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MASTER

DOSIMETRY OF BEAMS FOR NEGATIVE PI-MESON RADIATION THERAPY*

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ABSTRACT

Several new facilities have been built in the last few years which can produce high intensity beams of pions. As a result, a significant amount of new data related to pion dosimetry is available. Results of beam composition, beam shaping, and collimation are given along with depth dose curves and iso-dose contours. Experimental data which describe the radiation quality of pion beams and the change in radiation quality with position are presented. Experimental data determining the fraction of the dose resulting from neutrons are discussed. The present techniques used in pion dosimetry are summarized, and those areas of pion dosimetry which require additional effort in order to achieve routine treatment planning for patients are reviewed.

* Investigation supported by grants from National Cancer Institute, Division of Research Resources and Centers to University of New Mexico Cancer Research and Treatment Center, and by the U. S. Energy Research and Development Administration

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INTRODUCTION

Negative pions are probably the most esoteric and most complicated type of radiation which has been proposed for use in radiotherapy with the possible exception of the magnetic monopole. Pions are the elementary particles associated with the nuclear force and can be produced by the interaction of energetic charged particles or gamma rays (see, e.g., Rossi, 1952). Because the pions produced have a relatively long lifetime (2.6×10^{-8} sec, for π^+ at rest), they can be collected by use of a magnetic channel and transported to an appropriate target.

As pions pass through biological matter, they lose energy primarily through collisions with electrons with the probability of maximum energy loss occurring slightly before the end of their range. Thus, a plot of dose as a function of depth in a material, as in Fig. 1a for π^+ , will show the familiar Bragg peak. A negative pion, at the end of its range, attaches itself to a nucleus to form a mesonic atom with the pion ultimately being absorbed by the nucleus and breaking it apart (pion stars). The rest mass of a π^- is 139.6 MeV. About 40 MeV of this energy goes into overcoming the binding energy of the nucleus; approximately 30 MeV goes into the production of charged particles (including protons, alpha particles, and heavy ions); about 70 MeV goes into the production of neutrons (Fowler and Perkins, 1961). In addition, this entire process can result in the production of mesonic x-rays and γ rays. If the π^- depth dose curve in Fig. 1a is compared to the π^+ curve, the increased dose in the Bragg region for negative pions is almost totally a result of negative pion stars.

The Bragg-type depth dose curve allows one to shape pion beams so that the maximum dose is delivered to a highly localized treatment volume with minimum

dose to the surrounding tissue. The higher stopping powers of the heavier charged particles produced by the stars result in higher relative biological effectiveness (RBE) and lower oxygen enhancement ratio (OER) in the stopping region as compared to the entrance (or plateau) region or as compared to conventional radiations. Additional features related to the formation of mesonic atoms and pion stars allow visualization of the treatment volume.

More detailed discussions on pions can be found in the literature, e.g., Rossi (1952), Raju and Richman (1972), and Leon (1973).

The amount of basic physical data and dosimetric information even at this time is severely limited in the case of pions as compared to other modalities simply because of the fewer number of pion beams available. There are presently three facilities in operation which will be capable of delivering pion beams with sufficient intensities to begin human radiobiology. These are LAMPF (USA), SIN (Switzerland), and TRIUMF (Canada). Several other pion facilities have or will have available beam intensities appropriate for physical and biological research. Results recently obtained at these new facilities have contributed toward understanding the techniques and problems associated with pion dosimetry. The remainder of this paper will be a summary of some of the present techniques, areas under investigation, and future needs in pion dosimetry.

BEAM CHARACTERIZATION

Beam Shaping

The first objective of any pion dosimetry program is to be able to choose an initial pion beam, transport it, and shape it so that an appropriate volume is treated in the patient. In order to do this, it is necessary to predict the transport properties and the phase space (essentially the momentum and

directional distributions of the particles in the beam) for specific beams. Calculational methods must be able to predict the beam, collimation, and bolus needed to irradiate properly the desired treatment volume. In order to achieve this objective, experimental and theoretical work has been done at various institutions. Results at LAMPF, in this respect, have been reported by Paciotti, et al (1975). Figure 1 shows four examples of depth dose curves which illustrate some of the versatility in shaping pion beams. A great deal of effort has gone into producing beams for the irradiation of large tumors by the use of static collimators, dynamic range shifters, and multiport beam channels. Beams capable of treating volumes up to several hundred cm^3 are being produced at LAMPF on a fairly routine basis. Various static beams are being used for patient irradiations (e.g., Kligerman, et al, 1975) and a beam shaped by use of a dynamic range shifter, such as the one shown in Fig. 1b, will be used in the near future.

