ORNL-5436

Organ Dose Estimates for the Japanese Atomic-Bomb Survivors

G. D. Kerr

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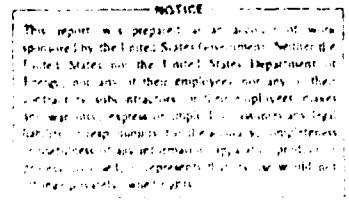
October, 1978



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G. D. Kerr

ABSTRACT

Recent studies concerning radiation risks to man by the Committee on Biological Effects of Ionizing Radiation of the National Academy of Sciences-National Research Council and the United Nations Scientific Committee on the Effects of Atomic Radiation have emphasized the need for estimates of dose to organs of the Japanese atomic-bomb survivors. Shielding of internal organs by the body has been investigated for fission-weapon gamma rays and neutrons, and ratios of mean absorbed dose in a number of organs to survivors' T65D assignments of tissue kerma in air are provided for adults. Ratios of mean absorbed dose to tissue kerma in air are provided also for the thyroid and active bone marrow of juveniles. These organ dose estimates for juveniles are of interest in studies of radiation risks due to an elevated incidence of leukemia and thyroid cancer in survivors exposed as children compared to survivors exposed as adults.

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BACKGROUND

Distance from the hypocenter and shielding by surrounding structures or terrain determine the radiation dose assignments for survivors denoted as T65D.[1,2] The quantity used in the development of T65D dosimetry for survivors was absorbed dose in a small mass of tissue in air. This quantity has been described in the literature on atomic-bomb survivors by a variety of terms, including "in-air tissue absorbed dose," "air dose," "free-field dose," and "first-collision tissue absorbed dose." According to recommendations of the International Commission on Radiological Units and Measurements,[3] the T65D assignments for survivors should be referred to as "tissue kerma in air."

In interviews with survivors, the site of each individual at the time of the bombings was documented using maps and aerial photographs. This information, together with data on the hypocenter in each city,[2,4,5] was used to determine the survivors' distance from the respective hypocenters. Decreases in prompt weapon radiation with distance from the hypocenters are given by the T65D air-dose curves[1] developed by the Oak Ridge National Laboratory (ORNL) and later verified by the National Institute of Radiological Science (NIRS) in Japan.[6] These curves are different for the two cities due to the designs and yields of the weapons. The Hiroshima and Nagasaki weapons have now been estimated to have released an energy equivalent to 12.5 and 22 kilotons of TNT, respectively.[1,7] Due to differences in weapon design, both neutrons and gamma rays contributed importantly to the radiation exposures of survivors in Hiroshima, while the radiation exposures of Nagasaki survivors were almost exclusively from gamma rays.

In interviews of survivors within 1600 and 2000 m of the hypocenters in Hiroshima and Nagasaki, respectively, the survivors' locations with respect to structures or nearby objects that may have shielded against radiation from the weapon were also carefully documented.[a] The approximate percentage of exposure conditions reported by these survivors[8] are broken down into four groups in Table 1. For survivors inside concrete and other heavy structures or in the open but partially shielded by structures and other objects, shielding was determined by a "globe technique" developed at ORNL.[1,9,10] Shielding of a survivor inside a Japanese house or other wood-frame structure was determined by "nine-parameter formulas," a technique also developed by ORNL.[b,1,11] These shielding and distance factors were then used with T65D air-dose curves to make the T65D assignments of each survivor. For Japanese residential structures, which are quite uniform in construction, typical or mean shielding factors (i.e., transmission factors) were determined from a large number of actual exposure cases to be 0.90 and 0.81 for gamma rays and 0.32 and 0.35 for neutrons in Hiroshima and Nagasaki, respectively.[2]

Due to scattering and attenuation of radiation within the body, doses to organs and tissues of the body are less than a survivor's assigned T65D values with the reduction being greater for neutrons than for gamma rays. Because most survivors were exposed inside Japanese houses and other light

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[a]The T65D values without any regard to shielding are about 20 rads at 1600 m and 2000 m from the hypocenter in Hiroshima and Nagasaki, respectively.[2]

[b]The nine parameters used in this technique take into account size of the house, location of survivor inside house, location of survivor relative to windows or other large openings in the house, shielding provided by nearby structures, etc.

Table 1. Approximate percentage of exposure conditions reported by survivors at distances less than 1600 m from the Hiroshima hypocenter and 2000 m from the Nagasaki hypocenter

Exposure conditions	Percent of Hiroshima survivors	Percent of Nagasaki survivors
Outdoors:		
Unshielded	10	5
Shielded	10	10
Indoors:		
Wood frame structures	75	65
Concrete and other structures	5	20

wood-frame structures; this group influenced most of our assumptions and approximations concerning the energy and angular distributions of the radiation fields.[12] The large amount of computer programming and computer time necessary to investigate organ doses from neutrons and gamma rays discouraged direct Monte-Carlo transport calculations in phantoms such as the one developed to simulate reference man of the International Commission on Radiation Protection (ICRP).[13] Instead, an existing Monte-Carlo transport analog was used to investigate depth-dose distributions in several different sizes of cylindrical tissue phantoms selected to represent the head or neck, a small torso, and a large torso.[12] These results are shown in Fig. 1 and 2.[a]

The energy spectrum of neutrons incident on a survivor's body was assumed to be the same as the leakage spectrum of the Health Physics

[a]These depth-dose curves or organ dose estimates based on these curves can be renormalized to tissue kerma in air using values of 4.54×10^{-10} rads per fluence gamma ray and 2.3×10^{-9} rads per fluence neutron.[12]

