Copied From Los Alamos
National Laboratory Archives

[Reprinted from RADIOLOGY, Vol. 128, No. 3, Pages 757-766, September, 1978.]
Copyrighted 1978 by the Radiological Society of North America, Incorporated

Radiation
Physics
A-91.011
73-2
MP-DO

712976

The Three Dose Components of a Negative Pion Beam and Their Role in Pion Radiotherapy[1]

Chaim Richman, Ph.D., Joe F. Rodriguez, Jr., A.S., Jack E. Malcom, B.S., and Myron L. Stein, B.A.

A new method has been developed for analyzing therapeutic negative pion beams into three LET (linear energy transfer) dose components inherent in such a beam. The technique utilizes thin silicon detectors to obtain pulse height spectra produced by the various particles in the beam traversing the detectors. It is shown that a low LET group is correlated with the incoming pions, muons and electrons; a medium LET group corresponds to protons, deuterons, tritons, and high energy alpha particles; and a high LET group is due to low energy alpha particles, ^{3}He and recoil particles. Several beams used clinically have been studied.

INDEX TERMS: Linear energy transfer • Mesons • Therapeutic radiology, instrumentation

Radiology 128:757-766, September 1978

NEGATIVE pions were first used to irradiate tumors in patients on October 21, 1974 at the Meson Physics Facility at Los Alamos, New Mexico (1). Since these first irradiations of tumor nodules, about 40 patients with superficial and deep-lying tumors have been treated with the therapeutic pion beam. The beam intensity has been increased from 5 rads/min over a small volume to the present value of 8 rads/min in a volume of about a liter. This improvement has been made possible by the increase in the primary proton current from 10 μA to the present current of 300 μA. Smith *et al.* (2, 3) have studied the dosimetry of the beams and the treatment planning. On the clinical side, Kligerman *et al.* (1, 4) have obtained information on the comparative response of human tumors to the pion peak and to x rays. Although much work lies ahead, a good beginning has been made for the study of pion treatment of human neoplasms.

The pion beam is produced by impinging a high intensity 800 MeV proton beam on a carbon target. The pions are then brought into the treatment room by means of a set of eleven magnets whose characteristics and "tuning" have been studied by Paciotti *et al.* (5, 6). Beams of given momentum and spatial distributions are made by using different wedges in the beam line and various magnet settings called tunes. The beam emerges as a vertical and approximately parallel beam of particles. At the end of the magnet system the beam is modulated and collimated in a manner appropriate for the patient.

An inherent feature of negative pion beams is that they have LET structure. That is to say that different LET components will generally be nonuniform in a tumor volume (7-9). With single port irradiations, therefore, a certain compensation is probably needed between the different LET components to arrive at a uniform biological response. When it is possible to treat a patient with parallel opposed ports, a compensation is achieved most simply, at least to first order.

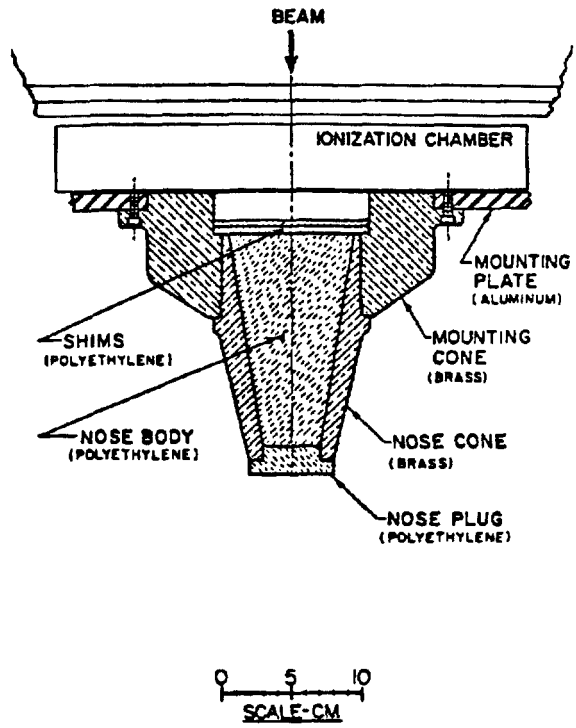

Fig. 1. The combination collimator-attenuator used in irradiating metastatic superficial nodules in selected patients. Nose cones of different sizes are screwed into the mounting cone for different size fields. The beam is collimated by the brass walls and attenuated but not stopped by the polyethylene.

An examination of the particle structure of pion beams (9) reveals that the principal part of the dose is produced by the pions in flight. These pions, together with a small

[1] From the Office of the Associate Director for Research, Los Alamos Scientific Laboratory, Los Alamos, NM 87545. Submitted for publication on 8 August 1977. Revision requested on 28 February 1978 and received 11 April 1978.

Supported by USPHS grants CA-16127 and CA-14052 from the National Cancer Institute, Division of Research Sources and Centers, and by the U. S. Department of Energy.

FILE BARCODE 00133401

COPIED FOR
HSPT
00133401.001

1087865

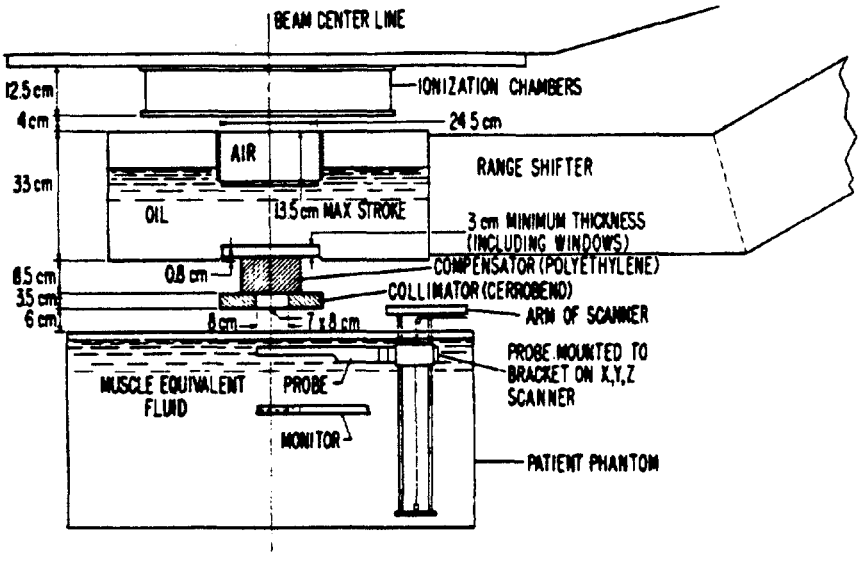

Fig. 2. One of the experimental setups for measurements with the range shifter. This arrangement closely parallels the patient setup. The beam enters from the top and passes successively through the monitoring ionization chambers, the range shifter, a polyethylene compensator block, a collimator and into the phantom. The beam is then scanned in the phantom in the usual way.

