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Penumbra Effect on Integral Absorbed Dose in Co-60 Teletherapy

Philip S. Moon

Korea Atomic Energy Research Institute, Seoul, Korea

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Abstract

Due to the Co-60 source size, the penumbra in Co-60 teletheraphy poses a serious problem, even if the extended collimators are used, Here an empirical formula for the calculation of integral absorbed dose in the penumbra region was derived. Through a numerical calculation, the penumbra effect on integral absorbed dose was investigated. The longer the source-to-skin distance, the larger the integral absorbed dose of penumbra region, and the larger the source diameter, the larger the integral absorbed dose of penumbra region. It was also found that in some case the integral absorbed dose in penumbra region becomes several times larger than the integral absorbed dose of treatment region itself if the source-to-skin distance becomes greater. Therefore, one must consider the penumbra effect in Co-60 teletherapy.

요 약

Co-60원격치료장치에 장진된 Co-60 선원의 크기 때문에 Co-60원격치료시 치료부위에 반영부분이 생기게 되어 불필요한 방사선조사를 받게된다. 반영부분에서의 흡수적산선량을 계산할 수 있는 식을 실험적으로 유도 하였고, 실제로 Co-60 원격치료에서 사용되는 조건을 실험식에 대입하여 반영의 크기가 흡수적산선량에 미치는 영향을 연구해 보았다.

선원과 표피간의 거리가 크면 클수록 반영부분의 흡수적산선량은 커지고, 선원의 직경이 크면 클수록 반영부분의 흡수적산선량이 커진다. 선원과 피부간의 거리가 커지는데 따라, 어떤 경우에는 반영부분의 흡수적산선량이 치료부분의 흡수적산선량의 수배가 될 때도 있음을 알았다. 따라서 Co-60원격치료시에는 반영효과를 고려에 넣어 불필요한 방사선조사를 피하도록 하여야 하겠다.

1. Introduction

The Co-60 teletherapy unit has a cylindrical Co-60 source and due to the Co-60 source size, the penumbra in Co-60 teletherapy results unnecessary irradiation to the penumbra region even if the extended collimator is used. Particularly the integral absorbed dose (volume dose) of penumbra region may pose a serious damage to the healthy tissue in Co-60 teletherapy[1]. Therefore, the study of the penumbra effect on integral absorbed dose was done in order to understand the unwanted penumbra effect.

The integral absorbed dose was defined originally by Mayneord[2]. According to the International Commission on Radiological Units and Measurements (ICRU) definition, the integral absorbed dose in a certain region is the energy imparted to matter by ionizing particles in that region[3,4]. The unit of integral absorbed dose is the gram rad. 1 gm-rad is equivalent to 100 ergs.

In Co-60 teletherapy it is desirable to keep the integral absorbed dose as small as possible while an adequate tumor dose is being delivered[5]. An ideal situation, which can never be achieved in Co-60 teletherapy, would be the case in which all the absorbed energy was concentrated in the tumor and none absorbed elsewhere. This would give the minimum integral absorbed dose for a given tumor dose. The gamma-ray will irradiate not only the tumor mass, but also the surrounding normal tissues. However, the integral absorbed dose is as important as the exposure dose to tumor mass.

The relationship between the penumbra effect and the integral absorbed dose in Co-60 teletherapy was studied in order to derive an empirical formula for the calculation of integral absorbed dose in the treatment region as well as in the penumbra region. Subsequently, by the numerical calculation of the empirical formula, the practical cases were also being studied in order to understand the importance of penumbra effect in Co-60 teletherapy.

2. Theory

The total integral absorbed dose to a depth d in tissue due to a parallel beam of radiation incident vertically on tissue surface is given by Mayneord[2] as

$$\Sigma_r = \int_0^d D_x A_1 \, dx, \tag{1}$$

where D_x is the dose at depth x and it can be written as

$$D_x = D_o e^{-\mu x}$$

D_o is the dose on the skin surface (in Co-60 teletherapy, it is the dose at 0.5cm below the skin surface). A_1 is the surface area $(2r)^2$ and μ is the linear absorption coefficient of absorbing matter.

