5-73
LA-5326-MS

INFORMAL REPORT

DR. 3H6

Uniform Dose Distribution with Moving Negative Pion Beams

los alamos
scientific laboratory

of the University of California

LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$4.00; Microfiche \$0.95

LA-5326-MS
Informal Report
UC-48

ISSUED: July 1973

Uniform Dose Distribution with Moving Negative Pion Beams

by

Eric Rodgers*

*University of Alabama, P. O. Box 1472, University, Alabama 35486.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER
REPRODUCTION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

UNIFORM DOSE DISTRIBUTION WITH MOVING NEGATIVE PION BEAMS

by

Eric Rodgers

ABSTRACT

Dense ionization in the stopping region as negative pions come to rest in matter makes them attractive for treatment of cancer. Pions of the same energy have essentially the same range in matter which means that a monoenergetic beam will produce a Bragg peak region of maximum ionization as they come to rest. In cancer therapy, the entire treatment volume should be exposed, if possible, to the Bragg peak. A distribution of energy and adjustment of lateral dimensions could theoretically adjust the Bragg peak to fit into most any treatment volume but this might be difficult in practice to accomplish. As an alternative, the beam can be tuned to produce a peak with known properties, and this peak can be moved in a controlled manner so as to scan the treatment volume. For a vertical beam, this method usually will require vertical oscillations of the beam as well as horizontal motion to cover the entire volume. Both of these motions can result in undesirable dose distributions. It is shown how to avoid or minimize the unwanted effects and it is also shown how velocity distributions can be determined for uniform effective dose throughout a treatment volume.

1. INTRODUCTION

Certain properties of negative pions make their use in treatment of cancer differ in a number of important respects from the use of high voltage x-rays or gamma rays. In the first place, their depth dose distributions are drastically different. A pion beam places the maximum dose in its stopping region known as its Bragg peak and which can be placed within a tumorous volume. The x-ray or gamma ray beam places its maximum dose near the surface of the body where it is not wanted in treatment of a tumor deep within the body. For the same maximum dose, the depth dose curves for pions and ^{60}Co gamma rays are somewhat as shown in Fig. 1.

A second difference is that of relative biological effectiveness (RBE). We define RBE as the number of dosage units of a chosen standard radiation per unit of the radiation in question for the same biological response. The standard radiation is usually taken to be 250 kV x-rays or ^{60}Co gammas which for the same dose produce essentially the same response. We shall subsequently refer to ^{60}Co only.

Fig. 1. Relative depth-dose curves for ^{60}Co and negative pions.

The RBE of the standard will by definition be 1. The RBE of any radiation will depend to some extent on the particular biological response that is compared.

The Bragg peak may have an RBE of 3-5 or even more as compared with ^{60}Co for some biological

responses. This high RBE in the peak is the result of the dense ionization along the tracks of the ionizing particles in the peak. The energy transferred to a medium by an ionizing particle per unit path length as it passes through matter is called its linear energy transfer (LET). As the pions slow down, their LET increases sharply. Also capture of the pions as they slow by atoms in the medium causes rupture of the atoms with emission of heavy "star" particles that also produce high LET ionization along their short ranges.

A third difference is also a consequence of the high LET in the peak. Experiment shows that cells deficient in oxygen (hypoxic cells) are more resistant to low LET radiation than similar cells that are fully oxygenated (aerobic cells). We define oxygen enhancement ratio (OER) for any radiation as the ratio of the dose required for hypoxic cells to that required for similar aerobic cells for the same biological effect. Hypoxic cells do not offer the same increased resistance to high LET radiation that they do to low LET radiation. The pion peak therefore has a lower OER value than ^{60}Co radiation.

As another significant difference, the dose in regions beyond the treatment volume is less for pions than for gamma rays. For a pion beam free of contamination with other particles, the dose beyond the Bragg peak would be very small.

We refer to the portion of the pion depth dose curve extending from the surface to the peak as the plateau of the curve because of its being rather flat. In this plateau region, the ionization is low LET in nature and it has an RBE that is approximately 1 and has a high OER.

