Neutron exposure accelerator system for biological effect experiments (NASBEE)

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Abstract

The neutron exposure accelerator system for biological effect experiments (NASBEE) has been developed to study biological effects of fast neutrons. NASBEE has been used to experimentally obtain several endpoints of the biological effects to fast neutrons. NASBEE neutron beams are characterised as energy spectrum, absorbed dose energy distribution and space distribution. The neutron energy spectrum extends to 9 MeV and a broad peak at 2.3 MeV. Neutron and photon absorbed doses occupy 82% and 18%, respectively, of the NASBEE neutron beam. We also developed narrowly-collimated neutron beams for irradiating fast neutrons to only lungs of mice. Absorbed dose distributions and beam profile of the collimated neutron beam were measured. For application of NASBEE, we innovated a real-time and non-destructive method of beam profile measurement on a target under large beam current irradiation. NASBEE has been widely used for not only biological study but also for physical and biological dosimetry.

Introduction

It is important to evaluate the biological effects of neutrons because the general public is exposed to neutrons in a variety of settings, in several radiation fields, for example, around nuclear reactors and accelerators, at nuclear accidents such as the Tokaimura nuclear accident in Japan, in radiation therapy (Boron Neutron Capture Therapy: BNCT, charged particle therapy) and at aviation altitudes, and in the international space station. The radiation weighting factor, w_R, for protection quantity is based on relative biological effect (RBE) data of life shortening due to cancer induction from in vivo investigations.

The National Institute of Radiological Sciences (NIRS) in Japan has started the biological study for neutrons. Biological study for high-energy neutrons of 10 MeV [1] [2] has been completed [3] [4]. To investigate biological sensitivity to fast neutrons in vivo, we constructed the neutron exposure accelerator system for biological effect experiments (NASBEE) at NIRS [5] [6]. NIRS has studied several biological effects: carcinogenesis (myeloid leukaemia, cancers of the mammary gland, lung, liver, brain, and intestine), age-dependent cancer risk, and lifespan shortening using NASBEE neutron beams. Neutron energy spectrum and absorbed dose distribution are necessary to evaluate the biological effects. Blood, cell and fishes other than mice have been irradiated by neutrons.

In this study, we characterise neutron energy spectrum, absorbed dose energy distribution, and space distribution. Also, focused neutron beams were developed for locally irradiation to mice.
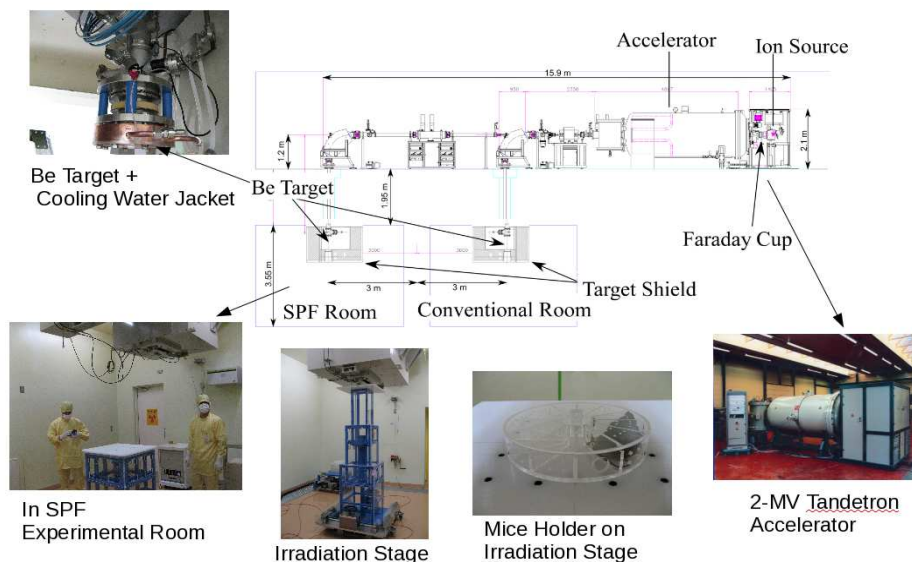
Neutron beam

Configuration of NASBEE

A 2-MV Tandetron accelerator from the high voltage engineering Europe was installed in NIRS. The accelerator produces 4-MeV proton and deuteron beams and has a capability of producing beam currents of 1-mA. Figure 1 shows the configuration of NASBEE. The accelerator was on the first floor; however, neutron targets are in the first basement. Beams were bent down to two irradiation rooms of conventional and SPF rooms, constructed in the first basement.

