SLAC-PUB-2706
March 1981
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# NEUTRON INTEGRAL DOSE TO PATIENTS UNDERGOING HIGH-ENERGY X-RAY THERAPY*

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## ABSTRACT

A simple, consistent, semi-quantitative description of the neutron dose received by patients undergoing cancer treatment by X-ray therapy is given. This discussion is intended as a contribution to the AAPM Task Group on Neutrons from High-Energy X-Ray Machines.

Submitted for Publication

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*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

# INTRODUCTION

There are two primary sources of neutrons which produce unwanted patient exposure:

(I) Photonuclear reactions in treatment-head components, mainly the high-Z collimator and jaws, and

(II) Photonuclear reactions within the patient's body.

## I. Accelerator-Produced Neutrons

There are three distinct types of accelerator-produced neutron dose distributions to consider:

(A) Neutrons direct from the source;

(B) Neutrons filtered by high-Z shielding;

(C) Room-scattered neutrons.

These are all characterized by a very rapid attenuation in tissue, as compared to X-rays of the treatment beam. An important consideration, therefore, is that the deeper-lying tissues are protected by attenuation within the first few centimeters. These three distributions are qualitatively discussed.

### A. Neutrons direct from the source (unfiltered)

The area of the treatment field receives a neutron dose component from neutrons which arrive at the surface with little or no spectral modification. These neutrons have a spectrum of mean energy of about 1 MeV

(if all neutron sources are of W) and a HVL in tissue of about 5.8 cm (or, equivalently, a dose-attenuation coefficient of $\lambda = 0.12\ cm^{-1}$).[1] The measured entrance dose is typically about 0.0004 neutron rad per treatment rad. [This, when added to the more diffuse filtered dose described in the following paragraph, accounts for the total dose of about 0.0006 - 0.0007 rad per treatment rad measured in the treatment beam (A179, Ax79, La79).] Owing to the shielding effect of overlying tissue, distal tissues receive only negligible doses from this source.

From these data it is easy to picture the dose distribution of these direct neutrons. They produce an integral dose which is proportional to the treatment area, and about half of it is deposited in the first 5.8 cm of tissue. The integral dose can be estimated from the entrance dose multiplied by the body area presented to the source and divided by the dose attenuation coefficient. As an example, take a $100\text{-cm}^2$ field:

$$\left(0.0004\ \frac{\text{neutron rad}}{\text{treatment rad}}\right) \times (100\ cm^2) \times (1\ g/cm^3) \ /\ (0.12\ cm^{-1})$$

$$= 0.33\ \text{neutron g rad / treatment rad}$$

for this field size. This would scale directly as field area approximately as follows:

| | |
|---|---|
| $A = 100\ cm^2$ | 0.33 neutron g rad / treatment rad |
| 600 | 2.0 |
| 900 | 3.0. |

These are only estimates to illustrate the nature of this dose component. However, for the same machine they would be roughly independent of treatment distance and vary only slightly with energy within the range

20 - 40 MV (Fig. 1).

Simplified estimate

A very transparent alternative way of estimating this accelerator-produced neutron integral dose, which avoids the use of attenuation information, is the following: Begin with the value $2 \times 10^5$ neutrons $cm^{-2}$ $rad^{-1}$ (read from the flat portion above 20 MeV of the curve of Fig. 1). Assume that the neutrons are produced entirely by W and have an average energy of 1.0 MeV[1] and the body area illuminated is A ($cm^2$).

$$(2 \times 10^5 \text{ neutrons cm}^{-2} \text{ / treatment rad}) \times (1.0 \text{ MeV / neutron}) \times (1.602 \times 10^{-8} \text{ g rad/MeV}) \times A(\text{cm}^2) \quad (1)$$
$$= 3.20 \times 10^{-3} \, A(\text{cm}^2) \text{ neutron g rad / treatment rad.}$$