To utilize a pion beam to its fullest advantage, we should arrange to have the treatment volume get as much of its total dose as possible from the Bragg peak. The LAMPF accelerator is expected to furnish an essentially monochromatic beam of negative pions that will penetrate to a depth of about 25 cm in water. The peak will occur at about this equivalent depth of absorbing material and presently is expected to be about 15 cm by 1.5 cm in horizontal dimensions and about 1.5 cm high. In the discussion that follows, we shall use a model that approximates the Bragg peak as being rectangular in cross section. It will probably be true that both vertical and horizontal relative motion of the peak will be neces-

sary in most cases to expose an entire treatment volume to the peak. The plan at LAMPF is to use a variable absorber to cause periodic vertical oscillations and to move the patient horizontally in a direction perpendicular to the 15 cm dimension of the peak, which dimension will also be varied by collimators. All motions will be computer controlled to give desired results in each case.

We shall describe motion patterns that will utilize the peak as much as possible and will give, for assumed beam parameters, a uniform dose throughout a treatment volume. First, however, we shall show that both vertical and horizontal motions can lead to undesirable dose distributions that are associated with edges of the moving peak.

II. EDGE EFFECTS

Let us consider vertical oscillations. In Fig. 2a, we assume that a treatment volume extends from AB down to GH, and that the Bragg peak which is represented by CDEF is oscillating between the limits defined by AB and GH. We assume that, at the instant, the peak is at a distance equal to its height CF above GH and that it is moving downward. This means that at the time indicated, the point b is just beginning to receive treatment. This will continue for b while FE moves down to GH and back to the position shown. The point c during this time will receive treatment only momentarily while the peak is in its lowest position. Points between b and c will receive a dose distribution that depends on the mode of oscillation. In Fig. 2b the straight line ca shows what it would be like for uniform motion of the peak. The dotted curve shows a typical distribution for simple harmonic motion. Obviously there would be a similar region at the top of the oscillation.

There is a similar and more extensive edge effect due to motion of the plateau. Again, let us look at Fig. 2a. The point p receives plateau dose during the entire oscillation from top to bottom and back. The point b, on the other hand, receives plateau dose only momentarily while the peak is in the lowest position. For points between b and p the plateau dose would follow some distribution similar to Fig. 2b but depending on the mode of oscillation. We see, therefore, that these edge effects together extend throughout the entire amplitude of the vertical oscillation.

Fig. 2a. Schematic representation of treatment volume.

Fig. 2b. Dose distribution in region between c and b of Fig. 2a for uniform motion and sample harmonic motion.

Now let us consider horizontal motion. For simplicity, let us momentarily forget vertical oscillations and assume a treatment to begin with the peak in the position shown in Fig. 3. We assume relative horizontal motion of the peak to the right. The point p would receive full peak dose but point q would receive dose only momentarily. Intermediate points would get doses that would increase from q to p. An exactly similar situation would exist as the peak is brought to rest at the end of the motion to the right.

This horizontal edge effect can be eliminated rather simply by absorbing blocks properly placed to move with the patient. Let us consider Fig. 4. The treatment volume is represented by T. If the treatment is started with the beam in position (1) and ended in position (2), the absorbing blocks A which move with the patient will remove the undesirable edge distribution for horizontal motion.

Fig. 3. Schematic representation of horizontal scan.

Fig. 4. Use of absorbing blocks, A, to shape the edges of horizontal scan.

III. TREATMENT METHODS

There is no way to remove the vertical edge effect if the beam is to be oscillated. The vertical and horizontal effects could simultaneously be avoided by the following procedure. Start with the beam in position (1) of Fig. 4 and with the variable absorber adjusted to place the bottom of the peak at the depth of the bottom of the treatment volume. Now, move the patient horizontally to bring the beam to position (2) at the necessary speed to give complete treatment to the slice traversed by the peak. Next, increase the absorber thickness to raise the peak vertically a distance equal to its height. Now move the patient horizontally to bring the peak back to position (1). The speed for this transit would have to be increased because this slice would have gotten plateau dose during the first transit. This process would be repeated until the treatment volume was covered.

There could be an objection to the method described in the last paragraph, since it would require matching peak edges between slices which might result in undesirable irregularities. However, the method probably should not be ruled out and may under some conditions be the best method to use.

For a smooth dose distribution throughout the height of a treatment volume, nothing other than possible energy spread of the beam itself, seems to offer the same possibility as controlled vertical oscillations. We cannot eliminate the peak edge effect but we can avoid it so far as treatment volume is concerned by starting and ending each half oscillation with the peak just outside the treatment volume. This gives extra dose to normal tissue but it is not serious. The method would add peak dose outside the treatment volume that would drop to zero in a distance equal to the peak height, or about 1.5 cm. This is much better than is possible with x-rays or gamma rays.

