DEVELOPMENT OF IN VIVO PROMPT GAMMA ACTIVATION ANALYSIS USING THE FILTERED NEUTRON BEAM AT THE DALAT REACTOR

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ABSTRACT

The development of a method for in vivo measurement of some elemental concentrations in organs making use of prompt gamma activation analysis with the filtered neutron beam at the Dalat reactor is being carried out. In this paper we present primary results in research and development of an IVPGNAA facility at the Dalat reactor. Beside the description of experimental set-up, they consist of determination of thermal neutron flux distribution in phantom, and the evaluation of the detection limit and analytical sensitivity for Cd in the kidney and the liver. Discussions are given to improve the IVPGNAA facility in the future.

INTRODUCTION

In vivo prompt gamma neutron activation analysis (IVPGNAA) involves the exposure of the living human body, or some relevant part of it to a small dose of neutrons. The prompt gamma radiation emitted on neutron capture is measured using external counters. Neutrons used in IVPGNAA systems can be generated from a particle accelerator, neutron generator, nuclear reactor, or isotopic neutron source. Two methods - total body IVPGNAA and partial body IVPGNAA can be used. The first method is used to determine Ca, Na, Cl, N, H, C in total body composition by prompt-gamma-ray analysis. The second one is used to determine elements (cadmium, silicon, mercury, etc.) in organs of interest, such as liver, kidney and lungs. Obtained data can be used in therapy evaluation and clinical diagnosis. For example, calcium is one of the major constituents of bone and reflect its status. Many reports in the literature concern comparative and longitudinal studies in a variety of bone disorders. Sodium, chlorine and potassium are important as body electrolytes and their relationship has been described in relevant conditions such as hypertension. Nitrogen is an excellent indicator of protein in nutritional studies. Oxygen and hydrogen reflect the body content of water. Carbon is expected to provide estimates of body fat, etc.

In later times there has been a growing concern among health specialists about the perils of heavier elements received by the human body. Especially studies have been focused on Cd and Hg. A characteristic property of Cd is that they have a tendency to accumulate in the kidneys and the liver, causing damage of these organs. Chronically Cd poisoning also may lead to bone and pulmonary damage and perhaps may also cause a form of cancer and high blood pressure. So Cd has become a serious danger to the health of mankind. Conventional clinical methods based on measurement of the concentration of the element in, for example, blood or urine are unsatisfactory for the control of contamination levels in the critical organs, especially for acute and unknown exposure situations. Toxicologically, the accumulation of organic mercury compounds in the brain is the most important problem. Inorganic mercury compounds are, like cadmium, preferentially retained in the kidney. Medical diagnosis of mercury poisoning is usually performed using *in vitro* bioassay methods, such as blood mercury measurement, quantitative urinalysis, and tissue assay by atomic absorption spectrophotometry. Since the kidneys are the principal organ for mercury accumulation, however, it would be valuable to monitor kidney levels directly.

In this situation we consider that the development of a method for in vivo measurements of some elemental concentrations in organs making use of prompt gamma activation analysis with a filtered neutron beam at the Dalat reactor is necessary and useful. In this paper we present primary results in research and development of such an IVPGNAA facility at the Dalat reactor. Beside description of experimental set-up, they consist of the determination of thermal neutron flux distribution in phantom and the evaluation of the detection limit and analytical sensitivity for Cd in the kidney and the liver. Discussions are given to improve the IVPGNAA facility in the future.

EXPERIMENTAL SET-UP

Filtered Neutron Beam

The filtered neutron technique has been developed at several reactors in the world to produce quasi-monoenergetic neutron beams in a wide energy range from keV to a few MeV. So far some kinds of neutron filters have been installed in the piercing beam port No.4 of the Dalat reactor to produce neutron beams at 144 keV, 75 keV, 55 keV, 25 keV, 1.2 MeV and thermal neutrons (Tan, 1996, Tan & Dien, 1997). Review on neutron beam experiments at the Nuclear Research Institute (NRI) has been given in (Tan, 1996). The filtered neutron beam at 144 keV from an single crystal Si filter in combination with additional B-10 and Ti filters has been used in this experiment. The filter combination gives a neutron flux of 10^7 neutron $cm^{-2}.s^{-1}$ at the outlet of the beam port. The advantage of using neutron of energies around 144 keV for measurement on internal organs depends on the fact that these neutrons penetrate into the body where they are thermalized. The thermalized flux reaches a maximum at around 3-5 cm depths from the body surface, that is corresponding to the position of internal organs in the body.