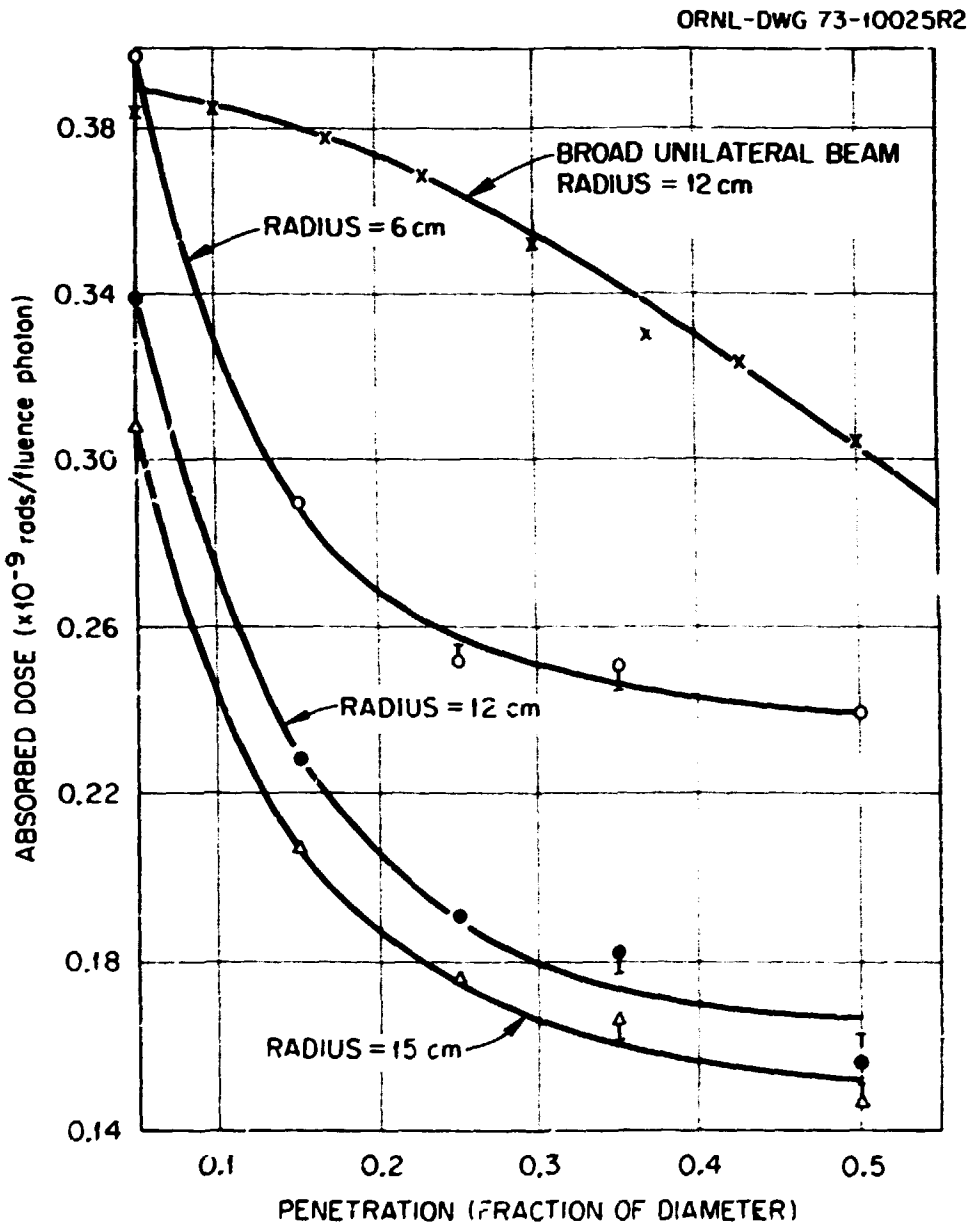

Fig. 1. Dose to tissue-equivalent cylinders from an isotropic source of photons having an energy distribution equivalent to the gamma-ray field in Hiroshima and Nagasaki.

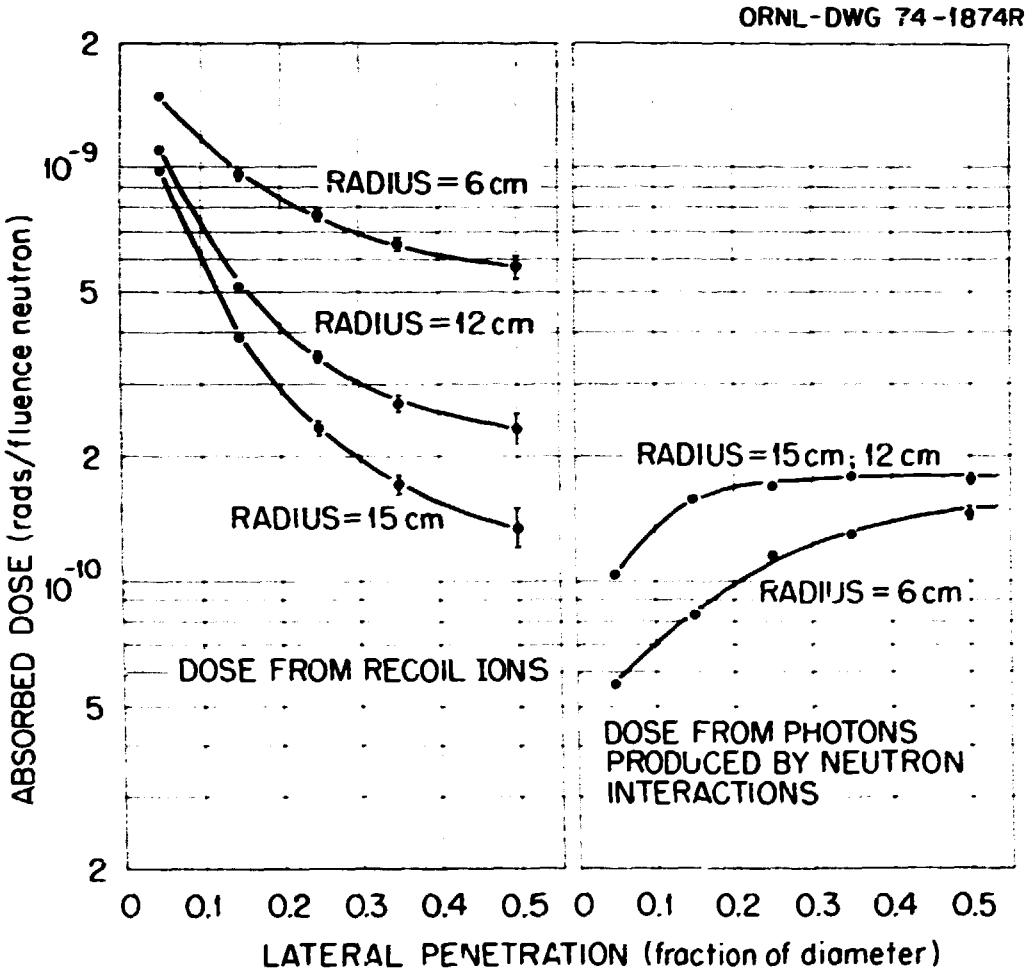

Fig. 2. Dose to tissue-equivalent cylinders from a source of neutrons having energy and angular distributions equivalent to the neutron field in Hiroshima and Nagasaki.

Research Reactor (HPRR), a small unmoderated and unshielded reactor with a critical assembly similar to that of the Hiroshima weapon.[14] Due to the thick metal shroud about the critical assembly of the Hiroshima gun-type device[15,16] and the large amount of high explosives about the critical assembly of the Nagasaki implosion-type device,[a,16,17] the leakage spectra from these weapons contained more thermal and intermediate energy neutrons, but these neutrons were moderated and absorbed more rapidly than fast-neutrons; so the air transported spectrum at several hundred meters can be approximated rather well by the HPRR leakage spectrum. The leakage spectrum of the HPRR is compared in Table 2 with ORNL neutron threshold detector unit (TDU) measurements of the air transported spectrum from a fission device made during early atmospheric weapon test operations.[10] Also summarized in Table 3 are some unpublished results of TDU measurements made inside facsimilies of Japanese residential-type structures.

The incident gamma-ray spectrum was approximated by a Straker-Gritzner spectrum of secondary gamma rays[18] at a fission device-to-survivor distance of 900 m in air. This distance was selected because the energy spectrum has reached equilibrium after initial rapid variations with distance, and and equilibrium spectrum would best approximate that inside Japanese houses and other structures. Angular distributions of gamma rays are difficult to

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[a]The high explosives about the ^{239}Pu critical assembly of the Nagasaki weapon moderated and absorbed most of the neutrons. Neutrons were also moderated by the metal shroud about the ^{235}U critical assembly of the Hiroshima weapon, but few were absorbed by the materials. Hence, the neutron doses at corresponding distances from the weapons were much greater in Hiroshima than in Nagasaki. The differences in radiation from the two weapons are due to design, rather than the ^{239}Pu used in the Nagasaki weapon and the ^{235}U used in the Hiroshima weapon.[1]

Table 2. Comparison of the fraction of fast neutrons in various energy regions of an ORNL-type neutron threshold detector

Energy region (MeV)	Fraction of HPRR leakage neutrons[a]	Fraction of air transported neutrons from Shot Fizeau — Operation Plumbbob[b]
0.001 to 0.75	0.40	0.55
0.75 to 1.5	0.30	0.25
1.5 to 2.5	0.15	0.10
2.5 to 10	0.15	0.10

[a]T. D. Jones et al., *Health Phys.* 28, 367 (1975).

