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TM-1021
1183.00
Dec., 1980

COMPARISON OF THE PHYSICAL CHARACTERISTICS OF A p(66)Be(49) NEUTRON THERAPY BEAM TO THOSE OF CONVENTIONAL RADIOTHERAPY BEAMS

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ABSTRACT

The build up, central axis depth dose, and penumbra characteristics of the Fermilab p(66)Be(49) neutron therapy beam are compared to those of representative photon therapy beams. Comparisons are made for nominal 10x10 cm field sizes in tissue equivalent liquid.

KEY WORDS: p(66)Be(49), neutron therapy, build-up, depth dose, penumbra, high LET.

INTRODUCTION

The physical characteristics of the treatment beam used at the Fermilab Neutron Therapy Facility[1,2,9] have been described in earlier reports.[6,12] Briefly, the neutron beam is generated by 66 MeV protons incident on a beryllium target which removes 49 MeV from protons which do not undergo nuclear scattering. This process is represented by the notation p(66)Be(49). The remaining energy is absorbed in a 0.5 mm thick gold backing disk. The diameter of the proton beam spot is no greater than 1.6 cm. No beam hardener or flattener is used. Beam shapes are obtained by means of 78 cm long polyethylene concrete collimators whose downstream ends are 109 cm from the center of the beryllium target.[2,12]

Photon and neutron transport in, and energy transfer to matter are very similar. The basic difference is that photons interact mainly with electrons while neutrons interact with atomic nuclei. In tissue, neutrons scatter from and transfer energy mostly to hydrogen, carbon, nitrogen, and oxygen nuclei. These recoiling heavy particles lose their energy primarily by ionization and excitation. Since these particles move rather slowly in comparison with the speed of light, they ionize the tissue heavily. For this reason, neutrons are a source of high linear energy transfer (high LET) radiation.

In tissue, along the central axis of the neutron beam, the dose builds up from an initial value close to 50% of maximum dose at the skin surface, to a maximum at a depth of 1.6 g/cm^2. Then it decreases almost exponentially with depth.[6,12] Furthermore, a sharp cutoff in dose is not observed perpendicular to the central axis of the beam at the edge of the treatment field.[12] The dose profile may drop in magnitude from 90% to 10% of its "on axis" value over one or more centimeters.

The above physical characteristics, namely; dose build up (BU) or skin sparing; central axis depth dose (CADD); and regions of penumbra at the field edges or off-axis ratio (OAR); are also analogous to the properties of the photon beams used in conventional radiation therapy. Even though the method of energy deposition in tissue and the biological nature and relative effectiveness of the beams may differ, it is the physical parameters associated with BU, CADD, and beam profile that are of paramount importance in patient treatment planning. It is therefore natural that many questions posed by the radiotherapy community deal with how the physical parameters of this highly penetrating neutron beam compare with those of their supervoltage X-ray beams. It is the purpose of this note to collate information from various sources and present these comparisons.

METHODS OF COMPARISON

Throughout this note, all values are reported for depths in TE-solution (1 cm = 1.07 g/cm^2). Therefore, corrections to the originally reported values have been made for density and $1/R^2$ as outlined in ICRU Report 26.[10] That is, for phantom density ρ and reference density ρ_0, the reference depth x_0 is related to the phantom depth x by $x_0 = \rho x/\rho_0$ and the measured ionization must be corrected by $(s + x)^2/(s + x_0)^2$, where s is the source to surface distance (SSD). Whenever possible, comparisons have been made for fields having the same nominal field size of 10x10 cm^2 at the surface of the phantom. The photon curves and data shown below are only meant to be representative of typical therapy beams. All values quoted in this note refer to the various beams in common clinical situations. Thus, the CADD, for example, is quoted at 80 cm SSD for ^{60}Co, but at 100 cm SSD for 8 MeV accelerators and at 190 cm SSD for the p(66)Be(49) neutron beam, as these are the distances at which patients are commonly treated. The quoted values, therefore, do not represent true comparisons of beam quality.

