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# Body Composition Analyzer Based on PGNAA Method

Hamed Panjeh and Reza Izadi-Najafabadi
*Ferdowsi University of Mashhad, Faculty of Science, Mashhad, Iran*

## 1. Introduction

Determination of the elemental compositions of a human body is a useful tool for understanding general physiology relationships, diagnosing some disease and cancers. Measurements of body composition yield data about normal growth, maturity and the process of ageing.

Practically, these measurements provide standards against which departures from normality may be judged. It is necessary to define differences between genetic groups, the sexes within each group, the systematic variations with age and body size and the distribution of the seemingly random differences between individuals that remain unexplained. Knowledge of the range of normality is of value in studying trends in disease processes and monitoring the response to treatment. Body composition data may influence the choice of the most appropriate treatment of wasting illness, sepsis, trauma, renal failure and nutritional disorders. So many experimental methods employed in the measurement of the composition of the human body over the past 50 years and in the consequence a lot of techniques have been applied to determine the weight percentage of body chemical compositions.

Early methods such as hydrodensitometry and skinfold anthropometry have been superseded by dual-energy x-ray absorptiometry and bioelectrical impedance spectroscopy. Also x-ray fluorescence can give important information of clinical significance. The relatively simple, rapid and risk-free electrical methods such as multifrequency bioelectrical impedance analysis, which can be employed at the bedside, have been found to be more complicated in their interpretation. Electromagnetic methods may only measure the composition of the human body at its surface. X-ray computed tomography and magnetic resonance imaging have not yet been employed much in body composition measurements.

One of the non-destructive and the most sensitive approaches is Prompt Gamma Neutron Activation Analysis (PGNAA) method (Miri & Panjeh, 2007, Chichester, 2004, Metwally, 2004) but neutron activation facilities in practice remain available in only a few centers worldwide.

In this method the sample is excited with neutrons. When an atom in the sample captures a neutron, that atom is transformed to another nuclear state of the same element. The new atom can be radioactive. If it decays with a short half life the radioactive signal can be

measured by special detectors simultaneously. So the active sample which is composed of some elements promptly releases several prompt gamma rays with various intensions and energies. The gamma rays are produced immediately and stop appearing as soon as the neutron source is removed. Ordinarily, the energy spectrum of these gamma rays is the characteristic sign of the special constituting elements.

## 2. Whole body counting and neutron activation analysis

In this method one of the practical measurements is total body measurement of nitrogen (TBN). A total body measurement of nitrogen provides a quantitative estimate of muscle mass and may prove of value in the assessment of patients with diseases associated with muscle wasting, for example, in malabsorption syndrome. Also the technique of in vivo neutron activation analysis has proved successful for measurement of total body calcium (TBC) (McNeill, **1973).**

Several body elements may be measured by the following prompt gamma reactions resulting from the capture of thermal neutrons. The most abundant or useful gamma energies measureable detectors such as NaI(Tl) scintillation are:

$^{1}H(n, \gamma)^{2}H$ $E = 2.223$ MeV

$^{14}N(n, \gamma)^{15}N$ $E = 10.8$ MeV, other energies

$^{35}Cl(n, \gamma)^{36}Cl$ $E = 6.11, 8.57$ MeV, many other energies.

$^{16}O(n, n'\gamma)^{16}O$ $E = 6.134$ MeV $E_T = 6.6$ MeV

$^{12}C(n, n'\gamma)^{12}C$ $E = 4.439$ MeV $E_T = 4.9$ MeV.

Figure 1 shows the prompt-gamma-emission spectra from bilateral irradiation of a normal male volunteer from the shoulder to the knee (Ryde *et al.* 1989). Regions of interest for hydrogen, carbon, chlorine and nitrogen are indicated.

The abundance of gamma ray emissions from other elements necessitates the use of a high resolution semiconductor detector to determine them. The most prominent feature of the prompt-gamma emission spectrum from neutron irradiation of the human body is the full-energy peak at 2.223 MeV from hydrogen, since these nuclei are most abundant. The gamma ray emission from nitrogen at 10.8 MeV is the highest-energy emission from any body element. Consequently it is free from any interference except background noise due to random summing of lower-energy gamma rays (at high counting rates) and neutron irradiation of the detectors. This has become the standard method for the determination of TBN, and therefore total body protein (TBPr), since nitrogen comprises 16% of protein (Mernagh *et al* 1977, Beddoe *et al* 1984, Ryde *et al* 1989, Baur *et al* 1991).

Nitrogen is a direct indicator of total body protein. A high nitrogen reading indicates healthy tissue. When this measurement is combined with measurements from the total body potassium, scientists can determine total organ and muscle mass. For online information refer o the following address (http://www.bcm.edu/bodycomplab/ivnamainpage.htm).