[b]R. H. Ritchie and G. S. Hurst, *Health Phys.* 1, 390 (1959).

Table 3. Results of ORNL-type TDU measurements inside facsimiles of houses from Shot Fizeau — Operation Plumbbob

House number[a]	Fraction of fast neutrons in various energy regions				Number of measurements
	0.001-0.75 MeV	0.75-1.5 MeV	1.5-2.5 MeV	2.5-10 MeV	
1	0.55[b] (0.50-0.65)[c]	0.22 (0.17-0.26)	0.12 (0.08-0.14)	0.11 (0.08-0.14)	15
2	0.53 (0.47-0.61)	0.25 (0.21-0.28)	0.11 (0.09-0.16)	0.11 (0.08-0.15)	15

[a]R. H. Ritchie and G. S. Hurst, *Health Phys.* 1, 390 (1959).

[b]Average of measured values.

[c]Range of measured values.

predict, even for the light shielding provided by Japanese houses, but past experience[11,12] indicates that it is approximately correct to assume that the gamma rays were isotropically incident on a survivor's body or the cylindrical phantoms used to represent the different regions of a survivor's

body (see Fig. 1). An anisotropic angular distribution was assumed for the incident neutrons,[12,19] but the first-collision dose contributions of the HPRR neutrons within the cylindrical phantoms were overwhelmed by multicollision dose contributions, and the angular dependency of the neutron field was lost in the depth-dose calculations.[a] Since the curves of depth dose from neutrons in Fig. 2 vary symmetrically with distance from the surface of the phantom, they may be treated the same as depth dose from an isotropic exposure in calculating organ doses to survivors.

Some previous ORNL estimates of dose to a fetus,[20] female breasts,[20] and active bone marrow,[21] which are of interest here, are summarized in Table 4. These estimates give low LET-absorbed doses, D_γ, from gamma rays (see Fig. 1) in terms of T65D values of tissue kerma in air from gamma rays, K_γ. High LET-absorbed doses, D_n, from recoil ions and low LET-absorbed doses, D_γ, from gamma rays produced by neutrons (see Fig. 2) are also specified in terms of T65D values of tissue kerma in air from neutrons, K_n. The values for breasts are based on the depth-dose curves for a small torso in Figs. 1 and 2, and on the assumption that the tissue at greatest risk lies at a penetration depth of 1 cm below the skin surface. This assumption is consistent with that used by the BIER Committee in estimating absorbed dose to breasts of women who were subjected to multiple fluoroscopies during artifical pneumothorax for pulmonary tuberculosis.[22]

The estimates of fetal dose by trimesters in Table 5 were obtained by combining the curves of depth dose in a small torso with information on

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[a]Test calculations in which the incident neutrons were followed through only their first collisions within the cylindrical phantoms indicated that the anisotropic field subroutine used in the Monte-Carlo transport analogue was working properly.

Table 4. Estimates of mean absorbed dose to the female breasts, a fetus, and the active bone marrow of an atomic-bomb survivor in terms of tissue kerma in air

Absorbed dose/tissue kerma in air	Breasts[a]	Active bone marrow[b]	Fetus[a]
D_γ/K_γ	0.80	0.55	0.42
D_n/K_n	0.55	0.26	0.14
D_γ/K_n	0.045	0.070	0.077

[a]G. D. Kerr, ORNL/TM-4830 (1975).

[b]T. D. Jones, *Radiat. Res.* 71, 269 (1977).

Table 5. Estimates of absorbed dose to the fetus of an atomic-bomb survivor in terms of tissue kerma in air as a function of fetal development by trimesters

	Stage of fetal development by trimesters		
	First	Second	Third
Penetration depth for incident radiation measured from surface of abdomen to center of uterus[a]	8 cm	6 cm	8 cm
Geometry of embryo or fetus:[b]			
Radius	0.13-1.0 cm	2-3 cm	4-5 cm
Crown-rump length	0.13-5.5 cm	10-20 cm	23-30 cm
Absorbed dose/tissue kerma:			
D_γ/K_γ	0.40	0.43	0.42
D_n/K_n	0.12	0.15	0.14
D_γ/K_n	0.078	0.076	0.077

[a]A. Tabuchi et al., *Hiroshima Daigaku Igakubu Zasshi* 12(1.2), 57 (1964).

[b]T. D. Jones et al., *Health Phys.* 28, 367 (1975).

fetal size[12] and distance from the abdominal surface to the center of the uterus[23] at different developmental stages.[a] In the first trimester, the fetus and slightly enlarged uterus remain centrally located within the body at an average distance (or penetration depth) from the surface of the abdomen to the center of the uterus of about 8 cm. In the second trimester, the fetus and greatly enlarged uterus move upward and forward, decreasing the average penetration depth to a minimum of about 6 cm, but in the third trimester, the greatly enlarged fetus and uterus settle back down into the body, increasing the average penetration depth to about 8 cm. Due to small variations in these estimates of fetal dose by trimesters (see Table 5) and to some uncertainties in the calculations of mean fetal dose,[20] use of the one set of values given in Table 4 seems reasonable for all stages of fetal development.

The active bone marrow doses in Table 4 were estimated from curves of depth dose in a large torso (see Figs. 1 and 2), and active-marrow penetration depths for isotropic exposure of the ICRP Reference Man phantom.[21] An isotropic-exposure distribution of penetration depths was obtained by first using Monte-Carlo methods to randomly select a small mass, dm, of active marrow in the phantom, and then calculating the distance, ℓ, to the closest irradiated body surface. This process was simply repeated until a probability distribution of penetration depths, $p(\ell)d\ell$, for the active marrow was well known statistically. The same technique can be used to calculate penetration-depth probabilities for other organs

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[a]These calculations assumed that the center of the uterus was also the center of the fetus. The depth dose curves were averaged over the volume occupied by the fetus at different stages of development to obtain a mean fetal dose.

and other exposure situations of interest.[a] As an example, Jones[23] has used the technique to provide the first accurate assessment of dose to active (red) bone marrow from isotropic, rotational, bilateral, anterior-posterior, and posterior-anterior irradiation by neutrons. And, he has extended bone-marrow dosimetry for gamma rays to energies and exposure situations that were previously unavailable in the literature. The doses to a number of critical organs for latent radiation effects observed in the atomic-bomb survivors are investigated here using a mathematical phantom of a Japanese adult.[24] By calculating distributions of penetration depths (or mean penetration depths for small organs) and using the curves of depth dose in Figs. 1 and 2 for a small torso (or the head and neck for the thyroid), organ doses for the Japanese atomic-bomb survivors have been obtained at a tremendous saving in computer programming and computer time compared to that which would have been required in direct Monte-Carlo transport calculations of dose in ICRP Reference Man-type phantoms.