SKIN-SPARING / BUILD UP (BU)

Build up curves relating relative dose to depth in tissue equivalent (TE) solution are presented in Fig. 1 for nominal 10x10 cm^2 fields. The p(66)Be(49) neutron beam values were derived from measurements made in A-150 TE-plastic[6] and are represented by the solid curve. The dashed curves represent the characteristics of the gamma-ray beam from ^{60}Co and the X-ray beams from 4, 6, and 8 MV electron accelerators. The photon beam values were derived from reported values in the British Journal of Radiology Supplement Number 11[7] and from measurements made in polystyrene by Manson, et al.[11] and Coffey, II, et al.[8]

It is to be noted that, whereas the neutron beam relative dose does not rise to 100% until depths comparable to d_{max} for the 6 MV and 8 MV beams, it reaches the 90% level sooner than either of those beams. It can also be seen that the entrance dose is larger in magnitude for our neutron beam than for the above X-ray beams. These characteristics are attributed mostly to the nature of energy deposition of neutrons in tissue and partly to charged particle contamination of the incident neutron beam from reactions in and around the collimator. Hence, whereas the usual figure of merit for skin sparing, the value of d_{max}, is large for our beam, the entire build up curve must be compared to the buildup curves of other beams to get a complete picture.

CENTRAL AXIS DEPTH DOSE (CADD)

The CADD characteristics of various 10x10 cm^2 beams in TE-solution may be seen in Fig. 2. Again, the solid line represents the neutron curve, this time measured in TE-solution.[12] The photon curves are from tables in B.J.R. Suppl. 11,[7] corrected for density as described above.

We note that the p(66)Be(49) neutron beam has CADD characteristics very similar to those of a bremsstrahlung beam from an 8 MV electron accelerator. The highly penetrating nature exhibited by this p(66)Be(49) neutron beam is due to the high incident proton energy and to the semi-thick target design employed,[3,4] and is also enhanced by the relatively large SSD.

PENUMBRA REGION

Comparisons of the penumbra regions of various beams having nominal 10x10 cm^2 field sizes may be obtained from the entries in Table 1. There, the partial widths of the penumbra regions are presented in terms of the width in centimeters between decrement lines at two depths in phantom, d_{max} and 10 cm. The neutron data were obtained from off axis ratios measured in a TE-liquid phantom.[12] The ^{60}Co data are from an irradiator having a 2 cm diameter source;[14] the 4 MV data are from 4 MV electron accelerators with lead flattening filters;[13] and the 6 MV data are from a 6 MV electron accelerator,[8] all measured in water.

The width of the penumbra region is seen to increase with depth for all beams, as expected from geometry and scattering processes. The penumbra region has been divided into areas with decrement lines greater and less than 50%. In the higher decrement regions (90-50, 85-50, 80-50) our neutron beam is seen to have penumbra characteristics not unlike those of a 4 MV bremsstrahlung beam. In the lower decrement regions however, it has a width much greater than even the ^{60}Co beam. This is attributed to the relatively large residual dose we observe for our neutron beam in the umbra region.[12] As indicated in Table 1, the OAR near three half-widths off axis is still 4% at the depth of d_{max} and 7% at 10 cm deep.

CONCLUSIONS

In summary, upon comparison with the physical characteristics of BU, CADD, and penumbra exhibited by representative standard photon therapy beams, we find that our p(66)Be(49) neutron therapy beam could be described as having:

a) the build-up characteristics of a 6-8 MV X-ray beam with some electron contamination,

b) the central axis depth dose characteristics of an 8 MV X-ray beam, and

c) the penumbra characteristics of a 4 MV X-ray beam in the region of decrement lines between 90% and 50%, but poor penumbra characteristics for decrement lines less than 20%.

The endpoint in obtaining the physical characteristics of any therapy beam is patient treatment planning. Figure 3 shows a typical plan used with our neutron beam for treatment of a pancreatic tumor.[5] As expected, this plan is comparable to those obtained with medium energy megavoltage photon therapy machines.

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TABLE 1

Comparison Between Photon and p(66)Be(49) Neutron Penumbra Regions.

Beam	SSD cm	Depth in Phantom (cm)	Penumbra Region Width (cm)* Between Decrement Lines 90%-50%	85%-50%	80%-50%	50%-20%	50%-15%	50%-10%	Ref.
^{60}Co	80	0.5 (d_{max})	0.70	0.60	0.50	0.50	0.65	0.90	14
4MV	80	1.2 (d_{max})	0.45	0.35	0.25	0.30	0.40	0.80	13
6MV	100	1.5 (d_{max})	0.40	0.30	0.20	0.35	0.45	0.55	8
p(66)Be(49) Neutrons	180	1.5 (d_{max})	0.55	0.40	0.30	0.60	1.10	2.1 (A)	12
^{60}Co	80	10.0	1.10	0.85	0.70	0.85	1.30	1.70	14
4MV	80	10.0	0.65	0.45	0.30	0.50	0.75	1.20	13
6MV	100	10.0	0.55	0.45	0.35	0.40	0.55	1.15	8
p(66)Be(49) Neutrons	180	10.0	0.60	0.40	0.30	1.70	2.80	5.5 (B)	12

Nominal 10x10 cm^2 fields at SAD.
* Rounded to nearest 0.05 cm.
(A) Dose at 15 cm off axis = 4%.
(B) Dose at 15 cm off axis = 7%.

