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COMPACT ACCELERATOR BASED EPITHERMAL NEUTRON SOURCE AND ITS APPLICATION FOR CANCER THERAPY

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Abstract

The world's first accelerator based epithermal neutron source for clinical boron neutron capture therapy (BNCT) was designed, developed, and commissioned between 2008 and 2010 by Sumitomo Heavy Industries in collaboration with Kyoto University at the Kyoto University Institute for Integrated Radiation and Nuclear Science. The Osaka Medical and Pharmaceutical University, Kansai BNCT Medical Center installed the same equipment in 2016. On March 11, 2020, the Japanese Ministry of Health, Labor, and Welfare approved the system as a novel medical device for the manufacture and sale of an accelerator BNCT system (NeuCure® System) and the dose calculation software (NeuCure® Dose Engine). On June 1st, 2020, the national health insurance system approved the reimbursement of these products for unresectable, locally advanced, and recurrent carcinoma of the head and neck. Commissioning tests were performed to evaluate the system before clinical use. Neutron and gamma ray distribution inside a water phantom was experimentally measured and compared with Monte Carlo simulation results. The peak thermal neutron flux inside a water phantom for a 12 cm diameter circular collimator was 1.4×10^9 n·cm^{-2}·s^{-1}. The experimental values closely matched the Monte Carlo simulation results.

INTRODUCTION

BNCT is a form of particle therapy that selectively targets cancer cells by producing high-LET particles by the nuclear reaction between a thermal neutron and a ^{10}B atom. Up until 2012, all clinical BNCT were performed using neutrons generated from a nuclear reactor. Nowadays, neutrons generated from an accelerator is increasing and more hospital-based BNCT centers are opening, worldwide [1, 2]. The NeuCure® BNCT system was installed at the Kansai BNCT Medical Center in the Osaka Medical and Pharmaceutical University, shown in Fig. 1. This is the first facility in the world to provide BNCT at a university hospital that is covered by insurance. The system installed at the Kansai BNCT Medical Center is the same type as the one installed at the Kyoto University Institute for Integrated Radiation and Nuclear Science [3, 4].

The accelerator system is a cyclotron and accelerates a proton up to an energy of approximately 30 MeV. Fast neutrons are generated when the accelerated proton strikes the beryllium target traverse through a beam shaping assembly (BSA) to reduce the energy of the neutron down to the epithermal energy range, which has been shown to be an effective energy for deep-seated tumours [5]. This paper describes the beam characterisation tests performed at the Kansai BNCT Medical center as part of the clinical commissioning of the system.

Figure 1. Image of the NeuCure® BNCT system at the Kansai BNCT Medical Center.

MATERIAL AND METHODS

NeuCure® BNCT System: Beam Characteristics

Cyclotron-based Epithermal Neutron Source Beam Model The simulation of the neutron and gamma ray distribution was performed using a general-purpose Monte Carlo particle transport simulation code system (Particle and Heavy Ion Transport code System: PHITS version 3.24 [6]). The parameters were evaluated inside a water phantom for a 12 cm diameter circular collimator. The neutron energy range was defined as 0-5×10^{-2} eV (thermal), 5×10^{-2} eV-10 keV (epithermal), and 10 keV-30 MeV (fast). Detail on the beam modelling and source information can be found elsewhere [7].

Neutron Flux Determination A common method for measuring the neutron spectrum is metal activation, with gold and indium being frequently used for the measurement of thermal and fast neutrons, respectively. An acrylic phantom filled with distilled water was used. A 10 cm long gold wire (diameter of 0.25 mm with a 99.95% purity, The Nilaco Corporation) was placed along the central axis and off-axis at a depth of 2 cm inside the water phantom. As gold reacts to both thermal and epithermal neutrons, measurements were performed with and without a cadmium cover to shield the thermal neutrons. A total of 0.3 C for the gold wire and 0.6 C for the gold wire with cadmium cover was delivered. After irradiation, the gold wire was

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cut into small pieces (approximately 5 mm in length) and the gamma rays emitted from the activated gold was measured using a germanium detector.