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[a]The penetration depth, ℓ, used to specify the depth dose, $D(\ell)$, in the more familiar case of anterior-posterior (A-P) beam exposures is quite different from the case of isotropic exposures. In A-P beam exposures, $D(\ell)$ and ℓ are specified in terms of distance from the front irradiated surface of the body along a vector in the direction of the incident radiation. In isotropic exposures, all surfaces of the body are irradiated by radiation incident from all directions, and $D(\ell)$ varies symmetrically with distance from the closest irradiated body surface. Thus, ℓ is specified in terms of distance from the closest irradiated surface of the body along a surface-normal vector. The penetration-depth probabilities, $p(\ell)d\ell$, for any organ will be less than the half-thickness of the body in the case of isotropic exposures, while $p(\ell)d\ell$ for some organs may range up to nearly the full body thickness in the more familiar case of A-P beam exposures.[21]

ORGAN DOSE ESTIMATES FOR ADULT SURVIVORS

The ICRP Reference Man, based mainly on anatomical data from European and American studies, has a total body mass of 70 kg.[13] A much smaller mean body mass of about 50 kg was indicated by anatomical data thought to be applicable to atomic-bomb survivors 20 years of age or older in 1945.[24] While these differences in body size can be significant in calculations of dose to organs within the torso of the body from gamma-ray and neutron fields similar to those experienced by the atomic-bomb survivors, the differences between a 1945 and present-day Japanese adult are negligible. Consequently, a mathematical model of a phantom with a total body mass of 55 kg was designed to approximate a present-day Japanese adult.[24] This phantom is suitable, therefore, for other dose estimation studies. As examples, the dose to active bone marrow and the genetically significant dose from diagnostic and therapeutic radiation practices in Japan have been of recent interest.[25-28]

Figure 3 shows some of the idealized representations of major organs in the head and torso of the phantom, and Table 6 summarizes the masses of all internal organs in the phantom. The lungs, skeleton (bone plus marrow), and other organs and soft tissues of the phantom were assumed to have specific gravities of 0.3, 1.4, and 1.0, respectively. Equations describing internal organs were developed from both Japanese autopsy data[29-31] and ICRP Reference Man data[32] specifying size and mass of the organs in terms of total body mass.[24] Masses of red and yellow marrow and their distributions in the skeleton were adopted from data of the Bone Marrow Research Group in Japan.[33] Figure 4 illustrates the distribution of red marrow in a normal adult and idealized skeleton of the Japanese adult

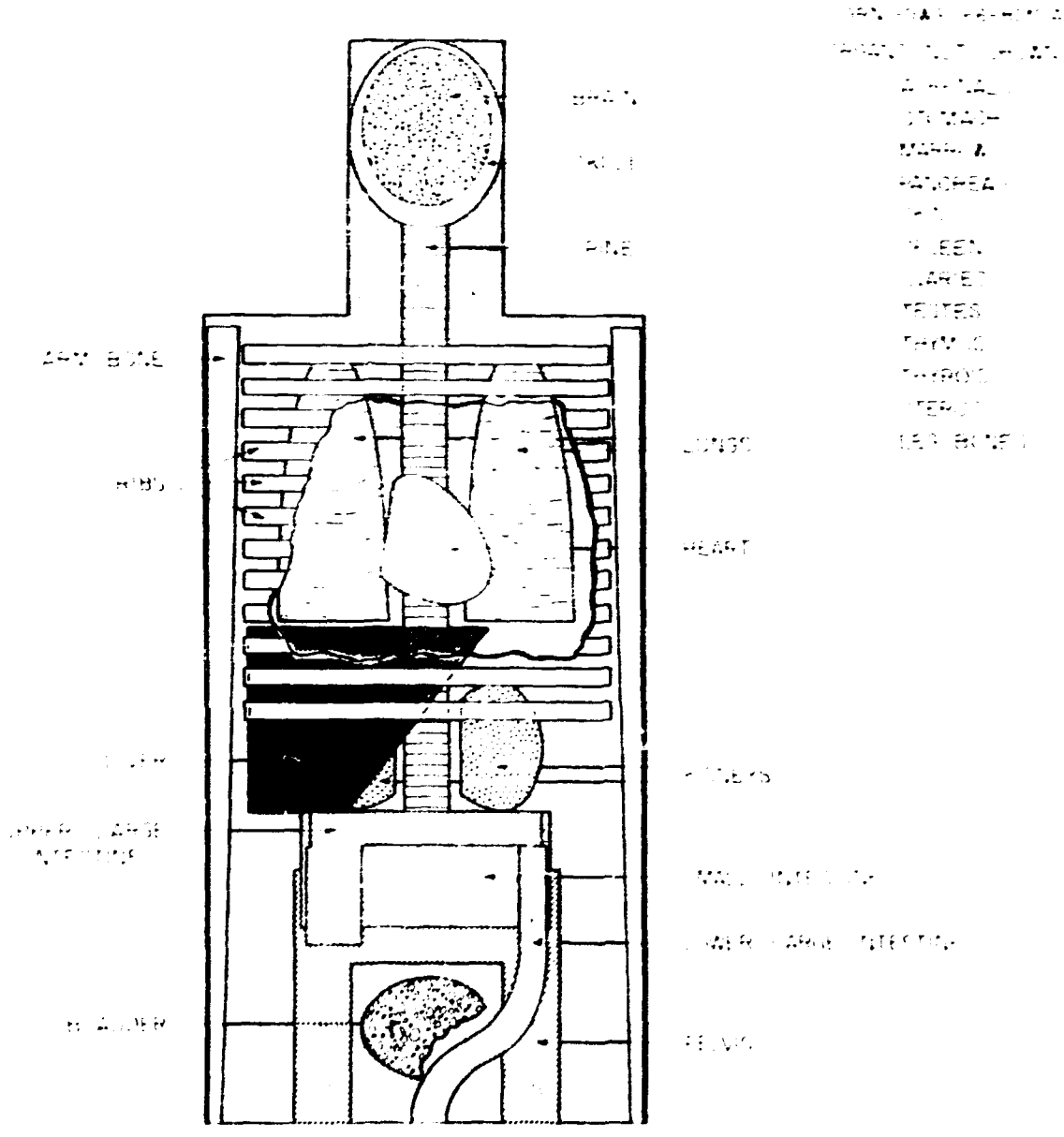


Fig. 3. Anterior view showing major internal organs in the head and torso regions of an ICRP Reference Man-type phantom. Reproduced by permission from W. S. Snyder et al. (13).

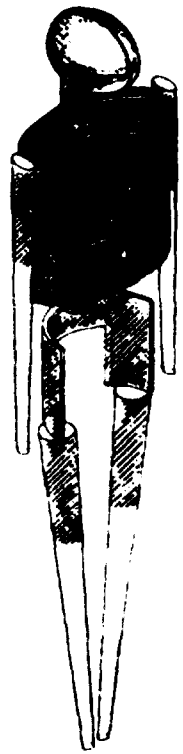
phantom. Estimates of dose to active bone marrow of adult survivors based on this phantom have been published by Kerr et al.[5]

Table 6. Summary of organ masses of a phantom simulating the body and major internal organs of a Japanese adult

Organ	Mass in grams
Adrenals	15
Bladder	36
Brain	1,470
Gastrointestinal tract	
Stomach	120
Small intestines[a]	829
Large intestines	302
Heart	329
Kidneys	233
Liver	1,492
Lungs	781
Ovaries	8
Pancreas	50
Skeleton	
Bone	6,055
Red marrow	784
Yellow marrow	986
Spleen	133
Testes	37
Thymus	26
Thyroid	20
Uterus	66
Total Body	55,200

[a]Includes contents of small intestines.

