用 14 MeV 中子和有關粒子飛行時間技術測量總體碳、氮和氧

Whole body measurement of C, N and O using 14 MeV neutrons and the associated particle time-of-flight technique

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Our aim has been to construct a portable prototype instrument for measuring the whole body composition in vivo of growing lambs in terms of fat, protein and water by determining the mass of carbon, nitrogen and oxygen present. A small and compact sealed tube neutron generator which has the capability of exploiting the associated particle time-of-flight technique has been used for prompt gamma 14 MeV neutron activation analysis of C, N and O. This technique allows only gamma rays generated by neutron reactions within a defined volume to be recorded and offers a superior signal-to-noise ratio over existing prompt gamma neutron activation techniques. Based on the results obtained from irradiating a 41.4 kg meat phantom, we anticipate that an instrument comprising the neutron generator and four 15 x 15 x 45 cm NaI(Tl) gamma ray detectors can be assembled to determine in vivo, protein, fat and water with precisions of 4.1, 5.4 and 1.2% (CV), respectively, within a 15 min scan. The radiation dose delivered would be ~0.03 mSv.

Introduction

Given the fixed stoichiometric proportions of N, C and O in protein, fat and water, proximate composition of the body can be derived from its elemental analysis. Despite use of in vivo neutron activation analysis for more than two decades to measure elemental composition of the human body[1–3], there is not yet an instrument which can measure N, C, and O during a single irradiation and detection procedure.

Instruments constructed during the 1980s have mainly used prompt gamma emissions to detect either N from the 10.83 MeV radiative capture emission[1] or in a few instances, C from the inelastic scattering reactions with 14 MeV neutrons[4,5]. Kehayias et al.[5] proposed that O be measured simultaneously. The major problems encountered have been the interferences and poor signal-to-noise ratios that result from scattered neutrons, and relatively high radiation doses.

We[6] and Hollas et al.[7] demonstrated the feasibility of using a coincidence system between the associated alpha particle and the 14 MeV neutron induced inelastic gamma ray to improve the signal-to-noise ratio so that N, C and O can be determined in large biological samples with good precision. Briefly, the alpha particle associated with a 14 MeV neutron produced by the ^{3}H(d,n)^{4}He reaction in the neutron generator is emitted in the opposite direction. Its detection specifies the neutrons in a given solid angle and, by appropriately gating the gamma detector, the resulting gamma ray spectrum is derived predominantly from neutron reactions within the defined volume of the sample.

A compact associated particle, sealed tube, neutron generator (APSTNG) with an internal alpha detector is now commercially available. Its success in detecting contraband drugs or explosives and use in coal analysis[8] (where the elements of interest are similar to those for body composition) has been demonstrated. Here we report first results for measuring the C, N and O content of a large meat sample.

Methods

The APSTNG

The APSTNG and its high voltage control system was supplied by Nuclear Diagnostic Systems Inc., USA. It contained a mixture of deuterium and tritium, that was ionized by a Penning ion source, accelerated by a potential of 95 kV between the ion source cathode and target and focused to a spot (~1 mm diameter) on the target to produce neutrons and alpha particles by the ^{3}H(d,n)^{4}He reaction. Ion beam current (typically, 1 μA to obtain 10^6 n/s) was controlled by heating a getter into which the ^{2}H and ^{3}H were absorbed. The tube also housed an alpha particle detector (3.7 cm ø ZnS screen positioned 4.5 cm from the target) which was interfaced to a Hamamatsu R580-15 fast rise time photomultiplier.

Data acquisition

Anode signals from both the alpha detector and a 12.5 cm diameter x 10 cm Bicron NaI(Tl) gamma detector were each fed to timing filter amplifiers and their outputs to constant fraction discriminators. For alpha pulses, the discriminator was set just above the photomultiplier dark current with the APSTNG off while for gammas, the discriminator was set to reject 0.5 MeV pulses and below. Resulting logic pulses from alpha and gamma detectors, respectively, started and stopped the time-to-amplitude converter (TAC). Its output, the time-of-flight spectrum, was recorded with an analog to digital converter (ADC) and multichannel analyzer (MCA). The full width half maximum portion, corresponding to the time when most prompt gamma rays were emitted from a sample within the neutron beam, was selected by a single channel analyzer

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(SCA). The SCA output triggered a linear gate which allowed only gamma-ray energies within the defined time window to be recorded by an MCA and stored in a computer for subsequent spectral analysis.

Phantom construction

A 38.2 kg calibration phantom containing physiological amounts of the major body elements (ICRP 1975)[9] was constructed. Its elemental composition by weight was 8.5% H, 18.2% C, 68.1% O, 2.7% N, 1.08% Ca, 1.02% P, 0.19% S, 0.17% K, 0.06% Na and 0.1% Cl. The solution was contained in polyethylene tubes (5 cm diameter x 80 cm) with a wall thickness of 0.15 mm and heat sealed. These were bundled into a cylindrical phantom (25 cm diameter by 80 cm) and wrapped with polyethylene sheeting. For a meat phantom of 41.4 kg we filled the same type of tubes with minced meat.

Irradiation and counting

The calibration and meat phantoms were each irradiated for 1 hour in scanning mode at a distance of 30 cm from the APSTNG. At this distance the neutron 'beam', defined by the associated alpha particle, was also 30 cm in diameter. The detector was positioned above the phantom and outside the defined neutron 'beam' with its face being 29 cm from the beam axis and perpendicular to it. The detector was shielded from direct neutrons by housing it in a 5 cm thick lead cave with an outer, 15 cm thick, layer of wax and borated polystyrene.

