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THE EFFECTS OF HYDROGENOUS AND NON-HYDROGENOUS FILTERS ON THE QUALITY OF A p(66)Be(49) NEUTRON BEAM

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ABSTRACT

The hardening effects of hydrogenous and non-hydrogenous filters on a p(66)Be(49) neutron beam have been investigated. It was found that all materials studied, Teflon, aluminum, lead, steel and polyethylene, harden the neutron beam, albeit polyethylene to a greater extent. Relationships were found to exist between the attenuation of a filter and its hardening effect, and also between the build-up characteristics and the depth for half-maximum dose of the hardened beams.

Key Words: neutrons, neutron beam, filters, depth dose, build-up, radiation therapy.

INTRODUCTION

At the Fermilab Neutron Therapy Facility,[1,2] the neutron beam is produced by 66 MeV protons incident on a beryllium target which removes 49 MeV of the incident proton energy by non-nuclear collisions. This is indicated by p(66)Be(49). No hardening or flattening filter is used with this beam, as the penetration, skin sparing and isodose distributions are clinically acceptable at the treatment distance used (SAD = 190 cm).[3,4] While considering a new generation of isocentric neutron therapy machines designed to operate at a similar high proton energy,[5] it was realized that, due to practical considerations, a shorter SAD would be necessary. To restore or improve the penetration characteristics of the proposed beams under those conditions, polyethylene filters may be added to harden the neutron beam. To that end, a study was made of the effects of polyethylene filters on the quality of the p(66)Be(49) beam currently available.

The hardening effect of hydrogenous filters on p-Be produced neutron beams has been well documented;[6-11] a similar effect is also present in d-Be produced beams,[12] due to the preferential scattering of lower energy neutrons.[13] The penetration of p-Be beams can also be improved by making the target thinner,[6,14,15] but, above a residual energy of

about 20 MeV, exiting protons still produce low energy neutrons in all practical backing materials,[16] thus limiting the effect of this approach. The best compromise would then be achieved using a semi-thick target and additional filtration.[6]

It might also be desirable for the new generation neutron beams to have their dose distributions modified by flattening filters. Certainly, the use of wedges will be continued. However, the very properties that make hydrogenous materials good hardening filters make them less suitable as materials for wedge or flattening filters.[17-19] This is due to the differential beam hardening associated with varying beam attenuation. In the case of wedge filters, this effect tends to decrease the isodose rotation angle.[20,21] In the case of flattening filters, it tends to enhance the "horns" produced at depths shallower than the depth for maximum flatness.[17] It would be ideal to use materials that do not harden the neutron beam for these purposes. Therefore, some non-hydrogenous materials, presently used or proposed for use as filters,[21,22] and commonly presumed to have negligible hardening effects on neutron beams, were also investigated along with polyethylene.

EXPERIMENTAL ARRANGEMENTS

For the present measurements, phantoms were positioned at an SSD of 170 cm, a probable isocentric distance for a high-energy, gantry-mounted, dedicated neutron generator.[5] A polyethylene-concrete collimator[23] of nominal field size 12x12 cm^2 (defined at 190 cm SAD)[3] was used throughout. This collimator defined a 10.7 x 10.7 cm^2 field size at 170 cm SSD.

The filters under study were machined to fit into a fixed opening in the collimation system, upstream from the interchangeable collimators.[3] The filters were far enough removed from the neutron beam monitor ionization chambers that backscatter could not affect chamber sensitivity, and deep enough upstream of the collimator such that very little scattered particle flux from them would reach the detectors. This meant, however, that charged particles released from the inside surfaces of the hydrogenous collimator could reach the phantom surface and possibly affect the measured build-up curves.[24] Therefore, one build-up measurement was also made with the addition of a thin steel plate at the downstream end of the collimator.

The depths for half-maximum dose for the various filters were measured in a tissue equivalent liquid phantom,[25] of density 1.07 g cm^{-3} using an air-filled 0.1 cc thimble ionization chamber, EG&G model IC-18.[26] The experimental arrangements were essentially the same as those reported elsewhere.[3] A microcomputer was used to monitor both the thimble chamber output and the transmission ionization chamber output as well as to control a remote positioner. Precision of $\pm$1% or better in dose measurement and of $\pm$0.5 mm in position were achieved. Measurements were taken for each filter configuration in the region of maximum dose (D_{max}) until its value was established. These measurements also provided precise determinations of the dose attenuation at D_{max} due to introduction of the absorbers. Additional measurements were taken at several depths bracketing the expected position of half-maximum dose, and a final value of the depth for half-maximum dose ($z_{0.5}$) was later derived by interpolation. All depths are defined from the upstream surface of the 3 mm thick entrance window of the Lucite tank to the center of the ionization chamber.