Figure 5 illustrates results of penetration-depth calculations for several organs of the adult survivors. The results of these calculations and calculations for other organs are summarized in Tables 7 and 8. In the case of larger organs, probability distributions of penetration depths are given (see Table 7), and in the case of smaller organs, mean penetration depths are given (see Table 8). Mean penetration depths of small



SKULL	7.6%
VERTEBRAE	25.8%
RIBS + STERNUM	20.9%
SCAPULAE	2.2%
HEAD AND NECK OF BOTH ARMS	3.6%
BOTH CLAVICLES	0.8%
HEAD AND NECK OF BOTH LEGS	11.2%
PELVIS	27.9%

RED BONE MARROW

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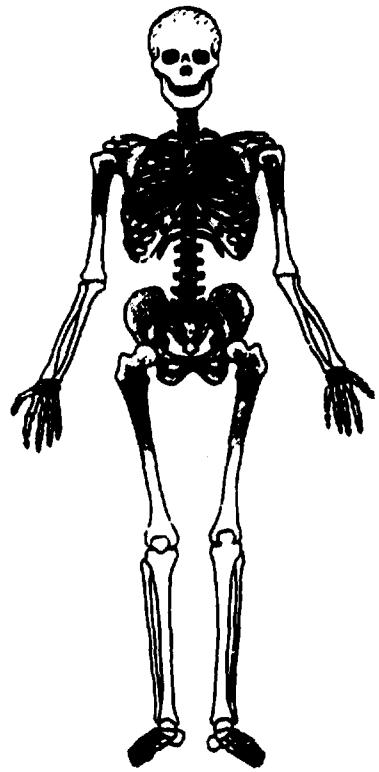

IDEALIZED SKELETON FOR DOSE CALCULATIONS

DISTRIBUTION OF RED BONE MARROW IN A NORMAL ADULT

Fig. 4. Distribution of active (red) bone marrow in a normal Japanese adult. Adapted by permission from W. S. Snyder et al. (13).

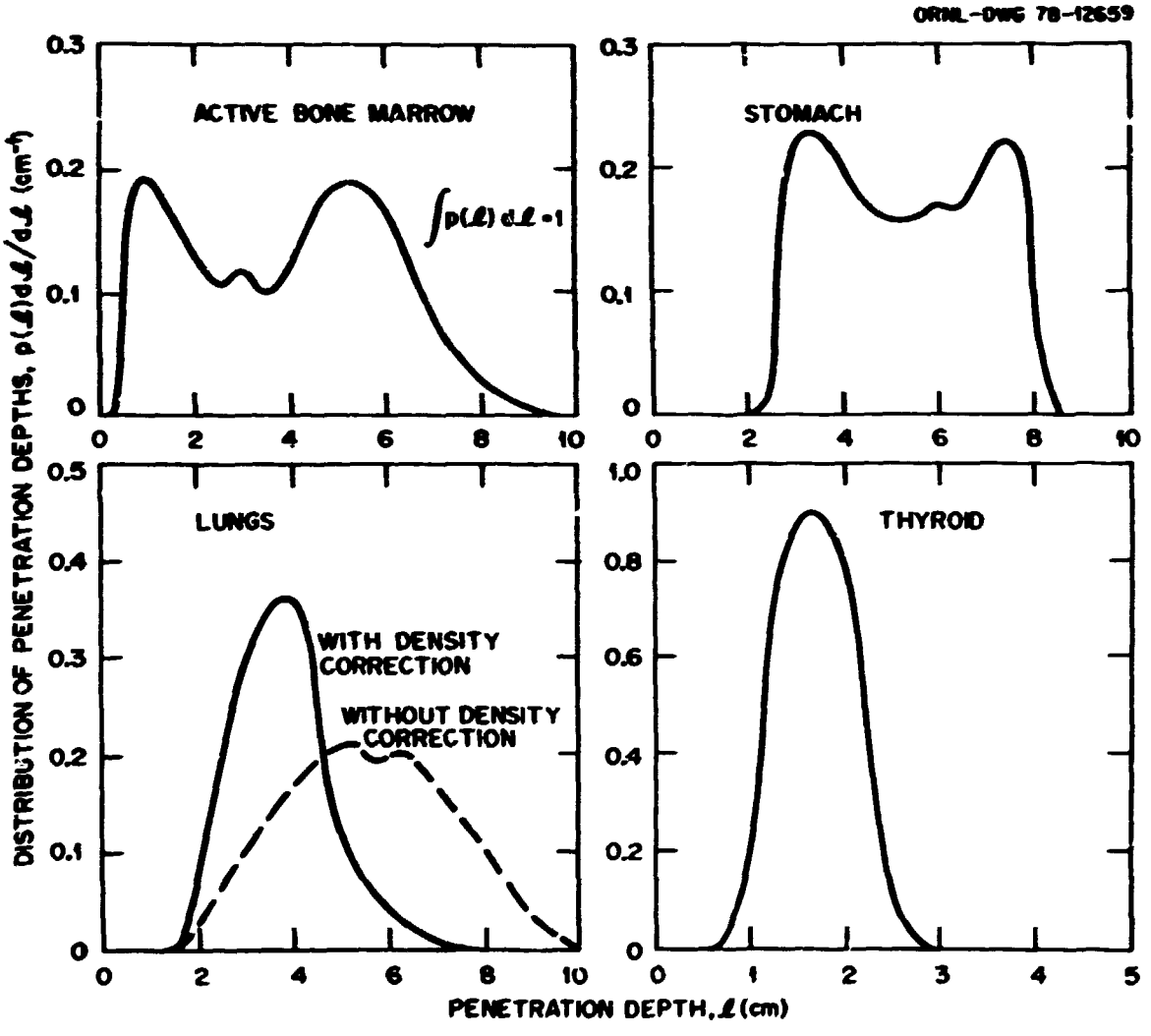

Fig. 5. Penetration-depth distributions for isotropic exposure of a Japanese adult.

Table 7. Probability distributions of penetration depths for larger organs of a Japanese adult.

Penetration Depth, x (cm)	Normalized probability distributions, p(x)dx, for isotropic irradiation										
	Active Bone Marrow	Bladder	Heart	Intestinal Tract	Kidneys	Liver	Lungs[a]	Pancreas	Stomach	Spleen	Uterus
0-0.5	0.0308										
0.5-1.0	0.0983										
1.0-1.5	0.0818										
1.5-2.0	0.0632				0.0288		0.0113				
2.0-2.5	0.0544	0.0189			0.1158	0.0462	0.0715		0.0086		
2.5-3.0	0.0610	0.0955	0.0006		0.1981	0.0812	0.1298		0.1102	0.0143	
3.0-3.5	0.0495	0.0887	0.0219	0.0007	0.2328	0.1027	0.1631		0.1150	0.0803	
3.5-4.0	0.0582	0.0841	0.0482	0.0156	0.2082	0.1142	0.1795	0.0029	0.1022	0.1245	
4.0-4.5	0.0801	0.0821	0.0657	0.0588	0.1506	0.1034	0.1645	0.0083	0.0846	0.1509	
4.5-5.0	0.0954	0.0781	0.0769	0.0616	0.0654	0.0928	0.1217	0.0139	0.0800	0.1671	
5.0-5.5	0.0944	0.0786	0.0866	0.0704	0.0003	0.0835	0.0697	0.0169	0.0806	0.1655	0.0050
5.5-6.0	0.0869	0.0797	0.0923	0.0886		0.0845	0.0425	0.0239	0.0852	0.1431	0.0681
6.0-6.5	0.0617	0.0765	0.0910	0.0968		0.0696	0.0261	0.0348	0.0838	0.1051	0.0723
6.5-7.0	0.0390	0.0770	0.0924	0.1172		0.0562	0.0145	0.0406	0.0970	0.0468	0.0801
7.0-7.5	0.0221	0.0793	0.0803	0.1197		0.0495	0.0051	0.0643	0.1102	0.0024	0.1101
7.5-8.0	0.0143	0.0765	0.0740	0.1204		0.0426	0.0007	0.0871	0.0426		0.1196
8.0-8.5	0.0072	0.0738	0.0694	0.0902		0.0312		0.1256			0.1362
8.5-9.0	0.0016	0.0112	0.0637	0.0700		0.0242		0.1952			0.1373
9.0-9.5	0.0001		0.0726	0.0581		0.0135		0.2548			0.1402
9.5-10.0			0.0650	0.0319		0.0047		0.1317			0.1311

[a]Includes a density correction for the lungs.

organs, with the exception of the thyroid, were estimated from equations for the organ and external body surfaces of the phantom. According to Fig. 6 drawn from a transverse view of the body in Grant's *Atlas of Anatomy*,[35] the thyroid is located too deeply within the neck of the Japanese adult phantom and other ICRP Reference Man-type phantoms. Thus, the thyroid was moved 1 cm closer to the surface of the neck,[a] and a distribution of penetration depths was calculated due to the complex shape of the thyroid (see Fig. 7). The resulting distribution of penetration depths shown in Fig. 5 indicates a mean penetration depth of 1.6 cm for the thyroid, and this value appears to be in reasonably good agreement with the transverse view of the neck and thyroid shown in Fig. 6. Transverse views of the body in Grant's *Atlas of Anatomy* and other cross-sectional anatomy books[36,37] can be used to estimate mean penetration depths for organs or tissues not included in the phantom.