The total integrated counts in a region of interest (ROI) for the 1 hour irradiation were normalized to a constant neutron flux based on the recorded number of alpha counts. From this information, and assuming that sections of sample outside of the defined beam were shielded, the radiation dose during a 1 hour scan was calculated to be 0.12 mSv[10].

Spectral analysis

Prompt gamma rays of interest from the fast neutron reactions: C; 4.43 MeV, N; 7.03, 5.1, 5.03 and 4.46 MeV and O; 7.12, 6.92, 6.13 and 4.43 MeV. Other intense gamma rays below 4 MeV are also detected but these suffer interferences from Ca, Cl, K and S (see Fig. 1). Consequently for the present report we have used only counts from the 4–7.5 MeV regions where the only elemental interferences are between C, N and O. Following the algorithm developed by Peters[11], ROI_1 was set at 5.35–6.25 MeV, ROI_2 was 4.85–7.28 MeV and ROI_3 was 4.22–4.68 MeV. Using liquid N_2 and H_2O we recorded pure spectra due to N and O, respectively, to define the interference coefficients. Background counts due to random coincidence events and from neutrons scattered from the sample into the detector within the defined time window were measured as follows: for ROI_1 and ROI_2 background counts were obtained from wax scatterers as there are no gamma rays from C above 4.68 MeV while for ROI_3, net counts were obtained by peak stripping from the underlying continuum.

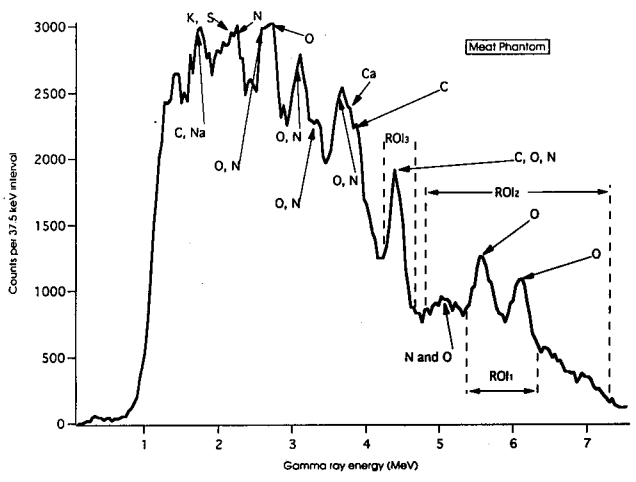

Figure 1. The γ spectrum of the meat phantom obtained within a 25 ns time window.

Results and discussion

In Table 1 we present estimates for radiation dose and the precision for measuring N, C and O in the meat phantom when compared with other detector geometries. Estimates for the four detector system for N utilizing the (n,γ) reaction are derived by scanning the same meat phantom at the Auckland Hospital, Body Composition Facility which uses two ^{238}Pu/Be neutron sources and four 12.5 cm diameter by 15 cm NaI(Tl) gamma ray detectors[12]. The six detector system (see Table 1, third line) scales our results, obtained using the APSTNG and a single detector, to the same detector volume and scanning time as used at Auckland Hospital. The results show that precision for estimating N is comparable while radiation dose to the subject would be substantially reduced.

Table 1. Dose and precision of measuring N, O and C in a 41.4 kg phantom of minced meat with different NaI detector configurations.

Number of detectors	Irradiation time	Dose mSv	Precision, CV%, (n=10) N	O	C
ONE (12.5 cm ø x 10 cm)	1 hour	0.12	11.5	2.3	9.2
FOUR (Auckland Hospital 12.5 cm ø x 15 cm)	30 min	0.2	5.0	–	–
SIX	30 min	0.06	6.7	1.4	5.4
FOUR (15 x 15 x 45cm)	15 min	0.03	4.1	<1	3.3

In order to obtain an acceptable precision for the measurement of body composition in farm animals, however, further enhancements of detection efficiency are required. In the fourth line of the table we have scaled our results from a one detector system to those which can be expected from the use of four large (15 cm x 15 cm x 45 cm) NaI detectors. These detectors are becoming available commercially and are obviously needed before the APSTNG system can achieve its full potential.

In Table 2 we compare analyses of meat composition by use of the APSTNG with existing procedures for proximate composition. The C, N and O content of the meat phantom was derived from the ratios of its elemental count rates with those obtained from the calibration phantom. Mass of protein was 6.25 x N while fat and water were determined from a four compartment model of body composition comprising protein, fat, water and minerals and their fractional content of C, N and O[9]. For this model, the small glycogen compartment has been ignored while 5% of phantom weight has been assumed for the mineral compartment[9]. Propagation errors that arise from errors in the counting of each element are shown in Table 2. It can be seen that there is excellent agree-

ment between the two methods of analysis for fat and water while we have a significant discrepancy for protein. Reasons for this are being examined.

Table 2. Measured content of protein, fat and water in the meat sample.

Component	NAA (14MeV) kg	%	Chemical analysis %
Protein	6.0±0.3 (4.1%)	14.5±0.6	16.5±0.4
Fat	7.84±0.42 (5.4%)	18.95±1.02	19.0±0.8
Water	24.66±0.29 (1.2%)	59.6±0.7	59.7±0.9
Sum		93.05	95.2
Ash			4.55±0.57

Conclusion

A transportable instrument based upon the APSTNG and four 15 x 15 x 45 cm NaI(Tl) detectors can be assembled for measuring the body composition of humans or farm animals in vivo. It would provide a simultaneous measure of protein fat and water to good precision within a 15 minute scanning time. The radiation dose (~0.03 mSv) would be almost one-tenth of the dose from existing facilities.

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