For any mode of vertical oscillation, the dose contribution from the plateau increases from bottom to top of the treatment volume. For a uniform total dose throughout, the dose from the peak must decrease as the peak moves upward to compensate for the increase in plateau dose. Liska¹ has suggested an upward motion with increasing velocity to accomplish this compensation. We now give a quantitative method for determining velocities needed for uniform total dose throughout the vertical treatment thickness for assumed beam parameters.

We begin by considering parameters that enter into the calculations. We must assume that depth dose data and shape of the pion beam are accurately known with distributions of RBE and OER values for the desired end point effects of each treatment. First we must study the depth curve and peak shape and decide on a value for the vertical thickness, which we call h , of the Bragg peak. Fortunately, the value chosen is not critical because values of other parameters depend on the value chosen for h in such a way that results of calculations vary insignificantly with small variations in h .

The second parameter that we need is K_0 , the average dose rate in the peak in rads/sec. For a given pion beam, K_0 varies inversely as h .

Now let us consider Fig. 5. The bottom of the treatment volume is indicated by GH. The beam is

Fig. 5. Schematic representation of vertical scan

considered at the instant to be in its lowest position with the peak of height h being indicated as the shaded region just below GH. The plateau will extend upward at the instant from GH. We now divide the region above GH into segments each of height h and number them as shown. With the beam in its lowest position, the plateau is divided into the numbered segments. We now need a ratio of peak effective dose to plateau effective dose for each of the segments. By effective dose we mean rads x RBE in each case and could mean (rads x RBE)/OER in each case. If all cells being treated were hypoxic, we would include OER in each effective dose and write effective dose as rads x RBE/OER. Since this is probably never the case, the radiologist will have to decide whether to include OER and to what extent. For the hypoxic cells, the proper ratio would require inclusion of OER, but aerobic cells would be overtreated with its inclusion.

Let k_n equal the estimated dose rate in the n th plateau segment in rads/sec and RBE_n and OER_n its values of these quantities. Then with the reservation concerning OER we write

$$r_n = \frac{K_0 \times RBE_0 \times OER_n}{k_n \times RBE_n \times OER_0} \quad (1)$$

where RBE_0 , K_0 and OER_0 refer to the peak in its lowest position. We let $D_0 = K_0 \times RBE_0 / OER_0$.

We need one other parameter to take care of a possible change in average dose rate in the peak as it moves upward. We take care of this by introducing R_n as the ratio of peak effective dose rate in the

nth position to that in the lowest position. Thus we normalize everything to the peak in its lowest position. R_n probably will be very close to 1 throughout.

Now we let $\bar{v}_n$ be the average velocity with which the peak crosses the lower boundary of the nth segment as the beam moves upward. This would also be the average velocity with which the leading edge of the peak crosses the nth segment. We shall find the expression for the dose given to the bottom boundary of the nth segment. From Fig. 5 we see that the first segment to cross this boundary is the $(n-1)$ st segment. The average velocity for this crossing is just the average velocity of the peak across the lower boundary of the treatment volume since the entire beam moves upward as a unit. The average velocity for the $(n-1)$ st segment is therefore $\bar{v}_1$, and the dose delivered by this segment is $hD_0/\bar{v}_1 r_{n-1}$. The next segment to cross is the $(n-2)$ nd and the dose from it is $hD_0/\bar{v}_2 r_{n-2}$. In a similar manner we express the dose from the remaining plateau segments. Finally the peak passes over and gives the dose $hD_0 R_n - 1/\bar{v}_n$. To get the total dose we add all contributions. We want the dose to be the same across all boundaries. We, therefore, set the sum of the contributions equal to a constant C to get

$$\left[\frac{R_n - 1}{\bar{v}_n} + \sum_{i=1}^{n-1} \frac{1}{r_{n-i} \bar{v}_i} \right] hD_0 = C \quad (2)$$

To get the value of C, we let $n = 1$. We get

$$\frac{hD_0}{\bar{v}_1} = C \quad (3)$$

This is the dose across the lower boundary of the treatment volume and depends on $\bar{v}_1$ which may be arbitrarily chosen.

