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Uniform Depth-Dose Distributions from Monoenergetic Negative Pion Beams

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UNIFORM DEPTH-DOSE DISTRIBUTIONS FROM

MONOENERGETIC NEGATIVE PION BEAMS*

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ABSTRACT

Negative pions are attractive for cancer treatment because of a sharp enhancement of the deposited dose at the end of their range. The volume of interest has to be exposed to a uniform dose. The problem of using an inhomogeneous filter absorber to transform a monochromatic negative pion beam with a known dose deposition into a beam which causes a uniform depth dose within the treatment volume is investigated. Various shapes of absorbers are discussed. Dose deposition as a function of depth is treated analytically. The influence of beam divergence and multiple scattering is studied for various arrangements, and numerical sample calculations illustrate the importance of these effects.

I. INTRODUCTION

The problem of transforming a focused, monochromatic negative pion beam into a beam which deposits a uniform dose within a specified treatment volume has been dealt with before.[1,2] The present paper concentrates on the dose uniformity along the incident beam direction. A broadening of the Bragg peak at the end of the pion range can be achieved by superposition of pion beams of different energies. Analytical expressions are desired for the relative abundance of a given pion energy in the mixture. Various filter absorbers (also called range-shifters) for transforming a monochromatic beam into a polychromatic mixture of the appropriate composition are discussed. They are alternate solutions to the scheme presently under construction at LAMPF which consists of a plane-parallel water absorber with variable thickness.[3] Studies are presented on the importance of non-parallel incident beams and multiple scattering.

The basis of our considerations will be a measurement of the depth dose obtained with a "monochromatic" π^- beam in a water target.[4] This dose distribution has been modified taking into account the higher relative biological effectiveness of the radiation near the end of the pion range by enhancing the peak dose with respect to the plateau dose. Thus we obtained a hypothetical depth distribution of "effective" dose which is employed throughout the remainder of this paper. A modification of this initially assumed depth distribution would affect the details, but not the essential conclusions of this paper. The purpose of the present paper is not to give a recipe for the construction of a particular scheme, but rather to show the available options and advantages or problems of different arrangements.

II. BASIC CONSIDERATIONS

The effective depth-dose distribution of a beam of negative pions is characterized by a sharp enhancement at the end of the pion range, composed by the Bragg peak and radiation contributed by π^- stars. We define as R the depth at which this peak occurs as measured from the surface of the stopping

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absorber. The dose $d(r)$ at a given depth r from the surface of the target can be expressed as a function of r and R. The latter is related to the incident pion energy. An analytical expression for the effective depth-dose distribution has been obtained by fitting numerical values which are a combination of experimentally determined dose[4] (using a beam with 2.5% momentum spread) and assumed values for the relative biological effectiveness:

$$d(r,R) = \begin{cases} 0.186 + 0.814 \exp\left[-\dfrac{(r-R)^2}{2.9}\right], & \text{for } r \le R \\ \exp\left[-\dfrac{(r-R)^2}{12.25}\right], & \text{for } r \ge R \end{cases} \quad (1)$$

This distribution has been normalized such that at the peak $d(r = R) = 1$. The lengths r, R are measured in centimeters. The expression (1) is plotted as a solid curve in Fig. 1.

In order to achieve a flat depth-dose distribution we superimpose beams of different intensity and range. In general we can formulate our problem as follows. We want to find a function $W(R)$ which measures the relative intensity (weight) of the

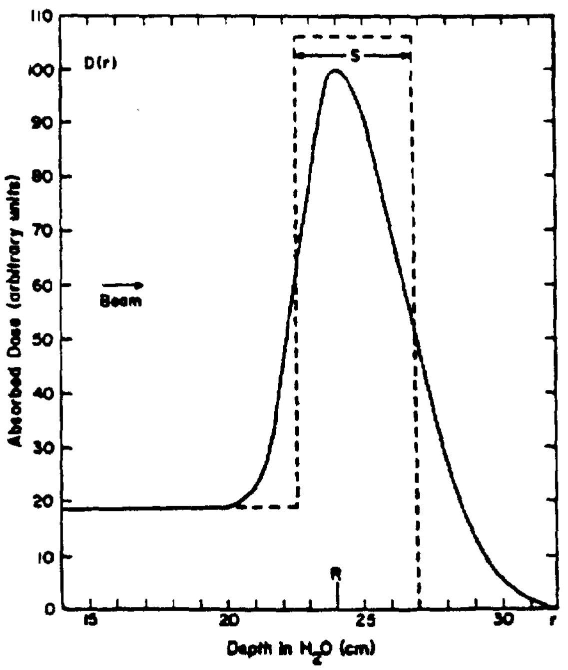

Fig. 1. Realistic and idealistic (rectangular) effective depth-dose in H_2O.

