DOSE, DOSE EQUIVALENT, EFFECTIVE DOSE AND CELL SURVIVAL FROM NEGATIVE PIONS*

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Abstract

Much interest has been shown recently in the use of negative pions for cancer radiotherapy. Several facilities are being constructed which will provide pion beams of sufficient intensity for radiotherapy and clinical trials are planned. Calculations are now being made to provide necessary information for the radiotherapist to plan the treatment of a tumor patient and also for the health physicist in insuring the protection of the patient as well as those working in the vicinity. Monte Carlo computer codes have been developed which take into account all of the relevant physical processes involved as pions penetrate tissue, e.g., inelastic nuclear interactions and the transport of all secondary particles produced, multiple coulomb scattering, range straggling, etc. Good agreement has been obtained between the results of these calculations and experimental measurements of absorbed dose. The codes can provide detailed information about the energy and spatial distributions of each type of primary and secondary particle throughout the phantom and also the LET distribution of the energy deposited. In this investigation these codes have been used to calculate the spatial distributions of absorbed dose and to study the effects of applying various types of weighting factors to the components of dose. The ICRP recommended quality factors have been applied as functions of LET to determine the spatial distribution of dose equivalent. Experimental RBE values for cell survival have been applied as functions of LET to determine the spatial distribution of "effective" dose. The cell survival model of Katz has also been applied for estimating cell survival of human T-1 cells. The results of these various weighting schemes will be discussed.

Introduction

Negative pion beams have been used for a number of years in radiobiological experiments. More recently, attention has been focused on their use for radiotherapy. At the end of its trajectory, a stopped negative pion is captured by an atomic nucleus, causing the nucleus to disintegrate into energetic, high-LET fragments, producing a "star". A large amount of energy is thus deposited within a small volume around the capture site. The interactions of pions are complex and

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difficult to measure. Few experimental data exist. Fortunately, a great deal of information can be obtained from calculations which, of course, should be checked by measurements whenever possible. This paper reports some results of various calculations for negative pion beams. Some of these results are parts of manuscripts to be published in the open literature.

Description of Calculational Programs

The Monte Carlo computer code, PION-1[1,2] was developed for the study of dose deposition by pion beams incident on water and tissue targets. The program includes all physical interactions known to be relevant: electronic interactions (expressed by means of stopping power), pion nuclear interactions, multiple coulomb scattering, and range straggling. Muon and electron beam contamination can also be included. The complete histories of all primary and secondary particles, arising from the irradiation of a target by a pion beam, are obtained. The computer program furnishes complete microscopic data for all particles. These data can be tabulated in any desired form to study dose as a function of position, LET distributions, etc. In what follows we shall calculate, for a particular pion beam, incident on a tissue target, depth dose curves, dose equivalent, average quality factors, RBE values, and cell survival.

Specification of Beam

The quantities below are calculated as averages in a thin cylindrical volume element of radius 3 cm, called the detector, placed at different depths along the beam axis. A beam of approximately elliptical cross section 6 x 7 cm was used for these calculations. The beam was the same as that employed in an earlier study,[2] except that no contamination (muons and electrons) is included here. The mean momentum of pions in the beam is 175 MeV/c. A Gaussian distribution is assumed with one-half of the pions having momenta within 2% of the mean value. The particle histories of 10,000 incident pions and all of the secondary products they generate were used in making each set of calculations.

Absorbed Dose

The absorbed dose, averaged over the dimensions of the 3 cm detector, is shown in Figure 1 as a function of depth in the irradiated tissue target. The various components that contribute to the total absorbed dose are also shown. The curve labeled "π" represents the ionization dose delivered by pions, that labeled "H" shows the dose from heavy particles (i.e., mass number > 1), "N" represents the neutron dose, and "P" the proton dose. Except in the peak the proton dose is almost identical to that from heavy particles.

The depth-dose curve is characterized by a plateau region to a depth of about 17 cm and by a peak which covers the region from 17 to about 23 cm. The ratio of the maximum dose to that at the surface is 3.3 for this pure beam of pions. The relative contributions to dose in the plateau and peak regions are given in Table 1. The high LET components, which arise from pion-nuclear interactions, contribute 30% of the dose in the peak.

Individual contributions to the absorbed dose can be weighted in various ways to make additional predictions about pion beams. Some examples are given in the next three sections.

Dose Equivalent

For occupational exposure to ionizing radiation, the International Commission on Radiological Protection has recommended[3] the use of certain quality factors, Q, for weighting the absorbed dose deposited in different LET intervals. These values of Q were used to weight the absorbed dose components as a function of LET for each primary pion and secondary particle to obtain the dose equivalent at each depth in the target. Above 1750 MeV/cm, the value Q = 20 was used. The resulting curve for the dose equivalent, H, as a function of depth is shown in Figure 2 together with the absorbed dose curve obtained from Figure 1.

