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DOSE DISTRIBUTION IN TISSUE FROM STAR NEUTRONS AND PHOTONS

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INTRODUCTION

In the use of negative pions in radiotherapy most of the dose delivered to the treatment volume arises from the secondary particles - especially heavy fragments - that are produced as a result of the nuclear capture of the pion. In addition to these short-range particles, neutrons and photons are also produced in the pion capture process ("star") and these particles - especially the neutrons - are responsible for the dose delivered outside of the treatment volume. Other sources of neutrons, such as those streaming through the pion channel and those penetrating the shielding, also contribute to the total body dose; however, these contributions are small compared to that due to the "star" neutrons.[1] The importance of a reliable estimate of the dose delivered by these long-range particles can be readily appreciated; and it is the calculation of such a dose distribution in tissue that is reported herein.

The basic computer program used to transport neutrons and photons in this calculation is ANDY[2] - a multi-energy-group, general geometry, Monte Carlo transport program capable of handling neutrons with energies up to 17 MeV and photons with energies up to 10 MeV. The energy limits are determined solely by the cross-section libraries currently available for the elemental composition of the medium assumed and are not an inherent limitation of the code. An attractive feature of the program is its capacity to deal with complex geometrical shapes which can be described in terms of planes, spheres, circular cylinders, ellipsoids and cones. Also, inhomogeneous media, consisting of regions with different elemental compositions, can be accommodated. Thus, it should be noted, that very complex systems can be modeled using ANDY. For the purpose of this first calculation, however, we have assumed a homogeneous medium of constant elemental composition representing tissue.

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SOURCE GEOMETRY AND SPECTRA

Although treatment volumes will, in general, be rather complex in shape, we have assumed, for simplicity, that the pions are captured randomly throughout a 1 liter spherical treatment volume (6.2 cm radius) centered within a sphere of tissue of 40 cm radius. The elemental composition used for the tissue together with elemental densities (g/cc), is: oxygen (0.61), carbon (0.23), hydrogen (0.10), nitrogen (0.026).

The spectra of various reaction products that result when a π^- is captured by a nucleus have been calculated for carbon, nitrogen, oxygen and aluminum using a Monte Carlo intranuclear cascade and evaporation model.[3] The calculated spectra for the lighter products are in fair agreement with experiment. Some of the results obtained in Ref. 3 for neutron spectra are reproduced in Table 1. Unfortunately, the highest-energy group that is available in the ANDY cross-section library is 15-17 MeV. Some idea of the biological effectiveness of the higher-energy neutrons can be obtained by looking at the flux density (n cm^{-2} sec^{-1}) equivalent to a dose of 1 millirem/hr. For neutron energies between 10 and 100 MeV, the dose-equivalent flux density decreases from 6.8 to 5.5 (n cm^{-2} sec^{-1})[4]. Thus, the error introduced by including all of the neutrons (from Table I) with energies greater than 17 MeV into the highest-energy group (15-17 MeV) is not very large - i.e., $\lesssim 10\%$. If we make this approximation and, in addition, adjust the energy intervals of the neutron spectra given in Table I so that they match ANDY's energy-group structure, we then obtain the neutron source spectrum for tissue shown in Figure 1.

It can be expected that the dose due to gamma rays is less important than that due to neutrons. Nevertheless, this should be checked, even if only in an approximate way. For example, the high-energy gamma ray spectrum resulting from radiative pion capture in ^{12}C ($\sim$2% branching ratio) peaks strongly around 120 MeV.[5] In addition, the low-energy spectrum for ^{16}O contains several peaks below a few MeV (up to $\sim$2% branching ratio) resulting from nuclear de-excitation.[6] Approximately 1/2 to 2/3 of the high-energy gammas will escape from the body without interaction, so that we are mainly interested in modeling a source to represent the low-energy spectrum, including x-rays. We have assumed a spectrum with an exponential fall-off up to 10 MeV and a "half-width" of 1 MeV. The

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normalization is fixed by the assumption that the total energy contained in this spectrum is ~7% of the pion's rest mass - i.e., ~10MeV. This amounts to a total gamma ray energy of 13 MeV including the high-energy photons, which should be somewhat conservative. The resulting spectrum is shown in Figure 2.