We substitute the value of C into (2) and solve for $\bar{v}_n$. We get

$$\bar{v}_n = \frac{R_n - 1}{\frac{1}{\bar{v}_1} - \sum_{i=1}^{n-1} \frac{1}{r_{n-i} \bar{v}_i}} \quad (4)$$

The quotient $h/\bar{v}_n$ gives the time t_n required for the peak to cross the various segment boundaries.

The average velocities given by (4) make the various boundaries between segments get the same dose but doses may vary between boundaries. We desire a scheme that makes the dose the same everywhere. Perhaps the simplest scheme that would give the same dose everywhere is that for which the peak would move with constant velocity across each boundary equal to $\bar{v}_n$. To show that this would give uniform dose, we refer to Fig. 6 which is similar to Fig. 5.

Let P be any point in the nth segment and let x equal its distance above the lower boundary of the segment. As the beam moves up P will get its first dose from the portion of the nth segment below P. The time for this to cross P at constant speed $\bar{v}_1$ is $x/\bar{v}_1$ and the effective dose is $x D_0/\bar{v}_1 r_n$.

We divide the treatment from the $(n-1)$ st segment into two parts. First it will move upward a distance $h-x$ at speed $\bar{v}_1$, and the dose contribution is $(h-x) D_0/\bar{v}_1 r_{n-1}$. Next it will move upward a distance x with speed $\bar{v}_2$ and its dose contribution is $x D_0/\bar{v}_2 r_{n-1}$. As we consider other segments we must divide each into two parts of widths $h-x$ and x respectively and note that they move with different speeds but have the same r values. Finally, as the peak passes, it contributes the terms $R_{n-1}(h-x)D_0/\bar{v}_n$ and $R_n x D_0/\bar{v}_{n+1}$ to the

Fig. 6. Schematic representation of vertical scan.

dose. We get the total dose at P by adding all contributions. We get dose at P

$$\begin{aligned}
 &= \left[\frac{x}{\bar{v}_1 r_n} + \frac{h-x}{\bar{v}_1 r_{n-1}} + \frac{x}{\bar{v}_2 r_{n-1}} + \frac{h-x}{\bar{v}_2 r_{n-2}} \right. \\
 &+ \dots + \left. \frac{R_{n-1}(h-x)}{\bar{v}_n} + \frac{R_n x}{\bar{v}_{n+1}} \right] D_0 \\
 &= \left[x \sum_{i=1}^n \frac{1}{\bar{v}_i r_{n+1-i}} + (h-x) \sum_{i=1}^{n-1} \frac{1}{\bar{v}_i r_{n-i}} \right. \\
 &+ \left. \frac{R_{n-1}(h-x)}{\bar{v}_n} + \frac{R_n x}{\bar{v}_{n+1}} \right] D_0 \quad (5)
 \end{aligned}$$

We can simplify this expression by using Eq. (4) to expand the last two terms in the bracket. We get

$$\begin{aligned}
 \frac{R_{n-1}(h-x)}{\bar{v}_n} &= \frac{h-x}{\bar{v}_1} - (h-x) \sum_{i=1}^{n-1} \frac{1}{\bar{v}_i r_{n-i}} \\
 \frac{R_n x}{\bar{v}_{n+1}} &= \frac{x}{\bar{v}_1} - x \sum_{i=1}^n \frac{1}{\bar{v}_i r_{n+1-i}} \quad (6)
 \end{aligned}$$

If we substitute these expanded values for the last two bracketed terms, everything cancels except the expression $h/\bar{v}_1$. This multiplied by D_0 is $h/\bar{v}_1 D_0$, which is the dose across boundaries. Since P is an arbitrary point in an arbitrary segment n, we see that this plan gives the same dose everywhere.

The method just described would require sudden increments in velocity as the leading edge of the peak reaches each boundary.

Liska and Wallace² have described two mechanical systems for varying the absorber thickness to cause the beam to oscillate vertically. One of these would vary the thickness by insertion of thin plastic slabs. The other would vary the depth of a column of water through which the beam would pass. We shall discuss the thin slab method first.

The thin slabs should be identical and should be of such thickness that the insertion of some integral number of slabs would cause the peak to rise exactly its height h, or in our terminology, exactly one segment height. If the slabs as described are inserted at exactly equal time intervals for any segment n so that the sum of these time intervals for the segment is $t_n = h/\bar{v}_n$, the resultant effective dose for this segment is completely uniform and equal to the constant dose $hD_0/\bar{v}_1$ of the

boundaries. If this procedure is repeated on all segments, the dose at every point in the vertical strip of the treatment volume will be exactly $hD_0/\bar{v}_1$. Obviously, the removal of slabs in reverse order will assure this same dose for the downward journey of the beam.

