV, Polymicro Technologies) was adopted because it can overcome the limitations of the bending radius (5).

An organic scintillator with a cubic shape and a side length of 2 mm was installed at the tip of a quartz optical fiber with length 6 m and core diameter 1 mm. To discriminate between gamma rays and neutron events, a ^{6}LiF neutron convertor was surrounded by an organic scintillator. The quartz fiber was covered with a light-shielding tube to prevent stray light input.

Figure 1 shows the schematic layout of the developed system. Scintillation light generated by the incidence of the neutrons and gamma rays was guided to a photomultiplier tube (PMT) by an optical fiber and fed to a discriminator through an amplifier (AMP). Signals above the threshold level were converted to digital signals by analog-digital convertor (ADC) and counted with a scaler with up to a 300-MHz counting rate. The drive system consisted of a module that provided a pulse signal as an output for stepping motor control, a computer automated measurement and control (CAMAC) crate controller, and a personal computer. This system could process input signals from many detectors at

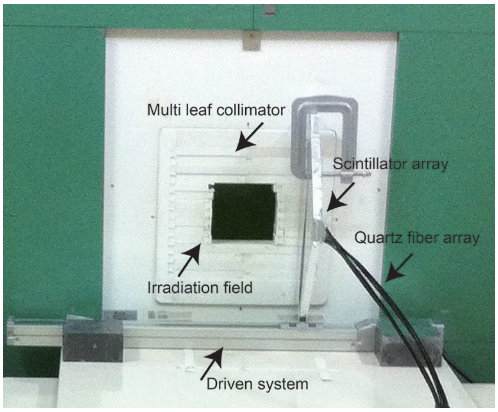

Figure 2 Photograph of the experiment for measuring two-dimensional thermal neutron flux.

high speed. After counting the signals from each detector, this system drove the stepping motor to move the one-dimensional detector array. The next measurement was then started. The gate signal that determined the measurement time could be changed from 1 to 99 s.

Because the stepping motor moved in 1 mm increments over 100 pulses, it was possible to move in increments of 0.01 mm. The detection count during the measurement time was stored in the database.

Accelerator neutron source

To obtain the counting rate characteristics of this system, irradiation experiments using a cyclotron-based epithermal neutron source (C-BENS) were performed. C-BENS generates fast neutrons by injecting 30-MeV protons from the cyclotron accelerator into the beryllium target and generates epithermal neutrons through a moderator such as lead, iron, aluminum, and calcium fluoride. Details are provided in references (6,7).

A 20-cm cubic water phantom was placed on an irradiation port of diameter 10 cm. A scintillator was set at a depth of 20 mm. A gold wire of diameter 250 μm and a gold wire in a cadmium cover were installed at a depth of 20 mm to measure the thermal neutron flux derived by the gold activation method. Because the gold-activated foil and scintillator were measured at the same position, there was no change in spectrum. Furthermore, as the capture cross-section of thermal neutron was larger than that of the epithermal and fast neutrons, the detector count was converted as thermal neutron flux.

Nuclear reactor neutron source

To confirm whether a two-dimensional distribution of neutrons can be acquired using this system, an irradiation experiment was carried out using HWNIF of KUR. In HWNIF, it is possible to moderate a range from fast neutrons from the reactor core to epithermal neutrons using aluminum and heavy water. Details are provided in reference (8). The irradiation field can form an arbitrary shape with a piece of LiF-containing polyethylene. The piece size was 15 mm in height, and the horizontal width was arbitrarily changeable. As shown in the *Figure 2*, a collimator irradiation field of size 105×110 mm^2 was formed. A scintillator array was set in front of a collimator, and two-dimensional distribution was acquired by scanning the scintillator array.

Results

Count rate characteristic

After the irradiation of the gold wire and the gold wire inside the cadmium cover set at a 20-mm water phantom depth, the saturated radioactivity of the gold was measured using a germanium semiconductor detector. The thermal neutron flux was derived from the cadmium ratio. The thermal neutron flux was estimated to be 1.1×10^9 $\mathrm{n/cm^2/s}$ under the condition of a proton current of 1 mA.

Because the relation between the proton current incident on the beryllium target and the thermal neutron flux showed good linearity, the proton current was changed to obtain the relationship between the thermal neutron flux and the counting rate characteristic of this system.

The time trend of the current value when changing the proton current by 100-μA steps and the count number obtained with this system are shown in *Figure 3*. *Figure 4* shows the relationship between the thermal neutron flux at the depth of 20 mm in the water phantom and the count number of this system. The count rates of 1 and 0.9 mA are slightly saturated due to the double counting phenomenon. However, it was confirmed that this system can measure up to 8×10^8 $\mathrm{n/cm^2/s}$ with good linearity.

Figure 5 shows the results of the response test of this system when irradiated with 1 mA of proton current under the condition of a thermal neutron flux of 1.1×10^9 $\mathrm{n/cm^2/s}$. The counting rate of the system at 1.1×10^9 $\mathrm{n/cm^2/s}$ was 3,230 counts per seconds. As the proton current changed, it was confirmed that the count number of this system

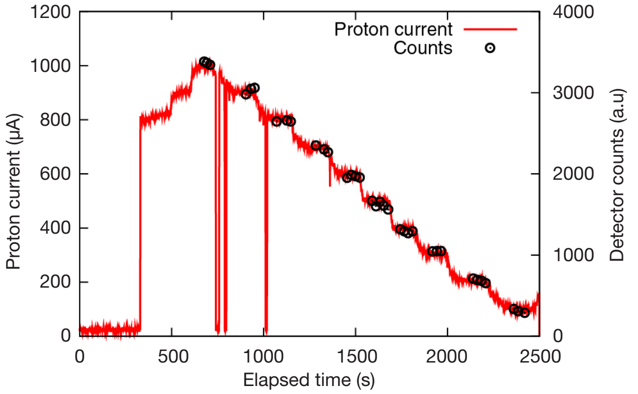

Figure 3 Relationship between elapsed time and proton current or detector counts.

