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An optimized pre-moderator improves uniformity of activation rate distribution in an ORNL phantom-IVNAA facility

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HIGHLIGHTS

- ► We model IVNAA facility to provide an elemental profile of body composition.
- ► It is essential that the thermal neutron flux distribution is uniform.
- ► We study type and shape of pre-moderator to increase the uniformity of thermal neutron flux distribution.
- ► We examine the role of pre-moderator to assess uniform distribution.
- ► We conclude that 1.8 cm thickness of paraffin increase the uniformity of flux distribution.

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ABSTRACT

Uniformity of activation rate distribution through the human body is extremely important for in vivo analysis of the body elements by neutron activation method. Achieving uniformity can be difficult because of the non-homogenous body shape and compositions. Pre-moderator is one of the most essential parts of the irradiation facility to provide uniform distribution over the sample. The aim of the present study was designation of an optimum pre-moderator, in terms of shape and material, which compensates the destructive effects of body shape and allows a satisfactory uniformity of activation rate in the sample. Our final calculations indicated that using two slabs of paraffin with a thickness of 1.8 cm as a pre-moderator in the presence of a reflector/moderator, achieve the most uniform distribution of activation rate in the body.

1. Introduction

The quantitative determination of the elemental composition of human body can provide valuable information about the health and may help diagnose certain diseases. Removal of a small amount of tissue is technically rather simple, however, the procedure is not always feasible or without risk for the person. In vivo Neutron Activation Analysis (IVNAA) is a non-destructive and highly accurate method to provide an elemental profile of body composition (Anderson et al., 1964). This technique is a "Gold Standard" method to measure essential body elements (such as nitrogen, hydrogen, calcium, etc.). Assessing such an accuracy, activation rate should be uniform over the whole body (Chamberlain et al., 1968; Chettle and Fremlin, 1984; Ellis, 1990). This means that the probability of activation should be constant for all atoms irrespective of their locations. In other words, non-uniform activation makes different activation probabilities for identical isotopes placed in different locations in the body. Therefore, they will not have similar contributions in the gamma ray spectrum obtained from the neutron irradiated human body. It has been demonstrated that, there is a linear relationship between activation rate and neutron flux (Knoll, 2010)

$$\text{Reaction rate density} = N\sigma\varphi \quad (1)$$

where N is the number of nuclei per unit volume, σ is the microscopic cross section, and ϕ is neutron flux. Since the thermal neutron absorption cross section is too high, by setting σ and ϕ as absorption cross section and thermal neutron flux, in Eq. (1), reaction rate turns into activation rate. Thus, uniform distribution of thermal neutron flux with depth, length, and width, provides uniform activation rate over the sample. Therefore, accurate measurement using IVNAA depends upon obtaining uniform thermal neutron flux.

The uniformity of thermal neutron flux in the body is influenced by the energy spectrum of neutron sources, the construction of the irradiation facility (reflector and moderator materials),

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the type and shape of the pre-moderator used to generate thermal neutrons, and the size and shape of various regions of the human phantom (Elliott et al., 1978). Although, none of the irradiation facilities used for IVNAA are identical, the pre-moderator plays an important role in many of them.

In the late 1960s, several key reports were published by Battye et al. (1967), Chamberlain et al. (1968) and Palmer et al. (1968) who used a hydrogenous pre-moderator to produce uniform thermal neutron distributions in large samples. The main basis for research in 1970s was to design a facility that would increase the uniformity of activation rate in water phantoms. During this period, we found only two reports that described the thermal neutron profile in different cross sections of the body (Chamberlain et al., 1970; Nelp et al., 1970). In the early 1980s, due to a lack of professional code and advanced technology, research on this subject came to a halt for 10 years. The development of computers and calculation codes made simulation a strong instrument in nuclear medicine. Dr. I.E. Stamatelatos is one of the researchers who used simulation to improve the IVNAA archetypal. In 1992 and 1993 he presented results from a study comparing neutron produced from (α,n) reactions and spontaneous fission sources on increasing uniformity. In addition, he amended flux profile by simultaneously applying a reflector and pre-moderator (Stamatelatos et al., 1992, 1993).

Neutron Activation Research Group of Ferdowsi University of Mashhad recently tried to develop an IVNAA facility to study body composition at the Monash Medical Center (Borovnicar et al., 1996). This apparatus was designed to simultaneously measure total body nitrogen and chlorine in children. Previous work has demonstrated that ^{241}Am–Be source has the advantage of better activation rate uniformity in comparison with ^{252}Cf source. Miri et al. showed that thermal neutron flux and activation rate are higher for ^{252}Cf, however, ^{241}Am–Be provides better uniformity. In that study, two collimator shapes (pyramidal and rectangular), four collimator materials (polyethylene, polyethylene borated, graphite and the heavy water) and two configurations (unilateral and bilateral) were also investigated (Miri-Hakimabad and Rafat-Motavalli, 2009). In the next article, the effects of collimator aperture dimensions and presence of the reflector/moderator and paraffin pre-moderator were surveyed to provide uniform distribution in a water phantom (Miri-Hakimabad and Rafat-Motavalli, 2010).