We shall prove the statement of the last paragraph for the case where each slab moves the peak up 1/3 of a segment height and we shall do the proof for the middle 1/3 of the nth segment. The method of proof would be the same for any other slab thickness and for any other slice of segment n.

Let us again view the beam as being in its lowest position as shown in Fig. 7 with the bottom of the treatment volume at GH. We again divide the beam into segments of height h, but now we divide each segment into 3 slices as shown. We shall compute the dose given to the slice marked A as the beam crosses it on the way up. Slice A will get its first treatment of the upward journey as the slice marked 1 moves to A and remains for the time $\frac{1}{3} h/\bar{v}_1$. Since slice 1 is in the nth segment, its r value is r_n . Therefore the dose given is $hD_0/3r_n \bar{v}_1$. Next slice 2 will move to A and give dose $hD_0/3r_{n-1} \bar{v}_1$. Slice 3 will supply the same dose as slice 2. We continue this for all segments

Fig. 7. Schematic representation of vertical scan.

and slices that are to supply dose to A until finally it gets dose from the peak. The last contribution to the dose will come from the bottom slice of the peak and it will be $R_n hD_o / 3\bar{V}_n + 1$. We sum all of these contributions to get the total as follows:

$$\text{Total dose} = \left[\frac{1}{3} \sum_{i=1}^n \frac{1}{\bar{V}_i r_n + 1 - i} + \frac{2}{3} \sum_{i=1}^{n-1} \frac{1}{\bar{V}_i r_n - i} + \frac{2}{3} \frac{R_n - 1}{\bar{V}_n} + \frac{R_n}{3\bar{V}_n + 1} \right] hD_o \quad (7)$$

We again use (4) for the last two terms in the bracketed expression.

$$\begin{aligned} \frac{2}{3} \frac{R_n - 1}{\bar{V}_n} &= \frac{2}{3\bar{V}_1} - \frac{2}{3} \sum_{i=1}^{n-1} \frac{1}{\bar{V}_i r_n - i} \\ \frac{R_n}{3\bar{V}_n + 1} &= \frac{1}{3\bar{V}_1} - \frac{1}{3} \sum_{i=1}^n \frac{1}{\bar{V}_i r_n + 1 - i} \end{aligned} \quad (8)$$

Substitution of these values gives again the value $hD_o / \bar{V}_1$ for the dose.

We should point out that the method just described provides uniform dose only if no time is required for actual insertion of the plates. The mechanism used should, therefore, insert the plates as quickly as possible.

The variable water column can be used to move the peak upward in continuous motion, but it can also be used to move it in discrete steps. If it were made to move the peak in three steps of equal time intervals across the various segments, the analysis and result would in all respects be the same as shown for the slabs. We now discuss the case where the column of water is varied to cause continuous motion.

We begin by plotting the average velocities of the leading edge of the peak across the various segments as given by (4). We plot velocities as ordinates and distances moved by the peak from its lowest position as abscissas. Since we are dealing with average velocities, we plot each velocity at the center of its respective segment interval.

We would now like a curve that would represent the velocity at every point and have the average values that we have computed for the various segments. Unfortunately, there is no unique curve with these properties. An unlimited number of such curves exist which provide the dose $hD_o / \bar{V}_1$ across

curves exist which provide the dose $hD_o / \bar{V}_1$ across all boundaries but with variable doses between boundaries. Fortunately, we can easily choose one of these curves for which dose variations between boundaries are negligible. We proceed as follows:

Let V_1, V_2 , etc. be actual velocities of the leading edge of the peak as it crosses boundaries 1, 2, etc. We now choose a value of V_1 that is a little smaller than $\bar{V}_1$. We then assume a uniform velocity increase across each segment, which requires the following

$$V_{n+1} = 2\bar{V}_n - V_n \quad (9)$$

With our trial value of V_1 this expression can be used to find quickly all other resulting V values. We find these values and compare them. If they tend to oscillate in value rather than increase smoothly, we reject them and start with a different value for V_1 . This trial and error method rather quickly yields a set of satisfactory values.