Build-up measurements were also made for several of the filter configurations using an A-150 TE-plastic[27] parallel plate extrapolation chamber and A-150 disks of different thicknesses, all made by EG&G.[26] The chamber was operated at +300 V polarizing voltage and with a plate spacing of 2.3 mm.

The chamber fitted snugly into a large TE-plastic build-up phantom. The experimental arrangements were essentially the same as described in detail elsewhere.[4] Extrapolation and polarity reversal studies were also done using different filter combinations. For each situation, measurements were taken at the surface (behind the thin mylar window of 2.9 mg cm^{-2}), at several points in the broad region of maximum dose (1500-2000 mg cm^{-2}), and at several depths bracketing the build-up thickness required for 90% of maximum dose (400-800 mg cm^{-2}). A final value for this latter depth was then derived by interpolation.

RESULTS

The hardening effects produced by filters made out of five materials were studied: polyethylene ($[CH_2]_n$), Teflon,[28] aluminum (Al), steel (Fe), and lead (Pb). Various thicknesses of each material were investigated, some of them more than once to test for reproducibility of results.

A summary of the results is presented in Table 1. The uncertainty of $\pm$1% in measured dose ratios translates to $\pm$1.5 mm in the interpolated value of the depth for half-maximum dose ($z_{0.5}$). This uncertainty, added in quadrature to uncertainties in positioning the chamber

($\pm$0.5 mm) and to uncertainties in interpolation ($\pm$0.5%), produces a total uncertainty of $\pm$2 mm in the stated values of $z_{0.5}$. For the build-up measurements, the uncertainties in relative dose rates ($\pm$ 0.5%) and in the scatter of the points for interpolation ($\pm$0.5%), add up to a total uncertainty of $\pm$10 mg cm^{-2} in the value of the depth for the 90% build-up level and of $\pm$0.5% of D_{max} in the value of the entrance dose.

Fig. 1 shows relative dose versus depth in the region of the 90% build-up for some of the filters. The curves joining the data points represent least square fits of a quadratic to the data points. The depths for 90% dose build-up shown in Table 1 were obtained from these fits.

The variation in the depth for maximum dose with beam hardening was also investigated. The 100% dose peak around 1700-2000 mg cm^{-2} was so broad for all filtrations investigated that the collected charge per monitor unit from the extrapolation chamber varied only by $\pm$0.3% over a $\pm$200 mg cm^{-2} range. Nevertheless, a shift in the position of the maximum could be observed. These results are also given in Table 1.

Measurements were made with the extrapolation chamber at different plate spacings and with both polarities for different filter combinations. The effect of polarity on the

charge collection was always less than 1% and the averages of both positive and negative polarity readings were used. The readings at the surface (2.9 mg cm^{-2}) and near the 90% build-up level for each plate spacing were normalized to the corresponding readings at a depth of 1750 mg cm^{-2}. The normalized doses near the 90% build-up level showed no dependence on plate spacing, while the normalized entrance doses exhibited a small but real correlation and were extrapolated to zero separation. These corrected values are also shown in Table 1.

DISCUSSION

It can be seen from Table 1 that all materials investigated in this experiment have a hardening effect on the p(66)Be(49) neutron beam. The efficacy of polyethylene in increasing the beam penetration at relatively little cost in attenuation, even for a semi-thick target, is consistent with previously reported results.[6-11] Somewhat unexpectedly, the non-hydrogenous materials also harden the neutron beam, albeit to a smaller extent. One of the consequences of this hardening effect is that some care should be taken in reporting the exact amounts of materials interposed between the beryllium target and the patients.

Discrepancies have previously been noted in the reported effectiveness of nominally equal thicknesses of polyethylene filters in beam hardening.[15] These discrepancies could be due in part to a variation in the density of commercially available polyethylene,[29] and in part to the unreported presence of different amounts of filter holder materials. Thus, a more consistent, and also physically and clinically more relevant, description of beam hardening results would be attained by relating the increased penetration of a neutron beam to the attenuation produced by the hardening filter. Accordingly, the depth for half-maximum dose of each filter has been plotted in Fig. 2 as a function of the attenuation of D_{max} corresponding to that filter. The lines joining the data points represent least square fits to the linear expression:[6]

$$z_{0.5}(\text{filter}) = z_{0.5}(\text{open}) \left\{1+m \left(1- \frac{D(\text{filter})}{D(\text{open})}\right)\right\} \quad (1)$$

where D represents the dose per monitor unit at maximum and m is a material dependent coefficient. It can be seen from Fig. 2 that this expression fits the data very well, within the experimental uncertainties, even for the large range of attenuations measured for polyethylene and steel.