Using simulation, in the present study, the investigation on the type of pre-moderator was expanded. Then, the water phantom was replaced with a simple representation of human body and three different shapes of pre-moderator were studied. The acceptable agreement which was observed between simulated data and experimental results, made the simulation trustworthy (Miri-Hakimabad and Rafat-Motavalli, 2010).

All results in this work were estimated with the statistical uncertainties, less than 2% and so, the data errors are not shown in the tables. It is worth to mention that statistical error arises as an inherent feature of the Monte Carlo algorithm due to the finite number of histories contributed in tallies.

2. Materials and methods

The initial step in the study of pre-moderators is the evaluation of the thermalizing capability of different materials. The use of cubic water phantom is most suitable, since determination of pre-moderator material is independent of the phantom's shape. To assess the best choice of pre-moderator material, six materials (paraffin, graphite, urea ($CO(NH_2)_2$), heavy water, paraffin–bismuth, and paraffin–tungsten) were evaluated.

After determining pre-moderator material, the water phantom was replaced with a human phantom. The main goal at this stage was specification of pre-moderator shape with regard to body shape. Three pre-moderators were considered. In addition, three other cases, namely those without a reflector/moderator, without a pre-moderator, and without either a reflector/moderator or pre-moderator, were evaluated.

2.1. Facility description

The archetypal IVNAA facility was designed according to the Monash Medical Center's system in Australia (Borovnicar et al., 1996). The bilateral rectangular shape collimator contains graphite with four ^{241}Am–Be neutron sources. A concrete shield surrounds the collimator to protect the IVNAA operator. Two pairs of 10 cm × 10 cm × 15 cm NaI(Tl) detectors are positioned on both sides of the scanning bed, along a horizontal axis perpendicular to the vertical neutron beam. Each detector is shielded from neutrons by 2.5 cm thick borated-paraffin housing. In addition, there are two lead sheets on the collimator to protect the detectors from undesirable gamma rays. To increase thermal neutron flux at the lateral surfaces, and to reduce neutron loses, moderator/reflector objects, which cover the sides of the phantom, were prepared.

Fig. 1 shows a cross-sectional view of the irradiation facility. Only one pair of detectors and sources can be seen in this figure.

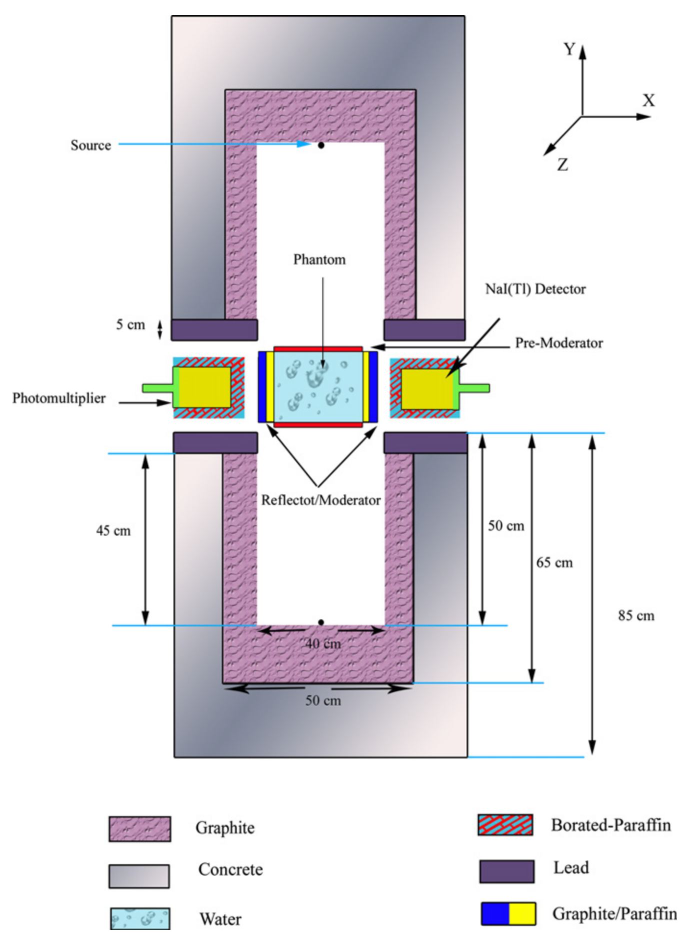

Fig. 1. Optimized IVNAA facility at Ferdowsi University of Mashhad.