Table 8. Mean penetration depths for smaller organs of a Japanese adult

Organ	Mean penetration depth ℓ (cm)
Adrenals	3.5
Breasts	1.0[a]
Ovaries	9.2
Testes	1.8
Thymus	4.1
Thyroid	1.6

[a]BIER Report, pp. 141-143 (1972).

[a]The placement of the thyroid in the neck region of ICRP Reference Man-type phantoms is probably acceptable for internal radiation dose calculations, but it is located too deeply within the neck for calculations of dose from external fields. To move the thyroid 1 cm closer to the neck surface, (Y + 6) is replaced by (Y + 7) in equations A33 of the Japanese adult phantom.[24]

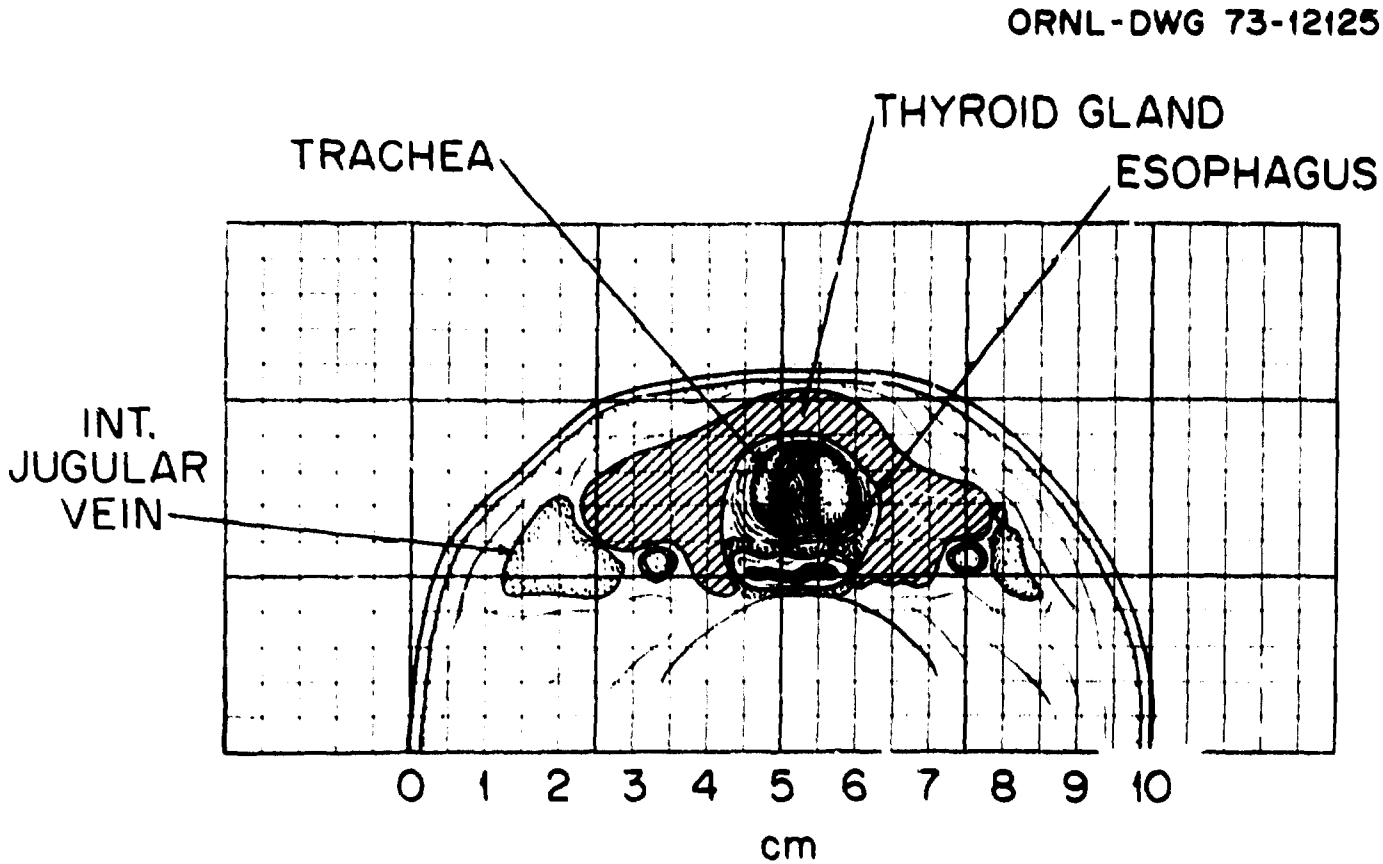

Fig. 6. Cross section of neck at the level of the thyroid gland.