This formula expresses the assumption that almost all neutron energy fluence within the area A is transferred to tissue (i.e., tissue is both "opaque" and nonreflective), and gives these results for the following field areas:

| | |
|---|---|
| A = 100 $cm^2$ | 0.32 neutron g rad / treatment rad |
| 600 | 1.9 |
| 900 | 2.9. |

The agreement with the preceding estimate is gratifying. This approach has the advantage that no knowledge of the neutron dose attenuation in tissue is needed as long as it is known that the attenuation occurs in a distance short in comparison with the thickness of the body. This estimate should be quite reliable because only two factors are involved, the

maximum neutron fluence per treatment rad and the average neutron energy; these are both known to about ± 25% or better.

B. Neutrons filtered by high-Z shielding

The body surface facing the treatment head is "illuminated" by a rather uniform neutron field which leaks through the W and/or Pb shielding of the treatment head. Because of frequent collisions within the high-Z shielding the spectrum is considerately moderated; the mean neutron energy is reduced in 10 cm of W, for example, by about a factor of 0.4 (see Mc79, Fig. 3). The resulting HVL of neutron dose in tissue is about 3.5 cm (or a dose attenuation coefficient of $\lambda = 0.20\ cm^{-1}$).[2] The entrance dose of this neutron field is about 0.00025 rad per treatment rad for the typical accelerator operating above about 20 MeV (A179, Ax79, La79). Due to the shielding effect of overlying tissue, distal tissues receive only negligible doses from this source. There is an even more rapid attenuation such that about half of the integral dose is deposited in the first 3.5 cm. The integral dose can again be estimated from the entrance dose multiplied by the body area presented to the source and divided by the dose attenuation coefficient. For example:

$$0.00025\ \frac{\text{neutron rad}}{\text{treatment rad}} \times (100\ cm \times 30\ cm) \times$$

$$(1\ g/cm^3)\ /\ (0.20\ cm^{-1}) = 3.75\ \text{neutron g rad / treatment rad.}$$

This figure is only an estimate but is approximately constant for the same machine, independent of field size or treatment distance. It will

also vary only slightly with treatment energy assuming the energy is in the range 20 - 40 MV (Fig. 1). It would of course vary somewhat with the phantom geometry assumed.

Simplified estimate

The alternative estimate, using Eq. (1), is as follows: For the entire body area, assumed to be 100 cm × 30 cm = 3000 $cm^2$, illuminated by a neutron field filtered by 10 cm of W we have

$$3.20 \times 10^{-3} \times 3000\ cm^2 \times 0.4 = 3.8 \text{ neutron g rad / treatment rad},$$

where the factor "0.4" represents only the softening of the neutron energy spectrum by the filtering of the tungsten; the same fluence is assumed for both the "direct" and filtered neutrons.[3] Again, for the same phantom area, this direct estimate is in excellent agreement with that obtained by use of the attenuation coefficient.

Ratio of neutron doses within and outside of beam

It has been pointed out (Mc79) that very few neutrons are absorbed in passing through a W or Pb filter, whereas the scattering may reduce their average energy substantially (Mc79, p. 77, Figs. 3 and 4). The difference in neutron dose measurements in and out of the beam is qualitatively explained by this effect:

$$R \equiv (\text{Dose in beam}) / (\text{Dose out of beam}) =$$

$$(1 + 1 \times \sqrt{0.4}) / (1 \times \sqrt{0.4}) = 2.58,$$

where "1" represents unit neutron fluence for both the direct and filtered neutron fields and the multiplier $\sqrt{0.4}$ represents the reduction in average neutron energy of the filtered fields. The square-root is used here because the kerma for tissue varies approximately as the square root of neutron energy for 0.1 - 10 MeV (this is easily seen, for example, in ICRU69, p. 35, Fig. IV.4). This energy interval contributes over 90% of the kerma for either neutron field (Ax79). The ratio R so estimated agrees exactly with a simple average of 13 measurements summarized by Laughlin (La79, p. 10, Table 1): $R_{avg} = 2.58$.