A 3-mm-thick Be target was used to produce fast neutrons. Same targets, shielding and cooling systems are configured in both irradiation rooms. In the conventional room neutron irradiation is performed without sample limits. Physical neutron specifications were measured in this room. On the other hand, in the SPF room specific pathogen is controlled to minimise several factors inducing biological effects other than radiations and measure biological effects due to only radiations. In the rooms temperature and humidity are, also, controlled for mice.

**Figure 1: NASBEE configuration of accelerator and
two neutron irradiation rooms of conventional and SPF rooms**

Neutron target

High-intense neutron beam is produced by irradiating 4-MeV deuteron beam into the thick beryllium target. This high-intense neutron beam is required to irradiate 2-Gy neutron beams to mice during 20 minutes, which is shorter than an anaesthesia period of approximately 30 minutes. To produce high-intense neutron beams, the tandetron accelerator with the highest beam currents in the world was installed in NIRS. The accelerator produces proton beams up to 800 µA and deuteron beams up to 500 µA. Proton and deuteron beams are accelerated up to 4 MeV.

Neutrons are produced at the ^{9}Be (d, xn) reactions. The 1.6 kW target heat by deuteron beam is cooled by coolant water with 10-20 litter per minutes, attached at the downstream of the beryllium target.

Neutron energy spectrum

Neutron energy spectrum was measured using an organic liquid scintillator, EJ-399, with a half inch thickness. This scintillator is based on naphthalene and has a particle discrimination property of neutrons and photons. From neutron discriminated pulse height, the energy spectrum was obtained using unfolding technique. Neutron response functions were evaluated with measurement and MCNPX simulations [7]. Figure 2-(A) shows the neutron energy spectrum at NASBEE. The spectrum is normalised with incident deuteron beam current at the target. The neutron spectrum consists of three components: in the low-energy region, mainly scatter neutrons in the irradiation room; from 1 to 4 MeV, neutrons created from the deuteron stripping reaction; in the highest-energy region, neutrons produced at the ^{9}Be(d,n)^{10}B reaction with +4.36-MeV Q-value. Average neutron energies by weighting the neutron energy spectrum with flux, kerma and RBE calculated are 2.3, 3.0 and 2.4 MeV, respectively. Using the keller biological model the RBE value obtained is 3.9 for the NASBEE neutron beam.

Figure 2: (A) Neutron energy spectrum at NASBEE

(A)

(B)
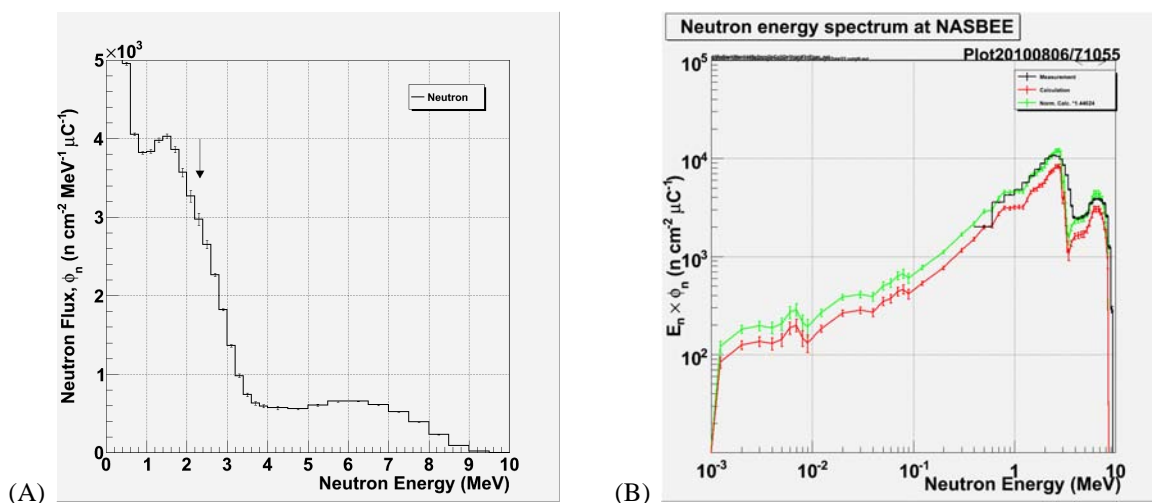
An arrow indicates average neutron energy in flux and (B) simulated neutron energy spectrum from 1 keV to 10 MeV, compared with measured result.