fraction of the total beam which has a maximum dose at a depth R. This function $W(R)$ should be determined such that the total dose $D(r)$ inside a given depth interval is constant.

$$D(r) = \int_{R_1}^{R_2} W(R)\,d(r,R)\,dR = \text{const for } r_1 < r < r_2 \quad (2)$$

In order to gain some basic insight, we might, for a moment, replace the realistic dose distribution, $d(r,R)$, by a hypothetical rectangular distribution, which is defined such that it has the same value in the plateau, the same integral over the peak, and intersections with $d(r,R)$ at half the maximum of the respective Gaussian slopes (dashed line in Fig. 1). The fraction, g, of the dose in the plateau as compared with the peak of the rectangle is $g = 0.176$. The width, S, of the rectangular peak becomes $S = 4.33$ cm. It is easy to see (Fig. 2) that in this simple case the weight-function $W(R)$ is an exponential of R:

$$W(R) = e^{-\frac{g}{S}(R_o-R)} = e^{-\eta(R_o-R)}, \quad (R < R_o) \quad (3)$$

where R_o is the maximum R in the beam mixture (deep edge of distribution). Furthermore, it is obvious that the dose in the plateau relative to its value at the peak must increase if the peak has to be broadened by superposition. If the broadened peak width is S' the new ratio of plateau to peak dose g'

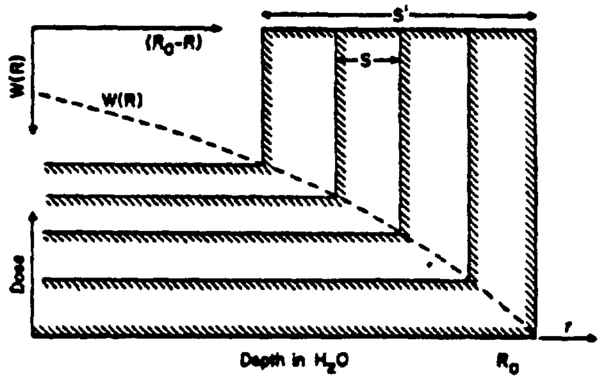

Fig. 2. Superposition of idealistic (rectangular) effective dose distributions.

is

$$g' = 1 - e^{-g\frac{S'}{S}} \qquad (4)$$

Giving a numerical example, we find that the relative plateau dose doubles for a broadening to $S' = 11$ cm.

One can now ask for the exponent η in the weight function (3) which causes a total dose D(r) with a flat, broad peak in the case of a realistic dose distribution d(r,R). In Fig. 3 the depth-dose distribution D(r) as a function of η is shown in the form of isodose curves with a spacing of 1% of the peak dose in the flat region. A maximum range shift of $(R_o-R)_{max} = 15$ cm has been chosen. The value $\eta = 0.045$ has been selected and is employed in all following calculations. The depth dose curve obtained with $\eta = 0.045$ is shown in Fig. 4. We want to point out that η has changed by only 10% by going from a rectangular to a realistic dose distribution. This documents that the approximation (3) for the weight function is quite accurate since it is only weakly dependent on the peak shape and exactly true for a rectangular distribution.

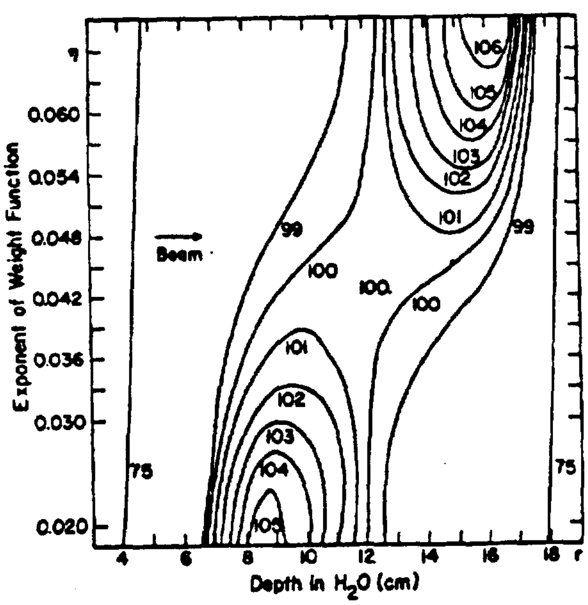

Fig. 3. Contour map of the effective depth dose $D(r,\eta)$ (arbitrary units) as a function of exponent in weight function and depth in H_2O.