FIGURE CAPTIONS

Figure 1. Comparison of the dose build-up characteristics of various photon beams[7,8,11] to those of a p(66)Be(49) neutron beam.[6]

Figure 2. Comparison of the central axis depth dose characteristics of various photon beams[7] to those of a p(66)Be(49) neutron beam.[6]

Figure 3. Neutron treatment plan for pancreatic tumor. All three fields deliver equal doses at the isocenter.

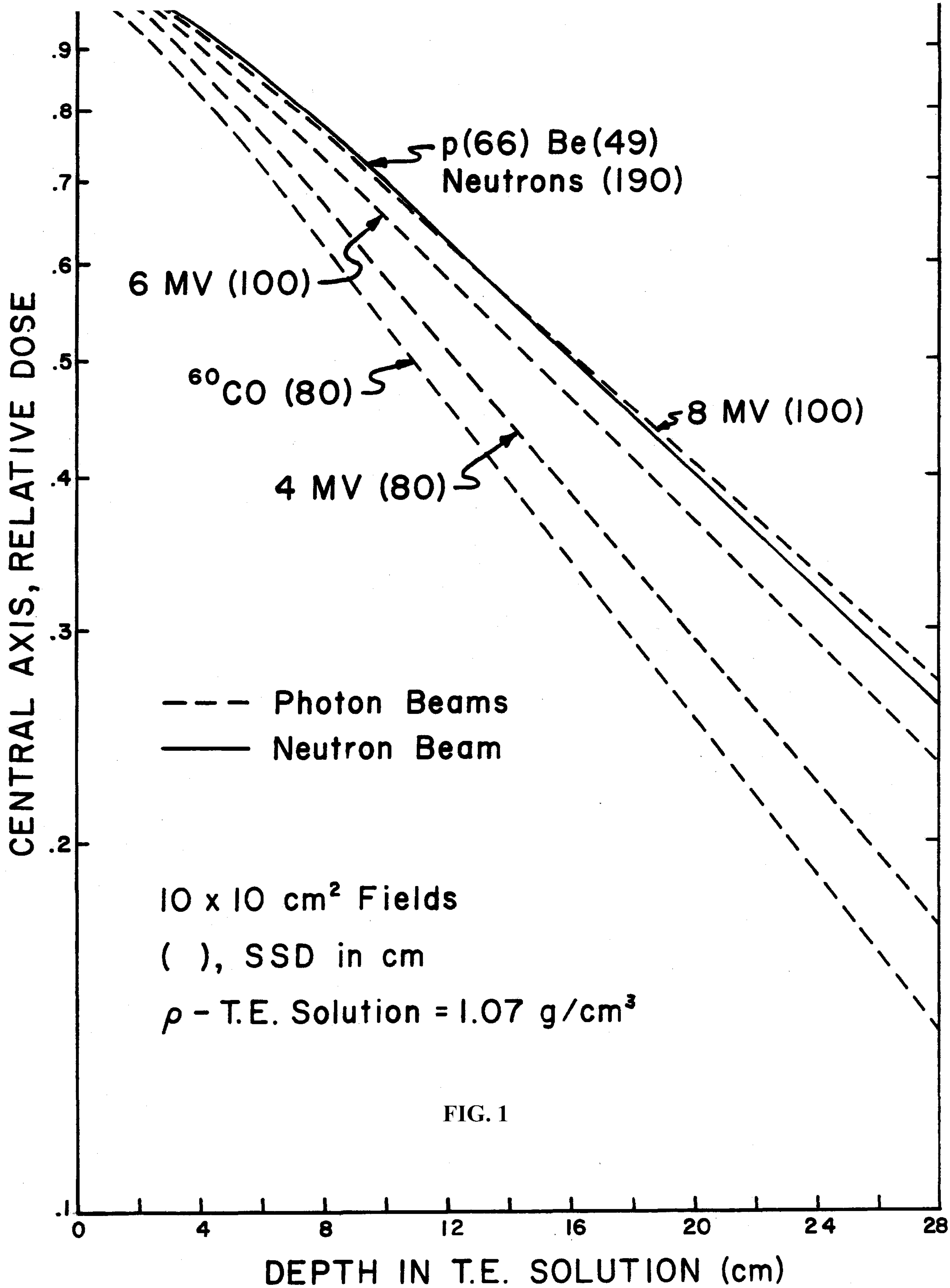
CENTRAL AXIS, RELATIVE DOSE
.9
.8
.7
.6
.5
.4
.3
.2
.1
p(66) Be(49)
Neutrons (190)
6 MV (100)
60CO (80)
8 MV (100)
4 MV (80)
Photon Beams
Neutron Beam
10 x 10 cm2 Fields
( ), SSD in cm
ρ - T.E. Solution = 1.07 g/cm3
0
4
8
12
16
20
24
28
DEPTH IN T.E. SOLUTION (cm)