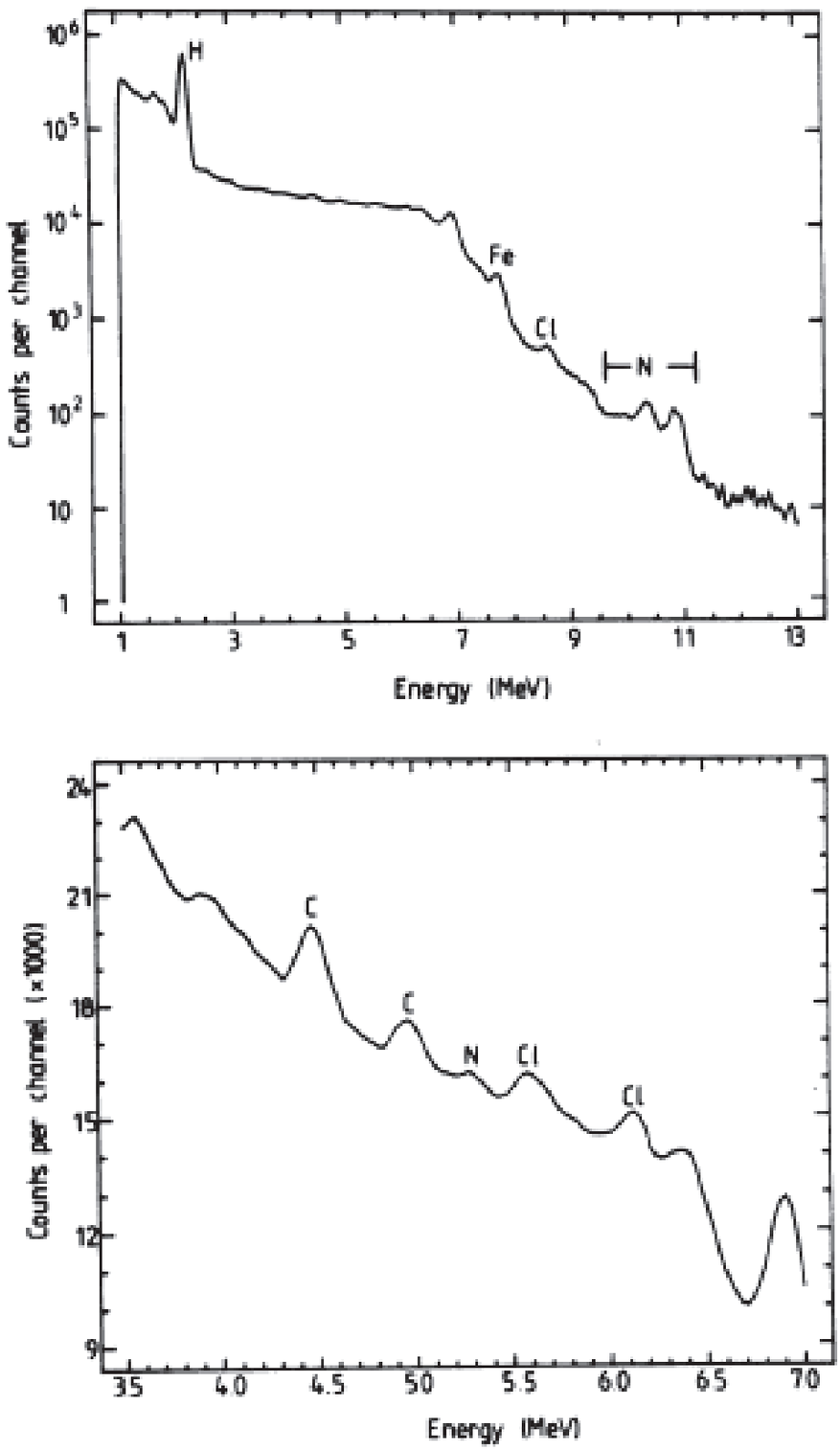


Fig. 1. The prompt gamma spectrum from bilateral irradiation of a male with a 252 Cf neutron source

## 3. Detectors

NaI(Tl) scintillation detectors are more suitable for this measurement than semiconductor detectors because of their greater stopping power. The most precise measurement of TBN reported is 1.6% for a neutron dose of 0.45 mSv (Ryde *et al* 1989) using a 4 GBq 252Cf fission source. A commonly employed technique in the measurement of body nitrogen is to measure the ratio of the emissions from nitrogen and hydrogen. This ratio is much less sensitive to variations in body size, neutron fluence and detector characteristics, which affect the signal from each element alone. It also permits the determination of TBN from partial-body irradiation (of the torso and thighs, thereby minimizing the radiation dose to radiosensitive tissues such as the eyes) assuming that hydrogen comprises one-tenth of body weight (Vartsky *et al* 1979). This requires correction since the proportion of body weight due to hydrogen has been estimated to vary from 9.5 to 10.8% in a large population of patients.

Chlorine may be determined from its emission at 8.57 MeV after deduction of the underlying background noise due to random summing and scattered gamma rays from nitrogen (Mitra et al. 1993). It may also be determined from its prominent emission at 6.11 MeV, but a high-resolution semiconductor detector (Ge(Li) or hyper pure Ge) must be employed to distinguish this emission from the emission from oxygen at 6.134 MeV.

