A METHOD FOR ESTIMATING NEUTRON FLUXES AND NEUTRON DOSES FROM THE ACTIVATION OF COMPACT BONE

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Today 14 MeV neutron generators are widely used for industrial and medical purposes. With the increasing use of these fast - neutron generators it is also of importance to develop a simple method for estimating neutron doses in case of accidental irradiation of personnel. In the present report we outline a method for estimating neutron doses by making use of the neutron induced activity in tissue, in particular compact bone. For the bone mineral hydroxyapatite $Ca_{10}(OH)_2(PO_4)_6$ contains calcium and phosphorus, the different isotopes of which are easily activated in a 14 MeV neutron flux [1-4].

Using the well-known formula for neutron activation analysis

$$N_{obs} = \frac{\sigma_A \Phi_{14} N_o m_A \Theta \epsilon f_\gamma}{M_A \lambda} (1-e^{-\lambda t_i})(e^{-\lambda t_o} - e^{-\lambda t_f}) \qquad (1)$$

it is possible to deduce Φ_{14}, the neutron flux at the energy 14 MeV, if the mass m_A of element A is known and N_{obs} is measured.

In the present work 14.7 MeV neutrons were produced in a neutron generator using the D,T -reaction. A rotating target assembly was used and the neutron production was approximately 10^{10} n/s. Samples of compact bone were first irradiated in polystyrene containers, before being transferred to nonactivated containers. The gamma ray spectra which were then measured with a 110 cm^3 coaxial Ge(Li) - semiconductor detector, were stored in a PDP-9 computer. In this way it was possible to measure and store four consecutive 4096 channel spectra, ready for analysis by the VIPUNEN - program [5,6] on a Burroughs computer. For the energy and intensity calibration of the detector set-up IAEA standard sources were used in addition to the well-known sources of ^{56}Co and ^{152}Eu [1,7,8].

The present in vitro activation measurements were carried out using small samples of femur bones from cows. The masses of the bone samples were small, varying from 60 mg to 5 g. The irradiation times varied from 1 to 30 minutes, and the spectra