Also plotted in Fig. 2 is the effect of a multi-material filter, as might be encountered in a beam hardened with polyethylene and flattened using a steel flattening filter.

The broken line represents the predicted effect of adding 3.8 cm of steel to a beam already filtered by 2.5 cm of polyethylene. The prediction agrees very well with the measurement and illustrates the usefulness of the above expression.

The coefficient $\underline{m}$ in Equation 1, which may be interpreted as percent increase in $z_{0.5}$ per percent attenuation, could be used as an index of merit (or demerit if hardening is not desired) to characterize the properties of different materials. If a choice of material has to be made for a wedge or flattening filter, where the attenuation is designed to vary across the field, a low value of this index would be advantageous to minimize differential hardening. Table 2 gives the values of this coefficient for the materials studied in the present experiment with the p(66)Be(49) neutron beam, as well as the values for polyethylene derived from a previous study on a p(42)Be beam.[6] It can be seen from Table 2 that, as expected, this coefficient is highest for polyethylene, and that it decreases monotonically for lead, Teflon, aluminum and steel. It can also be seen that, at least for polyethylene, the parameter $\underline{m}$ is only weakly dependent of the incident proton energy, but that, due to beam divergence, it depends somewhat on the SSD used in the measurements. Also included in Table 2, for comparison, is the value of $\underline{m}$ derived from the

reported effects of a polyethylene flattening filter on a d(49)Be neutron beam.[12] The hardening effect of polyethylene on d-Be produced neutrons is seen to be less marked than for p-Be produced neutrons.

The build-up region is also affected when the beam is hardened, as can be seen from Table 1 and Fig. 1. This has been reported previously in p-Be beams hardened by filtration,[8,10] and was suspected to be the case for a p(42)Be beam hardened by making the target thinner.[6] To illustrate the change in build-up characteristics with beam quality, the measured entrance dose (behind 2.9 mg cm^{-2} of mylar) relative to D_{max} has been plotted in Fig. 3 as a function of the corresponding depth for half-maximum dose (taken as a measure of beam quality), while the depth for the 90% build-up level (in mg cm^{-2} of A-150) has been plotted as a function of the same parameter $z_{0.5}$ in Fig. 4.

It can be seen from Fig. 3 that a strong linear correlation exists between the entrance dose and the depth for half-maximum dose, seemingly irrespective of which of the two beam hardening materials is used to achieve a given penetration. It can further be seen from Fig. 4 that the correlation of the depth for 90% build-up with $z_{0.5}$ is also approximately linear.

The fact that the open beam point lies on the same line as the polyethylene filter points in Fig. 3 seems to indicate that charged particles from the target assembly and monitor chambers do not contribute significantly to the entrance dose. The alternative possibility, that all filters contribute fluxes of such particles equivalent to what they remove, seems less likely since the steel filter point also lies on the same line.

The arrows linking the two steel filter points in Figs. 3 and 4 represent the effect of placing a 3.2 mm steel plate (which would stop 42 MeV protons) at the patient end of the collimator, when a 19 mm steel filter is inserted at the upstream end. (The penetration for this filter combination was not measured, but obtained using Equation 1 from the measured attenuation). The observed drop in entrance dose due to the downstream steel plate, (Fig. 3) seems to indicate that, for this beam, the extra dose at the skin is contributed by charged particles produced by narrow angle scatter in the internal faces of the collimator and is not more than 1% of the dose at maximum, or 2% of the entrance dose. Furthermore, it can be seen from Fig. 4 that the effects of this "collimator shine" are all but lost by the time 90% of the maximum dose is reached. Thus, the very small effect that charged particles from the collimator have at this depth does not warrant any preoccupation about excess

skin reactions,[24] which have not in any case been observed with this beam even at relatively high doses.[30]

CONCLUSIONS

The hardening effects of polyethylene and of non-hydrogenous filters on a p(66)Be(49) neutron beam have been investigated. It was found that all materials under study harden the neutron beam, albeit by different amounts. Therefore, all materials placed between target and patient should be carefully specified when describing a neutron beam. Furthermore, it has been shown that a linear relationship exists between the dose attenuation by a filter and its effect on increasing the penetration of a p-Be neutron beam.

The effects of beam filtration on the entrance dose and on the depth for 90% build-up, have been shown to exhibit monotonically increasing skin sparing with increasing penetration.

The contribution of charged particles from the internal surface of the collimator to the dose at the 90% build-up point has been shown to be negligible for this neutron beam.