Gamma Spectrometer

Prompt gamma rays in our IVPGNAA measurements are detected by N-type hyperpure germanium HPGe-90cc detector placed next to the water phantom as shown in Figure 1. The system resolution under 1.5 μs shaping time in amplifier is 5 keV at 2223 keV, which is the most intense prompt gamma ray photopeak in the spectrum from $^{1}H(n,\gamma)^{2}H$ reaction. Prompt gamma rays detected by the HPGe-90cc detector were stored in 8k-channel spectrum by an 8k channel ADC/MCD combination interfaced with a PC/AT. In the range of gamma energies up to 3.5 MeV, the energy scale can be calibrated with an accuracy of about +-0.1 keV by means of radioactive sources. From 3.5 MeV to 10.8 MeV, we calibrated the energy scale mainly with accurately measured lines from neutron capture in iron, chlorine, nickel and nitrogen. Measured prompt gamma spectra were subsequently analyzed by GAMMAW or our own software depending on peak statistics.

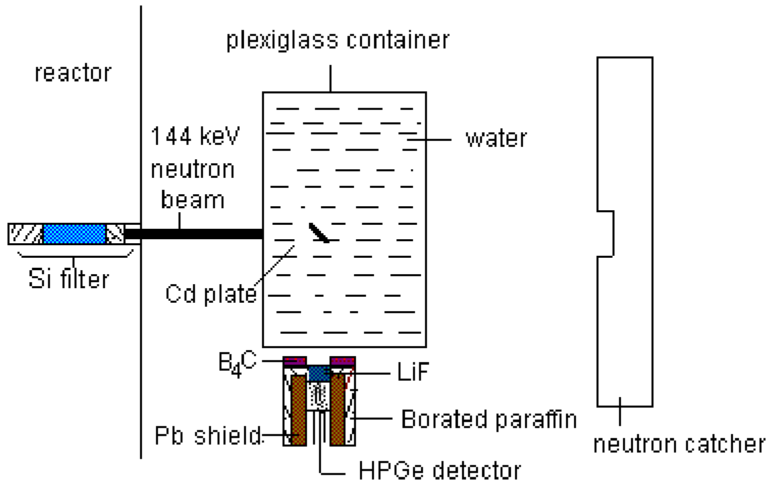


Figure 1 The set up used for IVPGNAA measurements at NRI

Phantom

To simulate the irradiation conditions for the human body, a man-like trunk phantom was made up from 0.5 cm thick lucite, 20 cm thick, 40 cm wide, and 70 cm high. The phantom liver and kidney with the volume of 1,833 cm^3 and 144 cm^3 respectively, were made by polyethylene bags. Their position was fixed in the man-like trunk phantom as in living body and the neutron beam was guided to their center.

Sample Preparation

The trunk phantom is filled with distilled water to form a liquid phantom. In order to study the analytical sensitivity of cadmium in both liver and kidneys in the water phantom, cadmium chloride ($CdCl_2$) extra pure solution is filled in the sealed polyethylene liver and kidneys for neutron irradiation. The cadmium contents in the range 1 - 10 mg in the kidneys and 1 - 5 mg in the liver have been prepared for the IVPGNAA measurements in this work.

RESULTS AND DISCUSSION

Neutron Flux Distribution

In the IVPGNAA experiments the activating neutron flux should be as uniform as possible throughout the relevant organ or region of the body and in other tissues the radiation dose should be minimal. Utilization of thermal neutrons will give a higher nonuniformity in neutron flux distribution because of their rapid attenuation. Otherwise irradiation with neutrons of higher energy results in partial thermalisation within the body, producing a maximum thermal neutron flux at about several centimeters depth. This can give a higher detection limit for IVPGNAA measurements in comparison with using thermal neutrons with the same intensity of the incident beam.

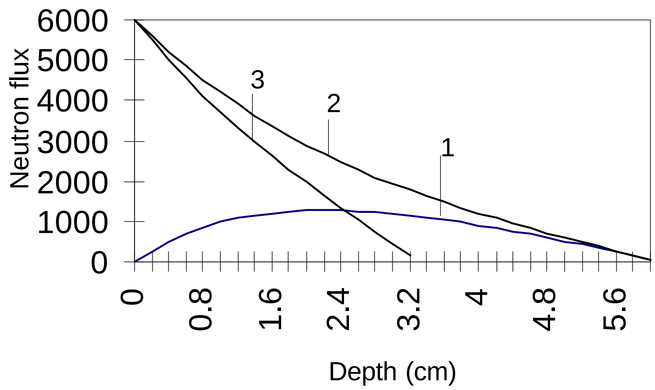


Figure 2 Neutron flux distribution in the phantom

Thermal neutron flux distribution in the phantom was calculated by the two-groups diffusion method (Son, 1996). Calculated results are shown in Figure 2, where curves (1) and (2) are respectively thermal and 144 keV neutron flux distributions with depth in the phantom produced by the 144 keV incident neutron beam. The curve (3) is the attenuation of neutrons with depth in the phantom of the incident thermal neutron beam having the same intensity as the 144 keV neutron incident beam. It can be seen that the thermal neutron flux distribution of curve (1) has a nearly wide plateau at the depths from 1.5 cm to 4.5 cm (The depth of kidney is about 1 to 7 cm for healthy adults), while curve (3) decreases so fast that at the depth of 3.5 cm it become zero. That verify the recommendation on utilization of the fast neutron beam in IVPGNAA experiments as given above.