These results show that the dose equivalent has its peak value approximately one cm beyond the depth at which the absorbed dose is a maximum. The dose equivalent peaks at a greater depth because a larger number of pions stop there. This fact can be seen from Figure 1, where the "star" dose has its maximum. Even though the dose is smaller behind the peak, the weighted contribution from high LET components is greater.

The individual contributions to the dose equivalent in the plateau and peak regions are also summarized in Table 1. Dividing H by D gives the "average quality factor," $\overline{QF}$, for the pion beam at various depths. A somewhat more extensive study of quality factors for both negative and positive pion beams is being reported elsewhere.[4] The value of $\overline{QF}$ is approximately 1.6 in the plateau region (about 5 cm depth) and rises to a value near 5 behind the region of peak dose.

Use of Todd's RBE Values for Human T-1 Kidney Cell Survival

Todd has summarized RBE values as functions of LET for different survival levels of T-1 human kidney cells exposed to ion beams.[5] These values have been used as weighting factors for the absorbed dose in different LET intervals to obtain a weighted total dose, or "effective dose" as a function of depth for the pion beam. The ratio of the effective dose and the absorbed dose provides an estimate of the RBE for the beam at different depths. The weighting factors for 50% and 1% survival levels have been used to compute the curves labeled Todd in Figure 3. These curves give the estimated RBE for a given survival level at a given depth. The results indicate that the RBE's are somewhat greater than unity in the plateau region and rise to maximum values of 1.7 and 1.4 at depths slightly beyond the depth of the peak dose. The present calculations, utilizing the code PION-1,[1] represent a refinement of previous work.[6]

Use of Katz's Model

Katz has developed a model for calculating cell survival.[7] This model has been incorporated to estimate human T-1 kidney cell survival levels as functions of depth in the target exposed to the pion beam. The dose was normalized so that the cell survival probability at the surface of the target was 50% in one case (190 rad at the surface) and 30% in another (280 rad at the surface). Figure 4 shows the results obtained. The survival probability in both cases increases slightly in the first 10 cm of depth, reflecting the small decrease in the absorbed dose (Figure 1). At 15 cm the survival probability begins to drop rapidly, reaching a minimum around 20.5 cm. The upper curve, for 50% survival at the surface, drops about 2 orders of magnitude to its minimum; the 30% curve drops 3 orders of magnitude.

RBE values were also calculated with Katz's model for given survival levels at each depth. Results for 50% and 1% survival are shown in Figure 3 by the curves labeled Katz. These curves can be compared directly with those labeled Todd which illustrate the same quantities computed by using Todd's RBE values[5] as weighting factors. The RBE values found with Katz's model at large depths are larger than those based on Todd's values for the survival levels considered here. At smaller depths Katz's 1% curve and Todd's 50% curve are about equal. The discrepancy between the curves for the same survival levels could be due to a number of factors. Perhaps the most fundamental question is the validity of applying Todd's RBE values from experiments with individual ions to the star components produced by pion capture.

References

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Figure Captions

Figure 1. Absorbed dose calculated as a function of depth for detector of radius 3 cm. As described in text, various contributions to the total dose are also shown: "π" shows the dose from pion ionization, "H" that from heavy particles (mass number > 1), "P" from protons, and "N" from neutrons.

Figure 2. Dose equivalent, H, and absorbed dose, D, as functions of depth.

Figure 3. Comparison of RBE values for 50% and 1% survival levels based on Todd's summary of RBE and on Katz's model.

Figure 4. Cell survival probabilities for two examples calculated as functions of depth with Katz's model. In one case the survival level at the surface is 50%; in the other case, 30%.

Table 1. Relative Contributions (Percent) to Absorbed Dose in Plateau* and Peak** Regions

	Absorbed Dose		Dose Equivalent	
	Plateau	Peak	Plateau	Peak
Pion Ionization	89	38	55	10
Heavy Particles	6	30	34	64
Protons	4	27	4	14
Neutrons	1	5	6	12

*Averaged between 5 cm and 6 cm.