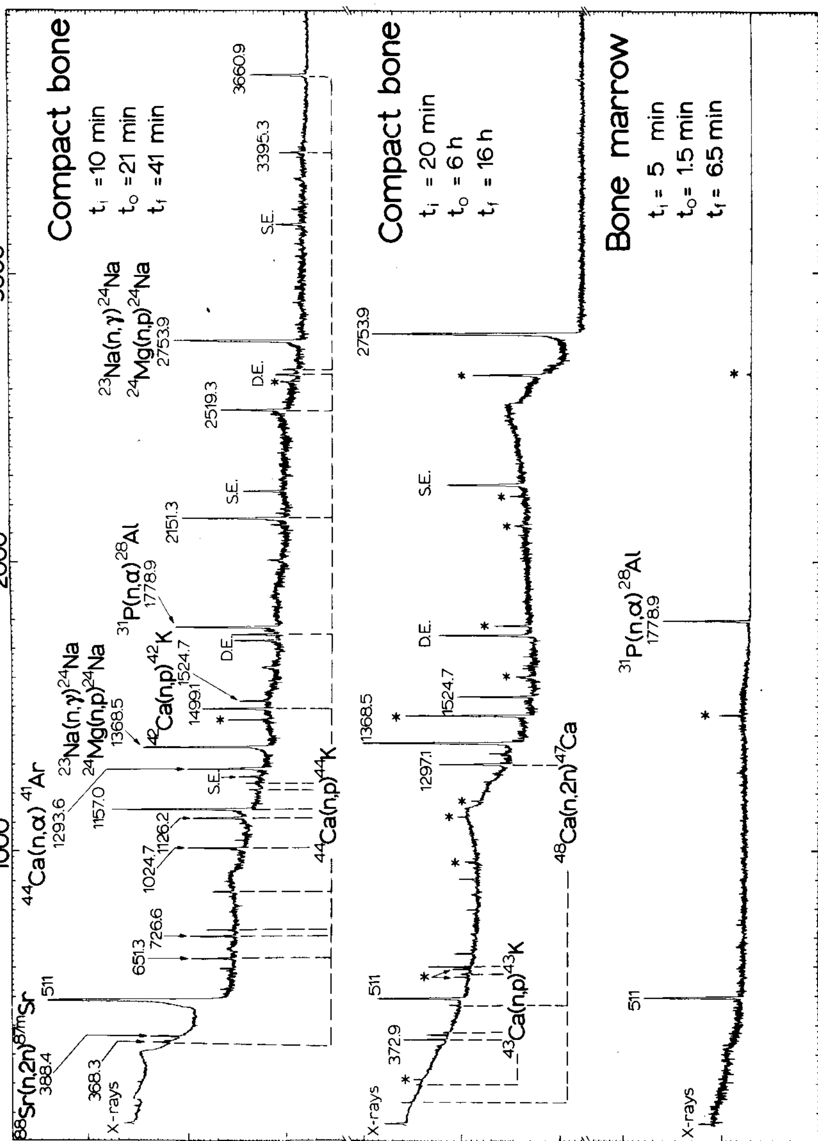

Fig. 1 Gamma ray spectra from activated compact bone and bone marrow (* = background peak)

were recorded after waiting times ranging from 1 minute to 24 hours, depending on the half-life of the activity to be determined. Furthermore, the time taken to measure each spectrum varied from 5 minutes to 6 hours. In Fig. 1 we show a series of spectra recorded under different conditions. The spectra were analysed and on the basis of peak-energies and half-life determinations the gamma rays were assigned to their reactions. This is also indicated in the figure.

The upper part of Fig. 1 shows a spectrum recorded 21 minutes after exposure of compact bone to radiation. The irradiation time was 10 minutes and the measuring time was 20 minutes. In this spectrum several activities due to the neutron reactions on calcium are observed, the measuring conditions being favourable for the short-lived activities. Spectral peaks due mainly to the $^{44}Ca(n,p)^{44}K$ reaction ($T_{\frac{1}{2}}$ = 22 min) are seen. Even the 1779 keV gamma ray from the $^{31}P(n,\alpha)^{28}Al$ reaction ($T_{\frac{1}{2}}$= 2.24 min) can still be detected. Furthermore, some longer lived activities are observed, although they come out more clearly in the next spectrum.

The middle part of Fig. 1 shows a spectrum recorded 6 hours after the irradiation of a sample of compact bone. The irradiation time was 20 minutes and the measuring time was 10 hours. In this spectrum the long-lived activities due to the $^{42}Ca(n,p)^{42}K$ ($T_{\frac{1}{2}}$=12.36 h), the $^{42}Ca(n,p)^{42}K$ ($T_{\frac{1}{2}}$=22.2 h) and the $^{24}Mg(n,p)^{24}Na$ ($T_{\frac{1}{2}}$=15.0 h) reactions are clearly seen. Also the $^{48}Ca(n,2n)^{47}Ca$ ($T_{\frac{1}{2}}$= 4.6 d) reaction is observed at the energy E_{γ} = 1297 keV.

By comparison, the lower part of Fig. 1 gives a spectrum recorded 1.5 minutes after the irradiation of a bone marrow sample. The irradiation time was 5 minutes, the waiting time 1.5 minutes and the measuring time was 5 minutes. The only activity clearly seen is that due to the $^{31}P(n,\alpha)^{28}Al$ reaction (E_{γ} = 1779 keV).

From these measurements we observe that the induced activities in compact bone can be recorded immediately after irradiation because of the presence of short-lived activities, mainly the $^{31}P(n,\alpha)^{28}Al$ and $^{44}Ca(n,p)^{44}K$ reactions. As the waiting time increases the $^{42}Ca(n,p)^{42}K$ and $^{43}Ca(n,p)^{43}K$ reactions are more suitable for activity measurements. For still longer waiting times the $^{48}Ca(n,2n)^{47}Ca$ reaction can be used.

As can be seen from Fig. 1, there is a continuous change in the spectral shape arising from the different half-lives of the induced activities. As the isotopic composition of the hydroxy-apatite is known, the changes provide a method for estimating both the irradiation time and the waiting time t_o by spectral analysis.

The neutron flux values Φ_{14} can now be obtained from eq. (1) and it is possible to deduce the neutron spectrum $\Phi(E)$ at different sites in tissue. The corresponding dose equivalent D.E. can then be calculated from the formula

$$D.E. = \int_{0}^{14\ \mathrm{MeV}} \Phi(E)\ g(E)\ dE \ ,$$

where g(E) is a conversion factor which takes the neutron energy loss mechanism into consideration. A method for the deduction of doses is outlined by Prouza, Heřmanská and Rakovič [9].

Compact bone has been chosen as reference material for neutron flux and dose estimates, because the several neutron reactions which occur cover a wide range of half-lives. Thus, depending on the irradiation procedure, different reactions can be used for the evaluation of Φ_{14}.

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