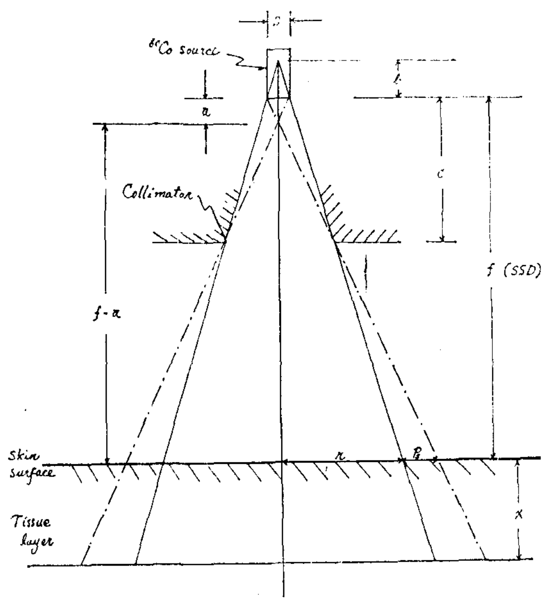

Fig. 1. Diagram illustrating the penumbra region in Co-60 teletherapy.

Considering the divergence factor F_1 of Co-60 gamma-ray beam in tissue, (1) can be modified as

$$\Sigma_r = \int_0^d D_o e^{-\mu x} A_1 F_1^2 dx, \tag{2}$$

where $F_1 = \frac{f+b+x}{f+b} = 1 + \frac{x}{f+b}$ (3)

From Fig. 1, $b = \frac{sf}{2r-s}$ (4)

Substituting (4) into (3), we get

$$F_1 = 1 + \frac{(2r-s)x}{2fr}$$

Let $B_1 = \frac{(2r-s)}{2fr}$,

then $F_1 = 1 + B_1 x$ (5)

Substituting (5) into (2),

$$\Sigma_r = D_o A_1 \int_0^d (1+B_1x)^2 e^{-\mu x} dx \quad (6)$$

If $d_{\frac{1}{2}}$ represents the depth of the 50% isodose surface, then $d_{\frac{1}{2}}$ can be considered as the half value layer in tissue and is related to μ by the equation $\mu=0.693/d_{\frac{1}{2}}$ By substituting this value for μ, we obtain

$$\Sigma_r = 1.44\ D_o\ A_1\ d_{\frac{1}{2}} \Big[1+2.88B_1d_{\frac{1}{2}} + 4.15B_1^2d_{\frac{1}{2}}^2 - (1+2B_1d+B_1^2d^2+2.88B_1d_{\frac{1}{2}} + 2.88B_1^2d_{\frac{1}{2}}d+4.15\,B_1^2d_{\frac{1}{2}}^2)e^{-0.693d/d_{\frac{1}{2}}}\Big] \quad (7)$$

If $d \gg d_{\frac{1}{2}}$ of extremely obese case, then (7) becomes

$$\Sigma_r = 1.44\ D_o\ A_1\ d_{\frac{1}{2}}(1+2.88\ B_1d_{\frac{1}{2}} + 4.15B_1^2d_{\frac{1}{2}}^2) \quad (8)$$

In Fig. 1, the area including penumbra region A_2 is $(2r+2p_s)^2$ and considering the divergence factor F_2 the total integral absorbed dose of this region becomes

$$\Sigma_{r+p} = \int_0^d D_o e^{-\mu x} A_2 F_2^2 dx \quad (9)$$

Where $F_2 = \dfrac{f-a+x}{f-a} = 1+\dfrac{x}{tf-a}$ (10)

From Fig. 1, $a = \dfrac{f \cdot s}{s+2r+2p_s}$ (11)

where p_s is the penumbra width and it can be written as

$$p_s = \frac{s(f-c)}{c} \quad (12)$$

By substituting (12) into (11), we get

$$a = \frac{cfs}{2cr+2sf-cs} \quad (13)$$

and substituting (13) into (10)

$$F_2 = 1+\frac{2(cr-sf)-cs \cdot x}{2f(cr+sf-cs)} \quad (14)$$

Let $B_2 = \dfrac{2(cr-sf)-cs}{2f(cr+sf-cs)}$, then

$$F_2 = 1+B_2x \quad (15)$$

Substituting (15) into (9),

$$\Sigma_{r+p} = D_o A_2 \int_0^d (1+B_2x)^2\ e^{-\mu x}\ dx \quad (16)$$

$$\Sigma_{r+p} = 1.44D_oA_2d_{\frac{1}{2}}\Big[1+2.88B_2d_{\frac{1}{2}}+4.15B_2^2d_{\frac{1}{2}}^2 - (1+2B_2^2d+B_2^2d^2+2.88B_2d_{\frac{1}{2}} + 2.88B_2^2d_{\frac{1}{2}}d+4.15B_2^2d_{\frac{1}{2}}^2)e^{-0.693d/d_{\frac{1}{2}}}\Big] \quad (17)$$

