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EFFECTS OF NEGATIVE PIONS AND NEUTRONS ON THE GROWTH
OF *VICIA FABAE* BEAN ROOTS*)

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ABSTRACT

Vicia faba bean roots have been irradiated with neutrons of various energies and with negative π -mesons, and the effect on the 10-day growth of the roots has been determined. The neutron irradiations were made in beams of 400 and 600 MeV maximum energy, as well as with neutrons from a plutonium-beryllium source (mean energy 4.4 MeV) and from a 14 MeV neutron generator. The bean roots have also been irradiated at various points along a negative π -meson slowing-down depth-dose curve, including the region where the pions annihilate on coming to rest.

The results show a maximum relative biological effectiveness (RBE) of 3.7 for 50% reduction in 10 days growth for stopped negative pions and values up to 3.3 for high-energy neutrons, compared to 5.5 for 14 MeV neutrons. The biological effectiveness of high-energy radiation shows a more pronounced dependence on dose than does the effect with low-energy radiations. The implications that can be drawn from this observation are discussed.

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1. INTRODUCTION

Radiobiology research at CERN is primarily concerned with the study of the biological effects of high-energy particle interactions. This research has been limited to low dose-rate effects because of the low intensity of the secondary particle beams available (high-energy neutrons and pions) from the CERN accelerators. The aim of the research has been to determine the biological effectiveness of the high-energy radiation in order to provide some check on radiation protection norms for high-energy particles, which are essentially based on extrapolation from effects observed with low-energy radiations. The growth inhibition of the primary roots of *Vicia faba* seedlings was chosen as a suitable biological test system on account of its high sensitivity and the possibility of giving extended exposures by irradiating the beans at low temperature (4°C). Another advantage with this system is the possibility of making *in vivo* oxygen enhancement ratio (OER) studies.

Radiobiological research using high-energy particles has been further stimulated by the advent of high-intensity cyclotrons and the possibility of using their pion beams for radiotherapy. Similarly, studies using high-energy neutrons contribute information that may be useful for the optimization of neutron energy for radiotherapeutic applications.

2. BEAMS AND DOSIMETRY

The proton, neutron, and pion beams from the CERN 600 MeV Synchro-cyclotron (SC) that were available prior to 1972 and were used for these studies have been described elsewhere (Baarli et al., 1971). The main facility now in use for radiobiological studies using the improved CERN SC is the high-energy neutron beam produced by 600 MeV protons incident on a beryllium target (Baarli et al., 1977). The beam used had a uniform intensity distribution over 14 cm diameter, and the dose-rate in the beam, measured as a function of depth in a polythene absorber, is shown in Fig. 1. The bean roots were irradiated at the minimum depth possible when in a water tank (2.5 mm) and at the depth of the maximum dose (20 cm). The dose to the beans was estimated using a 0.1 cm³ tissue-equivalent ionization chamber, positioned in the bean irradiation tank. The same dose corrections were applied as for the 400 MeV neutron beam (Baarli and Sullivan, 1972). The dose to the beans expected at the front of the irradiation tank and therefore at a small absorber depth will primarily be due to the short-range products from nuclear interactions. As the depth increases, the dose due to fast protons produced in the absorber builds up. Calculations indicate that at a depth of 20 g/cm², fast protons account for more than 75% of the dose in a monoenergetic neutron beam (Alsmiller et al., 1970).

The first series of negative pion studies were carried out using the beam from the CERN SC. More recently, irradiations have been made in the biomedical facility of the cyclotron at SIN (Swiss Institute for Nuclear Research, Villigen). The pion beam in this facility enters the irradiation cave vertically and has been set up to have a circular profile at the irradiation position (Baarli et al., 1976; Nordell et al., 1977). The bean-root tips are held at a precisely determined depth beneath a variable water absorber, as shown in Fig. 2. Also shown is the transmission ionization chamber used to control the irradiations, and an additional small ionization chamber placed underneath the bean tray to ensure that conditions remained constant during the irradiations. The dose-rate in the pion beam was measured using a parallel-plate tissue-equivalent ionization chamber with a diameter of 2 cm and spacing of 2 mm.

The relative dose as a function of water absorber depth for the two pion beams of the different momentum spreads (4.5% and 8% of the initial momentum, which was 172 MeV/c) that were used for irradiations, is shown in Fig. 3. The actual peak dose-rate of the 8% beam was about twice that of the 4.5% beam. The doses that are measured are those to the tissue-equivalent ionization chamber, and no correction has been applied for possible differences between energy deposition in the chamber and in the beans due to differences in composition (Baarli and Sullivan, 1973).

As the pions slow down they interact with nuclei in the absorbing material, when a part of their rest mass is dissipated as kinetic energy of the nuclear fragments produced (nuclear star). The proportion of the dose from these nuclear stars to the total dose varies along the beam and reaches a maximum at a point on the back edge of the stopped pion peak, where the maximum biological effectiveness may be expected.

Reference irradiations were made using ^{60}Co γ -rays at dose-rates from 15-80 rad/h. Irradiations were also carried out with neutrons from a 14 MeV neutron generator (Laurent, 1974) and from a 50 Ci ^{238}Pu -Be source. The latter irradiations were made with the root tips positioned at 6 cm from the source, where a dose-rate of about 4 rad/h was obtained.