Polyethylene remains the material of choice for beam hardening. Steel is a material which should be considered for use in the construction of field flatteners and wedge filters stored inside an isocentric gantry. For externally mounted flattening and/or wedge filters, Teflon should be given first consideration.

RECOMMENDATION

Due to the steepness of the dose-response function, the depth for the 90% build-up level may be more clinically relevant than the entrance dose. This depth is much easier to determine precisely than the depth for maximum dose, and, moreover, it may be a more relevant parameter in deciding on the need for bolus to ensure adequate dosage of subcutaneous lesions. In view of these considerations, it is recommended that beam quality in the build-up region be expressed with two numbers. The first number would give the depth for 90% of D_{max}, the second (in parenthesis) would give the depth for D_{max}. For example, for the unfiltered p(66)Be(49) beam, the build-up characteristics would be given as 470(1700) mg cm^{-2} of A-150 TE-plastic.

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TABLE 1

Penetration and build-up of a p(66)Be(49) neutron beam as a function of filtration by various materials.

Filter Material	None	Polyethylene				Lead		Teflon		Aluminum		Steel				Poly-eth.+ Steel	Notes
Nominal Thickness (cm)	0	2.5	5.1	7.6	12.7	5.1	7.6	3.8	7.6	5.1	10.2	1.9	1.9 + 0.32	3.8	7.6	2.5 + 3.8	
Attenuation at D_{max}	1.00	.79	.65	.55	.39	.47	.33	.65	.42	.59	.37	.69	.64	.47	.25	.38	(a)
Depth half maximum dose $z_{0.5}$(cm)	15.6	16.6	17.1	17.6	18.3	16.8	17.0	16.3	16.8	16.2	16.6	16.0	—	16.3	16.6	17.0	(b)
Entrance Dose (% of D_{max})	42.7	41.7	40.4	—	38.9	—	—	—	—	—	—	42.2	41.4	—	—	—	(c)
Extrapolated Entrance Dose (% of D_{max})	42.4	—	—	—	38.1	—	—	—	—	—	—	—	41.1	—	—	—	(d)
Depth for 90% of D_{max} (mg cm^{-2})	467	495	550	—	626	—	—	—	—	—	—	494	497	—	—	—	(e)
Depth for D_{max} (g cm^{-2})	1.7	—	1.9	—	2.0	—	—	—	—	—	—	1.7	—	—	—	—	(f)
Notes													(g)			(h)	

Table 1 (Continued)

Notes:

(a) Doses measured per Monitor Unit at D_{max} in TE Liquid[25], and normalized to unity for the unfiltered beam. Uncertainties: ±1%.

(b) Measured in TE Liquid (ρ=1.07 g cm^{-3}) at SSD = 170 cm. Uncertainties: ±0.2 cm.

(c) Measured behind 2.9 mg cm^{-2} of mylar. Plate separation 2.3 mm, +300 V collecting voltage. Uncertainties: ±0.5%.

(d) Measured behind 2.9 mg cm^{-2} of mylar. Values extrapolated to zero plate spacing. Uncertainties: ±1%.

(e) Measured in A-150 TE plastic, with extrapolation chamber as in (c). Uncertainties: ±10 mg cm^{-2}.

(f) Measured in A-150 TE plastic with extrapolation chamber as in (c). Uncertainties: ±0.2 g cm^{-2}.

(g) 3.2 mm steel plate was at mouth of collimator.

(h) Steel was downstream of polyethylene, both upstream of collimator.

TABLE 2

Coefficient of neutron beam hardening for various materials.

Neutron Beam	SSD (cm)	$z_{0.5}$(open) (cm)	Coefficient m [a]					Notes
			$(CH_2)_n$	Pb	Teflon	Al	Fe	
p(66)Be(49)	170	15.6	.28	.13	.13	.09	.08	present work
p(42)Be(42)	125	11.5	.25	—	—	—	—	(b)
p(42)Be(8)	125	13.5	.25	—	—	—	—	(b)
p(42)Be(42)	170	12.1	.26	—	—	—	—	(c)
p(42)Be(8)	170	13.8	.27	—	—	—	—	(c)
d(49)Be	140	13.2	.12	—	—	—	—	(d)

Notes:

(a) Coefficient m from

$$z_{0.5}(\text{filter}) = z_{0.5}(\text{open}) \left\{1 + m \left(1 - \frac{D(\text{filter})}{D(\text{open})}\right)\right\}$$

where $z_{0.5}$ is depth for half-maximum dose (in cm of TE liquid) and D is dose per monitor unit at D_{max}.

(b) From Ref. 6 for a 10x10 cm^2 field size.