percentage of electrons and muons, are singly charged light particles and have long ranges, *e.g.*, an 80 MeV pion beam has a range of about 19 cm of tissue. Electrons and muons have similar long ranges. These three types of particles constitute a clear group whose LET in silicon is between 0.3 and 4 keV/μm. (LET, or linear energy transfer, will refer to total energy loss by ionization in silicon, per unit distance in silicon with units of keV/μm.) This group, which we will call the low LET group, can be clearly separated experimentally from the other particles.

The star products are produced at the end of the pion range and naturally fall into two groups, a medium and a high LET group. The medium LET group consists primarily of the singly charged heavy particles—protons, deuterons, and tritons. A small admixture of high energy α particles is possible for this group. These particles have ranges of the order of centimeters in tissue and their LET in silicon is between 4 and about 80 keV/μm. The high LET group consists of multiply charged heavy particles—low energy α particles, ^{3}He and recoils from the star. These particles have LETs in silicon above 80 keV/μm and ranges in tissue of the order of millimeters or less. The precise separation of these two groups is still being investigated.

The low and medium LET groups have RBEs near unity while the high LET group has RBE values between 1.5 and 5. This high LET group also has OER values near unity and plays a prominent role in pion therapy.

The purpose of the experiments to be described was to separate these LET groups and to measure their spatial behavior. We are now able to evaluate different beams and are following in a fundamental manner their radiobiological and clinical behavior.

For this work we have chosen the solid state silicon detector as the radiation probe. It will become fully clear that this kind of probe has several advantages over other devices. To begin with, it is a small probe—most of our detectors are wafers about 2–3 mm in diameter and 20–700 μm in thickness. This makes them ideal for handling the large fluxes of particles in therapeutic pion beams. The detector is essentially wall-less, and one can therefore choose the housing for the probe to be of any material including bone-simulating plastics (10). Even with the housing the entire package is quite small, and we have used it in the oral cavity of patients to check the LET dose components in this region of treatment fields. In the most recent experiments detectors of different thicknesses have been used for the different particles resulting in a very satisfactory analysis of the three groups of particles.

EXPERIMENTAL METHODS

Silicon detectors have been used in physics for many years, but to the best of our knowledge they have not been used for LET spectra before. The flat solid state wafer behaves essentially like a parallel plate proportional ionization chamber (11); that is, it produces a voltage signal which is proportional to the energy deposited in the detector by the various particles. The fact that the probe presents a uniform thickness to the beam means that for the incoming particles—the pions, muons, and electrons—the so-called "event spectrum" is the LET spectrum. The electronics used with these detectors is designed to carefully preserve the linearity of the signals. A small voltage biases the detector, and the signal goes to the

COPIED FOR HSPT 00133401.002

1087866

preamplifier (Ortec 125), then to a main amplifier (Tennelec 205A) and then to a pulse height analyzer (Canberra 8100). In a water phantom irradiated by a pion beam the detector is almost an idealized probe. It does not disturb the radiation field but records faithfully the energies deposited by the different particles either traversing the detector or stopping in the detector.

The silicon wafers are mounted in Lucite rings with Lucite caps that are screwed to the rings. When operating in water, the probes are held in a water-tight box with the cables running through rubber tubing which is attached tightly to the box. The detectors are checked and calibrated in a vacuum chamber with small radioactive sources. With the covers removed the detectors are exposed to ^{207}Bi and ^{111}Cd electrons and to α particles from ^{241}Am and ^{148}Gd. The detectors are also cooled in the vacuum chamber by running cold alcohol through the detector support. In the experiments, the detectors are always cooled to a temperature between 0° and −30°C by means of a thin rubber tubing that carries running cold alcohol and is looped around the detector housing. The cooling lowers the leakage current in the detector and usually lowers the electronic noise.

In the first phases of the work a single detector 100 μm thick was used to analyze all of the particles in the beam, although it was realized that this is not the ideal detector for all the particles. During this phase a number of important problems were solved, including monitoring the beam, gating with the machine gate and preventing pile-up of pulses. After these techniques were developed it became clear that the thickness of the wafer was a powerful factor for identifying the different particles. When the beam enters the phantom, all the particles are at either minimum or near minimum ionization. Bringing these pulses well out of the noise takes a detector between 700 and 500 μm to produce large enough pulses. For the medium LET group, detectors from 100 μm down to 10 μm are appropriate, whereas for the high LET particles because of their short range detectors 10 μm or less are most appropriate.

The proton beam (and therefore the pion beam) has the following time profile. The beam pulses occur at the rate of 120 pulses/sec, and each pulse is 550 μsec long. Since the intensity of pions in these pulses is usually too high for counting experiments, a low intensity pulse (called a 1-in-10 pulse) is generated in the injector once every ten pulses. This pulse was used in the early experiments, and the electronic system including a separate solid state monitor was gated with a gate pulse that coincided with the 1-in-10 beam. The method was adequate but cumbersome. For example, it could not be used to make measurements with patients during therapy.