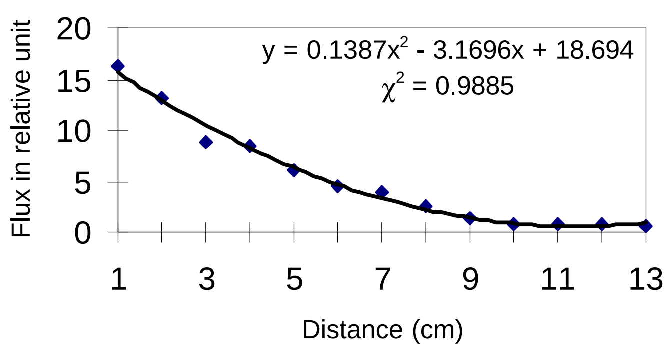


Figure 3 Neutron flux distribution along the beam

To determine the distribution of the slow neutrons in the phantom by irradiation with a 144 keV neutron beam, we use the method as given in (Ryde & Bergman, 1981). The distributions along the beam and perpendicular to the beam were determined by moving a Cd plate in the water phantom. The 559 keV prompt gamma-ray from ^{113}Cd(n.γ)^{114}Cd was detected by a HPGe-90cc detector. Figure 3 and Figure 4 show respectively the slow neutron flux distributions along and perpendicular to the beam measured in our experiments. The asymmetry distribution in Figure 4 is due to the detector shielding box placed directly next to the phantom on the right side and it reflects leakage neutrons back to the phantom.

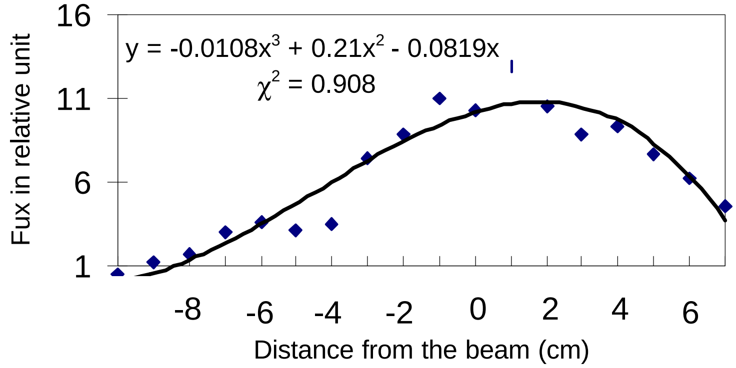


Figure 4 Neutron flux distribution perpendicular to the beam

Background Gamma Ray Spectrum

The background gamma ray spectrum with energy range up to 8 MeV from the water filled phantom is shown in Figure 5. The most intense photopeak in the spectrum is the 2223 keV prompt gamma rays from the H(n,γ)D reaction. Above the 2223 keV region, the background is mainly prompt gamma rays as well as their single/double escape peaks from the capture reaction on construction materials of the shielding boxes for the beam port and the HPGe-detector. In the low energy region, the background consists of Compton scattering components, prompt gamma rays from construction materials as well as the single and double escape peaks from 2223 keV, annihilation gamma rays of 511 keV from the pair production of high energy prompt gamma rays and prompt gamma rays from the Ge(n,γ) reaction within the HPGe-detector. A broad peak of 478 keV from the $^{10}B(n,\alpha)^{7}Li$ reaction due to borated paraffin and B_4C shielding materials for the HPGe-detector appears as seen in Figure 5.