Note that the coefficients used above in the primary estimates of integral dose (0.0004 and 0.00025 neutron rad / treatment rad), when combined in this manner yield

$$(4 + 2.5) \; / \; 2.5 = 2.60,$$

in complete consistency with these observations.

C. Room-scattered neutrons

There is a "sea" of accelerator-produced neutrons that scatter about the concrete room, irradiating the patient quite uniformly on all sides. These are further reduced in average energy, and, for 25-MV treatment increase the integral dose to the patient by about 20% (Ing80a). This integral dose scales in the same manner as the high-Z filtered neutron dose and thus is roughly independent of field size, treatment distance or treatment energy (for 20 - 40 MV), for the same machine. The room-scattered neutron field is also discussed by Ax79 and Mc79.

## II. Photoneutrons Produced Within the Patient's Body

This second neutron source is distributed practically identically as the treatment dose within the irradiated volume. However, the neutrons have considerable range and their absorbed dose distribution is broader than the source distribution. This results in a penumbra of about 10 cm (the distance in which the field drops from 80% to 20% of the maximum). Only for large fields will most of this dose be contained within the treatment volume; for small fields (~ 100 $cm^2$) most of the neutron integral dose is deposited outside. However, this integral dose also scales as field area and therefore becomes insignificant for small fields.

Horsley et al. have estimated that, for 24-MV treatment, about 0.3% of the treatment dose is deposited via photonuclear reactions in tissue (Ho53). Of this, about 90% is estimated to be contributed by charged secondaries (p and $\alpha$) so that the neutron integral dose is only about 0.03% of the treatment beam integral dose.[4]

The most complete study of the integral dose of neutrons produced within tissue as a function of treatment energy is that of Laughlin et al. (La79). These data, re-expressed as the ratio of neutron integral dose to treatment X-ray integral dose, are shown in Fig. 2, where a smooth curve has been drawn through the points. The difference between these data and the points of Horsley et al. can be traced to the use of more recent photonuclear cross sections.

New calculations by Ing et al. (Ing80b) for 25-MV treatment are also shown in Fig. 2. Using current photonuclear cross sections, to-

gether with computer programs to study the transport of both photons and neutrons, they find that neutrons produced within the patient contribute integral absorbed doses of about 0.012% of the treatment X-ray integral absorbed dose for 25-MV treatment. From the results of Ing et al. one can also infer the fraction of the tissue-produced neutron integral dose which is imparted outside of the treatment volume. This unwanted fraction is about 0.53 and 0.20 for fields of 100 and 600 $cm^2$, respectively. If we now multiply by the treatment X-ray integral dose imparted per treatment rad for these field sizes (nominally taken as 18 rad per $cm^2$ of field area) we find unwanted tissue-produced neutron integral doses in the range 0.1 - 0.3 g rad per treatment rad. Calculations by the same authors for a 35-MeV betatron beam are qualitatively similar in the relative distribution of neutron dose but they are higher by about a factor of 3.6, meaning that the tissue-produced neutron integral dose is about 0.043% of the treatment X-ray integral absorbed dose. There appears to be complete agreement between the calculations of Laughlin et al. and Ing et al.

## CONCLUSIONS

Estimates of accelerator-produced neutron integral doses may vary somewhat, depending on the geometry and other parameters assumed. However, for treatment energies above 20 MV, the integral doses for small fields are typically about 4 g rad and for large fields about 7 g rad, if only W is used as the neutron source and filter. These estimates are in good agreement with those obtained by numerical integration over

a cylindrical phantom (Sw80, p. 142, Table I). Specific accelerator models may give different results depending on the materials struck by the beam but most should lie within a factor of two of these estimates; if Pb were substituted for W the integral doses would be approximately double, primarily because of the higher average neutron energy at production but also because of the smaller reduction in neutron energy by filtering. Those accelerators whose neutron dose is significantly above the values indicated here probably have multiple neutron sources along their beam transport systems.