## 4. Simulation and advantages

In according to the latest recommendations of international institutes of radioprotection, an increasing attention must be paid to the patient protection during cancer radiotherapy. Therefore one of the primary attempts should be protection of the patient from hazardous radiation and minimizing un-useful doses. Designing a Body Chemical Composition Analyzer (BCCA) in order to use for cancer therapy while having the lowest gamma and neutron dose equivalent rate in the soft tissue is desirable. The Design of the BCCA need to be modeled by Monte Carlo N-particle general code (MCNP) (Briesmeister, 2000) before the construction. By this way we can assess all the geometry and material's effects and other parameters affect the dose received by the patient and the personnel. Also if we have an improving idea we can investigate its subsequent role in simulation design before the real structure.

## 5. Sources

In applying this technique many kinds of neutron sources have been used and suggested. The compact and portable neutron sources such as $^{252}$Cf and $^{241}$Am-Be are commonly used in the PGNAA method because of their high flux and reliable neutron spectrum. Also Anderson et al. (1964) and then Cohn et al. (1972) suggested using the fast neutron reaction 14N(n, 2n)I3N. This proved unsuitable because of interferences from other reactions and because of problems in maintaining a uniform fast (>11.3 MeV) neutron flux. The Birmingham group (Harvey et al. 1973), however, have shown that a suitable nitrogen measurement can be made by using the thermal neutron capture gamma rays from the reaction 14N(n,y )15N*. 15N is stable but in this reaction is formed in the excited state, 15N*; 15% of the time de-excitation results in the release of a 10.83 MeV gamma ray.

In another works we see that viable signal/background ratio can be obtained using Pu-Be neutron sources and heavy shielding of both sources and detector. (Mernagh et al. 1977)

## 6. Absorbed dose quantities and attentions

Absorbed dose, D, is the energy imparted by ionizing radiation to matter per unit mass at a point given in units of J $kg^{-1}$ (commonly called the Gray, Gy) (Alpen, 1998).

$$D = \frac{dE}{dM}$$

The effective dose, *E*, which is a summation of differing risks to organs in the human body in units of Sieverts (Sv), is given by (Clark et al., 1993).

$$E = \sum_T w_T H_T$$

Table 1 lists all the tissue weighting factor based on two reports.

Because of biological effects and absorbed dose don't always have one-to-one correspondence, so another factor called quality factor is introduced.
And $H_T$ is the equivalent dose (in Sv) in tissue or organ, T, and is given by (Clark et al, 1993).

$$H_T = \sum_R w_R D_{T,R}$$

Where $w_R$ is the radiation weighting factor (or quality factor) due to radiation of type R (for example neutron, alpha etc.) and $D_{T,R}$ is the absorbed dose averaged over a tissue or organ, T, due to a radiation of type R.
Radiation weighting factors ($w_R$) for neutrons, according to ICRP Publication 60 can be chosen from either a step function or a continuous function to avoid discontinuity. The following formula (ICRP 60,1991) is used to calculate the $w_R$ continuous values:

$$w_R = 5.0 + 17.0e^{\frac{-[\ln(2E_n)]^2}{6}}$$

where $E_n$ is the neutron energy in MeV. Another set of new $w_R$ data, is also released from ICRP Publication 103 (ICRP 103, 2008). The new radiation weighting factors function was expressed as:

$$w_R = \begin{cases} 2.5 + 18.2\, e^{\frac{-[\ln(E_n)]^2}{6}}, & E_n < 1MeV \\ 5.0 + 17.0\, e^{\frac{-[\ln(2E_n)]^2}{6}}, & 1MeV \leq E_n < 50MeV \\ 2.5 + 3.25\, e^{\frac{-[\ln(0.04E_n)]^2}{6}}, & E_n > 50MeV \end{cases}$$

| **ICRP 1991** | | **ICRP 2005 DraftReport** | |
|---|---|---|---|
| Tissue or organ | Tissue weighting factor, $wT$ | Tissue or organ | Tissue weighting factor, $wT$ |
| Gonads | 0.20 | Gonads | 0.05 |
| Bone marrow (red) | 0.12 | Bone marrow (red) | 0.12 |
| Colon | 0.12 | Colon | 0.12 |
| Lung | 0.12 | Lung | 0.12 |
| Stomach | 0.12 | Stomach | 0.12 |
| Bladder | 0.05 | Bladder | 0.05 |
| Breast | 0.05 | Breast | 0.12 |
| Liver | 0.05 | Liver | 0.05 |
| Oesophagus | 0.05 | Oesophagus | 0.05 |
| Thyroid | 0.05 | Thyroid | 0.05 |
| Skin | 0.01 | Skin | 0.01 |
| Bone surface | 0.01 | Bone surface | 0.01 |
| Remainder: adrenals, brain, Lower Large Intestine, Upper Large Intestine, Kidneys, muscle, pancreas, spleen, thymus, uterus | 0.05 | Brain | 0.01 |
| | | Kidneys | 0.01 |
| | | Salivary glands | 0.01 |
| | | Remainder: adipose tissue, adrenals, connective tissue, extrathoracic airways, gall bladder, heart wall, lymphatic nodes, muscle, pancreas, prostate, small intestine wall, thymus, uterus/cervix | 0.10 |

Table 1. ICRP 60 (1991) and ICRP 2005 proposed tissue-weighting factors.

