A METHOD OF EFFECTIVELY WIDENING THE BRAGG PEAK IN DEPTH
IN THE PATH OF CHARGED HEAVY PARTICLES IN TISSUE

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Proposed running head: Widening the Bragg Peak in Tissue

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Heavy particles are very much heavier than electrons-- the deuterons some 4,000 times heavier--and do have by virtue of their physical properties some unique and important applications in medicine and biology. Due to their mass the angle of scattering in a given collision is reduced by about the same ratio of mass difference. They also possess a definite range of penetration in matter instead of following an exponential law as do X- or gamma rays.

In passing through a material the particle loses some of its energy per unit length of path. This rate of energy loss is called the linear energy transfer (L. E. T.) of the particle in the material it traverses. The particles lose their energy to the material they traverse by means of ionization, elastic scattering, inelastic scattering, and excitation.

Ionization occurring in tissue along the path of penetration particles increases in density as the particle continuously loses its energy. In the final portion of the path, the energy given up per unit of path length rises to a peak just before the end of the path is reached. This has been observed experimentally and the process has also been treated theoretically. The classical treatment (1) gives the relationship

$$\frac{dE}{dx} = \frac{4 e^4 z^2}{m v^2} N B$$

Where the factor B, known as the electronic stopping power, is given by:

$$B = Z \log \frac{2 n v^2}{I}$$

In these equations the properties of the incident particle appear as its initial energy E, its velocity v, and its charge ze. In the material

under irradiation, the distance is x , N is the atoms/cc, Z is the nuclear charge, and I is the average excitation potential. Electrons in the target material have mass m : the mass of the incident particle does not come into this relationship. But it must be remembered that the range or depth of penetration is an important function of the mass of the incident particle. The Bragg ionization curve is a plot of the relative specific ionization of a collimated beam of particles as a function of the thickness of absorber that the beam has traversed. The curve can easily be obtained experimentally by taking the ratio of currents from two ionization chambers—one placed before, and the other behind an absorber. A graph demonstrating the Bragg curve for 20 Mev deuterons traversing tissues and aluminum (3) are depicted in Figures 1 and 2. This is a measured curve for a beam with about 1% energy spread.

It is obvious from this curve that with every increment of aluminum mass traversed there is a larger increment of energy loss. This proportionally larger energy loss in comparison to the thickness of aluminum mass traversed takes on very much larger dimensions near the end of the path of the deuterons in aluminum. At the end of their track in aluminum the deuterons deposit a very large proportion of their energy—approximately six times more per unit thickness of aluminum traversed than in the beginning. This very narrow area of high energy loss or intense ionization at the end of their path is known as the Bragg peak, so named after Sir William Bragg (2).

In studying the biological effects of charged heavy particles in biological materials and trying to compare the effect of a certain number of particles in the beginning of their track to the effect of the same number of particles at the end of their track; it becomes evident that the

region of intense ionization is so narrow in depth that it is very difficult to observe effects on tissue exposed only in that region. In normal brain, Malis, Baker, Kruger, and Rose (3) have demonstrated lesions as thin as 50 microns. The time that lapses to demonstrate morphologically the Bragg absorption peak in fast growing tissue, e.g., animal neoplasms is more than sufficient to allow the cells on either side of this region to replace cells in that intense ionization region, thus obscuring effects that may have occurred in the highly localized region.

The objective of the present studies was to effectively widen the Bragg peak in depth in the path of the charged heavy particles through tissues; in order to allow study of the biological effects of a certain number of particles in the beginning of their track compared to the effects of the same number of particles at the end of their track.

Material and Methods

The 60-inch cyclotron at Brookhaven National Laboratory which accelerates deuterons to energies of 20 Mev; a current density of 1.83×10^{-11} amps/cm² has normally been used. With this beam 1.15×10^8 deuterons/cm²/sec is delivered.

In initial studies an aluminum filter of appropriate thickness was introduced into a deuteron beam which decreased the energy of the beam and resulted in the production of a Bragg peak at a lessened range in the tissue. In order to get many Bragg peaks at different depths throughout the tissue so close to each other that all the tissue would be in this intense ionization area, it was possible to interrupt the exposure at short intervals and to introduce successively thicker aluminum filters between the radiation port and the tissue. It was found necessary to introduce sixteen different

filters in order to achieve this objective. This makes it necessary to deal with short exposure times that can not be measured accurately apart from the fact that it is time consuming.

These difficulties were obviated by introducing a disc filter driven by an electric motor that revolves in front of the radiation port (Depicted in Figures 3 a and b).