(c) Reduction of data in Ref. 6 to 170 cm SSD by inverse square law.

(d) From Ref. 12 comparing flattened and unflattened isodose curves for a 11.1 x 11.1 cm^2 field size using a polyethylene flattening filter.

Figure Captions

Fig. 1. Relationship between relative dose and depth in the build-up region near the 90% level, for various filter combinations, for a 10.7 x 10.7 cm^2 field at SSD = 170 cm. The symbols and solid curves represent measurements and fits with, from left to right: no filter, 2.5 cm, 5.1 cm and 12.7 cm polyethylene filters. The dashed curve represents the fit to the measurements with a 1.9 cm steel filter (for clarity, data points are not shown). The curves were obtained by a least square fit to a second order polynomial.

Fig. 2 Relationship between hardening effect and transmission for filters of various materials. The materials investigated were:

Polyethylene (O — O);

Lead (∇ ---- ∇);

Teflon (□ —•— □);

Aluminum (+ --- +) and

Steel (● ——— ●).

The curves represent least square fits of Eq. 1 in the text. A combination filter of 2.5 cm polyethylene and 3.8 cm steel was also measured

(▲). The broken line (—·—·—) represents the predicted effect of adding this amount of steel to a beam already filtered by 2.5 cm of polyethylene.

Fig. 3. Relationship between penetration and entrance dose for various filter combinations. The full circle corresponds to the unfiltered beam, the open circles to polyethylene filters, and the squares to steel filters. The arrow joining the two steel filter points represents the effect of adding a 3.2 mm steel plate at the patient end of the collimator while leaving the previous steel filter in place at the target end.

Fig. 4. Relationship between penetration and depth for 90% build-up for various filter combinations. The full circle corresponds to the unfiltered beam, the open circles to polyethylene filters and the squares to steel filters. The arrow joining the two steel filter points represents the effect of adding a 3.2 mm steel plate at the patient end of the collimator while leaving the previous steel filter in place at the target end.

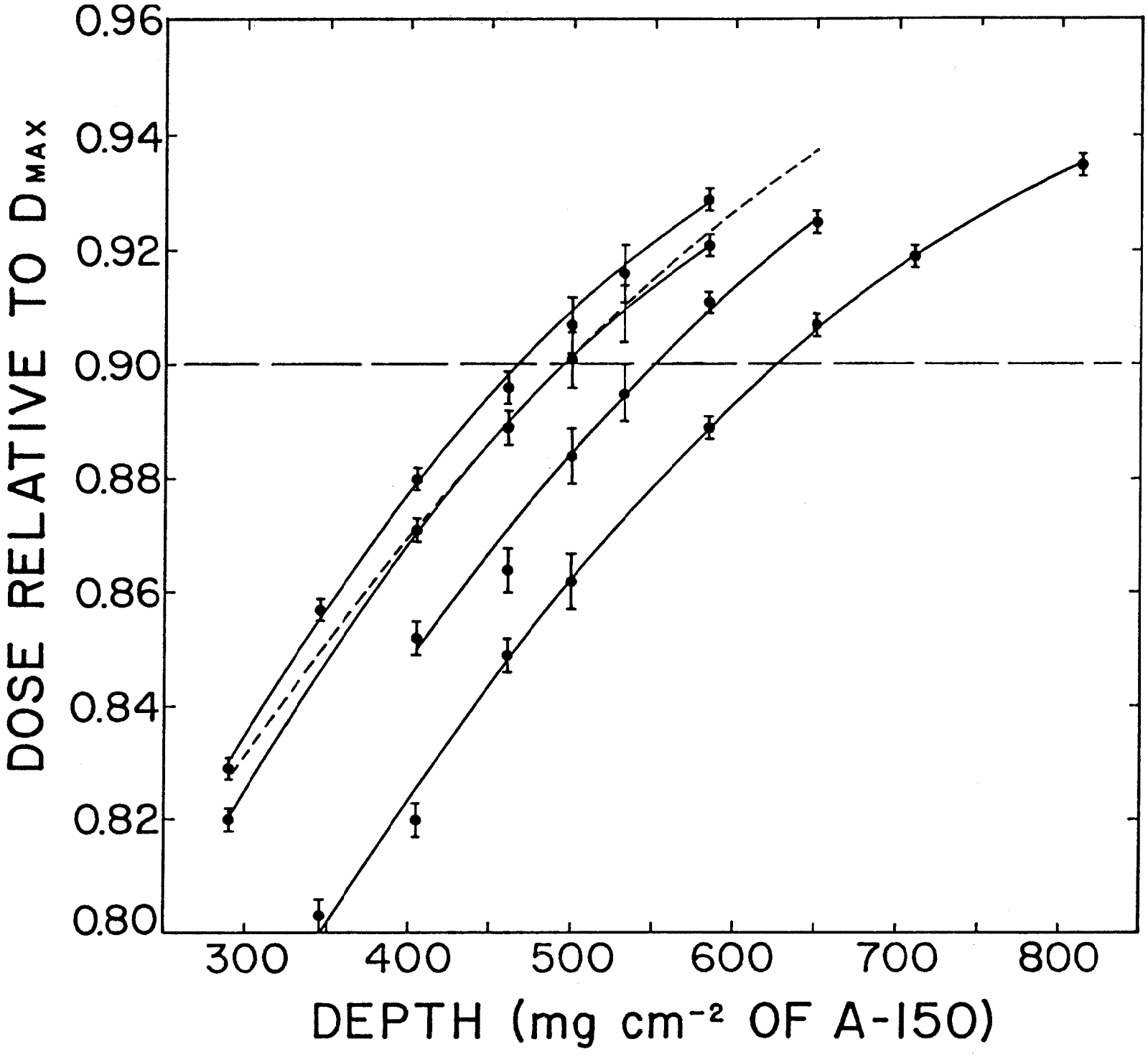
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
DOSE RELATIVE TO D_{MAX}
300
400
500
600
700
800
DEPTH (mg cm^{-2} OF A-150)