FIG. 1

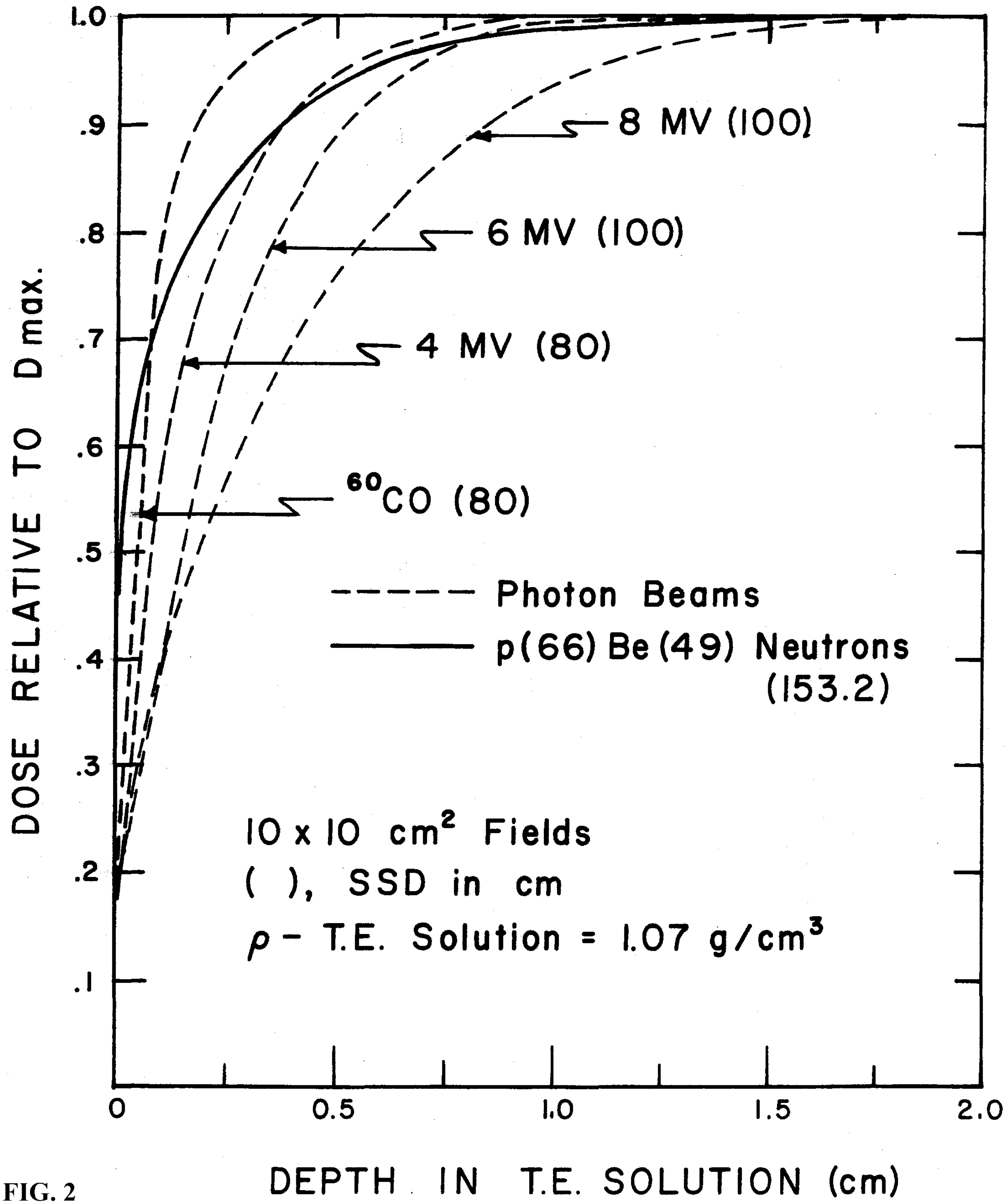
DOSE RELATIVE TO D max.
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0.5
1.0
1.5
2.0
DEPTH IN T.E. SOLUTION (cm)
8 MV (100)
6 MV (100)
4 MV (80)
60CO (80)
Photon Beams
p(66) Be (49) Neutrons (153.2)
10 x 10 cm2 Fields
( ), SSD in cm
ρ - T.E. Solution = 1.07 g/cm3