A different approach was adopted. First, the detectors were made small in area, about 3 mm^2. For a run on a given particle group the pion production target was pulled out of the beam until only a fraction of the beam traversed the target and a plateau of count rate vs. pion current was always taken. This ensured that there was no pile-up of pulses. One can expect a small error because of a diminished electron component. The magnitude of this error is still being investigated, but it is certainly less than 5% of the dose (9). Since the full pion beam is now used, the ionization chambers at the end of the beam line are used to monitor the beam. With the α particle group the count rate is low enough so that retracting the target is unnecessary, and the full target is put into the beam.

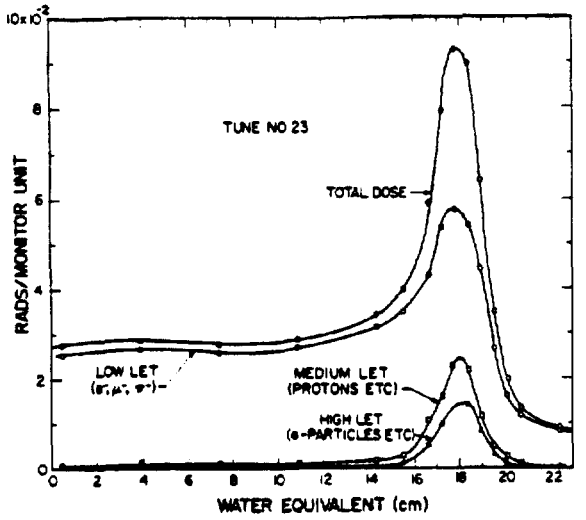

Fig. 3. The three LET groups as a function of depth along the central axis for the basic medium energy tune, No. 23.

THE FASHIONING OF PION BEAMS FOR PATIENT IRRADIATION

The initial clinical studies on the use of negative pions were made in patients with skin nodules and superficial tumors. These irradiations utilized the narrow momentum pion beam which stops in 3–5 cm of tissue, full width at half maximum. The beam had an energy of around 80 MeV and was attenuated and collimated by means of a brass cone filled with polyethylene. This unit is shown in Figure 1. Different size nose cones were used for different size tumors. A final adjustment of beam penetration was made by means of polyethylene shims that were added to the top of the collimator. This method proved to be quite suitable for these clinical studies; however, it cannot be used with deep-lying tumors.

To obtain a broad pion peak, a range shifter is used to modulate the narrow peak by varying the residual range of the pions that emerge from the range shifter. This modulation is accomplished by varying the height of a column of oil in the path of the beam in accordance with a prescribed function (12, 13). In this way beams have been made with the peak spread over a depth of 5–10 cm along the central axis. Figure 2 is a schematic drawing of the range shifter in place above a phantom.

Beams have been made which give a uniform total dose on the central axis. Such beams, however, in general do not give a uniform biological response because (as will be

COPIED FOR HSPT 00133401.003

1087867

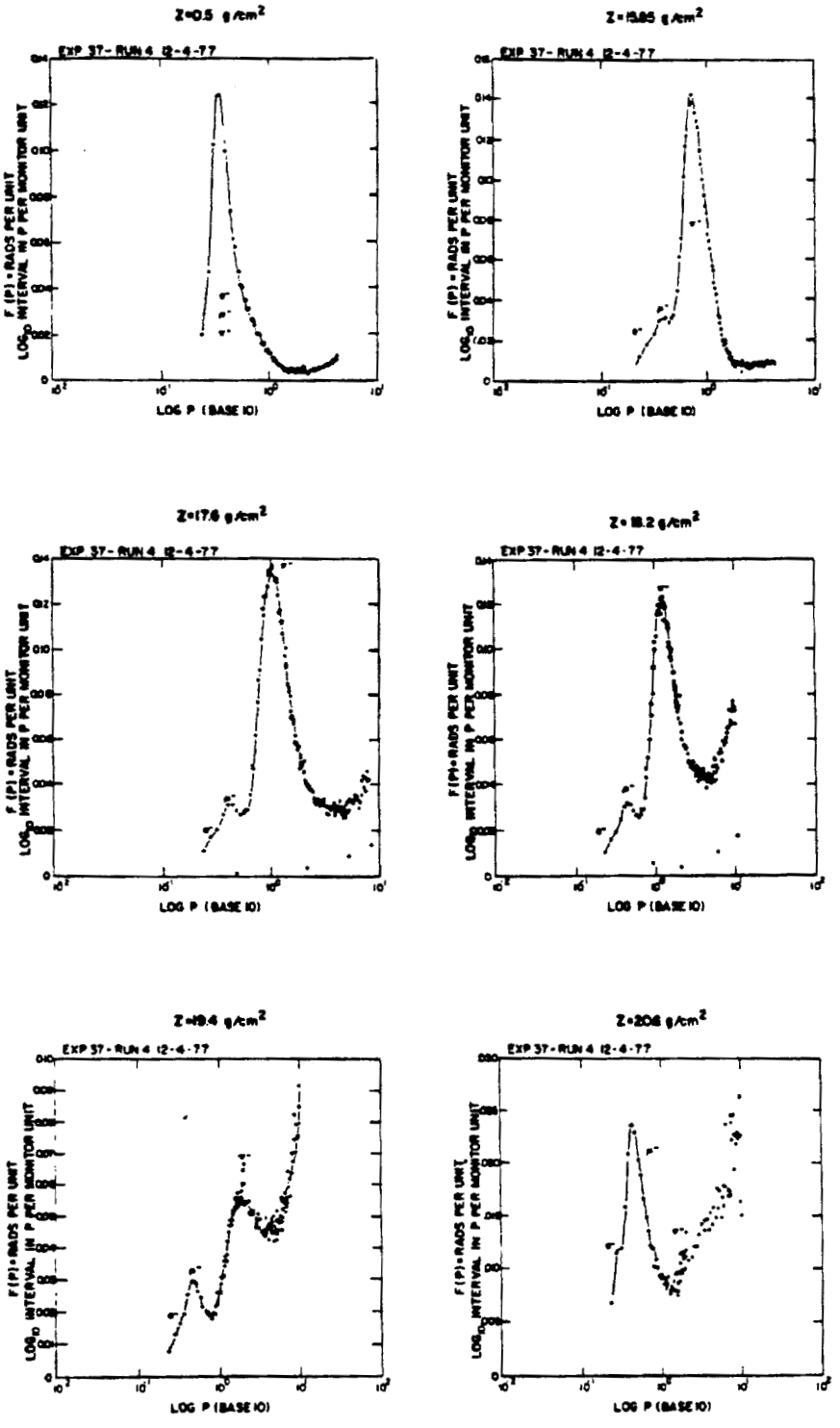

Fig. 4. The function $F(P)$, the dose per unit interval in $\log_{10}P$ and per monitor unit for the electrons, muons and pions at several depths in the Lucite phantom. The 700 μm thick probe is too thick for studying the transition to the medium LET group. In a thick detector the star products occur as a single pulse (9).