Fig. 1

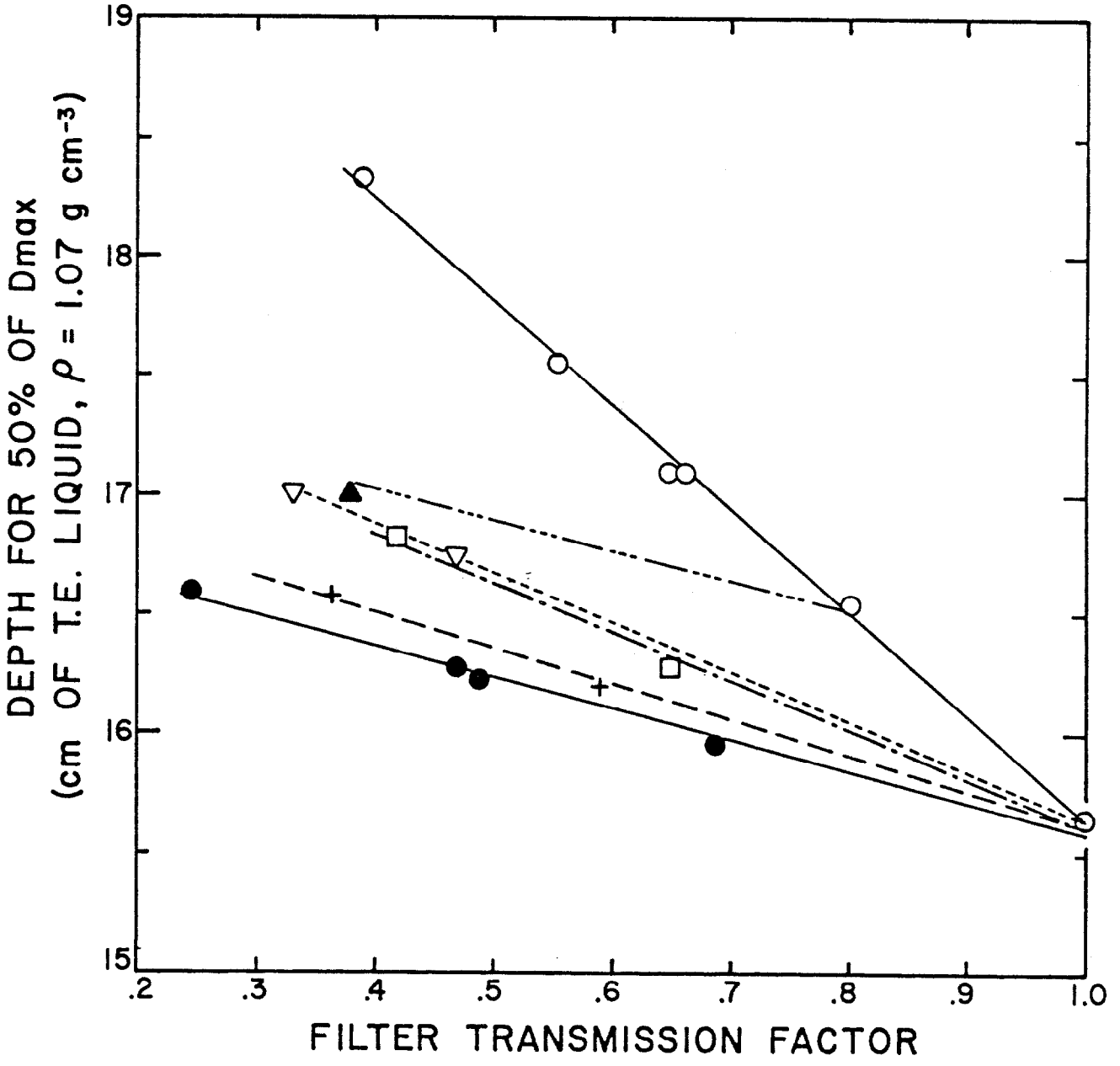
DEPTH FOR 50% OF Dmax
(cm OF T.E. LIQUID, ρ = 1.07 g cm⁻³)
19
18
17
16
15
.2
.3
.4
.5
.6
.7
.8
.9
1.0
FILTER TRANSMISSION FACTOR