## 7. Technique problems

One of the disadvantages of the neutron sources is that they don't generate only neutron but also they emit high-intensive gamma-rays. When using PGNAA method for medical purposes, the sample is a human body so these gamma-rays can cause destructive effects on it.

Another major problem of this technique is thermal and epithermal neutron capture by the iodine in the detecting crystal (NaI(Tl)), plus pile-up of gamma-rays from lower energy reactions or from the source of the neutrons. The Birmingham group has largely solved this problem by the use of a pulsed neutron beam and gated circuits (Harvey *et al.* **1973).**

Note that the activation of gamma detector is only in prompt gamma technique but in the delay gamma neutron activation analysis since the detection of delayed gamma rays is after irradiation so this worry vanishes.

## 8. Delayed-gamma-emission neutron activation analysis

When the body is irradiated with neutrons, penetrating gamma rays are emitted both during irradiation (prompt) and for some time afterwards (delayed). These gamma rays originate from atomic nuclei which have absorbed energy from the neutrons or captured the neutrons themselves, and the energies of the gamma rays are characteristic of the nucleus which emits them. Therefore energy sensitive detectors may identify the emitting nucleus and the number of gamma rays detected at a given energy may be used to determine the abundance of the emitting nucleus in the body.

The majority of gamma rays are emitted during irradiation, but the elements sodium, chlorine, calcium, nitrogen and phosphorus may be determined after irradiation, if the subject is transferred from the irradiation facility into a whole-body counter within a short period, typically 5 min. Sodium and chlorine are extracellular ions from which the extracellular fluid space of the body may be determined. Calcium is contained almost entirely within the skeleton, comprising 34% of bone mineral. Phosphorus occurs mainly in the skeleton but is also found in lean soft tissue, in association with the energy metabolism. Nitrogen is uniquely a constituent of protein, 16% by weight, so that measurement of total body nitrogen (TBN) is used to determine total body protein (TBPr). These nuclear reactions are given as follows:

| | | |
|---|---|---|
| $^{23}Na(n, \gamma)\,^{24}Na$ | $E = 1.369, 2.754$ MeV | $t_{1/2} = 15$ h |
| $^{37}Cl(n, \gamma)\,^{38}Cl$ | $E = 1.642, 2.168$ MeV | $t_{1/2} = 37.3$ min |
| $^{48}Ca(n, \gamma)\,^{49}Ca$ | $E = 3.084$ MeV | $t_{1/2} = 8.72$ min |
| $^{40}Ca(n, \alpha)\,^{37}Ar$ | $E = 2.6$ keV | $t_{1/2} = 35.1$ d |
| $^{14}N(n, 2n)\,^{13}N$ | $E = 0.511$ MeV | $t_{1/2} = 9.96$ min |
| $^{31}P(n, \alpha)\,^{28}Al$ | $E = 1.779$ MeV | $t_{1/2} = 2.24$ min |
| $^{16}O(n, p)\,^{16}N$ | $E = 6.134$ MeV | $t_{1/2} = 7.2$ s |

Where E denotes the energy of the characteristic gamma rays emitted and t1/2 is the half life of the induced activity.

The minor elements magnesium, copper, iodine and iron may also be determined from the delayed emission of gamma rays.
The reaction with oxygen has been successfully employed, where the subject was transferred (within 30 s) from the irradiation facility to a whole-body counter. The reactions with nitrogen, oxygen and phosphorus only occur with fast neutrons above an energy threshold: 11 MeV for the reactions with oxygen and nitrogen and 2 MeV in the case of phosphorus. Two configurations of the delayed gamma neutron activation analysis system have been shown in Figures 2. And 3.

