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Quality control and quality assurance procedures at the THOR BNCT facility

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ABSTRACT

Various quality control (QC) and quality assurance (QA) procedures of the boron neutron capture therapy (BNCT) beam at the Tsing Hua Open-pool Reactor (THOR) are established to ensure beam availability and quality. The QC/QA methods mainly employ foil activation and paired ionization chambers, respectively, for beam intensity check and dose assessment. Beam intensity is monitored on-line by using three dead-time corrected fission chambers. In addition to the periodic QC/QA activities regarding beam quality and the monitoring system, the quick QC/QA performed in an all-in-one phantom will be executed less than 70 min before the clinical treatment to guarantee beam quality. The QC/QA procedures have been gradually established and the actual performance satisfied the preset criteria defined for the BNCT facility at THOR.

1. Introduction

At the Tsing Hua Open-pool Reactor (THOR), the quality control (QC), and quality assurance (QA) procedures are the necessary means to ensure that its epithermal neutron beam satisfies the need for the boron neutron capture therapy (BNCT). Trustiness and correctness are the most demanded aspects that QC/QA seeks to cover. To achieve the mentioned goals, a series of actions were taken to establish a proper QC/QA system at the THOR BNCT facility.

Since the second half of 2009, a series of standard operation procedures for QC/QA have been proposed and gradually implemented. The QC/QA procedures at the THOR BNCT facility cover many different aspects concerning mostly patient safety, such as fire inspection, emergency evacuation, power supply, BPA examination, and the most important one – beam availability and quality. This paper aims to introduce the QC/QA procedures performed in order to assure the validity of the epithermal neutron beam at THOR.

2. Materials and methods

Several measuring techniques are applied for the beam QC/QA check/calibration, among which, activation detectors and paired ionization chambers are the most used. The following sections introduce the two tools and the QC/QA activities. Note that, the tolerance/uncertainty values reported in this work were evaluated from long-term observation of corresponding dosimetry experiments performed in the epithermal neutron beam.

2.1. Beam intensity and beam spectrum check

The instrumental neutron activation analysis (INAA) is very commonly used in reactor dosimetry to study the characteristics of a neutron field. At THOR, a well-calibrated high purity germanium (HPGe) detector system is used while a set of triple activation foils are applied as activation detectors. To ensure the accuracy of the measurements, the HPGe is periodically calibrated by standard sources, including ^{60}Co, ^{137}Cs, and ^{152}Eu. The measuring distances are available at 8 and 14 cm away from the detector surface. The applied triple activation foils are, in sequence, AuAl (1 wt% Au), pure natural Cu, and MnNi (88 wt% Mn) foils. The foils are packed in a piece of rice paper. For the beam intensity calibration, the triple-foil package is posted at the center of the beam exit. During the activity measurements, their dead time is kept less than 1%.

Since the reaction rate per atom, *RR*, is proportional to the beam intensity, *RR* is used for beam intensity check. The foil set is positioned free in air at the beam center and irradiated at 1.2 MW. The *RR* of the activated foil at a given reference counting rate is determined by

$$RR=\frac{\lambda(C-B)}{N\times\varepsilon\times Y\times e^{-\lambda t_m}(1-e^{-\lambda t_c})\times\beta} \tag{1}$$

where λ is the decay constant of the radioactive nuclide (s^{-1}), C is the peak gross counts and B is the peak background counts, N is the number of atoms of the foil, ε is the peak efficiency and Y is the branch ratio of the peak of interest, t_m is the activity measuring time (s), and t_c is the cooling time between the end of

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irradiation and the start of the counting (s). And

$$\beta = \sum_{i=1}^{t_{irr}} \left[\frac{FC(t_i)}{FC_{ref}} \times (1-e^{-\lambda}) \times e^{-\lambda(t_{irr}-t_i)} \right] \quad (2)$$

where t_{irr} is the irradiation time (s), and $FC(t_i)$ is the counting rate at the ith second of the irradiation, read from one of the beam monitoring channels and FC_{ref} is the reference counting rate of that channel. Eq. (2) accounts for normalization of the time dependent beam intensity to the reference condition. The *RR* measured at different time with the same conditions should be constant or within an acceptable range.

At the THOR, the ratio of the reaction rate per atom of AuAl foil (RR_{Au}) to that of MnNi foil (RR_{Mn}) is used as a check indication of neutron spectrum due to their different sensitivities to thermal and epithermal neutrons. At THOR, this ratio is $60.1 \pm 2\%$ (tolerance level) for the free-in-air measurement (at 0 cm). The ratio of MnNi foil to Cu foil is used as a quality check of the performed measurement. Generally, the ratio should be $3.14 \pm 2\%$.