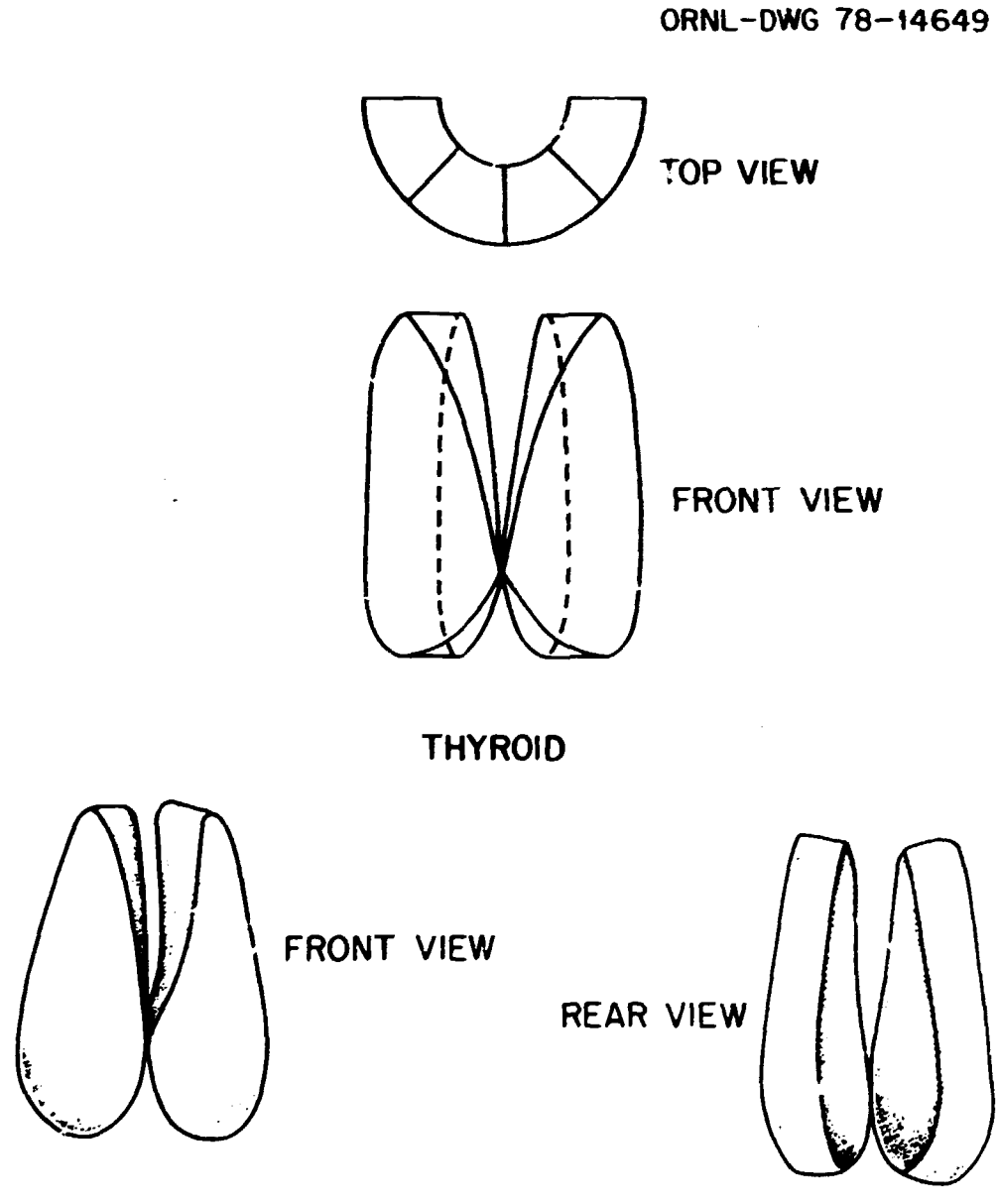

Fig. 7. Idealized shape of thyroid in an ICRP Reference Man-type phantom. Reproduced by permission from W. S. Snyder et al. (13).

A specific gravity and a composition typical of the soft tissues of the body were assumed in the calculations of depth dose in Figs. 1 and 2. Some distortion in these curves will occur within the body due to differences in the penetration of gamma rays and neutrons through the lungs and skeleton. These differences are illustrated in Figs. 8 and 9.[38] In isotropic exposures, only a small fraction of the radiation reaching most of the organs included in the phantom will have passed through the lungs or skeleton, and only the distortions in the depth-dose curves that occur in the lungs or skeleton are important.[a] Mean free paths of gamma rays at energies above about 10^5 eV or 100 keV (see Fig. 9) reflect the differences in specific gravity of the lungs, skeleton, and bulk tissues of the body At lower gamma-ray energies, mean free paths in the skeleton also reflect the higher photoelectric absorption of calcium and phorphous in bone. This enhanced photoelectron production will increase the dose in very small soft tissue inclusions in cortical bone, such as those found in the Haversian canal system.[39] However, the spaces in trabecular bone which contain the red marrow are larger on the average than the small tissue filled spaces in the Haversian system, and the mean marrow dose is not altered significantly by the photoelectrons from bone. As an example, Spiers[40] has calculated mean doses to trabecular marrow that are only 5, 10, 12, 10, and 3 percent greater than the dose to soft tissue at gamma energies of 25, 50, 75, 100, and 200 keV, respectively.[b] Theoretical

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[a] The distortion in depth-dose curves for soft tissues are more severe in therapeutic irradiations with small beams passing through the lungs or skeleton before reaching the target organ or tissue.[39]

[b] The atomic-bomb survivors were exposed to a broad energy spectrum of gamma rays so the increased dose at very low gamma energies should amount to only a few percent increase in the total dose to active bone marrow.

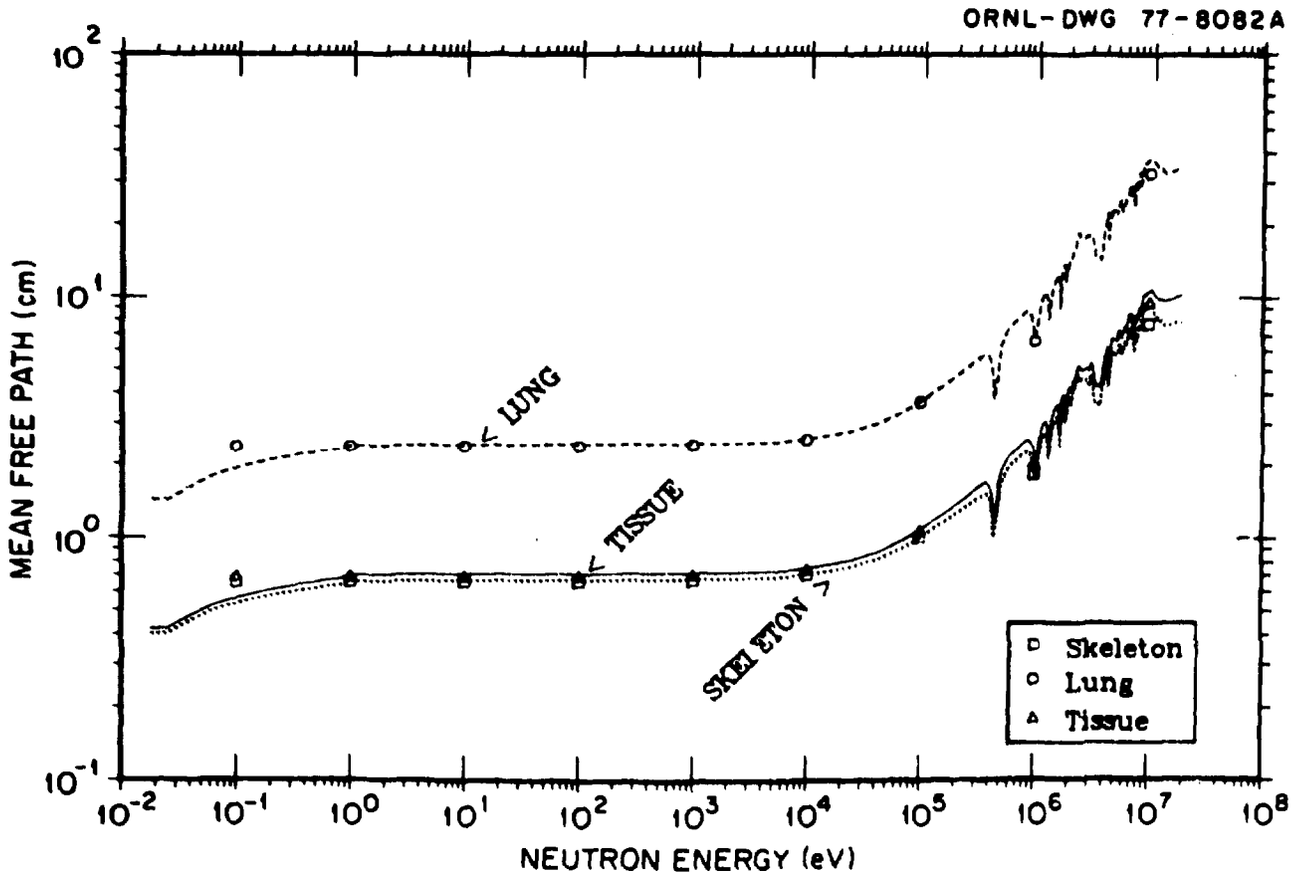

Fig. 8. Mean free path of neutrons in various tissues of Reference Man. Reproduced by permission from J. J. Shonka (38).