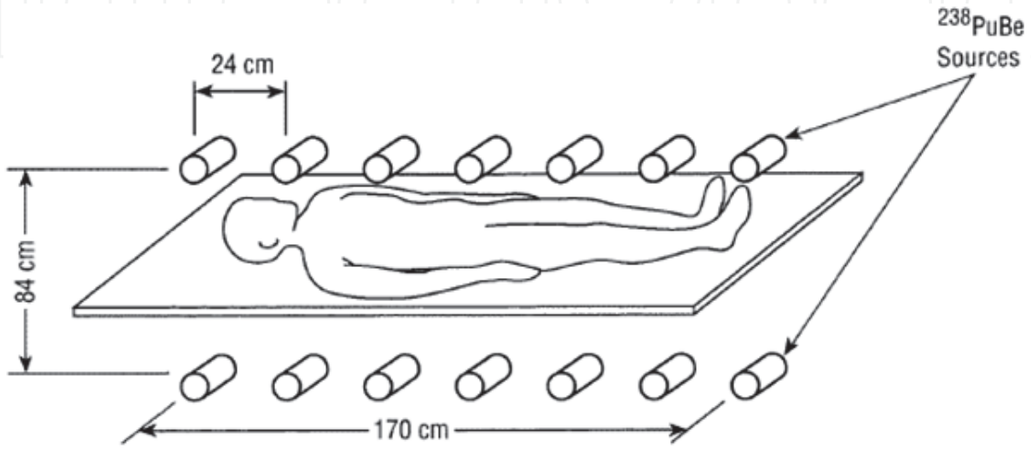


Fig. 2. Pu-Be neutron source arrangement for the Delayed Gamma Neutron Activation Analysis

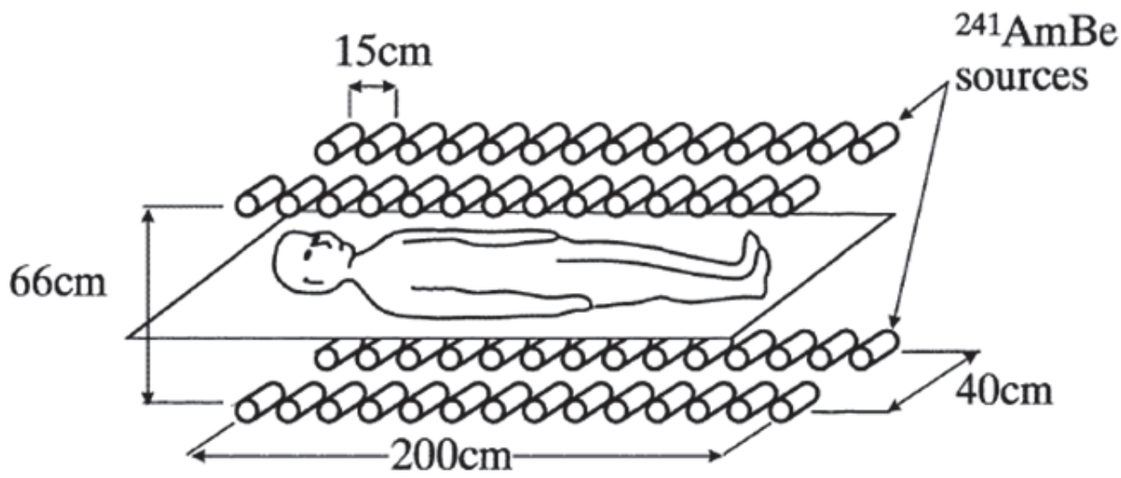


Fig. 3. 241Am-Be neutron source arrangement for the Delayed Gamma Neutron Activation Analysis

The reaction with nitrogen suffers from the disadvantage that the positron annihilation radiation (0.511 MeV) is common to many nuclear reactions, and it is not possible to distinguish this from another reaction which produces the same daughter nuclide which decays with the same half life:

$^{16}O(p, \alpha)\,^{13}N \qquad E = 0.511 \text{ MeV} \qquad t_{1/2} = 9.96 \text{ min}$
$^{12}C(n, 2n)\,^{11}C \qquad E = 0.511 \text{ MeV} \qquad t_{1/2} = 20.3 \text{ min.}$

The protons which produce the interfering reaction with oxygen originate as the result of elastic collisions between neutrons and hydrogen nuclei, the most numerically abundant element in the human body. There are many other minor reactions which also interfere, producing positron annihilation radiation at 0.511 MeV.

## 9. Prompt-gamma neutron activation analysis

The vast majority of gamma rays induced by the inelastic scattering and capture of neutrons by atomic nuclei in the human body are emitted within a few microseconds. The abundance of the emission, at all energies up to 11 MeV, makes it difficult to distinguish gamma rays of similar energies from different elements unless a high energy resolution detector is employed, such as the semiconductors Ge(Li) or hyperpure Ge. Otherwise NaI(Tl) crystal scintillation detectors, with an optically coupled photomultiplier tube, are usually employed, since they have a larger sensitive volume and greater stopping power for gamma rays.

The reason for the better energy resolution of the semiconductor detectors is that it requires the deposition of only approximately 3 eV of energy from the gamma ray in the detector's depletion layer to produce an electron–hole pair, whereas it requires around 100 times as much energy to be deposited in the NaI(Tl) crystal to produce one photoelectron at the photocathode of the photomultiplier due to losses of light in the crystal. The total number of electrons released in each type of detector is a measure of the amount of energy absorbed. Although the signal is amplified many times in the photomultiplier tube attached to the NaI(Tl) crystal, the anode current reflects the fluctuations in the number of electrons emitted from the photocathode. Therefore, for the detection of gamma rays of a given energy, there is a greater statistical variation in the signal from a NaI(Tl) detector than a semiconductor, so that the latter is used for high resolution gamma spectroscopy.