Fig. 2

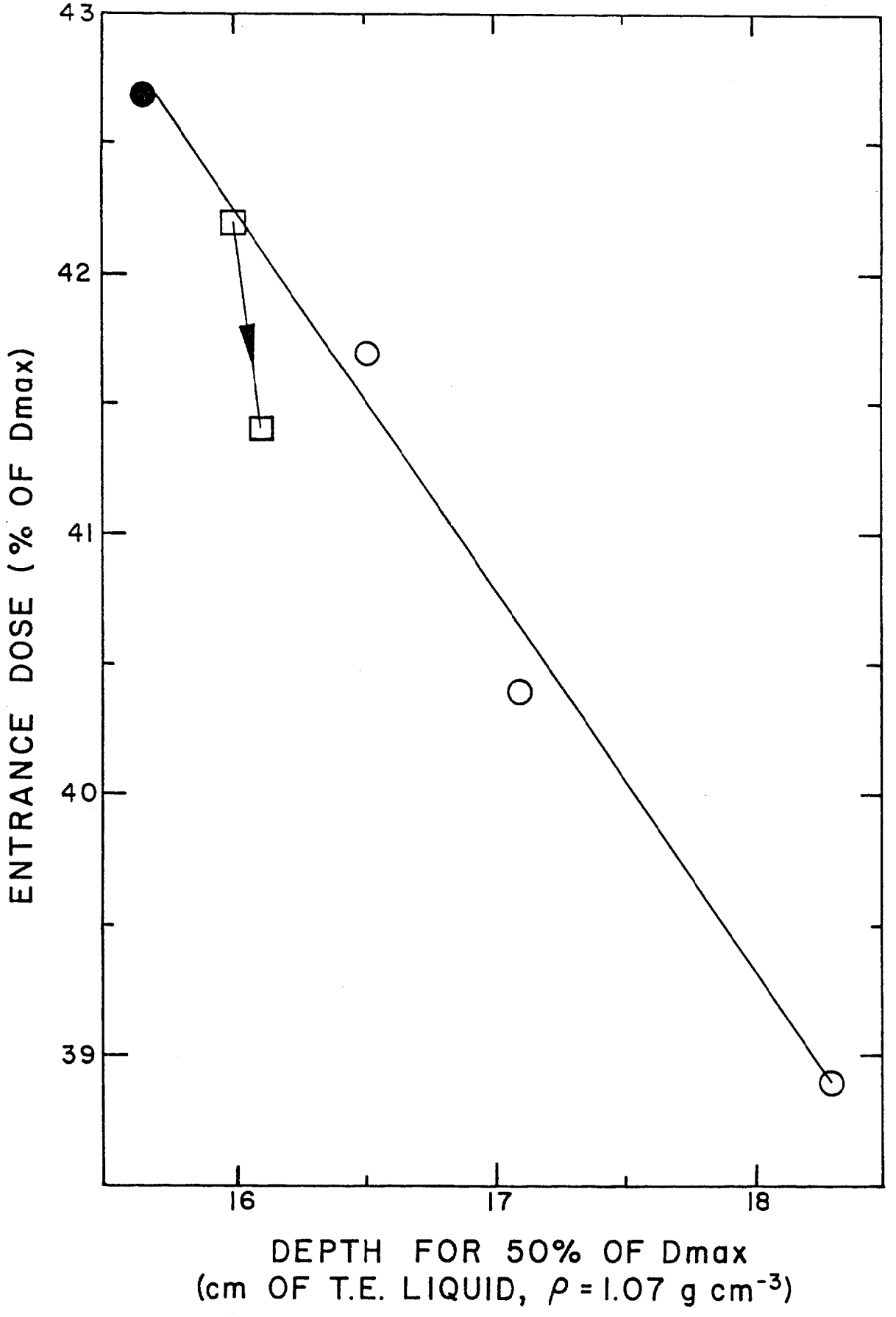
43
42
41
40
39
ENTRANCE DOSE (% OF Dmax)
16
17
18
DEPTH FOR 50% OF Dmax
(cm OF T.E. LIQUID, ρ = 1.07 g cm⁻³)