These estimates of integral dose consider only the high-LET component, as this has the major significance for somatic injury; doses delivered by capture gamma rays are disregarded.

These estimates are admittedly simplified, but they form a consistent picture which draws from different kinds of published experimental information. Part of the utility of this approach is that it shows in very obvious arguments the consistency which underlies what otherwise appears to be a very fragmented body of information.

## Acknowledgements

This work was supported by the Department of Energy, contract DE-AC03-76SF00515.

Footnotes

1. The mean energies are taken as twice the nuclear "temperature" T found in photoneutron experiments. Mutchler gives T = 0.69 MeV while Gayther and Goode give 0.44 MeV for tungsten. These correspond to mean neutron energies of 1.38 and 0.88 MeV, respectively. The average of these data is 1.13 MeV and their spread is ± 0.25 MeV. If Pb is substituted for W, the mean neutron energy is approximately doubled. See references and discussion in Sw79, pp. 71-75.

   The HVL value 5.8 cm is actually for a $^{252}Cf$ fission spectrum which is similar to that of an unshielded high-Z photoneutron source (Mc79, p. 78, Fig. 5). The $^{252}Cf$ spectrum actually agrees well with the photoneutron source from Pb, but is somewhat harder than that from a W photoneutron source. Thus 5.8 cm may be somewhat of an overestimate.

2. The value HVL = 3.5 cm is from MORSE Monte-Carlo calculations reported by McCall and Swanson (Mc79, p. 83, Fig. 2). From recent work by Brahme et al. (Br80) one can infer HVL's of 4.4 or 4.7 g $cm^{-2}$ in water for photoneutrons from a uranium target filtered by 4 or 8 cm of Pb, respectively. The filtering action of Pb is less than that of W (Mc79, p. 77, Figs. 3 and 4).

3. It has been pointed out (Mc79) that very few neutrons are absorbed in passing through a W or Pb filter, whereas the scattering reduces their average energy substantially (Mc79, p. 77, Figs. 3 and 4).

4. It should be pointed out that corresponding data given by Swanson

(Sw80, Table I, "Neutrons produced within patient") should be reduced by a factor of 10 to correctly reflect the statements of Horsley et al. The corrected data are then 0.5 and 5.0 g rad for 100 and 900 $cm^2$ fields, respectively.

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Figure Captions

Fig. 1. Neutron fluence per treatment dose as a function of treatment megavoltage (Mc79). The solid curve corresponds to the case in which all neutron-producing components are of W (alone, or in combination with Pb), and represents the maximum possible fluence if the electron beam strikes only these materials. The lower curve is for all neutron sources being of Cu, for comparison. Points are representative measurements for several accelerator types. Probable accuracy of curves is ± 25%.

Fig. 2. Estimates of integral dose of neutrons produced within tissue, expressed as a fraction of the treatment beam integral dose, and plotted as a function of X-ray treatment energy. The dashed curve is drawn through the points of Laughlin et al. (La79). Other references are to Fr64, Ho53 and Ing80b. Data of Ho53 are from their Table 3, divided by 10.