**Averaged between 20 cm and 21 cm.

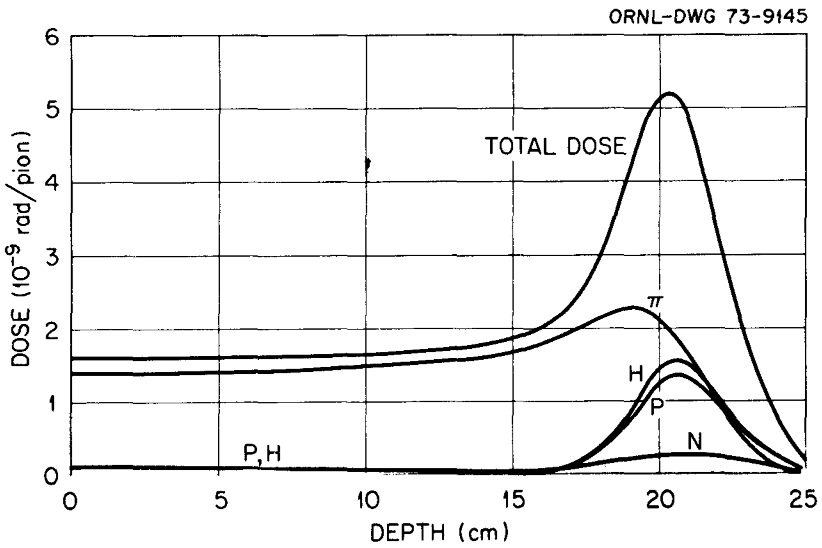

Figure 1.

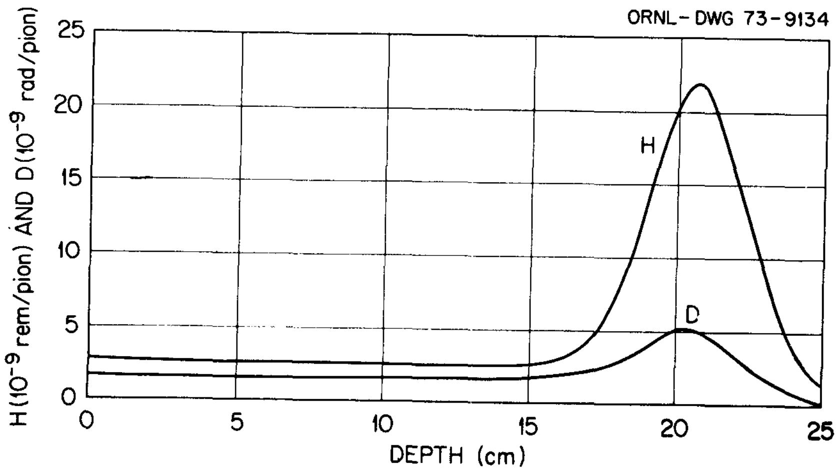

Figure 2.

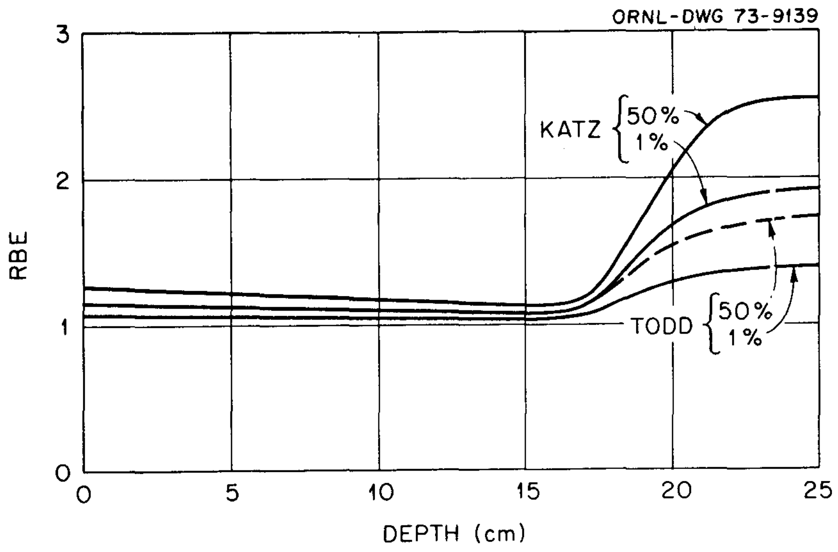

Figure 3.

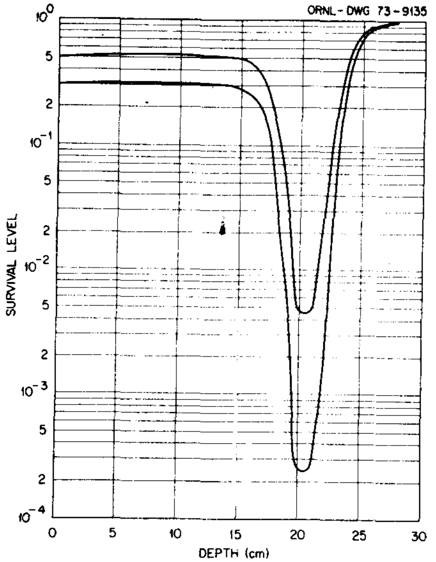

Figure 4.