DOSE CALCULATION

As the neutrons produced in the source region traverse tissue, they can produce other particles in their interactions with nuclei. Charged particles produced by these "star" neutrons have a very short range ($\lesssim$1 cm); however, secondary neutrons and photons can travel much farther. For a neutron source, the output of ANDY includes a tally of the total number of neutrons and photons in each energy group crossing specified tally surfaces in both directions. Knowing the number of "star" neutrons produced in a specified volume, as well as the net number of neutrons and photons leaving the volume, for each energy group, the net energy deposited (and, therefore, the dose) is easily determined. It is assumed that the energy lost by the neutrons is either carried off by the photons or deposited within the specified volume. For the present calculation, spherical tally surfaces were specified at 2 cm radial intervals, so this assumption regarding energy deposition is reasonable.

For a gamma ray source only photons are counted at the tally surfaces. In this case, any energy not carried off by photons is assumed deposited within the specified volume. Since neutrons can be produced by (γ,n) reactions, some of the energy assumed to be deposited close to the source is really deposited farther away. However, the error introduced by this approximation is not severe, and the results are at least a good indication of the "star" photon contribution to the dose.

The dose distribution due to "star" neutrons is shown in Figure 3. The number of source neutrons was 28,860, corresponding to 10^4 stopped pions. The statistical errors listed in the output of ANDY range from a few percent to about 10 percent, the smaller errors corresponding to the higher-energy groups, from which most of the dose results.

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The dose distribution due to "star" photons is shown in Figure 4. The number of source photons was 34,287, corresponding to 5×10^4 stopped pions. Here, again, the statistical errors indicated for the most important energy groups were a few percent.

RESULTS AND DISCUSSION

A random distribution of "stars", such as was assumed in this calculation, will not produce a uniform dose within the treatment volume; nevertheless, we can approximate the distribution as being constant. It has been estimated[7] that this dose level within a 1 liter treatment volume would be approximately 10^{-9} rad/π^- stop. A good idea of the total body dose to be expected can be had by referring to Figures 3 and 4. First, we should note that, as might have been expected, the dose due to photons is between one and two orders of magnitude less than that due to neutrons. The 1% dose level occurs at a radius of about 11 cm, and drops to 0.1% at about 24 cm (the radius of the treatment volume is 6.2 cm). Thus, the average dose delivered to the whole body, exclusive of the treatment volume is far below the 1% level.

The model treated here in this calculation is obviously over-simplified. For example, no allowance has been made for variations in density due to bone, lung tissue, etc. Also, a spherical shape is obviously unrealistic. All of these complications can be accommodated by the general geometry routine used in ANDY at some expense in computer time. A single production run for this calculation, starting 28,860 neutrons and including 20 tally surfaces, consumes about 47 minutes of computer time (the photon case used only 18 minutes). In addition, several hours were spent "debugging". Perhaps rather than trying to treat the general case, with the whole body more accurately modeled, we should try to answer a few specific questions (such as those dealing with the effects of bone, lungs, or other organs) using simple models similar to that used here. In any case, more input from radiotherapists regarding this problem is certainly indicated before any further effort is expended.

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TABLE I

ΔE_n (MeV)	^{16}O	^{12}C	^{14}N	$\left(\frac{\text{neutrons/MeV}}{\pi^- \text{ capture}}\right)$
0-1	0.135	0.102	0.128	
1-2	0.211	0.166	0.178	
2-3	0.196	0.170	0.193	
3-4	0.192	0.158	0.158	
4-5	0.186	0.156	0.160	
5-6	0.149	0.120	0.140	
6-7	0.140	0.106	0.120	
7-8	0.122	0.103	0.111	
8-9	0.100	0.109	0.0950	
9-10	0.0860	0.0927	0.0830	
10-12	0.0812	0.0733	0.0802	
12-14	0.0619	0.0629	0.0534	
14-16	0.0507	0.0558	0.0476	
16-18	0.0388	0.0490	0.0402	
18-20	0.0288	0.0398	0.0385	
20-25	0.0296	0.0278	0.0288	
25-30	0.0134	0.0104	0.0117	
30-40	0.0126	0.0121	0.0120	
40-50	0.0131	0.0164	0.0136	
50-60	0.0140	0.0162	0.0143	
60-70	0.0116	0.0131	0.0125	
70-80	0.00857	0.00904	0.00867	
80-90	0.00459	0.00437	0.00510	
90-100	0.00184	0.00281	0.00262	