We now plot the V values on the same graph, but with abscissa values at the beginning of the respective segment intervals. We then join consecutive V values with straight line segments. The relation between V and $\bar{V}$ values makes each $\bar{V}$ lie on a segment which it bisects.

This procedure gives a broken curve since it is made up of straight line segments. As we shall see in the example that we work out, the curve actually appears to have continuously varying curvature and with slight modification could be made continuously varying with negligible variations in dose. The dose provided by this method varies slightly throughout segments, but rather extensive checks in actual examples have failed to find a point where the dose differs by as much as 1% from the boundary dose of $hD_o / \bar{V}_1$.

We shall now exemplify the method by working out an example for an assumed set of parameters. We assume the following:

$$\begin{aligned} h &= 1.5 \text{ cm} \\ D_o &= 50 \text{ effective rads/sec} \\ r_1 &= 4.0 \\ r_2 &= 5.1 \\ r_3 &= 5.7 \\ r_4 &= 5.9 \\ r_5 &= r_6 = \dots = 6.0 \end{aligned}$$

$$\bar{V}_1 = 10 \text{ cm/sec}$$

$$R_0 = R_1 = \dots R_n = 1$$

Eq. (4) gives values of $\bar{V}_n$ that are shown in the second column of Table I. The third column gives the corresponding times $t_n = h/\bar{V}_n$. The fourth column gives a possible set of actual initial velocities of the peak across the various boundaries. These velocities were obtained by assuming $V_1 = 8.32 \text{ cm/sec}$. The graph in Fig. 8 shows a plot of all V values and $\bar{V}$ values with consecutive V values joined by straight line segments. It is easy to compute the velocity represented by any point on this broken curve. This has been done for two points on each segment and the dose calculated for each point. No point was found with a dose difference of as much as 1% from $hD_0/\bar{V}_1$.

If we should use the thin slab method with the data in our example and should insert three slabs per segment distance, each insertion would move the peak

TABLE I

Segment Number	V cm/sec.	t_n sec.	V_n cm/sec.
1	10.0	0.15	8.32
2	13.3333	0.1125	11.68
3	16.2227	0.09246	14.9867
4	19.1059	0.07851	17.4587
5	22.3607	0.06708	20.7531
6	26.0661	0.05755	23.9687
7	30.4477	0.04926	28.1639
8	35.5752	0.04216	32.7315
9	41.5650	0.03609	38.4189
10	48.5623	0.03089	44.7111
11	56.7368	0.02644	52.4137

TABLE II

Step beginning	Total dose (rads)	Peak contribution (rads)	Step beginning	Total dose (rads)	Peak contribution (rads)
0	7.500	7.500	7.5	7.500	2.878
0.5	7.500	6.875	8.0	7.500	2.739
1.0	7.500	6.250	8.5	7.500	2.601
1.5	7.500	5.625	9.0	7.500	2.463
2.0	7.500	5.291	9.5	7.500	2.345
2.5	7.500	4.957	10.0	7.500	2.226
3.0	7.500	4.623	10.5	7.500	2.108
3.5	7.500	4.391	11.0	7.500	2.007
4.0	7.500	4.158	11.5	7.500	1.906
4.5	7.500	3.926	12.0	7.500	1.804
5.0	7.500	3.735	12.5	7.500	1.718
5.5	7.500	3.544	13.0	7.500	1.631
6.0	7.500	3.354	13.5	7.500	1.544
6.5	7.500	3.195	14.0	7.500	1.470
7.0	7.500	3.036	14.5	7.500	1.396

up 0.5 cm. In Table II we show total dose and peak dose for segment slices lying at the distances given in the first column from the lower boundary of the treatment volume. We give all of these results to show that the contribution of the peak drops steadily as it moves upward. Its value becomes rather small if the treatment volume is 15 cm high. A divided treatment from opposite ports will give a much better distribution of peak contribution

Fig. 8. Velocity distribution with vertical distance.

Fig. 9. Schematic representation of combined vertical and horizontal scanning.