To evaluate lower neutron energy spectrum than the energy limit of particle discrimination, the neutron energy spectrum was simulated using the MCNPX code. In the other experiment, the angular distributions of neutron energy spectrum produced by bombarding 3-MeV deuteron beams into the thick beryllium target were measured using the time-of-flight (TOF) method at Tohoku university. The liquid organic scintillator having particle discrimination of neutron and photon was used. These angular neutron energy spectra without including scatter component were used as source spectrum in the MCNPX neutron transport. In the simulation, these materials are configured; polyethylene collimator, wall and floor in the room, and coolant water and copper holder. Figure 2-(B) shows the simulated neutron energy spectra at a wide range of neutron energy, compared with the measured result. The simulated neutron energy spectrum is smaller than the NASBEE spectrum because of lower incident deuteron energy. The simulated energy spectrum is normalised to the measurement in the energy region from 4 to 8 MeV. This energy spectrum is neutron flux multiplied by neutron energy. The neutron energy is decreased with decreasing neutron energy. The simulated neutron energy spectrum agrees with the measurement.

Photon energy spectrum

NASBEE photon energy spectrum was measured using high purity germanium (HPGe) detector and a liquid scintillator. In the HPGe pulse heights, several photopeaks are produced from the thermal neutron reactions of the n-H, n-Al, n-Fe, n-Be are identified. The energy of these photons extend to 9 MeV. The photon energy spectrum has been analysed.

**Absorbed dose distribution**

Figure 3 shows absorbed dose distributions of photon and neutron, which were measured using low-pressure proportional counters. The counter measured deposited energies in small site, equivalent to 1 μm tissue. The photon and neutron absorbed dose distributions, which are composed in the NASBEE beam, were discriminated using two types of proportional counters of A150 tissue equivalent and graphite walls [8]. From these absorbed dose distributions the photon and neutron absorbed doses composed of

18% and 82%, respectively, in the NASBEE neutron beam. This photon dose contamination is smaller than the neutron field of nuclear reactors, around 50% photon doses. Based on the microdosimetry technique, the RBE of NASBEE beam evaluated is 3.5 for crypt cell survival.

Also, the depth dose of the NASBEE neutron beam was measured using the low-pressure proportional counter. Maximum neutron dose is measured at near surface. On the other hand, photon doses show maximum values around 30 mm in depth. The neutron and photon depth-dose curves are different from each other.

At NASBEE neutron irradiation, absorbed doses were measured using A150 tissue equivalent ion chamber. At 117 cm from the target surface, the absorbed dose rates measured are 1.56 Gy/C, which is normalised with the deuteron beam current. This measured result agrees with the measured values (1.51 Gy/C) using the low-pressure proportional counters, within measurement uncertainty.

Figure 3: Neutron and photon absorbed dose distributions, normalised with incident deuteron beam
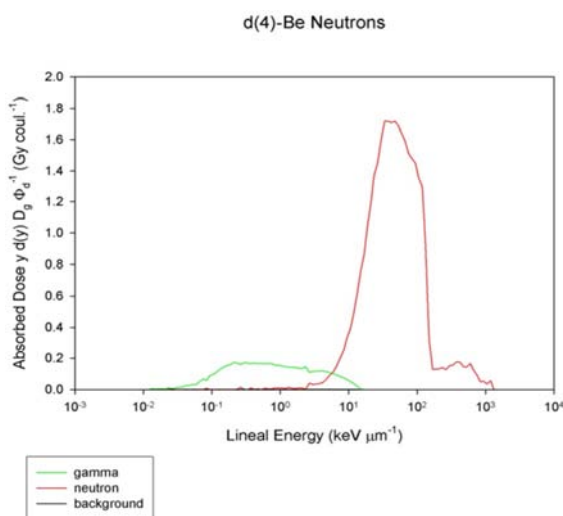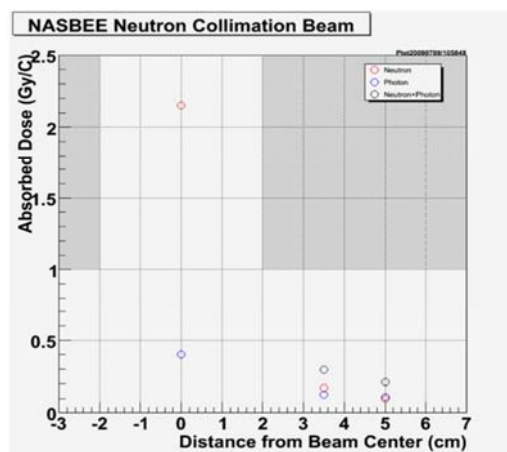