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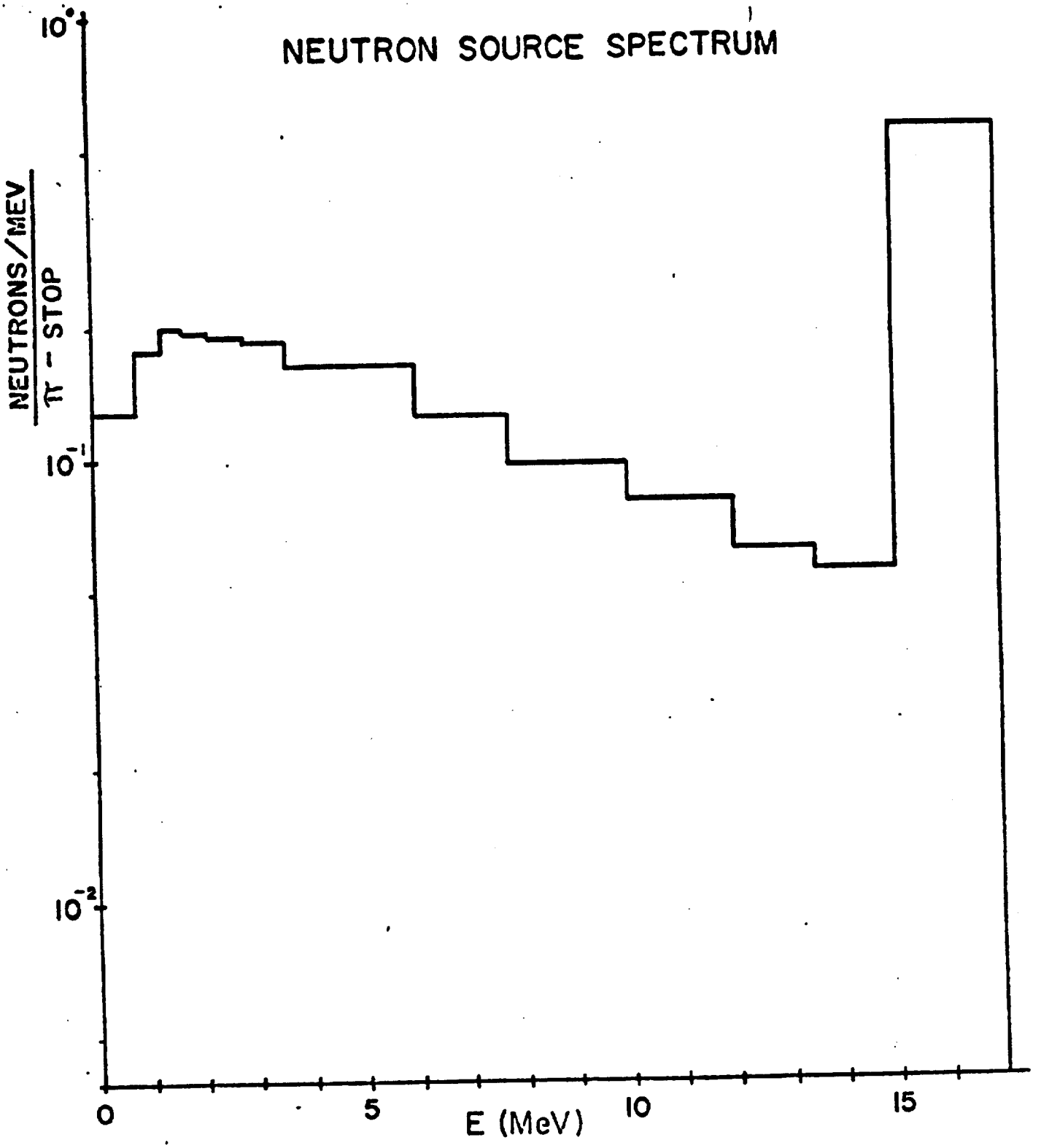