Beam Composition

A pion beam always contains a certain fraction of muons and electrons. The actual amount in a specific beam (typically 15 to 30% of the flux and 5 to 15% of the dose) is a function of the target material and shape, the channel acceptance and length and the momentum of the beam. Because muons and electrons have low linear energy transfer (LET), they are generally considered to be undesirable. Figure 2 shows some recent data obtained at TRIUMF with protons incident on a Be target. The contamination obviously changes rapidly as a function of momentum, and this must be taken into consideration. One also must consider that the relative composition of the beam will vary in the plane perpendicular to the beam axis.

RADIATION FIELDS

Dose Inside the Stopping Region

Isodose contours for a pion beam with a relatively wide momentum spread (12% full width, half maximum) are shown in Fig. 3. These distributions are representative of most pion beams prior to beam shaping. With the use of collimation, momentum selecting devices, and range shifting devices, such beams can be shaped into configurations such as that shown in 1b. Typically, the decrease from the 80 to 20% levels on the distal side of the peak occurs over a distance of approximately 1 cm in water, or less, depending on the initial momentum of the beam. In the plane perpendicular to the beam axis, collimation will result in a decrease in dose at the surface from 80% to 20% in 0.7 cm, or less, depending on the momentum spread and beam focus. Multiple scattering will increase this value with increasing depth. Dynamic systems, such as the range shifter used to produce the beam in Fig. 1b, can utilize a beam with a narrow spread in momentum with, correspondingly, sharp decreases in dose at the edges to produce relatively complex isodose contours in the intervening region.

Dose Outside the Stopping Region

It is obvious that the entrance dose from a pion beam and the exit dose from the muons and electrons are not negligible, although they are considerably reduced with the multiport system developed at Stanford (Boyd, et al, 1973). In addition, there is a significant contribution to the dose in both the stopping region and the surrounding region from neutrons produced by pion stars.

Schillaci and Roeder (1973) have calculated this neutron dose for several beams as a function of distance from the center of the beam. The only experimental data obtained to date were obtained at LAMPF. Tissue equivalent plastic proportional counters (amols et al, to be published), fission foils (Wilenzick et al, 1975),

and nuclear emulsions (Allred et al, unpublished) were used as detection systems outside the stopping region of a relatively narrow beam (a standard deviation of 2% in momentum). Results of two such measurements with the proportional counters are shown in Fig. 4. These data agree with the previous calculations within the quoted uncertainties. Both data indicate that the dose from neutrons for large treatment volumes will be significant and cannot be neglected.

Radiation Quality

The absorbed dose from negative π -mesons has a broad distribution in LET or microscopic energy deposition which changes rapidly between the peak and plateau regions, throughout the peak itself, and from beam to beam. Figure 5 shows some recent microdosimetric data for a relatively narrow beam of pions at LAMPF (Amols et al, 1975). In the plateau, most of the events result from low LET particles, although there is a small high-LET contribution from in-flight pion interactions and neutrons. There is a rapid increase in an intermediate (protons) and high (alpha particles and heavy ions) component throughout the peak region, with the maximum high-LET component on the downstream portion of the peak.

The rapid changes observed in the radiation quality cause corresponding changes in the response of most devices used to measure dose and in biological systems, including humans. Patient treatments require a knowledge of the radiation quality so that changes in biological responses can be taken into consideration in treatment planning.

TECHNIQUES AND METHODS

Monitoring Systems

Parallel-plate ionization chambers generally have been used as monitoring systems for pion channels along with, in some cases, current integration

proportional chambers and/or plastic scintillators. The accuracy and reliability of these systems have proven to be adequate. Some technological development will be necessary as the versatility of the treatment systems increases. However, no major complications are anticipated.

Measurements with Ion Chambers

Isodose contours usually have been obtained with systems utilizing ionization chambers constructed of Shonka Al50 plastic (which is tissue-equivalent for neutrons). This method probably represents the most common technique for pion dosimetry. Nevertheless, there are serious problems associated with its use. The Al50 plastic is not tissue-equivalent for pions. This results in a correction of 0 to 15% to obtain the dose in tissue. The introduction of a gas cavity into the beam can significantly perturb the radiation field. The Bragg-Gray principle is not generally applicable to pions and many of the relationships derived from it and used in conventional dosimetry are not applicable at all. Therefore, calculating correction factors, at present, is difficult.

These problems increase the uncertainties in both absolute and relative doses. However, it is probably the most precise and reliable technique for routine dosimetry available at the present time. A comprehensive review of this subject is not yet available. A somewhat more detailed presentation is given by Dicello (1976).

Microdosimetry

Determination of radiation quality is being accomplished by several means. Monte Carlo and semi-analytical methods have been developed by Armstrong and Chandler (1972) and Turner et al (1972). Four basic experimental methods are available: 1) Spherical proportional counters, 2) silicon solid state detectors, 3) recombination chambers, and 4) dielectric track recorders.

The spherical proportional counters can be used to obtain the distribution of energy deposition in microscopic sites having diameters of typically 1 μ m or less in unit density material and to determine LET distributions (Amols et al, 1975).