FIG. 2

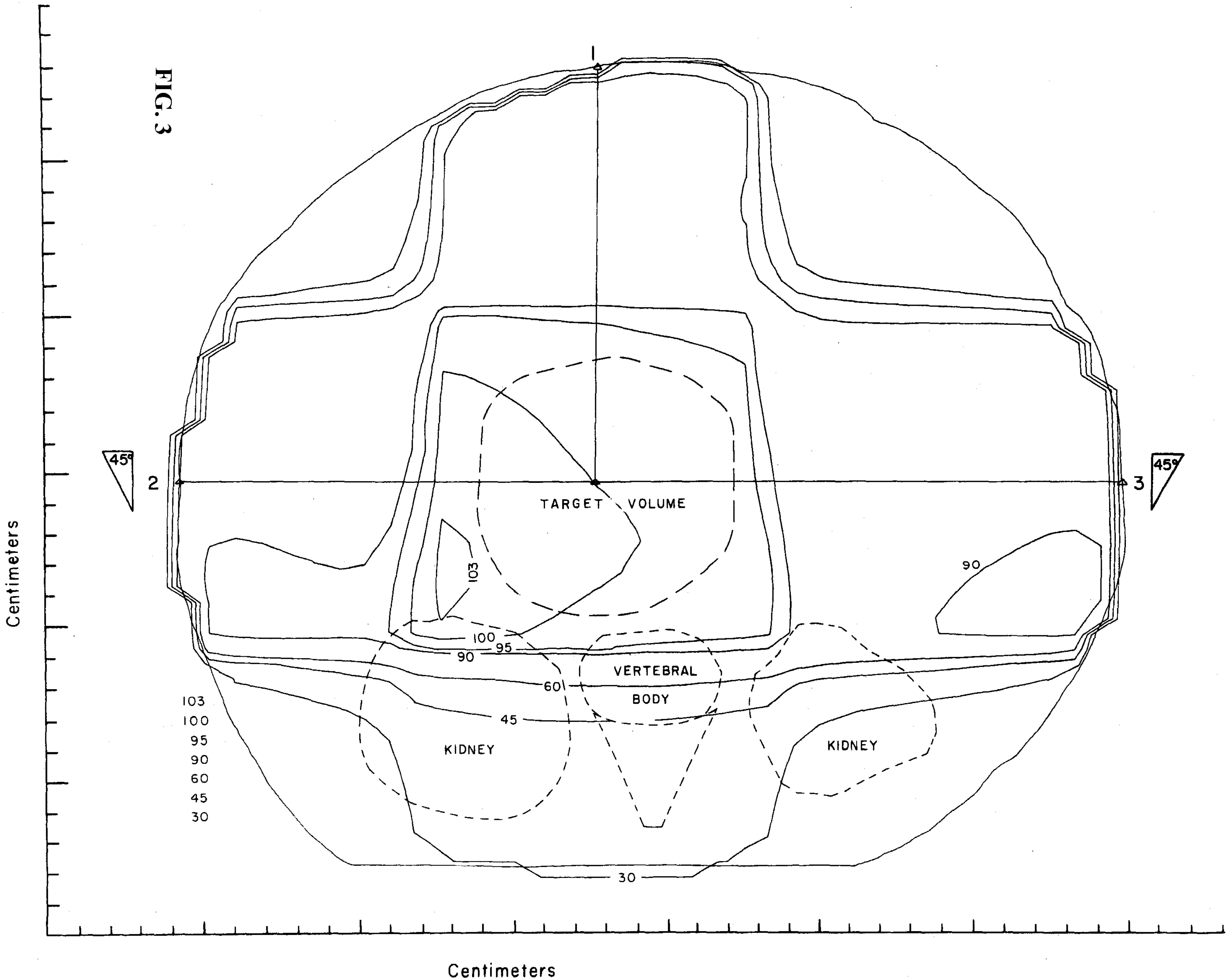
1
2
3
45°
45°
TARGET VOLUME
VERTEBRAL
BODY
KIDNEY
KIDNEY
103
100
95
90
60
45
30
90
103
100
95
90
60
45
30
Centimeters
Centimeters

FIG. 3

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