IV. DISCUSSION

Let us now take a close look at simultaneous vertical and horizontal motion. We shall assume for simplicity that two complete vertical oscillations are completed for a horizontal distance of one peak thickness. We assume that both motions start with the beam in position (1) of Fig. 9 where absorber A is stopping the beam and both motions continue until the beam is in position (2). The sloping lines represent path of the leading edge of the peak through the treatment volume. When the leading edge has reached P, the various triangular wedges have been treated the number of times shown in the figure. We see that when the beam arrives at position (2) every point in the treatment volume will have received four identical treatments. An interesting question now arises. Would there be much advantage of increasing the vertical oscillation frequency so that each point is treated more than four times? If the four treatments per point are sufficient, we could gain greatly in another respect from the slower oscillations.

To see the advantage of the slower oscillations, let us look at our numerical example. The assumed parameters in the example would deliver 15 effective rads per oscillation. For a treatment of 150 effective rads, we would have to have 10 complete oscillations for a horizontal distance of one peak thickness. If we could reduce this to 2 oscillations per peak thickness we would increase the times in column 4 of Table 1 by a factor of 5 and would reduce all velocities in Table 1 by a factor of 5. This would very much simplify the mechanical problems of oscillating the beam.

There is a problem connected with simultaneous motion that is independent of the oscillation rate. Suppose the bottom (or the top) boundary of the treatment volume varies in depth. We would like to adjust the oscillations to follow the contour. Here is where we meet the problem. Suppose that the lower boundary of the tumor volume curves upward sharply at the horizontal position of P in Fig. 9. If the lower limit of the oscillations were raised at P for the leading edge to follow the contour, the lower portions of segments marked 1, 2, and 3 would be grossly undertreated. This means that we cannot simply adjust oscillation amplitudes to follow lower (or upper) contours.

To see what can be done, let us consider Fig. 10 in which the curve represents a curving lower boundary. The upper boundary is taken to be horizontal although it could also be curved. Again the sloping lines represent the path of the leading edge of the peak and again we assume two complete vertical oscillations per peak thickness. This means that each point in the treatment volume is traversed by the peak four times for complete treatment.

For uniform dose, the peak must move upward in a manner that has been described earlier, and must exactly reverse its upward motion for the downward journey and must come all the way back to the starting point. Any shift in lower position must take place at the completion of an oscillation and before the next oscillation begins. Also a change in starting position must lag two complete oscillations behind the contour change that it is to follow.

Let us now look at Fig. 10 more closely. We have, in the figure, indicated bottom positions of oscillations by the letter a and have indicated new starting positions by the letter b. As the beam moves to the right, the triangular segment marked 4 gets its fourth and final treatment on the upward swing which gives segment 1 its first treatment. On the following downward journey, the peak must return to its starting level, but can then jump to the b_1 position to begin the next oscillation. This procedure is repeated as the beam moves to the right.

The jump from a bottom position to a new starting position should take place quickly but the time taken is probably not at all critical. With the parameters that we are assuming, and with a treat-

Fig. 10. Schematic representation of combined vertical and horizontal scanning with boundary variation.

ment height of 10 cm, the horizontal speed for a total dose of 150 effective rads is approximately 0.125 cm/sec. If the jump can be accomplished in 0.20 sec, the beam would move only 0.25 mm while the jump is taking place.

The time needed for a complete oscillation depends on the vertical distance traveled and can be found with needed interpolations from a table similar to Table I for any given set of parameters. As the oscillation period changes, the horizontal speed must change to keep the dose constant. The proper time for the change in horizontal speed is at the beginning of an oscillation.

The method just described puts some extra dose into normal tissue, but it is less than might at first appear for two reasons. In the first place the linear dimensions of the normal regions getting extra dose are usually small, and in the second place, most points in these regions will not get full treatment.

If a treatment volume has contours that change abruptly by large amounts, it might be in order to think of the volume as consisting of more than one part, and to treat the parts separately. Such a situation might be like that in Fig. 11.

The numerical results and the methods used in this paper follow from a definite set of assumptions concerning the nature of a negative pion beam. When full information is available on the properties of the beam, the methods will have to be modified accordingly.

Fig. 11. Schematic representation of a treatment scheme with varying thicknesses and depth contours.

REFERENCES

1. Donald J. Liska, "Determination of the Optimum Shape of Sweep Curve for the Biomed Energy Absorber to Give Uniform Dose with Depth," Los Alamos Scientific Laboratory, Unpublished report, Oct. 12, 1972.
2. Donald J. Liska and Jerry D. Wallace, "Biomed Pion Energy Control Actuators," Los Alamos Scientific Laboratory, Unpublished report, Sept. 1, 1972.