The reaction rate per unit charge of the gold sample was calculated using the expression below.

$$R = \frac{\lambda N}{\epsilon\gamma e^{-\lambda T_c}(1-e^{-\lambda T_m})\sum_{i=1}^{n}\left(\frac{Q_i}{\Delta t}(1-e^{-\lambda\Delta t})e^{-\lambda(n-i)\Delta t}\right)},$$

where ϵ is the detection efficiency of the detector of the gamma rays emitted from ^{198}Au, γ is the gamma ray emission rate from ^{198}Au decay, λ is the decay constant of ^{198}Au, Tc is the time from the irradiation to the start of the measurement, Tm is the measurement time, N is the peak count due to the detector measured gamma rays emitted from ^{198}Au and Q_i is the electric charge irradiated on the target at each interval, Δt.

Indium foil with a 99.99% purity and dimensions of 3 mm in diameter by 0.1 mm thickness was used to measure the fast neutrons. The (n, n') process excites the ^{115}In resulting in ^{115m}In, which decays to the ground state by emitting a 340 keV gamma ray. As indium also reacts to thermal neutrons, the indium foils were covered in cadmium to shield the low energy neutrons.

Gamma Ray Dose Rate Determination Thermoluminescence dosimeters (TLD) were used for the measurement of the gamma ray dose rate. A special-ordered BeO powder TLD enclosed in a quartz glass capsule was used to reduce the thermal neutron sensitivity. TLDs were placed along the central axis and off-axis at a depth of 2 cm inside the water phantom. Measurements were performed with the 12 cm diameter circular collimator.

RESULTS AND DISCUSSIONS

The central axis and off-axis thermal neutron distribution inside the water phantom are shown in Figs. 2 and 3, respectively. The simulation results closely matched the experimentally determined values. For the 12 cm diameter circular collimator, the peak of the thermal neutron flux inside the water phantom occurred at a depth of around 2 cm with a value of 1.4×10^9 n·cm^{-2}·s^{-1}. With this level of neutron flux, the irradiation time can be kept within 1 hour [8].

The central axis fast neutron distribution measured with indium is shown in Fig. 4. The gamma ray dose rate along the central axis and off-axis is shown in Figs. 5 and 6, respectively. The distribution closely resembled the thermal neutron distribution, which indicated most gamma rays detected inside the water phantom was due to the ^{1}H(n,γ)^{2}H reaction.

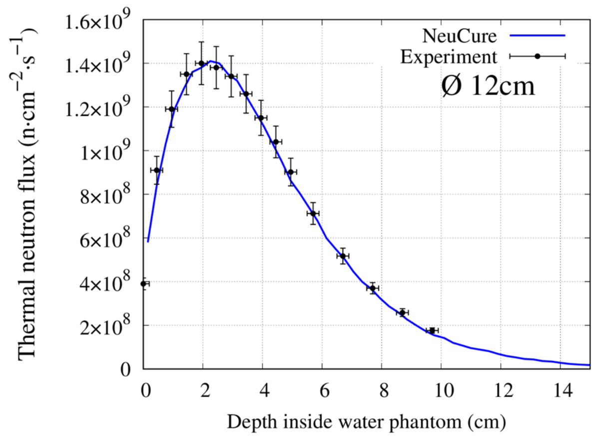

Figure 2. Thermal neutron distribution inside the water phantom along the beam central axis for the 12 cm diameter collimator.

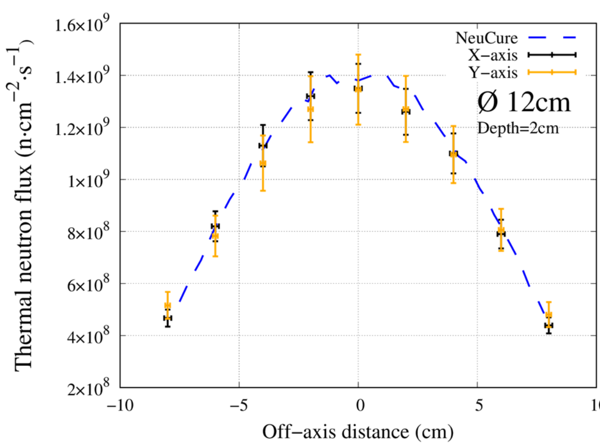

Figure 3. Off-axis thermal neutron distribution inside the water phantom at a depth of 2 cm for the 12 cm diameter collimator.