If the energy resolution of a Germanium semiconductor detector is 2 keV, the corresponding energy resolution of a NaI(Tl) crystal scintillator is around 80 keV. The semiconductor detectors suffer the disadvantage of having to be cooled with liquid nitrogen when in use, and, in the case of Ge(Li) detectors, cooled continuously.

Another problem associated with prompt-gamma neutron activation analysis is neutron irradiation of the detectors themselves, which in the case of semiconductors produces dislocations in the crystal lattice, and in NaI(Tl) crystals activates both the sodium and the iodine nuclei, from which the resulting gamma rays are counted with great efficiency.

This increases the background in the gamma ray spectrum upon which the characteristic emissions of body elements are superimposed. Therefore suitable neutron shielding of the detectors is necessary.

Bismuth germinate scintillation detectors have a greater stopping power for gamma rays than sodium iodide, and therefore may improve the signal to background for nitrogen, but this advantage has not been realized in practice due to activation of germanium. Multiple small NaI(Tl) crystals were found to give a better signal to noise ratio than a few larger crystals.

A third problem associated with prompt-gamma neutron activation analysis is the high count rate encountered. Since the output pulse from a detector is of a finite length (typically with a rise time of 0.25 _s and a fall time of up to 10 _s), any radiations being detected within this interval may be added to the original event, producing a pulse of greater amplitude. This process of random summing at high count rates has the effect of increasing the background in the gamma ray spectrum further. The statistical uncertainties in the determination of the abundance of any element in the body from the number of events in the corresponding full-energy peak in the spectrum are increased by the contribution from the underlying background. It is necessary to minimize this background. One method to reduce the random summing background to nitrogen is to electronically suppress the counting of events below 5 MeV for the major part of the measurement, and only count the whole spectrum (including the 2.223 MeV peak from hydrogen) for a short interval .
This increases the nitrogen signal to background by 18%. Since many (inelastic or non-elastic scattering) reactions (e.g. with carbon, oxygen) have an energy threshold of several mega-electron-volts, the optimum signal for a given dose is achieved when the subject is irradiated with monoenergetic neutrons at 14.4 MeV from a D–T neutron generator. These neutron generators, or alternatively cyclotrons, can be temperamental to operate, so that often neutron sources, comprising an alloy of beryllium and an alpha emitting radionuclide, are preferred.
These sources (241Am/Be, 238Pu/Be) produce a 4.439 MeV gamma ray per neutron which may interfere with the determination of carbon and add significantly to the problem of random summing of gamma rays in the detectors unless the source is well shielded.
Moreover, it is possible to improve the signal to background ratio in operating a neutron generator or cyclotron in a pulsed or cycled mode by counting short-lived induced activity between pulses of neutrons, thereby reducing the lower limit of the target element that can be measured.

## 10. Configurations of the PGNAA facility

In the progress of using PGNAA method for medical purposes many kind of setups and configurations suggested and applied. In the following some of them have been shown
Figure 5 is a schematic of a conventional machine used to measure the body composition. Another gold design is shown in figure 6. In this setup the uniform neutron flux will meet the patient tissue so we can get good results.
Figure 7 shows a cross-sectional view of the modified BCCA. Sheets of 2 cm thickness of Lead surround the neutron moderator (here paraffin wax) to provide radiation shielding for personnel. To protect personnel from biological effects of neutrons and to reduce background counts, neutron shielding must be considered. Since high-speed neutrons are more difficult to shield, at first neutrons must be moderated by a hydrogenous material such as paraffin wax (14.86 % H, 85.14 % C). Because of Hydrogen has a great absorption Cross Section for thermal neutrons, the risk of neutrons for personnel vanishes. One of the benefits that the moderator has been covered with a 2cm layer of Pb is that the gamma-rays (2.224 MeV) produced by the H(n, $\gamma$) interaction are filtered.
A sphere of Lead has been centered at the source position to filter gamma-rays of the neutron source. Another part of this configuration is an invert, rectangular, cuneus void cast within the paraffin wax block ( $40_{cm} \times 50_{cm} \times 60_{cm}$ ). To protect patient body from high-rate

2.224 MeV gamma-rays, the inner wall of the valley, made above the neutron source (Figure 7), was lined by Pb sheet of 2cm thickness. By this way, a rectangular neutron-beam aperture measuring 40 cm length (perpendicular to the paper sheet) and 20 cm (width) at the sample location is defined.