If $d \gg d_{\frac{1}{2}}$ of extremely obese case, then (17) becomes

$$\Sigma_{r+p} = 1.44D_oA_2d_{\frac{1}{2}}\ (1+2.88B_2d_{\frac{1}{2}} + 4.15B_2^2d_{\frac{1}{2}}^2) \quad (18)$$

From (7) and (17), the total integral absorbed dose in the penumbra region can be written as

$$\Sigma_p = K(\Sigma_{r+p} - \Sigma_r) \quad (19)$$

where K is the relative coefficient of radiation abrorbed dose between the treatment region and the penumbra region.

By substituting (7) and (17) into (19), we get

$$\Sigma_p = 1.44KD_od_{\frac{1}{2}}\Big\{A_2\Big[1+2.88B_2d_{\frac{1}{2}}+4.15B_2^2d_{\frac{1}{2}}^2 - (1+2B_2d+B_2^2d^2+2.88B_2d_{\frac{1}{2}}+2.88B_2^2d_{\frac{1}{2}}d + 4.15B_2^2d_{\frac{1}{2}}^2)\,e^{-0.693d/d_{\frac{1}{2}}}\Big] - A_1\Big[1+2.88B_1d_{\frac{1}{2}}+4.15B_1^2d_{\frac{1}{2}}^2 - (1+2B_1d+B_1^2d^2+2.88B_1d_{\frac{1}{2}}+2.88B_1^2d_{\frac{1}{2}}d + 4.15B_1^2d_{\frac{1}{2}}^2)\,e^{-0.693d/d_{\frac{1}{2}}}\Big]\Big\} \quad (20)$$

In (20) $B_1 \ll 1$ and $B_2 \ll 1$.

Therefore

$$\Sigma_p = 1.44KD_od_{\frac{1}{2}}\Big\{A_2\Big[1+2.88B_2d_{\frac{1}{2}} - (1+2B_2d+2.88B_2d_{\frac{1}{2}})\,e^{-0.693d/d_{\frac{1}{2}}}\Big] - A_1\Big[1+2.88B_1d_{\frac{1}{2}} - (1+2B_1d + 2.88B_1d_{\frac{1}{2}})\,e^{-0.693d/d_{\frac{1}{2}}}\Big]\Big\} \quad (21)$$

If $d \gg d_{\frac{1}{2}}$ of extremely obese case, then (21) becomes

$$\Sigma_p = 1.44KD_od_{\frac{1}{2}}\Big[A_2(1+2.88B_2d_{\frac{1}{2}}) - A_1(1+2.88B_1d_{\frac{1}{2}})\Big] \quad (22)$$

Substituting the value $K=0.38$ (it is taken from the experimental resuult) into (21) and (22), we get the total integral absorbed dose in penumbra region

$$\Sigma_p = 0.55D_od_{\frac{1}{2}}\Big\{A_2\Big[1+2.88B_2d_{\frac{1}{2}} - (1+2B_2d+2.88B_2d_{\frac{1}{2}})\,e^{-0.693d/d_{\frac{1}{2}}}\Big]$$

$$-A_1\Big[1+2.88B_1d_{\frac{1}{2}} -(1+2B_1d+2.88B_1d_{\frac{1}{2}})e^{-0.693d/d_{\frac{1}{2}}}\Big]\Big\} \quad (23)$$

If $d \gg d_{\frac{1}{2}}$ of extremely obese case, then

$$\Sigma_p=0.55D_o d_{\frac{1}{2}}\Big[A_2(1+2.88B_2d_{\frac{1}{2}}) -A_1(1+2.88B_1d_{\frac{1}{2}})\Big] \quad (24)$$

3. Experiment

In order to determine the K value in (19), an experiment was carried out for the practical conditions with LiF rod (1mm & 6 mm height cylinder) and the thermoluminescent dosimeter reader (Teledyne TLD 7100).