The wheel itself is of heavy aluminum 30 cms in diameter with 16 apertures of accurately determined width on its periphery. In each of the apertures an aluminum foil of appropriate thickness was clamped. The wheel was driven by a synchronous motor at 300 rpm. Each foil therefore passed the beam five times each second. One-fifth second was very short compared to the shortest exposure time used, thus a good averaging was achieved. The prescription for aperture size and foil thickness was:

<u>Foil Number</u>	<u>Foil Thickness in Inches</u>	<u>Angular Opening in Degrees of Circle</u>
1	0	73.6
2	0.0015	19.9
3	.003	23.5
4	.0045	14.7
5	.0065	16.2
6	.009	16.2
7	.0115	13.2
8	.014	13.2
9	.017	12.5
10	.02	12.5
11	.023	11.8
12	.0265	11.0

<u>Foil Number</u>	<u>Foil Thickness in Inches</u>	<u>Angular Opening in Degrees of Circle</u>
13	.03	11.8
14	.0335	11.0
15	.037	9.5
16	.0405	9.5

Figure 2 shows the ionization curve resulting. The top curve shows the variation of ionization with depth when using the full wheel. The middle curve shows the ionization curve which could be achieved if only the first seven openings were used. The bottom curve represents a single irradiation with no filter for comparison. The thicknesses and fractions of the circle defined for each filter were designed by approximate calculations and adjusted by trial to provide an essentially uniform distribution of dose throughout the range of depth studied. The variation in ionization is about 4 per cent from the mean. With more apertures and smaller steps in foil thickness a smoother result could be achieved.

Discussion

There are two words of caution. One, it should be noted that the prescription given in detail is specific to the particular accelerator and bombarding particle. Higher energy beams might require more than 16 steps, alpha particles or protons would require a different prescription and a beam with less energy spread might require more sectors with smaller variation to get the same smoothness.

The second caution involves a possible distortion of the curve. When used in a narrow beam geometry the deuterons undergo a certain amount of scattering in the aluminum foils. For example, in losing half its range in

aluminum the deuterons will be scattered through a mean angle of about $2\frac{1}{2}^{\circ}$ (4) and a beam that has lost 90 per cent of its range will be scattered through an angle of 5.1° . At great distances this scattering will result in a loss of intensity in the beam for those particles which have passed through the thickest filters.

This scattering should be taken into account in such circumstances in arriving at the correct prescription. At small distances such as five times the beam diameter or less the reduction in intensity by scattering is not significant.

In the experiments where this wheel was used, the specimen was 5 cms away from the wheel, and the wheel 5 cms away from the radiation port which was 2 cms. in diameter. Thus little reduction in intensity resulted. An improvement of about 35% in the scattering could be made with the use of plastic or other light element filters. They are not, however, as readily available in precise and uniform thickness.

With this filtration device it is possible by simply altering the thicknesses and position or elimination of the segments of aluminum to produce any width of intense ionization effect or even several layers of intense ionization at different depths separated by layers of less ionization effect. The limitation of this application is obvious; because with the introduction of every filter the "neck" of the curve builds up to equal or pass the tail of the curve (Figure 2). This method, however, retains the advantage of being able to produce a cylinder of uniform ionization which cuts off sharply in depth in tissue. It is, therefore, possible to do further studies in comparing the RBE of different energetic charged heavy particles at different energies not only in the beginning of their track in tissue but also at their intense ionization region in different tissues.

Summary-

A device is described for the filtration of charged energetic heavy particles resulting in the production of adjacent or separated Bragg peaks within the range of the particles in tissue. Two or more layers of intense ionization at different depths separated by layers of less ionization in tissue can be produced. A cylinder of uniform ionization which cuts off sharply in depth in tissue can also be produced.

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LEGENDS

Figure 1 This curve represents a plot of the relative ionization for 20 Mev deuterons in tissue. (BNL Neg. No. 9-83-60)

Figure 2 These three curves represent plots of the relative ionization for 20 Mev deuterons in aluminum.

The top curve represents the relative ionization following the successive introduction of sixteen filters of aluminum of different thicknesses as outlined on page 6.

The middle curve represents the relative ionization following the successive introduction of the first seven aluminum filters outlined on page 6.

The lower curve represents the resultant relative ionization of 20 Mev deuterons in aluminum. (BNL Neg. No. 3-836-61)

Figure 3A Shows the wheel viewed from behind with the motor driving it as well as the beam port. (BNL Neg. No. 1-497-61)

Figure 3B Shows the wheel viewed from the front as well as a mouse in position of irradiation and the sliding telescopic sight which is used to check the position of the anatomical region of the mouse to be irradiated accurately. (BNL Neg. No. 1-498-61)

BNL N59. No. 1-497-61 Fig. 3a

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