Figure 1

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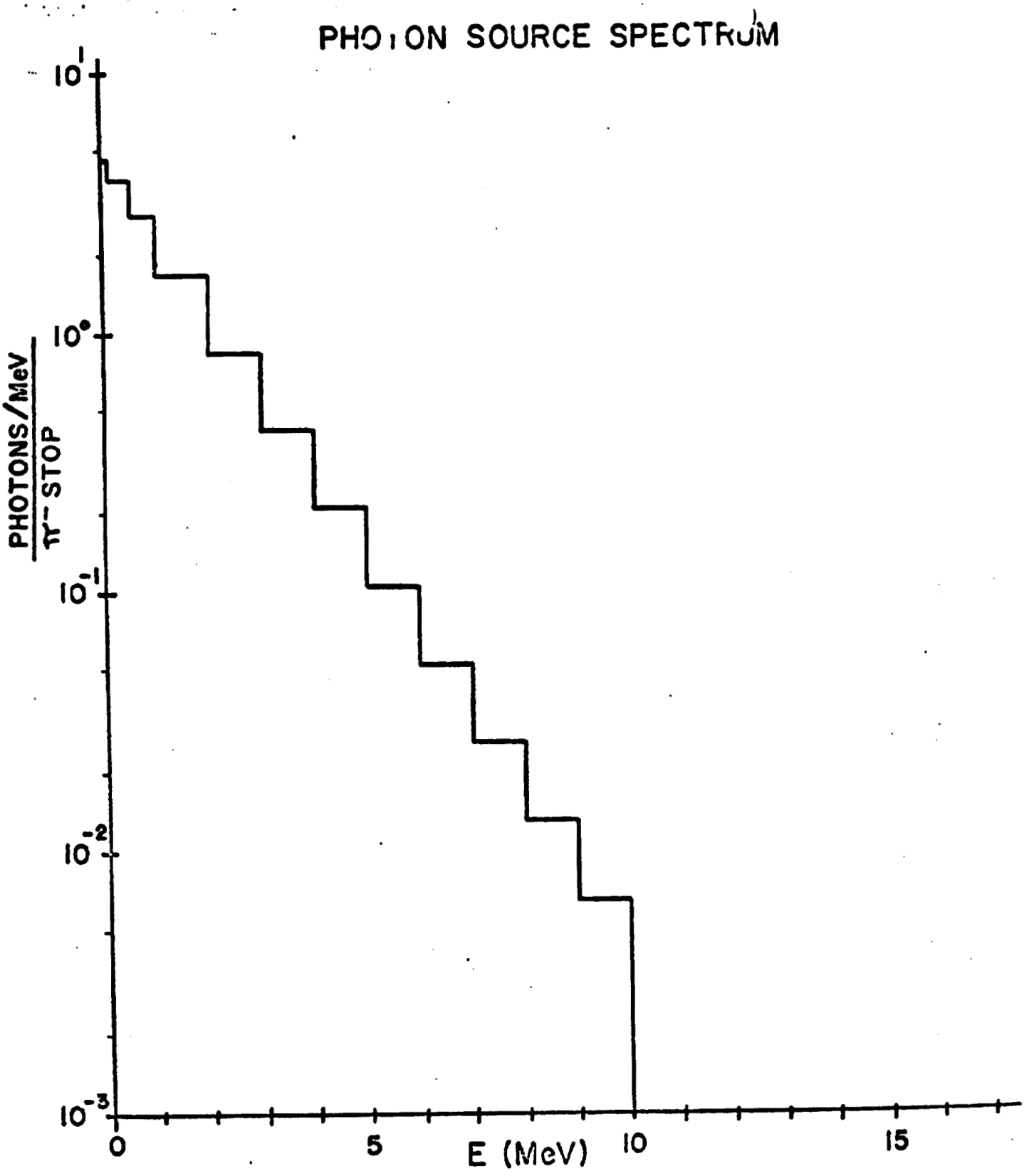