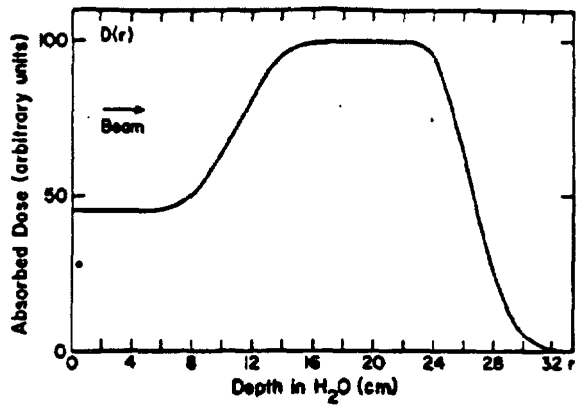

Fig. 4. Effective depth-dose distribution for $\eta = 0.045$.

The resulting analytical expressions for d(r,R) and W(R) provide the tool to quantitatively back up the statements which will be made in the following paragraphs.

III. STATIC FILTER ABSORBERS

One way to transform a monochromatic beam into a mixture of beams with ranges R of relative abundance W(R) is to attenuate the beam with an inhomogeneous filter absorber, where the probability of a given ray in the beam to find an absorber thickness which shifts the peak dose of this ray in a subsequent water target by R is equal to W(R). One way to build such an absorber is shown in cross section in Fig. 5. This is a static, two-dimensional version of an arrangement which has been suggested earlier by Helland.[2] The shape h(x) of one segment of the absorber structure has been found by integrating the

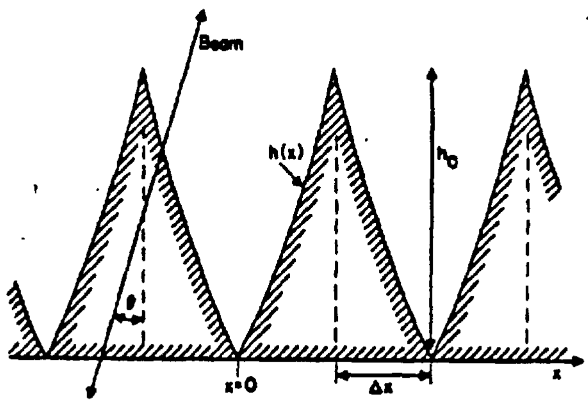

Fig. 5. A stationary range-shifter.

weight function W(R) under the given boundary conditions. Besides the choice of material used to build the absorber, there are also the free parameters; Δx, which determines the lateral repetition rate of the structure, and h_o, which is given by the maximum range shift ΔR_{max} the absorber should produce. The analytical expression for one segment hence becomes

$$\left.\begin{aligned} h(x) &= -\frac{1}{\eta} \ln\left(1 - \frac{x}{B}\right) \\ B &= \frac{\Delta x}{1-e^{-h_o \eta}}, \ \eta = 0.045,\ 0 \le x \le \Delta x, \end{aligned}\right\} \qquad (5)$$

where the unit of length is 1 cm.

An upper limit for the choice of Δx is given by the requirement that the energy composition of the beam in the stopping region, perpendicular to its axis, must be constant. This can only be achieved by washing out on the way to the stopping region the lateral energy structure which, of course, exists right after passage through the filter absorber. The selected Δx has therefore to be smaller than the increase in spot size at the end of the range caused by multiple scattering between the absorber and the stopping region. As a reasonable choice we set $\Delta x = 1$ cm for the following considerations.

For a parallel beam incident perpendicular to the plane of the filter absorber ($\theta = 0^\circ$ in Fig. 5), neglecting multiple scattering effects in the filter absorber, we obtain a dose distribution in a subsequent water target which corresponds exactly to the one shown in Fig. 4.

This is no more the case in a real situation, because of beam divergence and multiple scattering in the filter absorber.