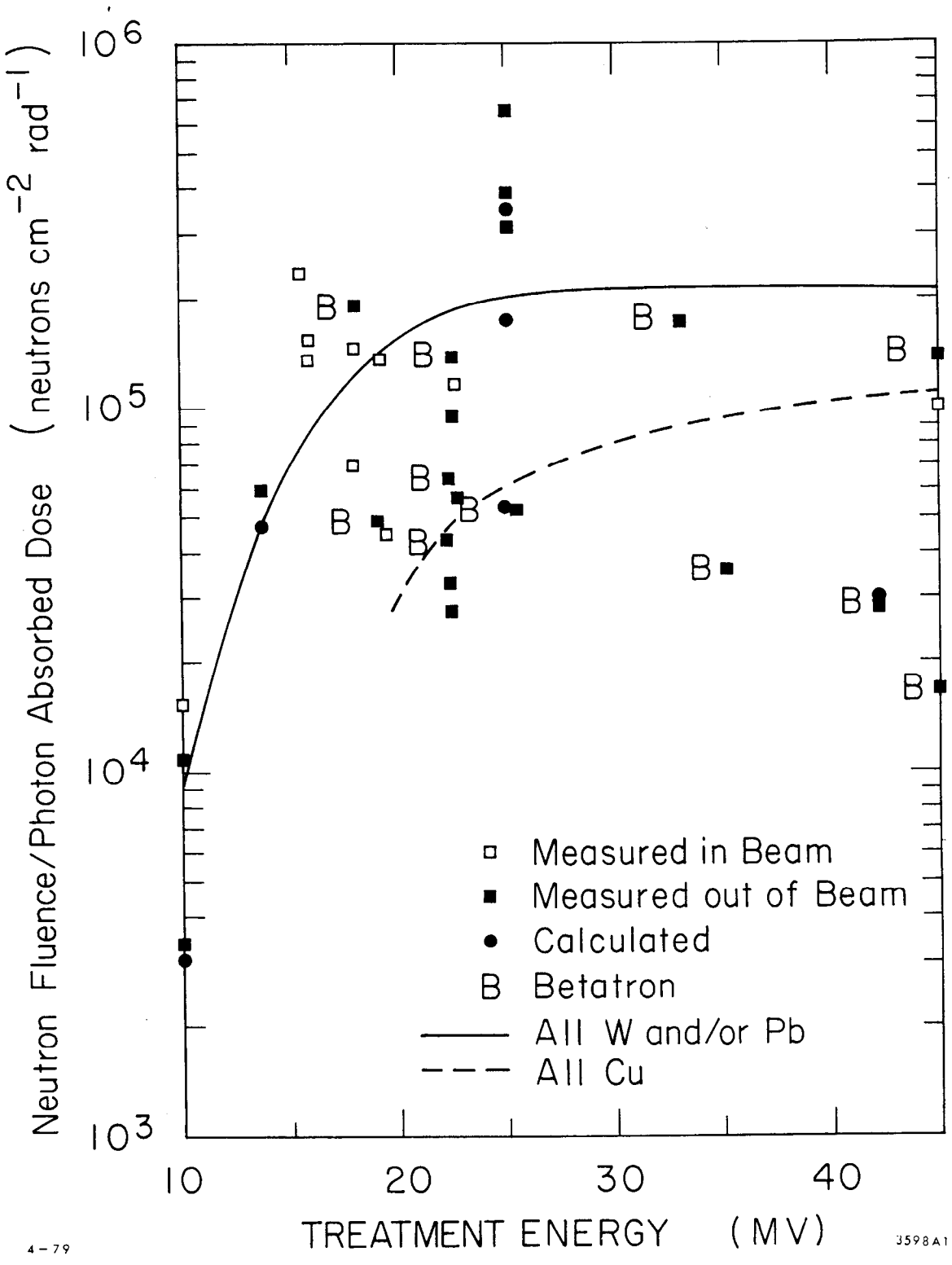
Neutron Fluence/Photon Absorbed Dose (neutrons cm$^{-2}$ rad$^{-1}$)
$10^6$
$10^5$
$10^4$
$10^3$
10
20
30
40
TREATMENT ENERGY (MV)
Measured in Beam
Measured out of Beam
Calculated
B Betatron
All W and/or Pb
All Cu
4-79
3598A1