Solid state detectors have been used to measure the energy deposited in detectors by the charged particles produced in a phantom (Richman, 1976).

Dielectric track recorders have been placed between collimator and patient during irradiations at Los Alamos (Knowles, et al, unpublished). Such detectors record heavy ion tracks from pion stars. Figure 6 shows contours obtained by counting track densities for one such exposure.

Recombination chambers (Baarli and Sullivan, 1974) can be used to measure a quantity which is proportional to the dose mean LET. However, the method is limited to obtaining only this quantity.

The first two techniques described are usually restricted to very low dose rates. However, both methods are presently being used at LAMPF with high intensity irradiations by activating the detecting systems only during selected low intensity beam pulses.

Dielectric track recorders are sensitive only to high LET radiations and their response to pions is not well understood at this time.

Biological Dosimetry

Certain biological systems, such as cells in culture, are used for the measurement of isoeffect contours or radiation quality (Raju et al, 1975). The limitations of these systems include 1) the long period of time between measurements and results, 2) the biological effects observed are not directly applicable to patients, and 3) the sensitivity to changes in dose or beam quality and the reproducibility are not always sufficient.

Calorimetry

No calorimetric measurements have been made with pions yet because of insufficient dose rates available until recently.

Although calorimetry is a direct measurement of absorbed dose in an irradiated medium, the lack of tissue-equivalent materials for pions results in a large correction factor in converting from dose in the medium to dose in tissue. This, and the lack of knowledge concerning thermal defects caused by pion interactions, will cause significant uncertainties in initial calorimetric results. The method will be most useful when compared to other techniques.

DISCUSSION

It seems appropriate to point out some areas where significant contributions can be made:

1. More basic physical data are needed for input into the calculations and for interpretation of dosimetric measurements.
2. Beam models, models for interaction mechanisms, biological models, and microdosimetric models sufficiently simple, yet accurate enough to be included in routine pion treatment planning must be developed.
3. Fast accurate dosimetric systems, comparable to film, TLDs, and diodes in conventional radiotherapy, are needed.
4. More data on the effects of collimation and inhomogeneities are needed.
5. Additional research must be done on visualization techniques before they can be used routinely during patient treatments.

Finally, because of space limitations, a great deal of other good work has not been presented. The fact that so much recent data are available is encouraging in view of the fact that the first pion biomedical channel became operational only in 1974 and none of the facilities is yet operating at maximum intensity.

LEGENDS

- Figure 1 a) Absorbed dose as a function of depth in water for a π^+ and a π^- beam.
- b) Absorbed dose as a function of depth in water for a π^- beam. The depth was broadened in each case by use of a range shifter, the thickness of which can be varied as a function of time. The small open circles are experimental data for a beam which is flat in dose over 5 cm of the peak region. The large open circles are experimental data for a beam which has constant biological effect over a 10 cm region in the peak for a specific experiment with cells in culture. The solid and dashed curves represent an attempt to calculate the 5 and 10 cm-wide depth dose curves, respectively. (Courtesy of H. Amols and M. Schillaci, LAMPF).
- c) Absorbed dose as a function of depth in water for a π^- beam. These data were obtained by use of the Stanford multiport pion generator. Notice the high peak-to-entrance ratio. (Courtesy of Peter Fessenden, Stanford University).
- d) Absorbed dose as a function of depth in water for a π^- beam. The same as 1c) except that the incident pion energy has been reduced.
- Figure 2 The relative contribution to the fluence of π^- , μ^- , and e^- as a function of the mean momentum of the particles (Courtesy of Mark Henkleman, TRIUMF).
- Figure 3 Isodose contours in three planes for a negative pion beam of initial momentum of 148 MeV/c with a FWHM of about 18 MeV/c (Courtesy of Mark Henkleman, TRIUMF).
- Figure 4 Microdosimetric spectra outside of the stopping region for a π^- beam. The solid curves are the dose per logarithmic interval of lineal energy versus lineal energy. The dashed curves are the corresponding integral curves. There are more events of low lineal energy in the y plane because of an asymmetry in the primary beam. The events of higher lineal energy are primarily the result of neutrons from pion stars (Amols et al, to be published).
- Figure 5 Microdosimetric spectra taken in a water phantom along the central axis of a negative pion beam. The notation is the same as used in Fig. 4 (Amols et al, 1975).
- Figure 6 Contours of constant track density in a dielectric track recorder irradiated in the stopping region of a π^- beam. Data were taken in the plane perpendicular to the incident beam (Knowles et al, unpublished).

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LONGITUDINAL ISODOSE CONTOUR

TRANSVERSE ISODOSE CONTOUR

WATER DEPTH = 12.75 cm

TRANSVERSE ISODOSE CONTOUR

WATER DEPTH = 7 cm