ESTIMATED DOSE TO BONE AND WHOLE BODY *VIA* ^{40}Ca AND ^{31}P FOR 14.1 MeV NEUTRONS

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An attempt has been made to calculate dose to bone and whole body *via* ^{40}Ca and ^{31}P for 14.1 MeV neutrons through all possible nuclear reactions by evaluating energy spectra. The computed—doses, cross-sections and average energies of the emitted particles in the various nuclear reactions (primary and secondary) with 14.1 MeV neutrons for ^{40}Ca and ^{31}P alongwith their recoil contributions are tabulated. The dose rates to whole body due to the induced activity of ^{28}Al and ^{31}Si are listed for 'β' and 'γ' radiations.

INTRODUCTION

FAST Neutrons are finding an important place in radiotherapy. Their use in radiotherapy lies in their low oxygen enhancement ratio (O.E.R.). On interacting with tissues, fast neutrons release charged particles of high LET and their biological effect is much less influenced by the availability of oxygen at the time of irradiation than that of X or gamma rays. For calculating LET distributions and for explaining low O.E.R. of fast neutrons, many workers (Randolph 1957; Bewley 1968; and Manocha & Mohindra — *Communicated*) have calculated energy deposition to human body and various tissues *via* H, C, N and O only.

Calcium and phosphorus are important constituents of bone and human body. In the present work, an attempt has been made to calculate (*i*) dose contribution to bone and human body *via* ^{40}Ca and ^{31}P through all possible nuclear reactions at 14.1 MeV and (*ii*) the dose rates to the human body due to the induced radioisotopes. The main isotope of calcium is ^{40}Ca (97%) and that of phosphorus is ^{31}P (100%) and in these calculations their isotopic abundance is assumed to be 100%.

In fast neutron therapy of bone tumours, the doses calculated in this work may prove useful for correlating dose rates to flux. However, no attempt has been made in this work to calculate the dose to individual cellular components of the bone. The present calculations have been made for the whole bone (femur) and the dose will vary according to the composition of bone e.g. cortical bone (Spiers 1968). But once the calculations are made, one can convert the same according to the composition of the bone under reference. The computed cross-sections may find use in activation analysis (McNeil *et al.* 1973; and Harvey *et al.* 1973) for evaluating the

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amounts of calcium and phosphorus in animals. Also the possibility of toxic effects described by Ehrenberg and Anderson (1954) and Manocha and Mohindra (1977) (though extremely small) from induced isoptopes can be considered.

METHOD OF CALCULATIONS

(*i*) *Cross-sections :* for calculating ^{40}Ca and ^{31}P cross-sections of particular reactions, Newton's (1956) equation was employed as described by Wadhwa and Mohindra (1975) which was compared earlier by (Wadhwa *et al.* 1974). Newton's equation gives better results (Manocha & Mohindra 1973, 1977) when compared with the experimental results of spectra and measured cross-sections. The reactions data considered are listed in Tables I and II. The peak value of the computed energy spectra was taken as the average energy ($\bar{E}$) of the emitted particles.

(*ii*) *Dose :* For calculating dose contribution, the recoil energy of ^{40}Ca and ^{31}P atoms and the energy of the charged particles was taken into consideration for each reaction. In all cases only the 'first collision dose' was evaluated. The method of Randolph (1957) was used for calculating the recoil energy. The dose was calculated as described in reference, Manocha and Mohindra (1977). The human body composition (Spiers 1968) has been taken as H = 10%, C = 18%, N = 3%, O = 65%, Ca = 1.5% and P = 1.0% and the composition (Johns & Cunningham 1969) of bone (femur) has been taken as H = 6.4%, C = 27.8%, N = 2.7%, O = 41.0%,

TABLE I

Dose via *Calcium*

Nuclear reaction	Calculated Q value in MeV	Calculated cross-section in mbs	Experimental values in mbs (Stehn *et al.* 1964)	Computed peak energy of the emitted particle in MeV	Computed dose to bone in rad. per unit neutron flux	Computed dose to whole body in rad. per unit neutron flux
^{40}Ca (n, n′) ^{40}Ca	0	840.7	—	2.5	188.1×10^{-13}	19.1×10^{-13}
^{40}Ca (n, n n) ^{39}Ca	—15.612	0	—	0	0	0
^{40}Ca (n, n p) ^{39}K	—8.333	366.4	205 ± 38	2.9	462.0×10^{-13}	47.0×10^{-13}
^{40}Ca (n, n α) ^{36}Ar	—7.038	31.1	—	4.5	56.9×10^{-13}	5.8×10^{-13}
^{40}Ca (n, p) ^{40}K	—0.531	181.4	298 ± 38	4.6	337.6×10^{-13}	34.3×10^{-13}
^{40}Ca (n, p n) ^{39}K	—8.333	64.7	—	1.9	56.8×10^{-13}	5.8×10^{-13}
^{40}Ca (n, p p) ^{39}Ar	—8.116	1.03	—	3.0	1.3×10^{-13}	0.13×10^{-13}
^{40}Ca (n, p α) ^{36}Cl	—7. 06	0.04	—	4.5	0.07×10^{-13}	0.007×10^{-13}
^{40}Ca (n, α) ^{37}Ar	+ 1.752	153.0	—	9.0	516.3×10^{-13}	52.5×10^{-13}
^{40}Ca (n, α n) ^{36}Ar	—7.038	1.4	—	1.5	1.06×10^{-13}	0.108×10^{-13}
^{40}Ca (n, α p) ^{36}Cl	—7.06	5×10^{-3}	—	1.0	—	—
^{40}Ca (n, α α) ^{33}S	—5.041	8×10^{-2}	—	3.5	—	—
^{40}Ca (n, n) ^{40}Ca	(elastic)	—	890	0.66 (Recoil)	208.6×10^{-13}	21.3×10^{-13}