COPIED FOR
HSPT 00133401.004

1087868

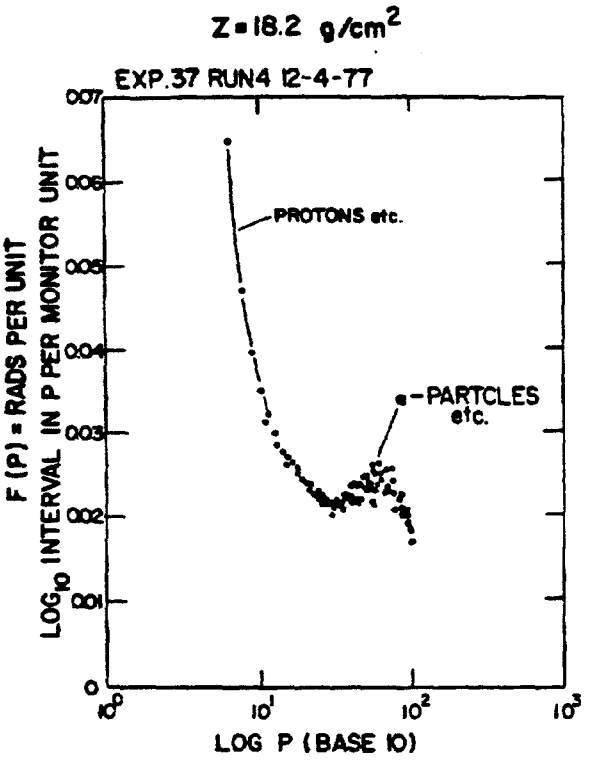

Fig. 5. A plot of $F(P)$ vs. $\log_{10}P$ for the medium and high LET group at a depth of 18.2 g/cm² in the Lucite phantom. On this plot the large energy depositions show up as a distinct peak.

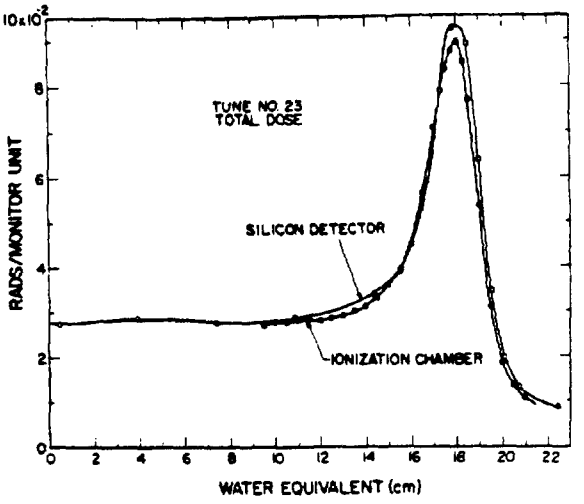

Fig. 6. A comparison of the total dose along the central axis measured with the solid state detector and an ionization chamber. The agreement both in the plateau and peak region is good.

shown later) the distal portion of the beam contains more high LET dose than the proximal region. All of the range-shifted beams used with patients have downward slopes in total dose with depth, thus compensating for the nonuniformity of the high LET dose. We have used silicon detectors to measure the LET components as a function of depth of these beams, and these measurements have provided a great deal of insight into the nature of these beams and a basis for judging their suitability for therapy.

ANALYSIS OF THE DATA

The detector together with the electronics is calibrated so that for a given amplification of the main amplifier, a pulse in the i'th channel of the analyzer represents a certain energy in keV deposited in the detector. This energy is called E_i. The spectrum of pulses represents all the energy depositions in the detector. Let N_i be the number of such pulses in the i'th channel, and let t be the thickness of the detector in microns. We now define a quantity

$$P_i \equiv E_i/t \quad keV/\mu m$$

which is the energy deposited per unit thickness of the detector. (This quantity plays approximately the same role for a slab detector as the lineal energy does in the case of the spherical proportional counter.) The spectrum N_i vs. P_i is commonly called the "event spectrum" in microdosimetry. We extend the meaning of this term here to

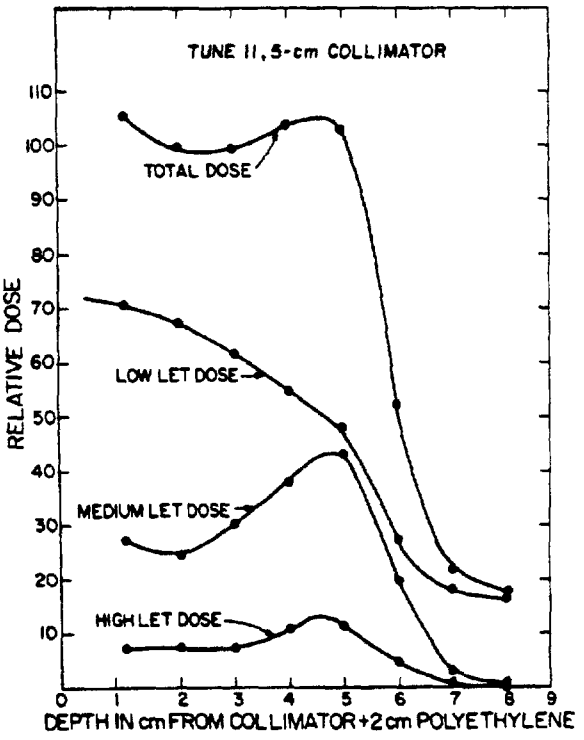

Fig. 7. The distributions along the central axis of the low, the medium, and the high LET components of a pion beam used to treat a superficial lesion. The behavior of the sum of the doses at each point is also shown.