Neutron beam profile

The NASBEE neutron beam profile was measured using neutron activation of an aluminium plate. A large aluminum plate was irradiated by neutrons, followed by an activated aluminium plate being exposed to an imaging plate. This technique has an advantageous about no sensitivity to photons. Measured neutron profiles were shown in Figure 4, compared with a mice sample holder. The neutron beam size is 30 cm in diameter. We confirm that the neutron beam size covers mice and blood samples.

Figure 4: Neutron beam profile, compared with sample holder
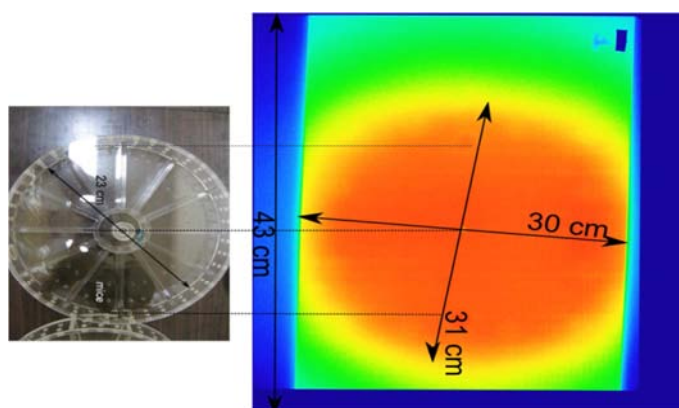
Neutron collimated beam

The NABEE neutron beam was applied to locally irradiate neutrons to only mouse lungs. The biological effects of lungs for alpha emitters of radon were evaluated. Neutron and radon have large RBE values, compared to photon and proton. To study both biological effects of lungs for neutron and radon, neutron beams are locally irradiated to only lungs of mice, which are 4 cm in length. Under local neutron irradiation, the biological effects are negligible due to other organ sources. Using this collimated neutron beam, the biological effects of lungs are experimentally obtained.

The neutron beam was collimated to 4 cm in width with polyethylene and iron blocks between the target and mice. Neutron profiles were measured using the neutron activation of aluminium plate. The neutron beam has a width of approximately 4 cm. Also, neutron and photon absorbed doses were measured using low-pressure proportional counters. Neutron and photon dose distributions were measured, separately. Figure 5 shows neutron and photon absorbed doses measured under the neutron collimator. The ratio of absorbed doses measured is 15 for the inside neutron beam to behind the neutron shields. Neutron absorbed doses are well shielded at a few percentage. Photon doses are only 30% behind the shields. Neutron irradiation carried out locally was completed at NASBEE, and after that, the biological effects were analysed.

Figure 5: Neutron and photon absorbed doses measured using low-pressure proportional counters inside of neutron beam and behind neutron collimator

Application of NASBEE

NASBEE has developed beam profile monitor and neutron targets using high-intense neutron beam. We innovated a real-time and non-destructive method of beam profile measurement on a target under large beam current irradiation [9]. This method does not require a complex radiation detector or electrical circuits. The beam profile on a target was measured by observing the target temperature using an infrared-radiation thermometer camera. The target temperatures were increased and decreased quickly by starting and stopping the beam irradiation within 1 s in response speed.

Conclusion

We have characterised the NASBEE neutron beams with the neutron energy spectrum, absorbed dose energy distribution, and space distribution. These distributions are useful for biological study. The results of this study will provide researchers outside of our institute with an opportunity to determine some of the biological effects of fast neutrons.

Acknowledgements

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