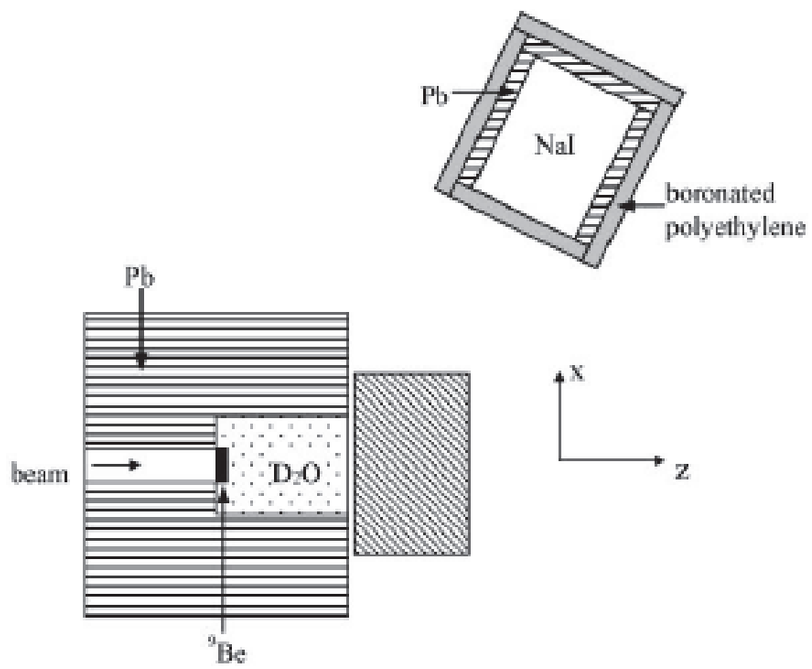


Fig. 4. A typical schematic representation of PGNAA setup based accelerator. In this setup the D2O is used as moderator.

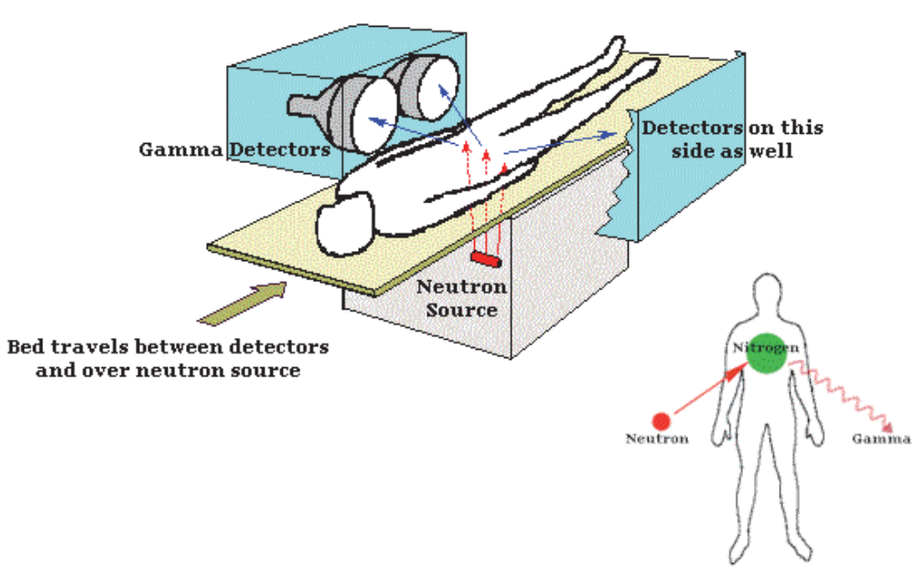


Fig. 5. Schematic of a conventional machine used to measure the Total Body Nitrogen (TBN)