COPIED FOR HSPT 00133401.005

1087869

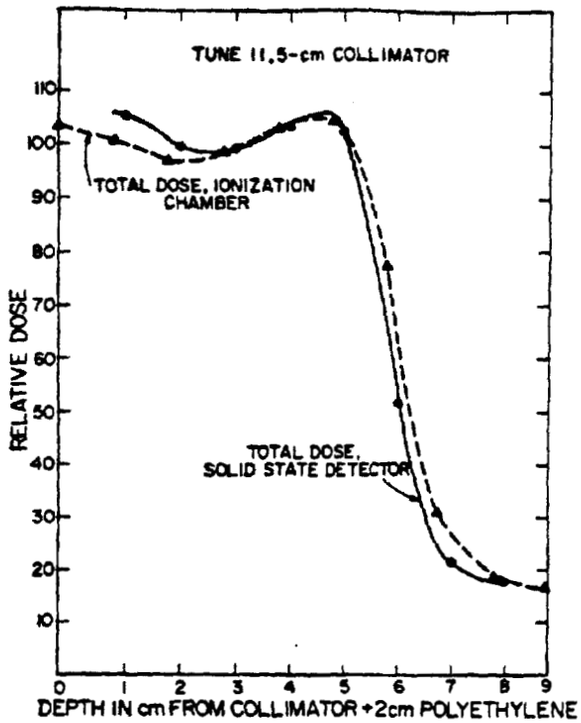

Fig. 8. A comparison of the relative total dose as obtained with an ionization chamber and with the silicon detector. The agreement is satisfactory.

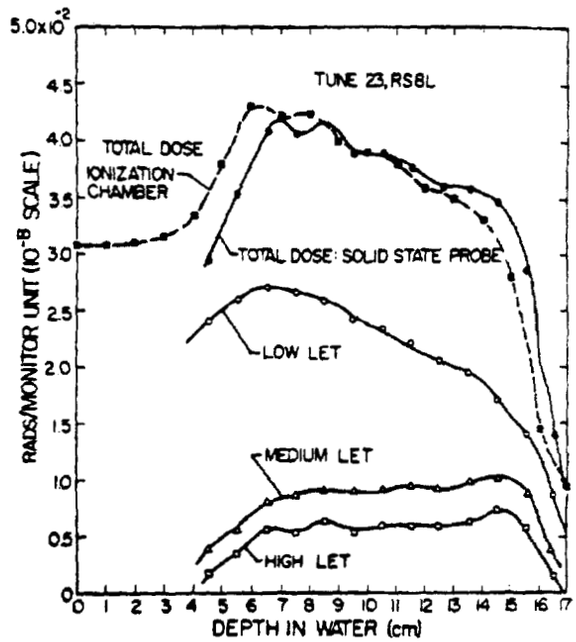

Fig. 9. The three dose components and the total dose for tune No. 23 with range shifter function 8L are shown along the central axis. Two detectors, one 102 μm thick and the other 18.1 μm thick, were used for different regions of the spectrum. The 102 μm probe was used in the region of $0.4 < P < 28$ keV/μm. The 18.1 μm probe was used in the region $8 < P < 640$ keV/μm.

cases in which the particle may not go through the detector but stops in the detector. It was pointed out before that since our initial beam is very closely a parallel beam which traverses the detector at right angles, that P_i is also the LET of these particles. This is not true for the other particles; the particles in the proton group and the α particle group enter the detector at all angles. For the present these groups are divided approximately by the size of the pulses observed. With very thin silicon detectors, it is possible to unfold the observed event spectrum into the LET spectrum of these particles (14).

The charge collected in the monitor ionization chamber is digitized. Let the number of such monitor units be designated by N_m. The energy deposited in the i'th channel per unit mass of silicon and per monitor unit, ϵ_i, is, therefore, given by

$$\epsilon_i = N_i P_i / \rho A N_m$$

Here A is the area of the detector and ρ is the density of silicon.

The energy deposited per monitor count per unit mass of tissue for a given group of particles is given by

$$\epsilon = \frac{1}{\rho A N_m} \sum_i \lambda_S^T N_i P_i$$

where the summation is taken over the channels that cover the group of particles. λ_S^T is the ratio of the mass stopping power in tissue to the mass stopping power in silicon and is a slowly varying function of the energy and type of particle.

As we go from electrons to α particles and recoils, we cover a range of P values from a few tenths of keV/μm to hundreds of keV/μm in silicon. To cover this range, it is helpful to use a logarithmic scale in P. We also define a function $F(P)$, such that the area under this curve is the dose per monitor unit in any interval of $\log_{10}P$.

$$F(P_i) = C\lambda_S^T \epsilon_i / \log_{10}(P_{i+1}/P_i)$$

C is a constant which depends on the units used. The plots of $F(P)$ vs. $\log_{10}P$ at different positions in the phantom give one a good understanding of the details of the energy losses being observed. At the same time the division of the doses into the three groups maintains a view of the physics and gives one a direct picture of the role of the different particles at different depths in the phantom and in the patient.

The event spectra obtained by the analyzer are put on magnetic tape, and the calculations and plots described above are made on a CDC 6600 computer.