Figure 2

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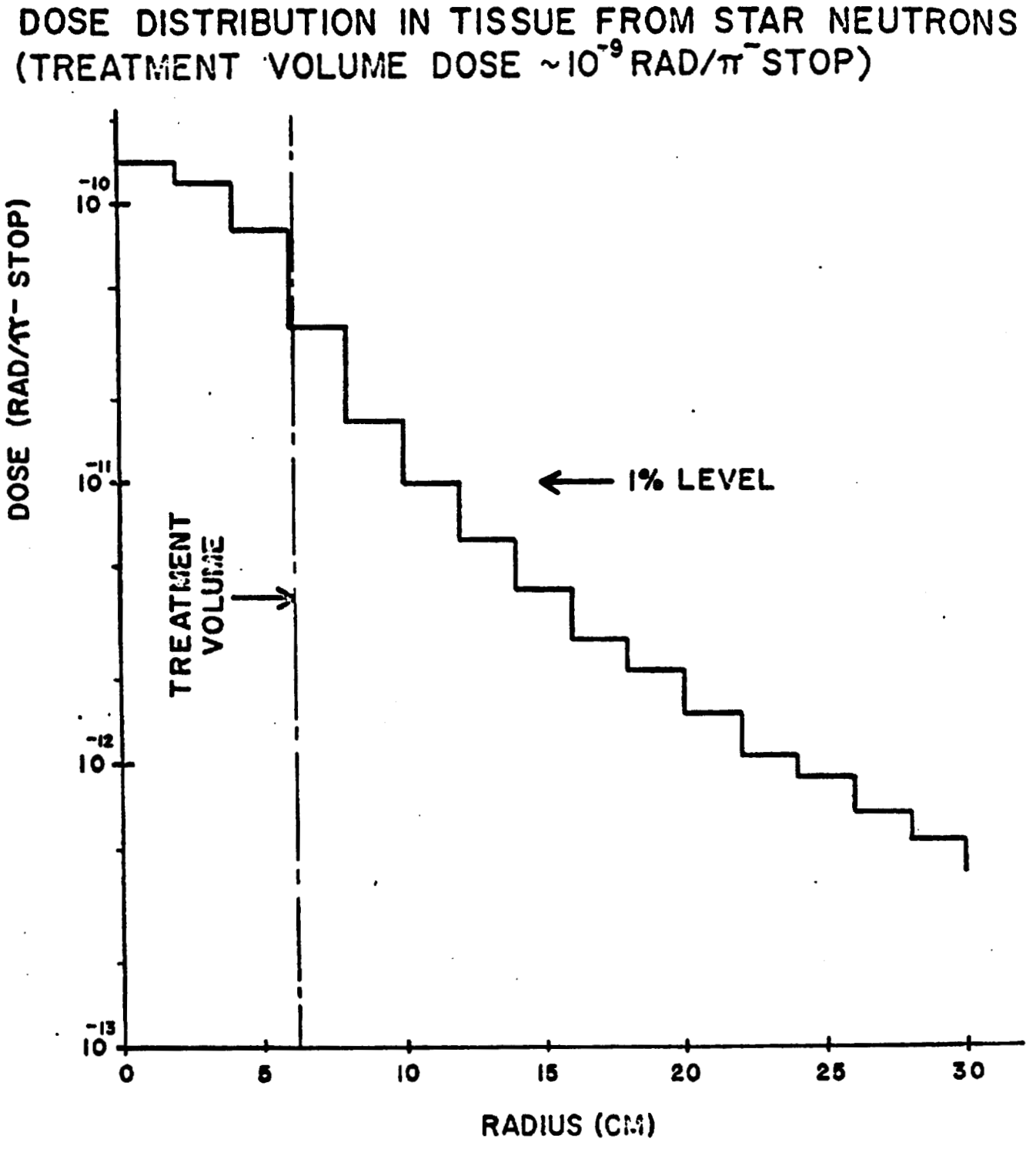