First we discuss the effects of beam divergence by calculating dose distributions for a parallel beam intersecting the absorber plane (Fig. 5) under an angle $\theta \neq 0^\circ$. It is evident that the dependence on θ of the track length distribution is strong because the beam intersects the surface of the absorber under small angles. One therefore wants to choose Δx as large as possible keeping in mind the upper limit for Δx given earlier. For the same reason the maximum absorber thickness h_o should be minimized for a given ΔR_{max} by using high density material for the filter absorber. Because of multiple scattering effects (discussed below) we also want low Z material for the absorber. The numerical examples shown in Fig. 6 compare polyethylene (ρ=0.9 g/cm^3) and Al_2O_3 (ρ=3.7 g/cm^3) for two different angles of incidence θ. In both cases ΔR_{max} = 15 cm and Δx = 1 cm were used and multiple scattering effects in the absorber were neglected. We note that in the case of Al_2O_3 effects due to beam divergence become important between $\theta = 5^\circ$ and $\theta = 10^\circ$, while for polyethylene the situation looks hopeless. Of course, decreasing the required ΔR_{max} (and therefore h_o) decreases also the importance of the divergence effect. Since ΔR_{max} = 15 cm can be considered an upper limit, we have investigated the worst case.

So far we have not yet made use of one additional degree of freedom. One surface of the filter absorber described above is a plane. However, we might deform the shape of the absorber if we only conserve the thickness h(x). As we pointed out earlier this deformation should make the angles between the rays and the surfaces large. Unfortunately this condition is contradictory for rays to the right or to the left of the tip of the pyramids, and we do not believe that divergence effects can be minimized by this method.

The second phenomenon which has to be considered in a real situation is multiple scattering in the material of the filter absorber. The point we want to make here is that this effect might be important but can be neglected if dealt with properly. The rms multiple scattering angle of the filter per unit

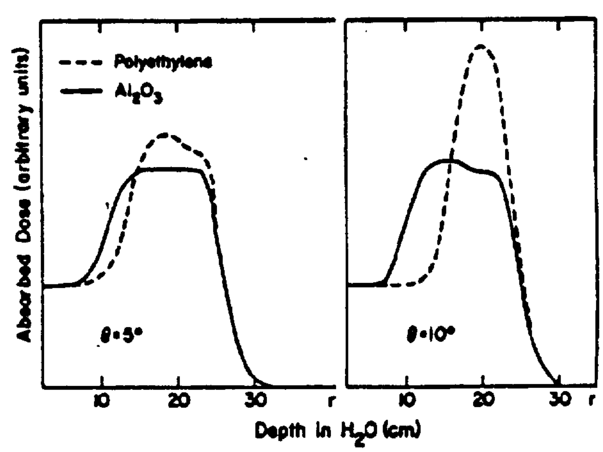

Fig. 6. Influence of divergence for a polyethylene and an Al_2O_3 absorber.

range shifting capacity is about 1.5 times larger for Al_2O_3 than it is for polyethylene because of the higher average Z involved. We pick the worst case and deal in the following with an Al_2O_3 absorber again using ΔR_{max} = 15 cm and Δx = 1 cm. Again it is obvious that multiple scattering effects will be enhanced if the outgoing rays intersect the surface of the filter absorber at small angles. If the beam enters the absorber from the tips of the pyramids at 0°, it will always exit at about 90° to the bottom surface and scattering effects are negligible. However, when the beam enters the bottom scattering effects are expected to be large. This is illustrated by the dose distributions in Fig. 7. A Monte Carlo method was used to calculate the effects of multiple scattering.

IV. DYNAMICAL DEVICES

The same effect which has been achieved by the structured static absorber, discussed in the previous section, can also be obtained by a completely different method. The principle here is to insert a time-dependent absorber thickness into the beam. The time interval during which a given thickness R of absorber is presented, is proportional to the weight function W(R) in Eq. 3, assuming constant beam intensity. Obviously there are an infinite number of mechanical arrangements that can fulfill this task.

The most obvious one consists of a layer of liquid with parallel boundaries, perpendicular to the beam axis. The distance between the plane walls of the container can be made variable and remotely controllable. A system like that is presently under construction at LAMPF.[3] The main disadvantage of the scheme is its limited frequency response, which might make it difficult to follow a desired time dependence of the thickness. The advantages are its versatility and the fact that the beam intersects the boundaries of the absorber at more or less right angles, minimizing scattering and divergence effects.