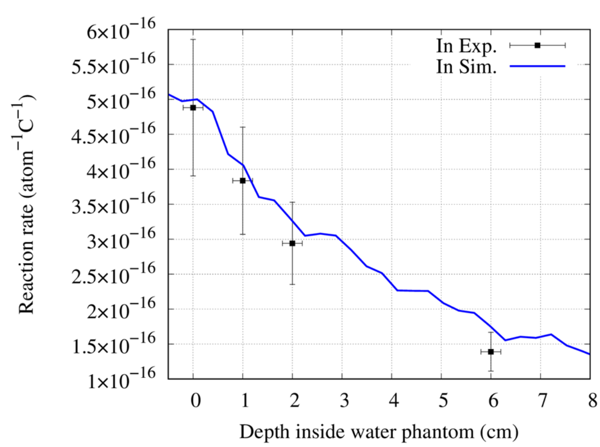

Figure 4. Fast neutron distribution along the beam central axis for the 15 cm diameter collimator.

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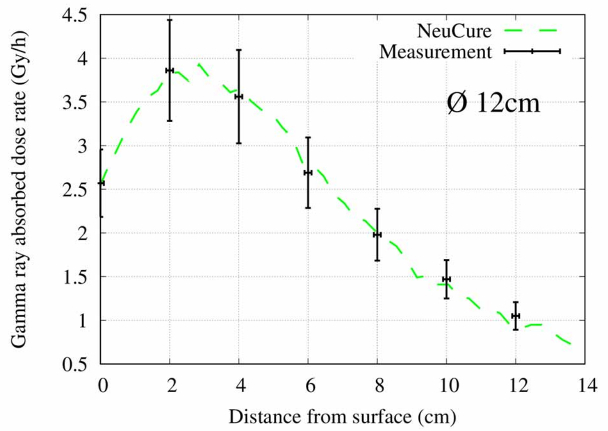

Figure 5. Gamma ray dose rate distribution along the beam central axis for the 12 cm diameter collimator.

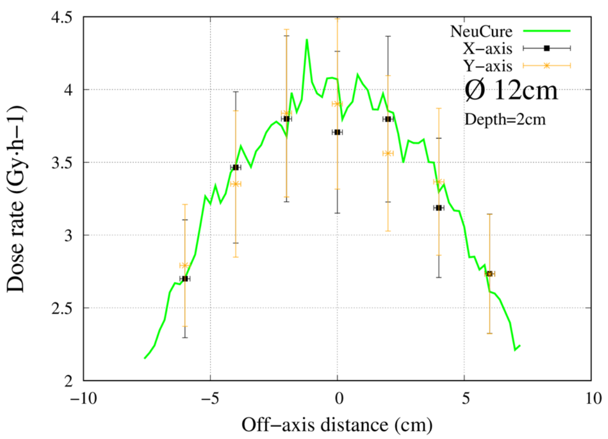

Figure 6. Off-axis gamma ray dose rate at a depth of 2 cm inside the water phantom for the 12 cm diameter collimator.

CONCLUSION

The world's first clinical accelerator based epithermal neutron source developed by Sumitomo Heavy Industries was installed at the Kansai BNCT Medical Center and performance tests were undertaken to verify the system before clinical use. The neutron and gamma ray distribution inside a water phantom was verified by experimental measurements and Monte Carlo simulations. The peak thermal neutron flux inside the water phantom for the 12 cm diameter circular collimator was measured to be 1.4×10^{9} n·cm^{-2}·s^{-1}. Using this accelerator system, patients can receive insurance covered BNCT in Japan for head and neck cancer.

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