Detection Limit of Cadmium in Kidney and Liver

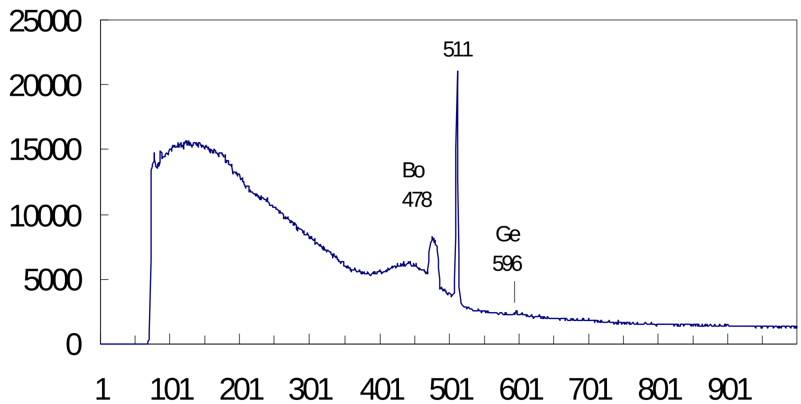
The minimum detection limit is defined (Jaklevic et al., 1977) as:

$$C(mdl) = 3.29\ (R_b/t)^{1/2}/S$$

where R_b is the count rate of the photopeak and t is the count (irradiation) time. S is the sensitivity for a given element, that is, the count rate of the element's photopeak per unit mass.

S can be determined by using the phantom liver and kidney with given contents of cadmium. Figure 6 gives experimental curves in function of the count rate of the 559 keV photopeak upon cadmium contents in kidney and liver. The dependence is nearly linear. Fitting experimental data allows receiving the value of the sensitivity S that is 0.734 c/s/mg for liver and 0.801 c/s/mg for kidney, respectively.

R_b is given as the count rate under the 559 keV photopeak in the background spectrum of the water phantom. Therefore, the minimum detection limit was calculated to be 0.155 mg for liver and 0.153 mg for kidney respectively, with the irradiation time of about 500 s. The detection limits are much lower than average concentrations of cadmium in liver and kidney of healthy adults. Compared to other IVPGNAA facilities used for in vivo measurement of cadmium in organs (Tsing Hua University, 1988), the detection limit and sensitivity of our IVPGNAA facility described with a 144 keV neutron beam were considerably better.



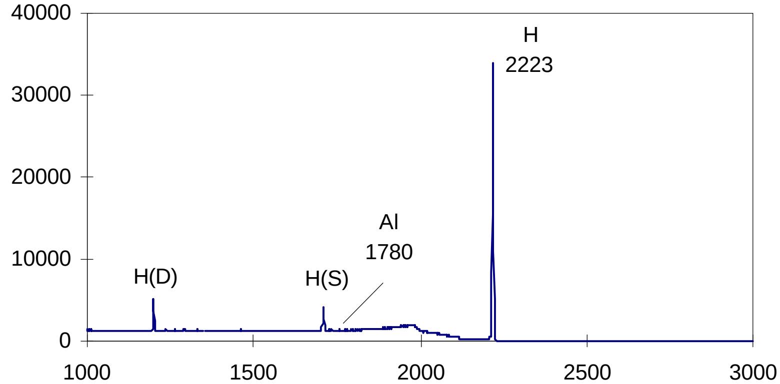


Figure 5 Background spectrum of IVPGNAA measurement obtained from a water phantom

Discussion

The comparison of the detection limit and sensitivity of our IVPGNAA facility with others cannot yet confirm any usefulness of our facility if it's neutron and gamma doses for a diagnostic process have not been evaluated. It can be seen from Figure 4 that neutron dose decreases about one order at a distance of 5 cm from the beam. Therefore, for other organs in the body far from the beam, the neutron dose will be very low. In order to reduce gamma dose, a bismuth filter is recommended. However, so far due to financial limitations we have not yet acquired a bismuth filter. Therefore, gamma dose of our facility is still high for a diagnostic process. We hope that in the near future we can upgrade our facility under the Government Project for upgrading the Nuclear Research Institute. In that case we can improve the capability of our facility for measurement of other elements like Hg, Si, in organs.

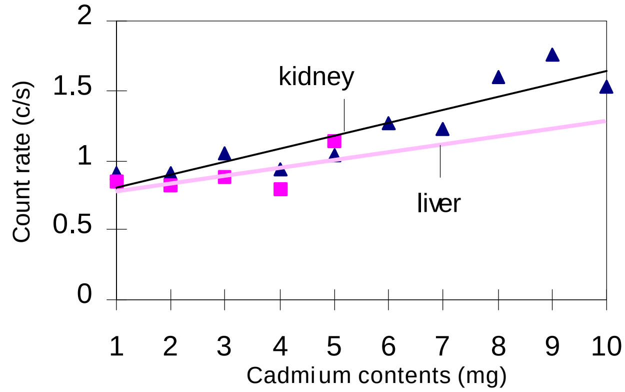


Figure 6 Dependence of the count rate of the 559 keV photopeak on cadmium contents in kidney and liver

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KEY WORDS

In-vivo prompt gamma neutron activation analysis (IVPGNAA), man-like trunk phantom, detection limit, sensitivity, cadmium, neutron and gamma doses, filtered neutron beam, gamma