RECENT UPGRADE OF THE IN VIVO NEUTRON ACTIVATION FACILITY AT BROOKHAVEN NATIONAL LABORATORY

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INTRODUCTION

The in vivo neutron activation (IVNA) facility at Brookhaven National Laboratory (BNL) consists of a delayed- and a prompt-gamma neutron activation (DGNA and PGNA) system and an inelastic neutron scattering (INS) system. The total body contents of several basic elements, including potassium (TBK), calcium (TBCa), chlorine (TBCl), sodium (TBNa), and phosphorus (TBP) are measured at the DGNA¹⁻³ system; total body carbon (TBC) is measured at the INS⁴ system; and the nitrogen-to-hydrogen ratio is measured at the PGNA system.⁵ Based on the elemental composition, body compartments, such as total body fat (TBF) and total body protein (TBPr), can be computed with additional independently measured parameters, such as total body water (TBW), body size, and body weight (BW).⁶ By means of least squares fitting, TBF, TBH (total body hydrogen), and TBPr can be obtained from the following empirically derived equations:

$$\text{TBH} = 0.11\text{TBW} + 0.12\text{TBF} + 0.07\text{TBPr} \quad (1)$$

$$\text{TBC} = 0.77\text{TBF} + 0.55\text{TBPr} + 0.05\text{TBCa} \quad (2)$$

$$\text{TBPr} = 6.25\text{TBN} = 6.25(\text{N/H}) \times \text{TBH} \quad (3)$$

$$\text{BW} = \text{TBW} + \text{TBPr} + \text{TBF} + 2.94\text{TBCa}. \quad (4)$$

MASTER

Information on elemental and compartmental body composition obtained through neutron activation analysis is useful, if not essential, for research on growth, malnutrition,

aging, and diseases, such as osteoporosis and acquired immunodeficiency syndrome (AIDS) in which the progression of the illness is closely related to changes in major body compartments, such as bone, adipose tissue, and muscle.

The DGNA system has been modified and upgraded several times since it was first built.³ Recently, all three systems underwent major upgrades. This upgrading and some preliminary studies carried out with the modified facilities are reported here.

THE DGNA SYSTEM

We upgraded the data acquisition system of the DGNA facility from a ND6700 to a Nuclear Data Genie Workstation system, based on a VAXstation 4000/Model 90. The new system uses ND556 AIMs (Acquisition Interface Modules) as the interface between the ADCs and the workstation. The workstation controls data acquisition through the AIM over an Ethernet-based network. New window-based software provides a user-friendly interface to the operator. The new system provides faster and easier collection, storage, display, and analysis of data. We also have automated the procedures for data acquisition and analysis.

The procedure used for taking measurements on the patient is essentially the same as that used since the early 1970s.^{1,2} However, two changes were made in data acquisition and analysis: 1) for the detector sensitivity and geometry correction, a universal set of correction numbers was derived and is now used for all DGNA processing; and 2) for the attenuation correction, the counting time of the uniform sheet source (UNIS)¹ with and without the patient was increased from 30 to 300 seconds. The statistical fluctuations introduced by the geometric and absorption corrections are negligible compared to the uncertainty in counts caused by other sources such as gain shifts in the detector and mispositioning of the patient.

A new phantom was made with an artificial skeleton inserted into a regular Bomab phantom (manufactured by Atlan-Tech Inc., Atlanta). The artificial skeleton was made from a mixture of calcium phosphate, calcium carbonate, and epoxy. The new phantom is used as a standard to calibrate the activation data. Compared to the Alderson phantom that contains a solution of calcium, we assume that the more realistic placement of calcium in the skeleton of the Bomab phantom more than compensates for the fact that its overall shape does not resemble that of a human as closely as does the Alderson phantom. However, this assumption has not been tested experimentally. The counts per gram of calcium obtained from neutron activation of the Bomab phantom filled with water are about 8% higher than that measured with the Alderson phantom filled with a calcium solution. This difference can be explained by the difference in the locations of calcium in the two phantoms and in the chemical compositions of the phantoms' shells.

The TBCa, TBNa, TBCL, and TBP of patients are obtained using the skeleton phantom as a standard, which is representative of a normal-sized male. A smaller Bomab phantom with skeleton, which is representative of a normal female, has recently been manufactured as have also two sets of overlays, one for the normal- and one for the small-sized skeleton phantom that simulates obese patients. Measurements of these phantoms will be carried out in the future. Interpolations for body sizes between them

will be used to improve the body-size response invariance, especially for obese and underweight patients.

THE PGNA SYSTEM

The PGNA system was originally designed by Vartsky *et al.*⁵ in the late 1970s; since then, several hundred measurements on patients have been made.^{5,6} Recently, the system underwent extensive upgrading to improve the precision of the TBN measurement and to improve system's reliability. The major modifications include 1) design and construction of a new neutron collimator and shielding for the $^{238}\text{PuBe}$ neutron source; 2) optimization of the detectors' positions and shielding; 3) upgrading of the data acquisition and patient motion systems.

The Redesigned PGNA System

The primary goal in redesigning the neutron collimator was to optimize the neutron energy spectrum to provide the highest thermal neutron flux in the body for a given radiation dose to the patient. The newly constructed collimator incorporates a neutron reflector made of graphite and bismuth (Fig. 1). The collimator provides a rectangular beam $20(\text{L}) \times 45(\text{W}) \text{ cm}^2$ at the level of the patient bed which is 75 cm above the $^{238}\text{PuBe}$ source. Three aluminum tanks containing heavy water (D_2O) were constructed to be placed alternatively over the collimator to serve as a premoderator. The maximum heights of D_2O in the tanks are 1.0, 2.5, and 5.0 cm.