Fig. 1

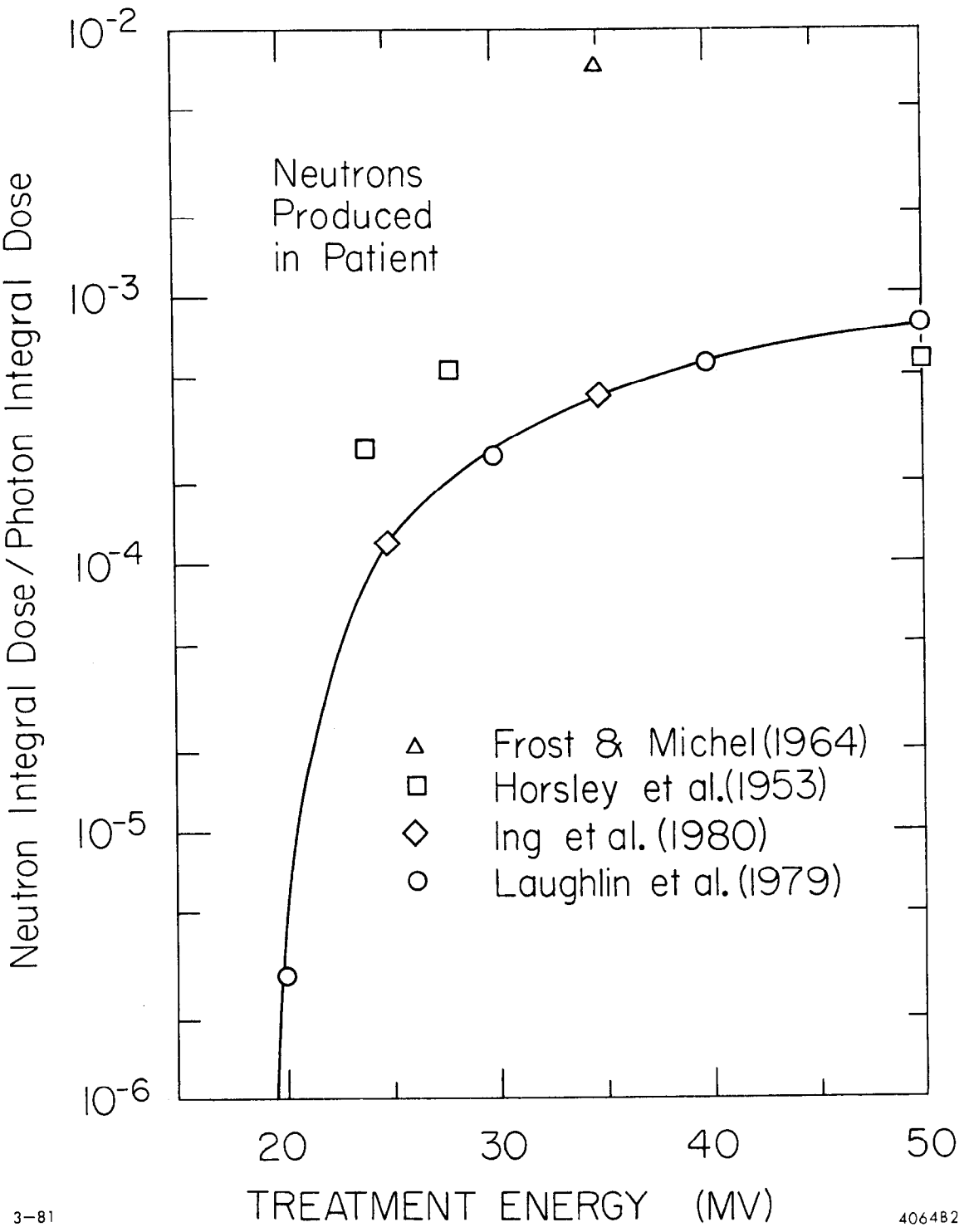
Neutrons
Produced
in Patient
Frost & Michel (1964)
Horsley et al. (1953)
Ing et al. (1980)
Laughlin et al. (1979)
Neutron Integral Dose / Photon Integral Dose
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
20
30
40
50
TREATMENT ENERGY (MV)
3-81
406482

Fig. 2