The LiF rods were annealed in a 300°C oven for four hours and then inserted them in an 80°C oven for 24 hours in order to eliminate all the trapped electrons in LiF.

Following the annealing, the LiF rods were uniformly immersed in a water phantom in different levels and ranges on a wooden lattice, and then placed the water phantom under the Co-60 teltherapy unit. The LiF rods were irradiated by Co-60 gammaray and the reading of each LiF rod was taken from the TLD 7100 reader. The average doses for the treatment region and the penumbra region were calculated and with these values, the K value was calculated as the ratio between the average dose of penumbra region and the average doses of treatment region. The K value is found to be 0.38 ± 0.02 for the conventional treatment distances and field size in Co-60 teletherapy. In this paper, the conventional treatment conditions are the source-to-skin distances of 50 cm and 60 cm, and field size of 100cm^2.

4. Results

By substitution of the following practical values into (7) and (23), the total integral absorbed doses Σ_r and Σ_p were calculated and plotted on the semi-log graph paper as shown in Figs. 2, 3, 4, 5, 6, 7 and 8.

$s=1, 2, 3$cm; $r=5$cm; $f=50, 60, 80, 100$cm; $c=27$cm; $d=20$cm; $D_o=1$ rad; $A_1=100$cm^2; p_s=values dependent on s and f values.

Fig. 2 shows the curves of Σ_p/Σ_r for different source diameters at SSD 50cm. Fig. 3 shows the curves of Σ_p/Σ_r for different source diameters at SSD 60cm and different field sizes. Fig. 4 shows the curves of Σ_p/Σ_r for different penumbra widths at SSD 50cm and different field sizes. Fig. 5 shows the curves of Σ_p/Σ_r for different penumbra widths at SSD 60cm and different field sizes. Fig. 6 shows the curves of Σ_p for different field sizes and SSD with 2 cm source diameter and $D_o=1$ rad. Fig. 7 shows the curves of Σ_p for different source diamters and SSD with 100cm^2 field size and $D_o=1$ rad. Fig. 8 shows the curves of Σ_p for different SSDs and field sizes with 2cm source diamter and $D_o=1$ rad.

5. Discussions

The idea of integral absorbed dose was originally introduced by Mayneord[2] as equation (1) for the calculation of total energy imparted to matter by ionizing radiation, but in this equation the penumbra factor of radiation was neglected. The penumbra size does not depend on the source diameter alone. The ratio of source-to-skin distance to source-to-diaphragm distance also affects penumbra[6]. However, the author has introduced the penumbra factor and developed the equation (1) for the calculation of the total integral absorbed dose in the penumbra region.

As we can see in the equations (7), (17) and (23), the total integral absorbed doses Σ_r, Σ_{r+p} and Σ_p are dependent upon the values of D_o, $d_{\frac{1}{2}}$, d, A_1, A_2, B_1. B_2, but if $d \gg d_{\frac{1}{2}}$ of extremely obese case, the Σ_r value is depends on the values of D_o, A_2, $d_{\frac{1}{2}}$, B_2, and Σ_p is depends on the values of D_o, $d_{\frac{1}{2}}$, A_1, A_2, B_1, B_2.