A different time-dependent range-shifter shall also be discussed briefly. It consists of a bar which has the cross section shown in Fig. 8 and rotates around an axis perpendicular to this cross section. The boundaries of the bar are manufactured such that a ray perpendicular to and through the axis of rotation intercepts an absorber thickness

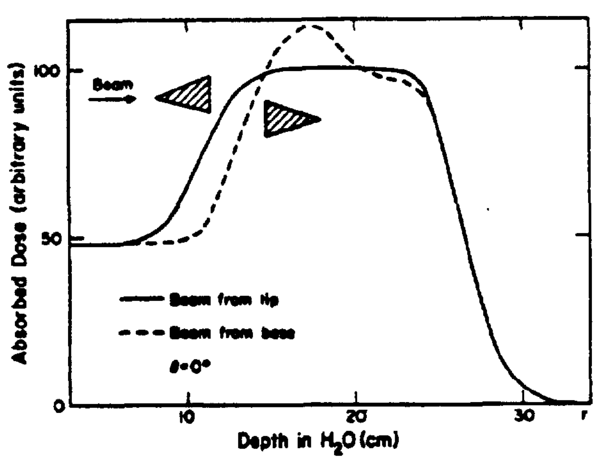

Fig. 7. Multiple scattering effects for two different orientations of the Al_2O_3 absorber for a non-divergent beam.

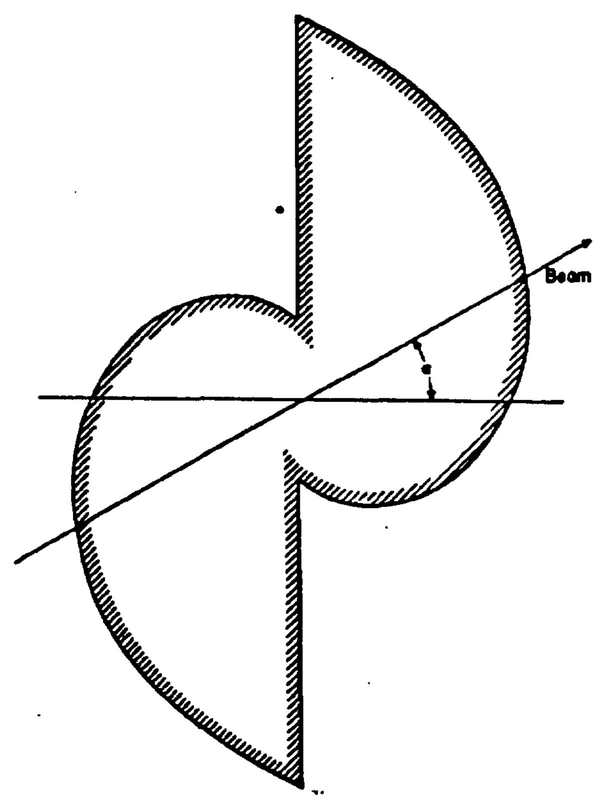

Fig. 8. Cross section through a rotational range-shifter.

h(x) (Eq. 5), where x now is proportional to the angle of rotation α. The divergence of the beam in the plane of the cross section in Fig. 8 needs not to be discussed because of the rotational motion. On the other hand one expects the shift distribution W(R) to be a function of the distance of a given ray from the axis of rotation. For the particular geometry displayed in Fig. 8 it has been shown, that the device is not useful for beam sizes larger than ± 0.5 cm. The influence of multiple scattering on W(R) is also expected to become very pronounced because of small angles of interception between the beam and the surfaces of the absorber. These two effects can be made smaller by moving the absorbing material away from the axis of rotation, but then the distance along the beam, which is taken up by the range-shifter becomes unfeasibly large.

For completeness we would like to point out one more possibility. The static absorber structure treated in Section III can also be moved uniformly in its plane. This removes the restriction we found for the maximum width of the pyramids since the lateral energy structure of the beam after passage through the absorber is washed out by the horizontal motion.

One also has to be aware of another problem of dynamic range-shifters. Besides the time periodicity of the thickness of the absorber there is also the beam time macro-structure and the lateral sweep of the target volume through the treatment region. It is possible that beat effects between the three periodic processes can introduce a dose inhomogeneity in the volume of interest, although this can generally be avoided by proper choice of the relative frequencies and phases. Also it should be pointed out, that fluctuations in pion beam intensity cause considerable difficulty for all non-static devices, since in such a case integrated dose replaces time as controlling parameter for velocity or position of the dynamic device.

V. CONCLUSIONS

Various problems involved in the design of pion range shifters have been discussed. It is obvious that there are several satisfying arrangements which generate beams of a desired energy spectrum. The effects of beam divergence and multiple scattering can not be neglected. In the case of a plane-parallel liquid absorber these effects are minimized. Also from the point of view of versatility this latter approach has to be favored since there is considerable uncertainty on the input parameters (e.g., RBE as a function of depth) which would enter the design of a static range-shifter.

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