RESULTS

Tune No. 23 is our basic medium energy tune. When it is used with various motions of the range shifter, it pro-

COPIED FOR HSPT
00133401.006

1087870

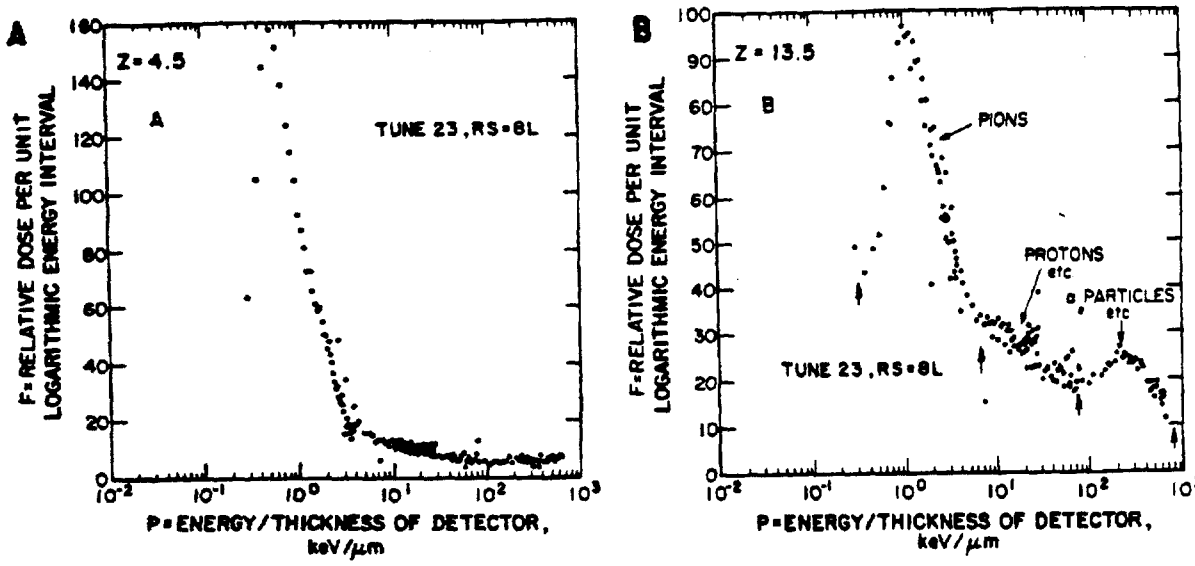

Fig. 10. A. The $F(P)$ function is plotted as a function of $\log_{10}P$ at a depth of 4.5 cm. This is the beginning of the peak region in dose, and there is no evidence of a high LET peak here as in the next plot.

B. The $F(P)$ function at a depth of 13.5 cm in the phantom for beam 8L. This plot shows up the particle groups well. The dividing points between the separate groups are determined from energy loss tables in an approximate manner. The arrows indicate the limits that determine the three groups.

duces a number of the patient beams. The pions have a range of about 18 cm in tissue. The envelope of the beam measured in the plane perpendicular to the direction of the beam is 7.5 × 4.9 cm rms (root mean square) (6). To study this tune a 700 μm thick detector was used for the low LET, and a 50 μm detector was used for the medium and high LET. These thicknesses are not ideal, but nevertheless the data give insight into the nature of this tune and also show the usefulness of the technique. Figure 3 shows the recent data on the behavior of the three LET groups on the central axis of the beam. It is important to note that in the plateau region the pion interactions in flight are few and there is very little medium and high LET dose in this region.

The low LET group is interesting, because as the pions and muons move deeper into the phantom, their LET increases in accordance with the Bragg relationship. The electrons stay at minimum ionization. This is shown in the series of curves of Figure 4. The plots give the function $F(P)$ vs. $\log_{10}P$ at different positions in the phantom. A small error is present here due to α particles and protons, etc. which give pulses in the detector in this interval of P, namely 0.2–4 keV/μm. It can easily be shown from the data that this error is less than 10% of the dose in this group.

Figure 5 shows $F(P)$ plotted vs. $\log_{10}P$ for the medium and high LET group. The data are shown at 18.2 g/cm². With a 50μm detector most of the α particles stop in the detector and the total energy is being recorded. For the time being, the dividing point at $P = 30$ keV/μm, that is $E = 1.5$ MeV, has been chosen as separating medium and high LET. With thinner detectors this portion of the spectrum will become clearer.

There is a special meaning to the high LET dose distribution. Since it is due to the particles which travel only a few millimeters from where they are produced, the distribution represents the stopping distribution of the pions for that beam. When the pulses observed in this way are summed to obtain the total dose, the distribution on the central axis agrees well with the total doses obtained with an ionization chamber (3). This is shown in Figure 6. Thus, the silicon detector not only separates the different components but also behaves like a good dosimeter.

One of the first studies made with this technique was of a beam designed for the treatment of a young patient with melanoma. The collimator shown in Figure 1 was used and the nose cone had an opening for the beam 5 cm in diameter. The distributions are shown in Figure 7, and the comparison with the total dose is shown in Figure 8. A single 100 μm probe was used for all three components. This method gives an approximate separation of the components. The cutoff between medium and high LET was taken for pulses with an energy of 10 MeV. This dividing line is qualitative. These distributions taught us that the two peaks in the total dose distribution were of different character.

We show next recent data on a beam which is produced with tune No. 23 and the range shifter function designated 8L. The purpose of the different range shifter functions is to obtain distributions over wide deep-lying regions of tissue with a given drop-off in the total dose from the

COPIED FOR HSRT 00133401.007

1087871

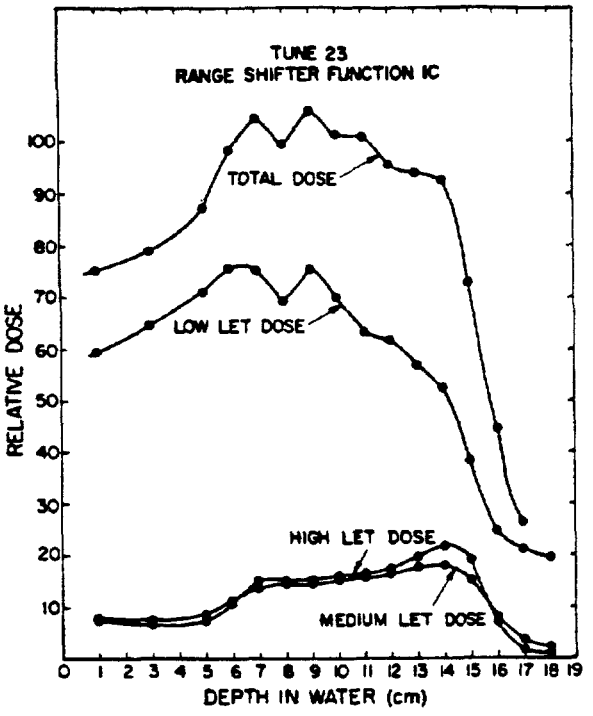

Fig. 11. The three LET components and the total dose distribution of a beam produced by the range shifter as a function of depth along the central axis. This beam was designed to have a fairly uniform total dose and was used for radiobiological studies.

proximal to the distal point. For this beam a drop-off of about 20% was chosen over a depth of 8 cm.