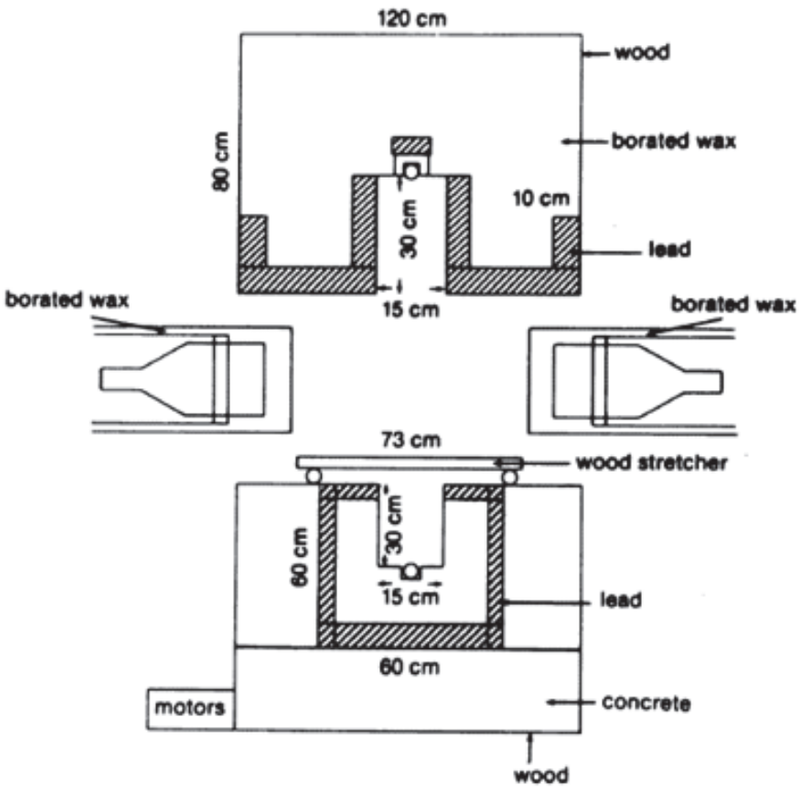


Fig. 6. A unique design of Body Chemical Composition Analyzer

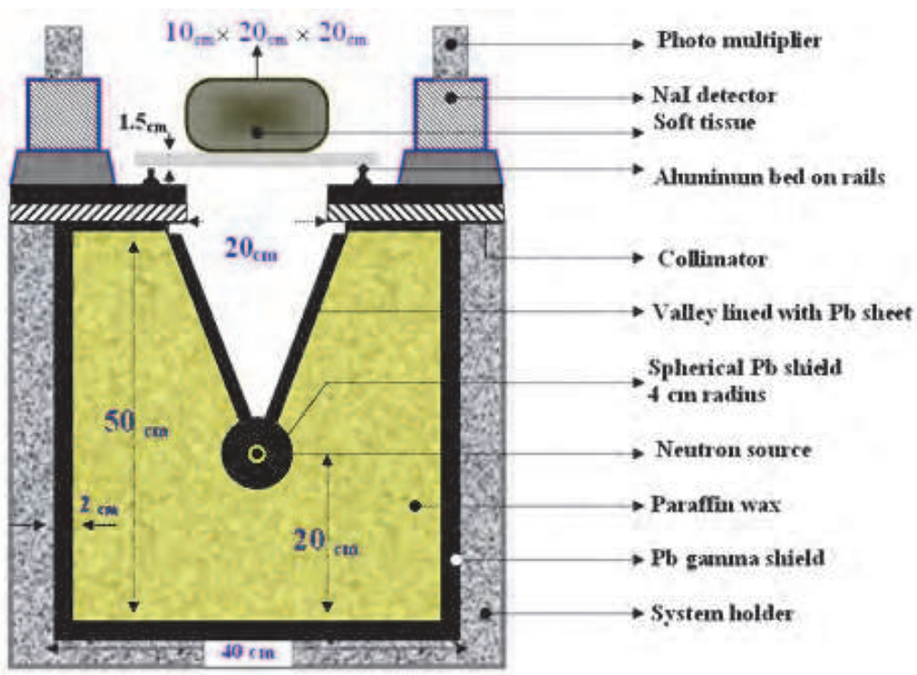


Fig. 7. Design and Geometry of a Body Chemical Composition Analyzer.

## 11. Future works

The authors are attempting to investigate all the aspects related to this topic and welcome any idea and proposal. Designing of a PGNAA setup for medical and industrial purposes need time and considering a lot of parameters which is under construction in Ferdowsi University of Mashhad, FUM Radiation Detection and Masurement Lab. For more information please don't hesitate to contact me (panjeh@gmail.com).

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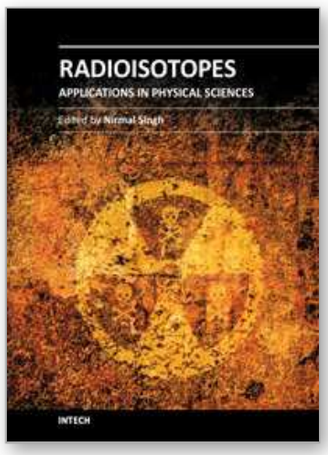


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Edited by Prof. Nirmal Singh

ISBN 978-953-307-510-5
Hard cover, 496 pages
**Publisher** InTech
**Published online** 19, October, 2011
**Published in print edition** October, 2011

The book Radioisotopes - Applications in Physical Sciences is divided into three sections namely: Radioisotopes and Some Physical Aspects, Radioisotopes in Environment and Radioisotopes in Power System Space Applications. Section I contains nine chapters on radioisotopes and production and their various applications in some physical and chemical processes. In Section II, ten chapters on the applications of radioisotopes in environment have been added. The interesting articles related to soil, water, environmental dosimetry/tracer and composition analyzer etc. are worth reading. Section III has three chapters on the use of radioisotopes in power systems which generate electrical power by converting heat released from the nuclear decay of radioactive isotopes. The system has to be flown in space for space exploration and radioisotopes can be a good alternative for heat-to-electrical energy conversion. The reader will very much benefit from the chapters presented in this section.

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Hamed Panjeh and Reza Izadi-Najafabadi (2011). Body Composition Analyzer Based on PGNAA Method, Radioisotopes - Applications in Physical Sciences, Prof. Nirmal Singh (Ed.), ISBN: 978-953-307-510-5, InTech, Available from: http://www.intechopen.com/books/radioisotopes-applications-in-physical-sciences/body-composition-analyzer-based-on-pgnaa-method

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**InTech Europe**
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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