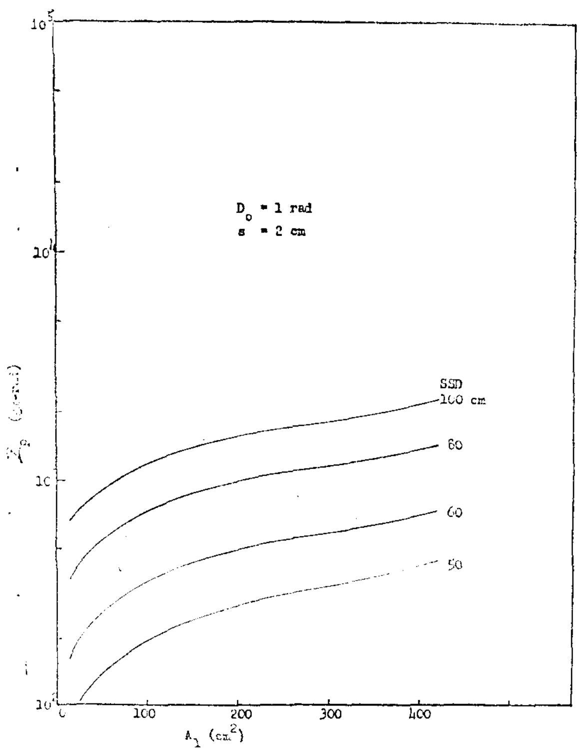

Fig. 2. Σ_p/Σ_r *vs.* **source diameter at SSD 50cm.**

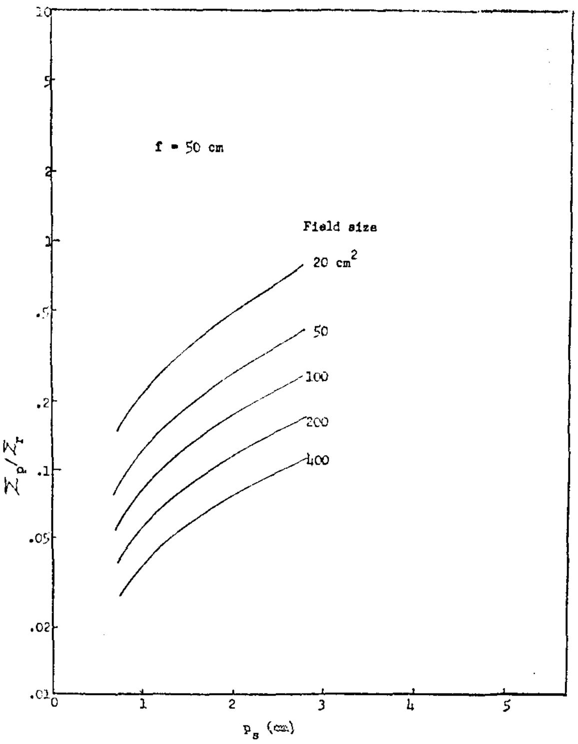

Fig. 4. Σ_p/Σ_r *vs.* **penumbra width at SSD 50cm**

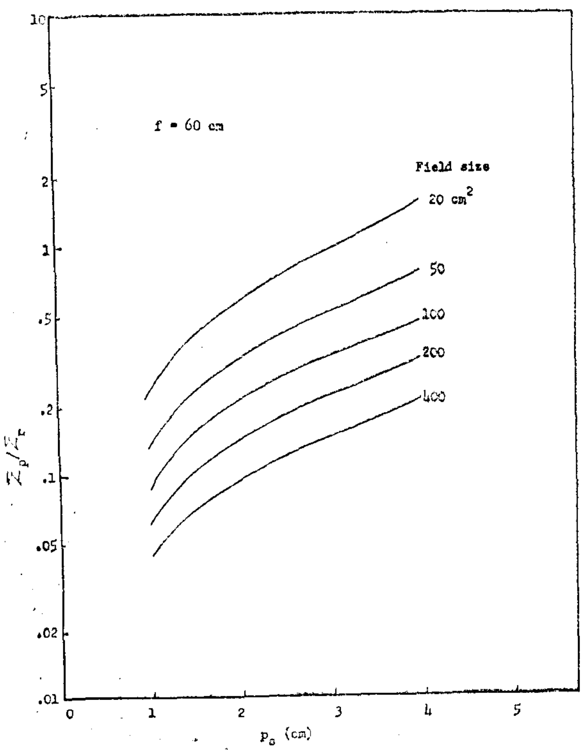

Fig. 3. Σ_p/Σ_r *vs.* **source diameter at SSD 60cm**

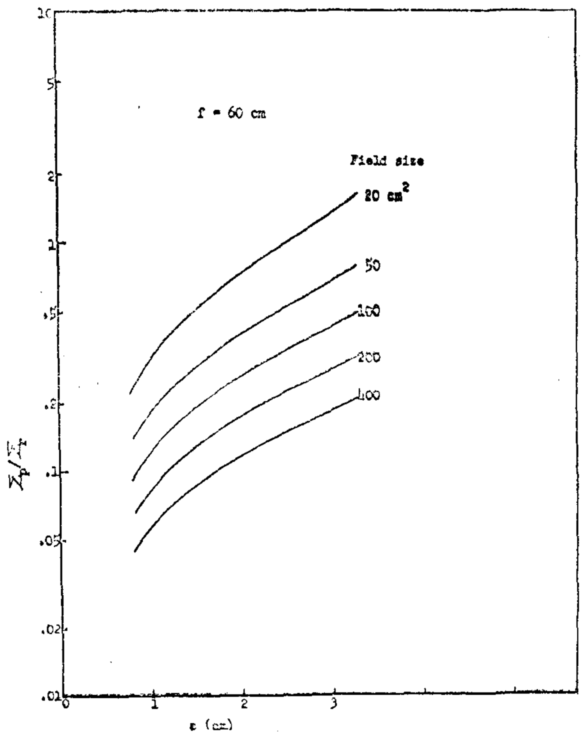

Fig. 5. Σ_p/Σ_r *vs.* **penumbra width at SSD 60cm**

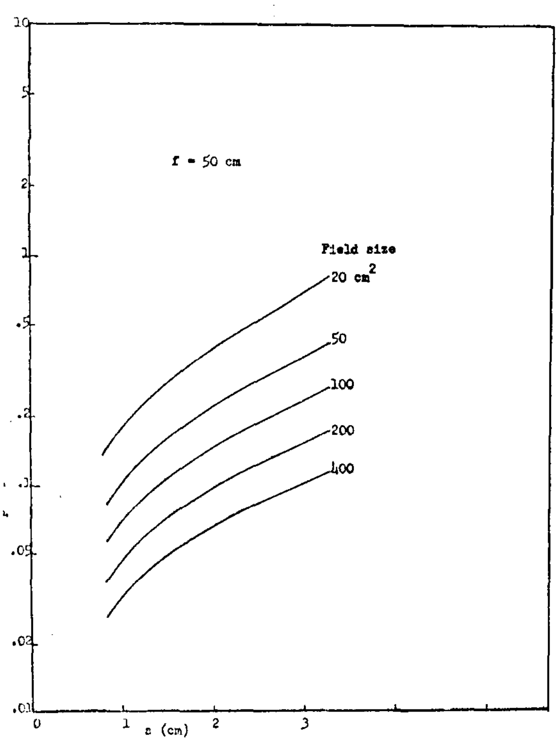

Fig. 6. Σ_p vs. field size

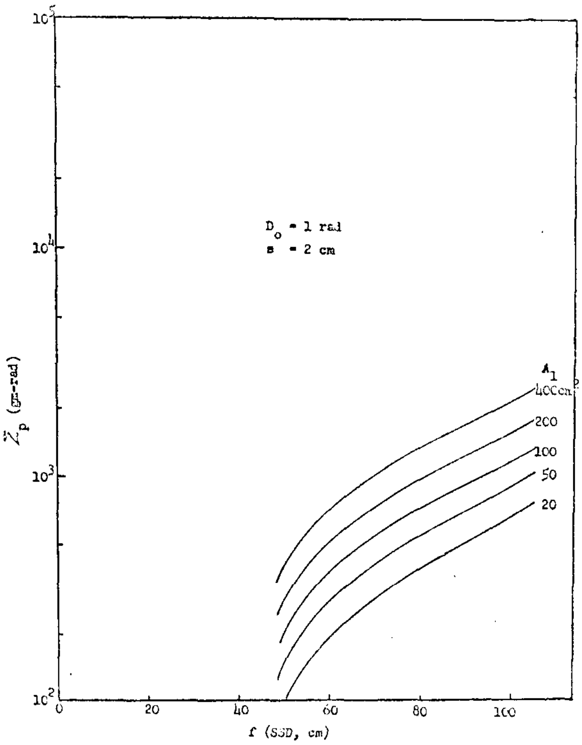

Fig. 8. Σ_p vs. source-to-skin distance

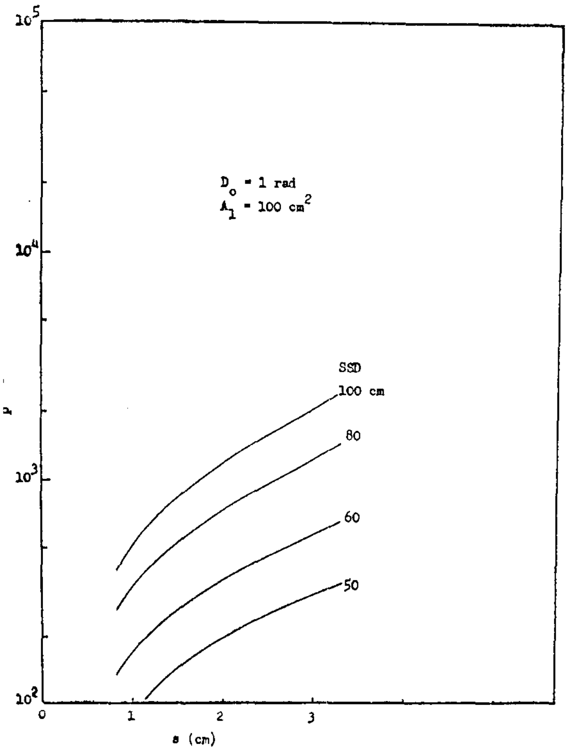

Fig. 7. Σ_p vs. source diameter

In Fig. 2 the ratio Σ_p/Σ_r is increasing as the source diameter increases and in case of 20cm² field size the integral absorbed dose of treatment region Σ_r is almost equal to that of penumbra region Σ_p. When the source diameter is 1cm, the ratio Σ_p/Σ_r drops to 18% or more. In Fig. 3, the Σ_p/Σ_r value becomes as high as 150% for 3cm source diameter and 20cm² field size, and it drops to about 30% for 1cm source diameter.

In Fig. 2 and 3, the Σ_p/Σ_r values are decreasing as the field sizes increase. In Fig. 4 and 5, the Σ_p/Σ_r values are increasing as the penumbra width increase and also as the field size are fixed to a certain length and size, then the penumbra width increases as the SSD increase. Therefore, it is a wise choice to select a shorter SSD for