Two detectors were used to measure the three dose components: a 102 μm wafer was used for the low and a portion of the medium LET group, and an 18.1 μm wafer was used for the remaining portion of the medium LET group and for the high LET group. The results are shown in Figure 9. Figure 10 shows the $F(P)$ function vs. the $\log_{10}$ of the event size, P, in the plateau and the peak regions. The 102 μm probe detects the pions well but misses some of the electrons and muons. The high LET group is clear from Figure 10, B. It appears as a fairly broad peak which is characteristic of all the data. Of course this peak is not present in the plateau region (Fig. 10, A). The overlapping of these spectra with different detectors is one essential test that the experiment has been done correctly and there is no pile-up of pulses.

Figure 9 also shows a comparison of the total doses obtained with the ionization chamber and the silicon detector for this beam. The agreement is good. These results show the value of choosing different thicknesses of detectors for the different regions. When the detectors for the medium and high LET fractions are thin enough compared to the ranges of the particles, the event spectrum can be unfolded into the LET spectrum.

A single 100 μm detector was used for the measurements of the final two beams studied. The next beam was used primarily for radiobiological studies. Here the total dose was made as uniform as possible. Figure 11 shows the distributions of the dose components, and Figure 12 shows the comparison of the total dose distributions, all on the central axis.

Finally, we show the distributions of a beam made with tune No. 23 and a range shifter function designated 8I. This beam was used with two patients with head and neck lesions. From the clinical data on skin nodules (1), it was decided that the RBE in the distal portion of the beam was approximately 1.4 and that to obtain a uniform biological effect, a drop-off in dose to 70% of its original value was appropriate. Figure 13 shows the behavior of the dose components and Figure 14 the comparison of the total dose on a relative scale. The cut between medium and high LET dose was made at 4 MeV pulses. With a 100 μm probe this separation is qualitative. These curves are intended to show that the medium and high LET doses tend to peak distally for the various beams we have studied and various shapes of the total dose can be used to compensate for this effect.

DISCUSSION

Pion beams that are fashioned for radiotherapy have a certain LET structure. This structure is not an isolated phenomenon; it is due to the presence of three classes of very different particles in the radiation field. The three groups which are characterized as the pion group, the proton group and the α particle group not only have different specific ionizations but also different ranges. In

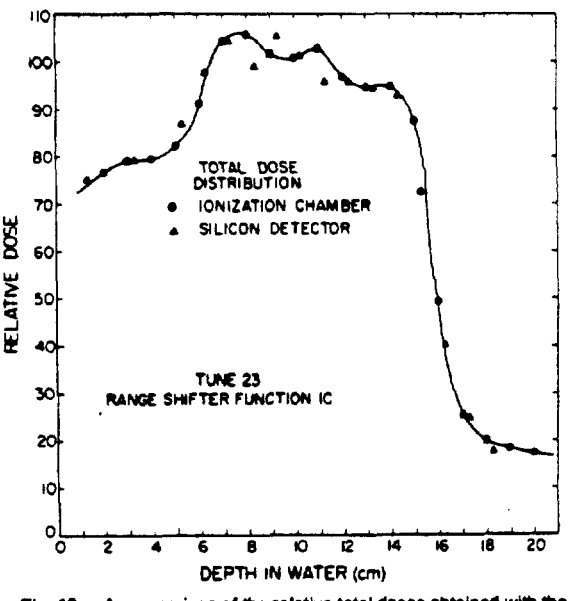

Fig. 12. A comparison of the relative total doses obtained with the ionization chamber and the silicon detector. Again, the agreement is quite good.

COPIED FOR
HSPT 00133401.008

1087872

working with therapeutic pion beams it is useful to keep in mind the three types of doses.

To follow the behavior of these three groups, we have found the solid state detector to be almost an ideal probe. Besides the basic property of linearity of response, the detector is physically small. This makes for very little disturbance of the dose distributions being measured. The fact that the probe is not tissue equivalent is not a significant drawback since the conversion to tissue is easily made. The freedom to use different thicknesses of detectors for the different components is of great importance.

In calculating the doses it is necessary to know the areas of the detectors as accurately as possible. This is not a simple matter since the detectors are small. For the present our data on actual doses are subject to a 20% uncertainty because of possible errors in this factor. We have learned to have the detectors made more carefully with this problem in mind. To check the areas given by the supplier, we have made radiographs of the detectors and have found good agreement between the quoted and measured areas. In the future the accuracy of the doses will therefore be greatly improved.

The pion radiation fields have very favorable geometrical distributions. There is a great deal of skin and tissue sparing, not only in terms of total dose, but also in terms of high LET dose. We see from all of the distributions that the high LET component is confined to the treatment volume on the central axis. With more sophisticated beams tissue sparing can be extended so that only the treatment volume has stopping pions in it.