Figure 3

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DOSE DISTRIBUTION IN TISSUE FROM STAR PHOTONS

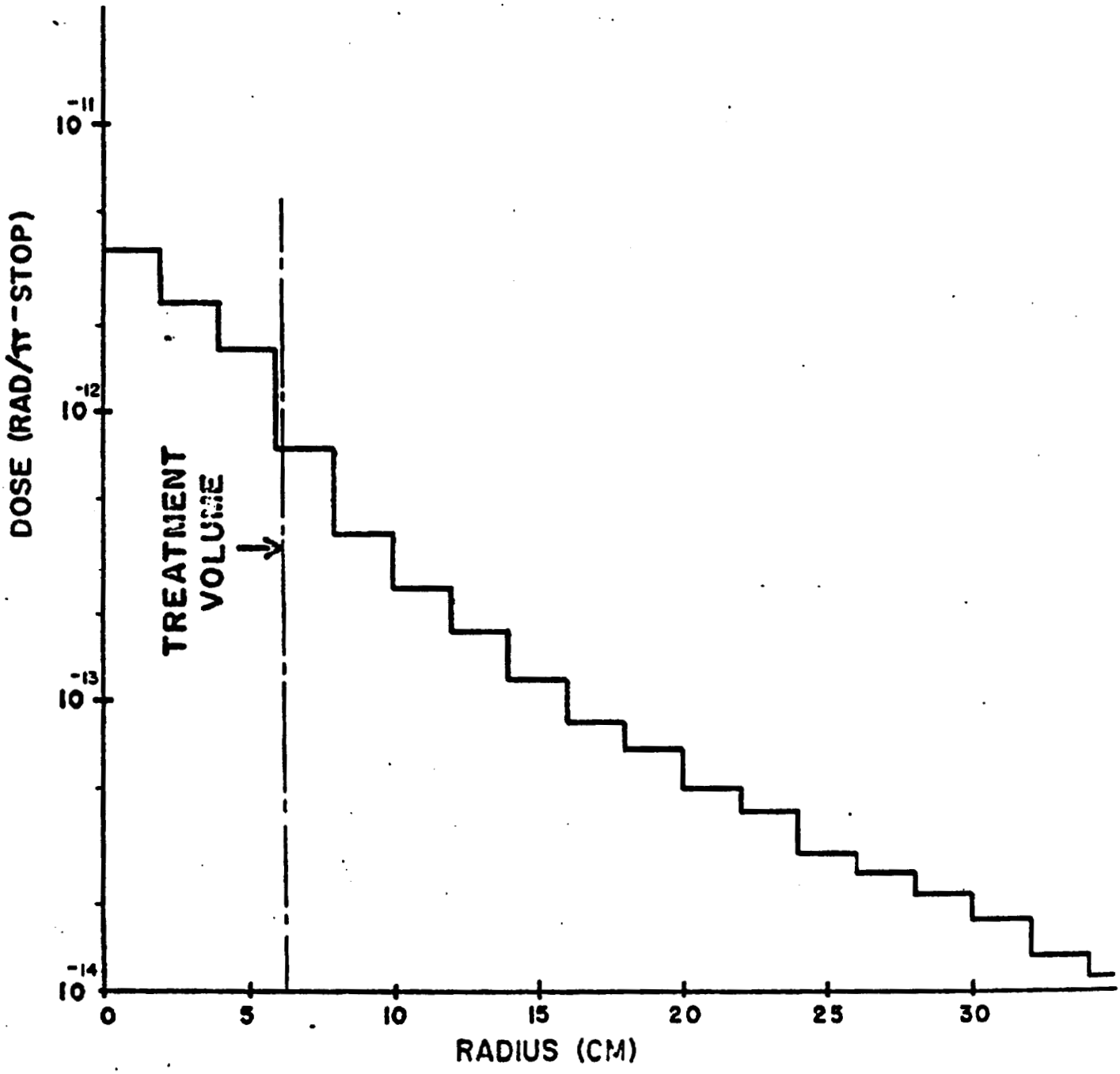

Figure 4

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