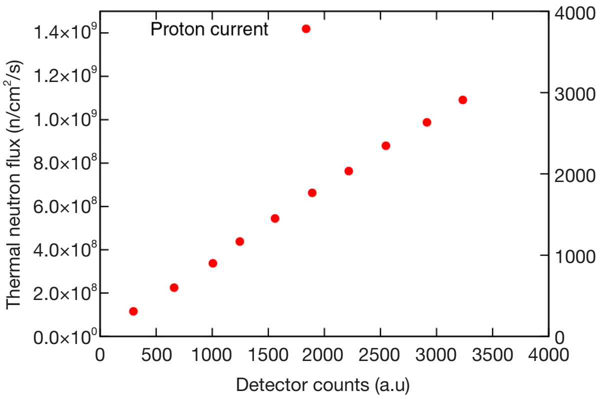

Figure 4 Relationship between the thermal neutron flux at a depth of 20 mm in the water phantom and the detector counts.

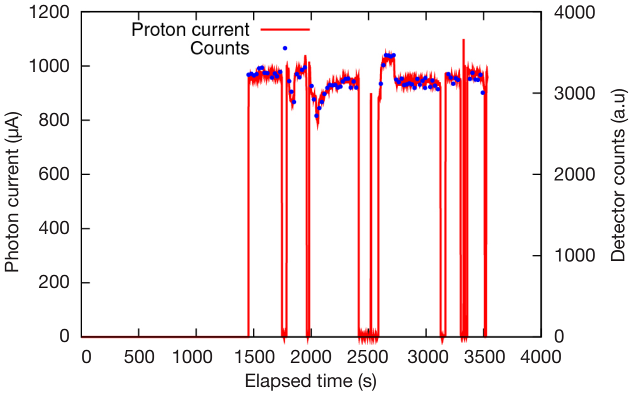

Figure 5 Results of the response test of this system when irradiated with 1-mA proton current.

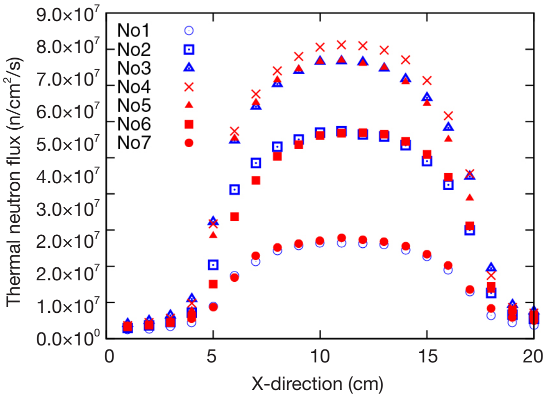

Figure 6 Neutron flux measurement results of scanning from each detector.

changed and the response characteristics were good. In addition, because there was no deterioration of the count number with time; it can be said that it also had radiation resistance characteristics.

Two-dimensional neutron distribution measurement

To perform the characteristic test of the two-dimensional thermal neutron detection system, a two-dimensional thermal neutron distribution was acquired in the HWNIF of KUR. The irradiation time at each position was 5 s. The data were scanned at intervals of 1 cm, and data were acquired from a total of 20 locations. The time taken to acquire one two-dimensional image was approximately 3 min. *Figure 6* shows the response of the thermal neutrons from scintillators No. 1–7 near the collimator. The distance between the scintillators was 2 cm. Monte Carlo simulation using PHITS 3.02 (9) was performed to confirm the disturbance caused by the array itself. The thermal neutron flux did not change when the adjoining scintillator was not installed.

Detector position No. 4 was set to be the center of the collimator. The distance between the scintillators was 2 cm, and the scintillator No. 1 measured the position 60 mm above the center of the collimator. Scintillator No. 7 measured the position 60 mm below the center of the collimator. Scanning positions from 5 to 9 cm measured by scintillator No. 6 had smaller fluxes than those measured by scintillator No. 2, indicating that the uppermost piece was asymmetrical in the left and right sides and was partially shielded as shown in *Figure 2*. In this way, when using a multi-leaf collimator, it is important to measure the two-dimensional neutron distribution with quality assurance before patient irradiation. It was possible to measure the thermal neutrons shielded by the LiF-containing collimator. By narrowing the spacing between the scintillators, it was possible to obtain a more detailed distribution.

Discussion and conclusions

As a method for measuring thermal neutrons in real time, we developed a detector based on a combination of quartz fiber and a scintillator resistant to radiation. By installing this scintillator in the array, one-dimensional thermal neutron flux distribution can be measured. Furthermore, by scanning the one-dimensional array, we succeeded in acquiring the thermal neutron distribution in the two-dimensional position. We also confirmed that we can measure up to 10^9 n/cm^2/s thermal neutron flux using counting rate characteristics with an accelerator neutron source. In the future, we plan to adapt to the actual clinical setting.

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None.

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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