Dose (D) to bone *via* various elements in MeV — barn per gram per unit neutron flux. $D_H = 1.85 \times 10^{23}$, $D_C = 0.42 \times 10^{23}$, $D_N = 0.04 \times 10^{23}$, $D_O = 0.57 \times 10^{23}$, $D_{C_\alpha} = 0.12 \times 10^{23}$, $D_P = 0.09 \times 10^{23}$.

TABLE II

Nuclear reaction	Calculated Q value in MeV	Calculated cross-section in mbs	Experimental value* in mbs	Computed peak energy of the emitted particle	Computed dose to bone in rad per unit neutron flux	Computed dose to whole body in rad per unit neutron flux
^{31}P (n, n′) ^{31}P	0	265.8	—	4.2	46.2×10^{-13}	6.6×10^{-13}
^{31}P (n, n n) ^{30}P	— 12.31	0.5	10	1.0	0.09×10^{-13}	0.02×10^{-13}
^{31}P (n, n p) ^{30}Si	— 7.29	101.9	—	3.5	96.1×10^{-13}	13.6×10^{-13}
^{31}P (n, nα)^{27}Al	— 9.66	—	—	—	—	—
^{31}P (n, p) ^{31}Si	— 0.694	247.4	93	4.5	284.9×10^{-13}	40.8×10^{-13}
^{31}P (n, p n) ^{30}Si	— 7.29	99.3	—	2.7	75.9×10^{-13}	10.9×10^{-13}
^{31}P (n, p p) ^{30}Al	— 13.79	—	—	—	—	—
^{31}P (n, p α)^{27} Mg	— 11.49	—	—	0	—	—
^{31}P (n) α^{28}Al	— 1.94	533.6	140	7.0	906.7×10^{-13}	129.8×10^{-13}
^{31}P (n, α n) ^{27}Al	— 9.66	2.6	—	1.0	1.0×10^{-13}	0.14×10^{-13}
^{31}P (n, α p) ^{27}Mg	— 11.49	—	—	—	—	—
^{31}P (n, α α) ^{24}Na	— 12.79	—	—	—	—	—
^{31}P (n, n) ^{31}P	(elastic)		850 (estimated)	0.85 (Recoil)	156.9×10^{-13}	22.5×10^{-13}

*D. De Soete *et al.* 1972, A. Schett *et al.* 1974)

P = 7.0% and Ca = 14.7%. The methods of dose evaluation of induced activity have been described earlier (Manocha & Mohindra 1976, 1977). In the present case classical dosimetry has been used since beta dose is highly dominating over gamma dose. All the betas are assumed to be absorbed inside the body.

(*iii*) Q values were calculated using the mass of the reactants and products (Mattuch *et al.* 1965) of the reaction.

RESULTS AND DISCUSSION

The computed data and the dose rates to bone and human body in rad per unit neutron flux due to the various nuclear reactions of 14.1 MeV neutrons with ^{40}Ca are listed in Table I. The corresponding values for ^{31}P are listed in Table II. The experimental values for cross-section for ^{40}Ca are from reference (Stehn *et al.* 1964) and for ^{31}P are from reference (Soete *et al.* 1972; and Schett *et al.* 1974). The theoretically estimated cross-sections and experimental cross-sections differ considerably particularly for lighter element ^{31}P. For light nuclei compound nucleus theory cannot give accurate results. At present no theory gives accurately 14 MeV neutron partial cross-sections. The total dose to bone *via* ^{40}Ca agrees well with that of Caswell *et al.* but the dose *via* ^{31}P is considerably low. Using the experimental values of cross-sections the dose to bone *via* ^{31}P is still lower.

The gamma dose to human body (standard man of 70 kg weight) per second per unit neutron flux contributed by the induced activity of residual nuclei ^{28}Al and ^{31}Si is about 2.5×10^{-13} m rad and 1.3×10^{-16} m rad respectively and beta dose is about 9.0×10^{-12} m rad and 3.0×10^{-14} m rad respectively. The percentage of dose contributed by ^{40}Ca and ^{31}P (in relation to the dose contribution by H, C, N, O) was calculated as described (Manocha & Mohindra 1977) earlier and shown in Table I. The dose contribution to bone *via* ^{40}Ca and ^{31}P is about 4% and 3% respectively and the dose contribution to human body is about 0.3% each. The dose contribution of these elements (^{40}Ca and ^{31}P) (about 0.6%) to the human body is quite large in comparison to the dose contribution by ^{56}Fe (10^{-4}). Also the dose to the bone *via* these elements is more than ten times to body.

Relative importance of elastic, inelastic and non-elastic interactions can be seen from the tables. As done by the earlier investigators (Bewley 1963) their only consideration of the elastic scattering can give highly under-estimated dose.

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