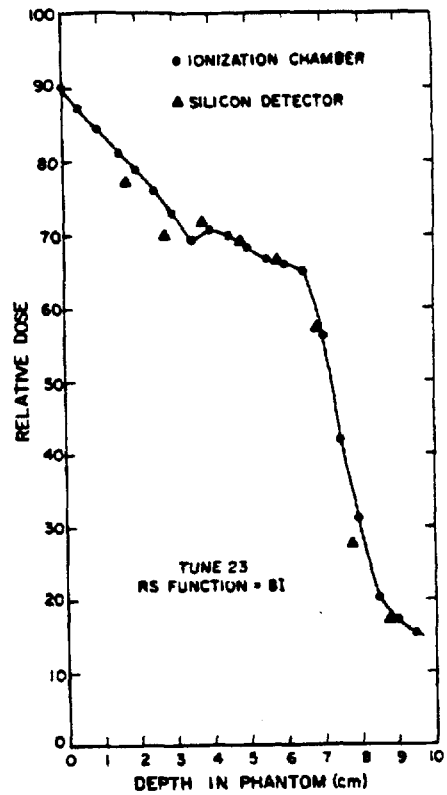

Fig. 14. A comparison of relative total dose as measured with the silicon detector and the ionization chamber for Tune No. 23 and range shifter function 8I.

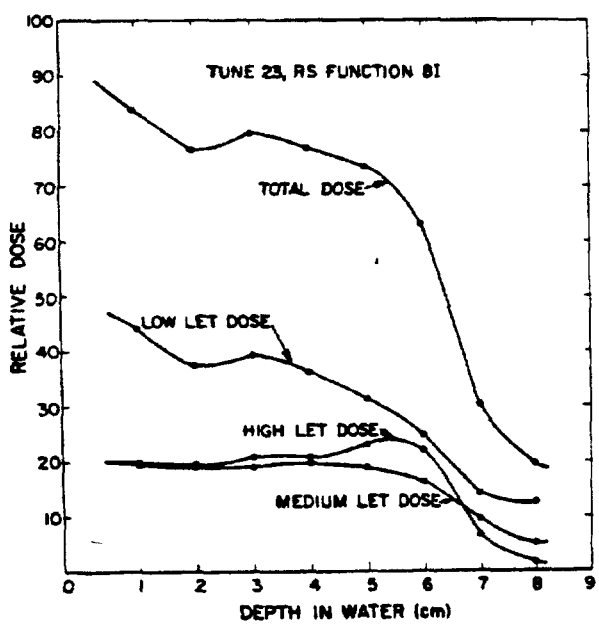

Fig. 13. For this beam the total dose was sloped downward distally to compensate for the higher RBE of approximately 1.4 of the distal dose.

One of the most interesting developments of this technique is the use of this probe *in vivo;* that is, with patients during treatment (15). We can check the treatment on skin, in the oral cavity and rectum of patients to make sure that both the total dose and the high LET dose agree with the treatment plan.

ACKNOWLEDGMENTS: It is a pleasure to thank the many people who have helped to make this work possible. First, we want to thank M. M. Kligerman and Richard Taschek for their vision and confidence in this program. Al Smith and Ken Hogstrom of the University of New Mexico Cancer Research and Treatment Center kindly gave us their ionization chamber data for the beams.

The entire Practical Applications Group (MP-3) at LAMPF has been very cooperative throughout the work. Jim Bradbury, Jerry Helland, Mike Paciotti, Pete Berardo and Sandra Zink have helped in innumerable ways. Jack Walton of the Lawrence Berkeley Laboratory made all of the fine detectors used in the experiments.

The people from our Electronics Division have kept the equipment working and have participated in the experiments. We would like to thank particularly David Woodwell, Gregory Wentz and Dick Hiebert. Jeff Richman has been very helpful with the experiments and with improvements in the manuscript.

COPIED FOR
HSPT
00133401.009

1087873

REFERENCES

1. Kligerman MM, West G, Dicello JF, et al: Initial comparative response to peak pions and x-rays of normal skin and underlying tissue surrounding superficial metastatic nodules. Am J Roentgenol 126: 261–267, Feb 1976

2. Smith AR, Kligerman MM, Kelsey CA, et al: Treatment planning for negative pi-meson radiation therapy: UNM/LASL experience. Int J Radiat Oncol Biol Phys (in press)

3. Smith AR, Rosen II, Hogstrom KR, et al: Dosimetry of pion therapy beams. Med Phys 4:408–413, Sep/Oct 1977

4. Kligerman MM, Smith AR, Yuhas JM, et al: The relative biological effectiveness of pions in the acute response of human skin. Int J Radiat Oncol Biol Phys (in press)

5. Paciotti MA, Bradbury JN, Halland JA, et al: Tuning of the first section of the biomedical channel at LAMPF. IEEE Trans Nucl Sci NS-22 (3):1784–1789, Jun 1975

6. Paciotti MA, Bradbury JN, Hutson RL, et al: Tuning the beam shaping section of the LAMPF biomedical channel. IEEE Trans Nucl Sci NS-24 (3):1058–1060, Jun 1977

7. Richman C: Characteristics of a negative pion beam in a therapeutic application. Radiology 116:187–189, Jul 1975

8. Amols HI, Dicello JF, Lane TF, et al: Microdosimetry of negative pions at LAMPF. Radiology 116:183–185, Jul 1975

9. Richman C: Characteristics of a negative pion beam for the irradiation of superficial nodules in cancer patients. Radiat Res 66: 453–471, Jun 1976

10. This was suggested to us by FH Attix

11. Derne S: Semiconductor Detectors for Nuclear Radiation Measurement. New York, John Wiley & Sons, 1971

12. Liska DJ: Pi-meson range shifter for clinical therapy. Rev Sci Instrum 48:52–57, Jan 1977

13. Amols HI, Liska DJ, Halbig J: Use of a dynamic range shifter for modifying the depth-dose distributions of negative pions. Med Phys 4:404–407, Sep/Oct 1977

14. Turner JE, Anderson VE, Birkhoff RD, et al: The determination of LET spectra from energy-proportional pulse-height measurements. II. A Monte Carlo unfolding procedure. Health Phys 18:15–24, Jan 1970

15. Richman C, Kligerman MM, Essen CF von, et al: Measurements of high LET dose in patients undergoing pion therapy. Presented at the Radiation Research Society meeting, May 14–18, 1978, Toronto, Canada

Chaim Richman, Ph.D.
Los Alamos Scientific Laboratory
MS-809
Los Alamos, NM 87545

COPIED FOR
HSPT

00133401.010

1087874