Fig.3

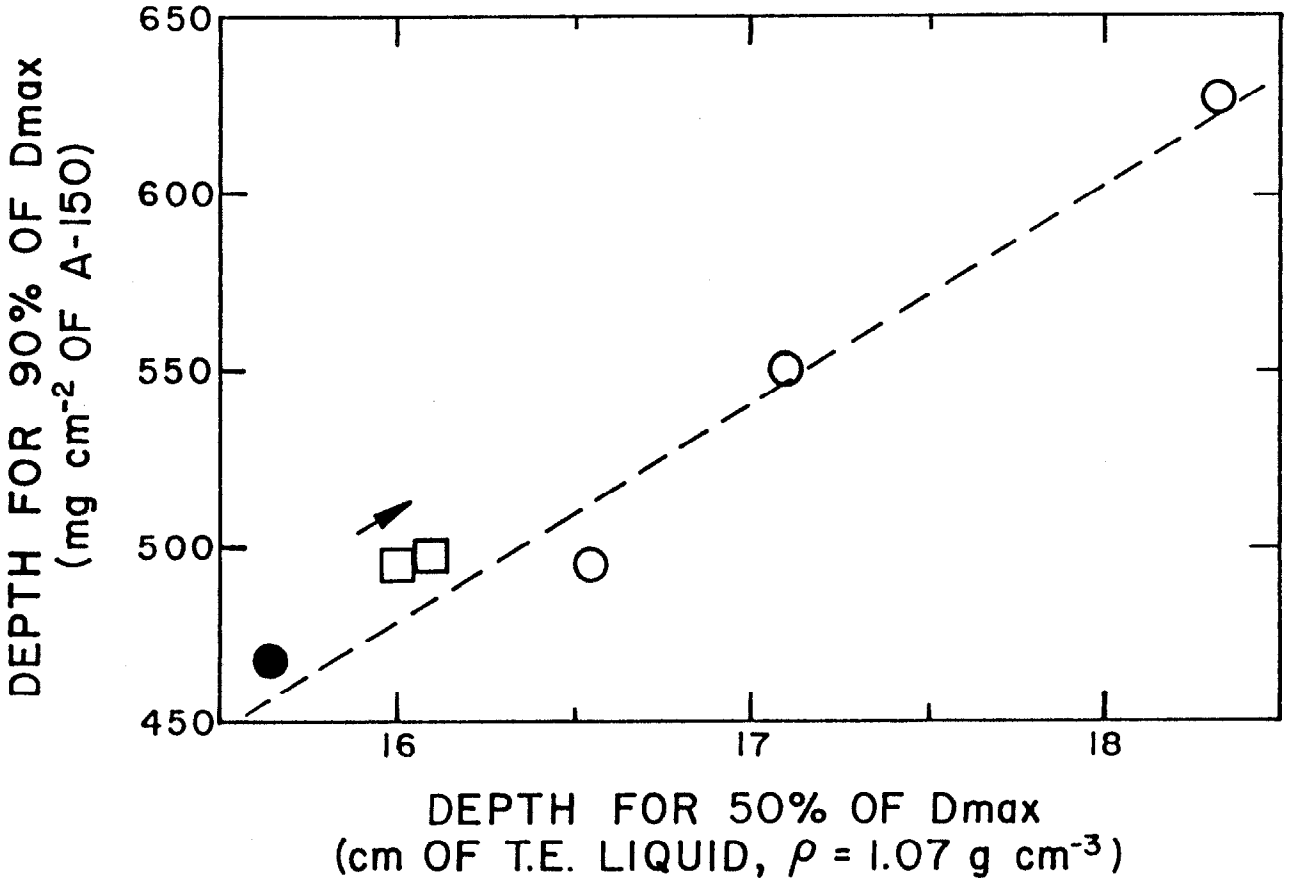
650
600
550
500
450
16
17
18
DEPTH FOR 90% OF Dmax
(mg cm^{-2} OF A-150)
DEPTH FOR 50% OF Dmax
(cm OF T.E. LIQUID, ρ = 1.07 g cm^{-3})

Fig. 4