The two $15.2 \text{ cm} \times 15.2 \text{ cm}$ NaI(Tl) detectors are shielded with bismuth, boron carbide, and boric acid to reduce background counting. This resulted in the reduction of pile-up, which is the major source of the background counts underneath the nitrogen peak. The positions of the detectors were optimized, based on measurements of nitrogen-detection efficiencies and nitrogen peak-to-background ratios obtained with phantoms. Consequently the two detectors were placed symmetrically at a 60° azimuthal angle from the body axis and a 30° angle from the horizontal plane.

The new data acquisition system in the upgraded PGNA facility uses an IBM PC/AT computer equipped with an Accuspec multichannel analyzer from Nuclear Data, which replaces a ND66 system. The new motion system uses a computer-controlled stepping motor. Patients are measured in five 20-cm sections, starting from the shoulder position, resulting in a 100 cm total body-length of the measurement. New software automates data collection and the motion of the bed. The skin dose to a patient from one measurement is 80 mrem, using a neutron quality factor⁷ of 20.

Calibration of the PGNA System

Three Bomab phantoms were used to calibrate the system and to provide corrections to compensate for differences in the body sizes of patients: small, normal, and obese. The process is described in detail elsewhere.⁸ Measurements were made, using the 2.5-cm D_2O tank, of the three phantoms filled with a tissue-equivalent nitrogen solution to obtain the net hydrogen counts (by triangular-fit background subtraction) and the

Figure 1: The side view of the source collimator.

gross nitrogen counts. The nitrogen background was measured using the same phantom filled with a tissue-equivalent nitrogen-free solution. From these measurements, we found that, for the same nitrogen-to-hydrogen ratio in the phantom, the count ratio of nitrogen to hydrogen (N/H) has a slight linear dependence on the section volume of the phantom.⁸ The N/H count ratio for the whole body, which is obtained by averaging the volume-corrected N/H ratios of each section (using section volume as a weighting factor⁶), is approximately proportional to the total measured volume of the phantom. Thus, the N/H count ratio $R(i)$ for a section of volume $V(i)$, and the average N/H count ratio $\bar{R}$ for a phantom of measured volume V can be written as:

$$R(i) = R_0(i) + A(i)V(i); \quad \bar{R} = \bar{R}_0 + AV. \quad (5)$$

Here, $R_0(i)$ and $A(i)$ are constants obtained by fitting the results of the three phantoms of the same section to a straight line as a function of the section volume, while $\bar{R}_0$ and A are constants obtained by fitting the $\bar{R}$ values of the three phantoms to a linear function of the total measured volume. The change of the $\bar{R}$ as a function of total phantom volume over the range 37800 to 86700 (cm^3), corresponding to phantom weights 60 to 100 kg, is $\approx 17\%$.⁸

The patient's body size is first measured and the results are used to estimate the total measured body volume. Based on this, a nitrogen-free phantom spectrum is chosen to estimate the nitrogen background, and a phantom constant, which is defined as the ratio of the N/H gram ratio to N/H count ratio,⁵ is chosen to obtain the N/H ratio for patients using the N/H count ratio.

Most of the patients are included in the body-size range of the three Bomab phantoms. The effect of extreme body sizes and body fat contents can not be treated in the described method, and requires further investigation. Those effects, as well as the system calibrations for different D₂O thicknesses are being studied.

THE INS SYSTEM

Because of the high carbon content in fat and because a high fraction of TBC is in the body fat, the INS method is considered the most direct measurement of total body fat. The INS system at BNL was built in 1987,⁴ using a pulsed *D-T* Zetatron generator to produce 14 MeV neutrons at a 10 kHz repetition rate. The 4.4 MeV γ -rays emitted from the subject are detected in two 15.2 $\times$ 15.2 NaI(Tl) detectors positioned on both sides of the subject. Recently, the system was upgraded with an IBM PC/AT-based data-acquisition system equipped with an Accuspec multichannel analyzer (Nuclear Data), and with a new patient motion system using a stepping motor. Patients are measured from the shoulder to the knee in both supine and prone positions on the bed that traverses the neutron source. Data collection and the motion of the bed are controlled by the computer. The total equivalent dose to the skin is 50 mrem⁴ for one measurement assuming a neutron quality factor⁷ of 20.

A 1.9 $\times$ 1.3 cm NE102 plastic scintillator is used to measure the total number of neutrons produced by the generator during the measurement. The energy scale of the neutron detector is calibrated using a ²⁰⁷Bi source placed on the front of the scintillator. The peak channel of the 1.05 MeV internal conversion electrons from ²⁰⁷Bi is used as the low-energy limit for integration of the number of neutrons in the neutron spectrum. This method eliminates the need to measure the gain and the offset of the spectrum separately. Figure 2a shows the output of the neutron generator, measured by the plastic scintillator, as a function of the target voltage of the Zetatron tube; Fig. 2b shows the counts attributed to carbon in a phantom as a function of the counts measured by the neutron detector.

Because the high carbon content of the shell of the Bomab phantom may cause a systematic error in carbon measurements, calibration of the INS system was carried out with an Alderson phantom. Measurements showed a linear relationship between counts attributed to carbon and the carbon content of the phantom. The carbon content of the patient is interpolated or extrapolated from the linear function based on the phantom calibration.

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Figure 2: a) Output of the neutron generator measured by the plastic scintillator as a function of the target voltage of the Zetatron tube; b) carbon counts as a function of neutron counts measured by the neutron detector.

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