3. BIOLOGICAL PROCEDURES

The Prolific Longpod variety of the bean *Vicia faba* was used for all neutron experiments, except the latest pion experiments where the Fillbasket variety was used. A comparison was made between the two varieties using ^{60}Co γ -rays at low and high dose-rates, and no significant difference was found in the growth characteristics after irradiation (Bianchi and Hill, 1977). The growth method followed closely that described by Hall (1961), where the beans are first soaked in water for three days then planted in vermiculite, and after a further three days transferred to the growing-tank. The beans are selected for irradiation on the basis of the mean growth rate of their primary roots during the following three days and of their mean

length. The selected beans were stored for a minimum of 24 h at 4°C, before being irradiated at this temperature. After irradiation their length was measured and they were then returned to a growing-tank through which aerated water at 19°C was continuously circulated. The bean root length was measured daily for the 10 days subsequent to the irradiation, and any lateral roots removed as they appeared.

4. RESULTS

The observed reduction in the growth of the bean roots after 10 days is shown as a function of dose for 400 MeV neutrons in Fig. 4 and for pions in Fig. 5 together with the results obtained using ^{60}Co γ -radiation. Straight lines have been fitted through the points by linear regression analysis over the range of 30% to 80% growth reduction. The results after irradiation in the stopped pion peaks of the 4.5% and 8% momentum spread beams were found to fit the same line. A summary of the results obtained, expressed as relative biological effectiveness (RBE) for a 50% growth reduction of the bean roots after 10 days, is given in Table 1 together with the dose-rates that were used.

5. DISCUSSION

The RBE of high-energy neutrons is found to be lower than that for conventional energy neutrons, as is expected from the calculations on which radiation protection norms have been based (ICRP, 1962). The values found for Pu-Be neutrons (average energy 4.4 MeV) and for 14 MeV neutrons agree well with those observed by Hall (1974). For the 400 MeV neutron beam at 20 g/cm² depth, where the neutrons are in equilibrium with their secondaries, the RBE is half the value obtained at small depths, where the proportion of short-range high-LET products from nuclear interactions to the dose is much higher. Both at small absorber depths and at maximum build-up, 600 MeV neutrons appear to have a slightly lower RBE than the 400 MeV neutrons, which is again consistent with predictions.

In the negative pion beam the dose from high-LET short-range interaction products is lowest in the plateau region where it accounts for only about 14% of the total dose, the rest being due to ionization by fast charged particles, whereas at the stopped pion peak this proportion is near to 60% (Nordell et al., 1977). The RBEs in the plateau and peak are consistent with a value of about 4 for the dose from the short-range nuclear star products. The high-energy neutron results are also consistent with this value for the RBE of the dose from the short-range secondaries. However, the physical data on the neutron and pion nuclear interactions and their biological significance are not sufficiently understood to enable a definite quantitative comparison to be made.

The proportion of dose from pion interactions is greatest on the back edge of the stopped pion dose-peak, and this proportion increases as the momentum spread of the pions decreases (Nordell et al., 1977). This explains the highest RBE for stopped negative pions of 3.7 being found on the back edge of the CERN pion beam, which had the narrowest momentum spread. An RBE of 3 has been reported for the stopped pion peak at Berkeley (Raju and Richman, 1972) and a similar value has been found for pion beams of different momentum spreads at Nimrod using the same biological end-point (Winston et al., 1973).

The dose-effect curves shown in Figs. 4 and 5 are not parallel to the ^{60}Co control curve; this implies that the RBE will increase with decreasing dose. This rate of increase is similar for 400 MeV and 600 MeV neutrons and for the stopped negative pions, and is much more pronounced than for low-energy neutrons, as shown in Figs. 6 and 7. This increase in RBE with decreasing dose could have important implications for radioprotection where high-energy particles are present.

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Table 1

Radiation used	RBE for 50% growth reduction	Dose-rate (rad/h)
600 MeV neutrons (2.5 mm depth)	3.3	14
600 MeV neutrons (200 mm depth)	1.7	46
400 MeV neutrons (10 mm depth)	(3.3)	6
400 MeV neutrons (200 mm depth)	(1.6)	12
14 MeV neutrons	5.4	≈ 8
PuBe neutrons	6.5	≈ 4
CERN π^- beams, front peak	(2.0)	3
back peak	(3.7)	3
SIN π^- beam, plateau	1.6	30
peak	2.8	≈ 40
back peak	3.5	75

() Lines extrapolated to 50% growth reduction.

Figure captions

- Fig. 1 : Dose in a 600 MeV neutron beam as a function of depth in a polythene absorber.
- Fig. 2 : The arrangement for the irradiation of beans at a defined depth in a vertical negative pion beam.
- Fig. 3 : Depth-dose curves for pion beams of 4.5 and 8% momentum spread, showing the irradiation positions.
- Fig. 4 : Dose-effect curves showing 10-day growth as a function of dose in the 400 MeV neutron beam.
- Fig. 5 : Dose-effect curve showing 10-day growth as a function of dose for negative pions.
- Fig. 6 : RBE variation with dose for neutrons.
- Fig. 7 : RBE variation with dose for pions.

Fig. 1

IRRADIATION of VICIA FABIA

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7