treatment, but it should not be closer than 15cm from the collimator end, which will prevent the secondary electron irradiation on the skin surface in Co-60 teletherapy. In Fig. 6, the Σ_p values are increasing as the field sizes increase and as the SSD increases for a fixed D_o and 2cm source diameter. In Fig. 7, the Σ_p values are increasing as the source diameter increases and as the SSD increases for a fixed D_o and $100cm^2$ field size.

In order to achieve the same homogeneity of absorbed dose over the volume of interest, a wider field would have to be used in the case of the beam with the large penumbra and this would bring about the unnecessary irradition of peripheral tissues and a larger integral absorbed dose[6].

As we can see in Figs. 6, 7, 8, the Σ_p value reaches about 2×10^3 gm-rad for $D_o=1$ rad. In practical case, D_o becomes as high as 500 rad in a single irradiation of Co-60 gamma-ray, and in this case, the total integral absorbed dose in penumbra region becomes 1×10^6 gm-rad, which is prohibitively larger value for a proper treatment of patient, and sometimes it will cause a serious side effect in Co-60 teletherapy.

6. Summary

The equations for the total integral absorbed dose in Co-60 teletherapy was derived empirically for treatment region as well as the geometrical penumbra region.

In order to determine the relative coefficient of radiation absorbed dose between the treatment region and the penumbra region, K, an experiment was carried out in a water phantom with thermoluminescent dosimetry using LiF rod. The K value for conventional treatment conditions was found to be 0.38 ± 0.02 in Co-60 teletherapy.

The Σ_p/Σ_r ratio was numerically calculated for the practical treatment conditions and was plotted against Co-60 source size, penumbra width, and the Σ_p value was also numerically calculated and was plotted against field size, source size, source-to-skin distance.

The Σ_p/Σ_r values are decreasing as the field size increases and are increasing as the penumbra width and the field size increase.

In some condition, the integral absorbed dose in penumbra region becomes several times larger than the integral absorbed dose of treatment region if the source-to-skin distance becomes greater.

The Σ_p value is increasing as the source size, the SSD and the field size increase. The larger the source-to-skin distance, the larger the integral absorbed dose of penumbra region, and the larger the source diameter, the larger the integral absorbed dose of penumbra region.

If it is at all possible, it is desirable that the integral absorbed doses in the treatment region as well as in the penumbra region should be kept as small as possible in Co-60 teletherapy.

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