2.2. Paired ionization chambers

Paired ionization chambers technique is used to determine gamma-ray and neutron doses (ICRU Report no. 45, 1989). A magnesium-walled ionization chamber with argon gas (denoted as Mg(Ar)) is used for photon component measurement. The other ionization chamber walled with A-150 tissue-equivalent plastic and filled with methane tissue-equivalent gas (denoted as TE(TE)) is used to determine total neutron and photon absorbed doses. In the QC/QA procedure, the gas ionization can be derived from the electrometer reading, corrected by temperature, pressure as well as time-dependent beam intensity. The corresponding neutron and gamma-ray doses are determined by the paired algebraic equations defined in ICRU 45 report.

Both chamber systems, including their cables and electrometers MAX4001 made by Standard Imaging Inc., are annually calibrated in a primary standard ^{60}Co beam at the Institute of Nuclear Energy Research in Taiwan.

2.3. On-line neutron monitoring system and its calibration

The THOR epithermal neutron beam is equipped with an on-line neutron monitoring system consisting of three miniature ^{235}U loaded fission chambers. The fission chambers were installed inside the collimator to avoid back scattering contributions. The dead-time influence was calibrated using a low counting rate fission chamber, whose dead-time influence can be ignored, as described in the previous study (Liu et al., 2006). For clinical irradiation, the system is controlled by a dedicated computer program named OMS-BNCT. According to fission chambers readings as well as an input function of boron concentration, this program calculates the real-time dose delivered to the patient and indicates the percentage of accumulated dose. Furthermore, OMS-BNCT plays an important role in the QC/QA procedures; it has a check list covering communication, reactor status, dose information, personnel evacuation, and all of the other relevant QC/QA items, that must be double checked one by one, by the on-site scientist and the corresponding clinician before the monitor can be turned on.

One of the most important QC/QA activities is the calibration of the online neutron monitoring system. The on-line neutron monitoring system determines when the irradiation should stop and thus it is crucial to the correctness of dose delivery. To guarantee the system functions correctly, the previously mentioned triple activation detectors are utilized in the calibration work. The monitor calibration factor k derived from *RR* is defined as

$$k = (RR/(FC_{ref})) \quad (3)$$

The monitor calibration factor can be viewed as the induced reaction rate per atom of a specific activation detector per count read from a given fission chamber.

2.4. Periodical and quick QC/QA activities

The QC/QA procedures, concerning the epithermal neutron beam availability and quality, are periodically performed. For different QC/QA terms, the execution period is different. Table 1 lists the corresponding QC/QA activities and their execution period. All of the performed QC/QA checks/calibrations have been well documented via electronic files and hard copies. Each document is checked and approved by an independent supervisor. In addition to the periodic checks/calibrations, one day before a clinical irradiation, the QC/QA checks for beam intensity and dose as well as the on-line monitoring system calibration will be performed. As long as a deviation of any measured detector response is larger than 3%, the whole procedure and system will

Table 1
The QC/QA items for THOR BNCT and their execution period.

Item	Period	Tool	Tolerance
Beam quality			
Beam intensity	Quarterly[a]	Triple foils	3%[b]
Beam spectrum	Annually	Multiple foils	3%[b]
Neutron spatial distribution	Quarterly	Imaging plate + Cu sheet	N/A
Neutron and gamma-ray doses	Quarterly[a]	Twin ionization chambers	3%[c]
Monitoring system			
On-line monitor check	Half-yearly	Oscilloscope + pulser	N/A
On-line Monitor Calibration	Quarterly[a]	Triple foils	3%[b]
Monitor dead-time calibration	Annually	Low sensitivity fission chamber	N/A
Area monitor calibration	Annually	Secondary ^{137}Cs source	N/A
Instrument			
Ionization chamber calibration	Annually	Primary ^{60}Co source	< 1%[d]
HPGe calibration	Quarterly	Standard sources	< 3%[d]
Imaging plate reader check	Half-yearly	Maintained by Fujifilm	N/A
Laser	Weekly[a]	Laser tool kit	< 1 mm
Communication system	Half-yearly[a]	Camera + microphone	N/A

[a] These items will also be performed one day before the clinical treatment.
[b] Compared to the standard reaction rate per atom of each activation foil, separately.
[c] Compared to the given standard current of each chamber, separately.
[d] Uncertainty of the calibration factor.