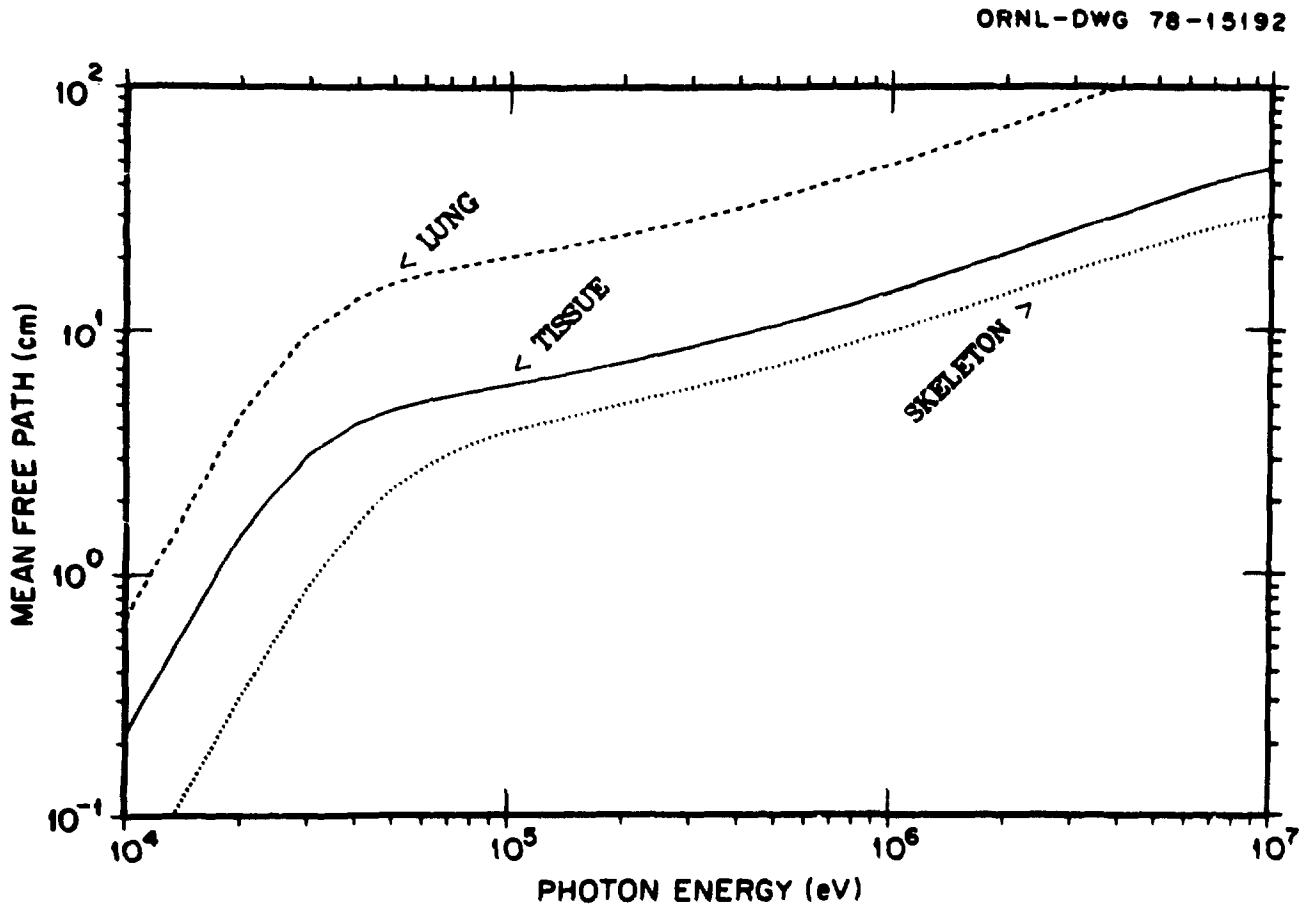

Fig. 9. Mean free path of photons in various tissues of Reference Man. Reproduced by permission from J. J. Shonka (38).

calculations for neutrons also indicate negligible differences in the dose to soft tissue and to red marrow in trabecular bone.[41] Thus, no corrections were applied to the estimates of dose to red or active bone marrow of survivors based on the depth-dose curves in Figs. 1 and 2.

At neutron energies below 20 MeV (see Fig. 8), the mean free paths are determined mainly by the hydrogen atom density, because the neutrons lose 70 to 90 percent of their energy in scattering interactions with hydrogen. Since bone has nearly twice the specific gravity of soft tissue, but only about one half as much hydrogen by weight, mean free paths of neutrons in the skeleton and soft tissue are nearly the same. Lung tissue has essentially the same hydrogen content as soft tissue, but less than one-third the specific gravity. Thus, the greater mean free paths of both neutrons and gamma rays in lung tissue compared to soft tissue are due to differences in specific gravity. The lower specific gravity of the lungs was taken into account by first calculating a total penetration depth, ℓ_T, for a small mass of lung tissue, and then calculating the portion, ℓ_L, of this total penetration depth within the lungs. A probability distribution of penetration depths, $p(\ell)d\ell$, with a density correction (i.e., a specific gravity correction) was obtained using $1.0(\ell_T - \ell_L) + 0.3\,\ell_L$ or $\ell_T - 0.7\,\ell_L$. Figure 5 shows penetration-depth distributions for the lungs with and without a density correction. An increase of approximately 15 percent in the dose to the lungs of an adult survivor is predicted by the probability distribution of penetration depths with a density correction (see Table 7). Table 9 summarizes all estimates of organ doses for an adult atomic-bomb survivor based on the penetration-depth data in Tables 7 and 8, and the depth-dose curves in Figs. 1 and 2.

Table 9. Estimates of mean absorbed dose to organs and tissues of an adult atomic-bomb survivor in terms of tissue kerma in air

Organ	Absorbed dose/tissue kerma		
	D_γ/K_γ	D_n/K_n	D_γ/K_n
Active bone marrow	0.56	0.28	0.067
Adrenals	0.52	0.24	0.065
Bladder	0.48	0.18	0.072
Breasts	0.80	0.55	0.045
Fetus	0.42	0.14	0.077
Heart	0.42	0.16	0.075
Intestinal tract	0.40	0.14	0.077
Kidneys	0.52	0.24	0.065
Liver	0.47	0.18	0.075
Lungs	0.50	0.22	0.070
Ovaries	0.40	0.12	0.080
Pancreas	0.40	0.12	0.080
Stomach	0.47	0.18	0.072
Spleen	0.45	0.16	0.075
Testes	0.65	0.40	0.050
Thymus	0.50	0.20	0.070
Thyroid	0.70	0.45	0.035
Uterus	0.40	0.12	0.080

Estimates of organ doses in Table 9 can be applied either to individual survivors or groups of survivors. As an example, Table a-7 of the BIER Report[22] gives a mean T65D value of 86 rads for survivors in Hiroshima with T65D assignments in excess of 10 rads and ages in excess of 10 years at the time of exposure. The mean T65D values of tissue kerma in air from gamma rays, K_γ, and neutrons, K_n, for these survivors are approximately 74 and 12 rads, respectively. Thus, the mean value of the high LET-absorbed dose to the active bone marrow, D_n, of these survivors is $0.28\ K_n = 0.28$ (12 rads) = 3.4 rads, and the mean value of the low LET-absorbed dose to the active bone marrow, D_γ, is $0.56\ K_\gamma + 0.067\ K_n = 0.56$ (74 rads) + 0.067 (12 rads) = 42 rads. These values

give a mean total absorbed dose to the active marrow of these Hiroshima survivors of about 45 rads compared to their mean total T65D value of 86 rads. The importance of using organ doses, rather than T65D assignments, in estimating radiation risks from epidemiological and medical data on the Japanese atomic-bomb survivors is obvious from the above example. Absorbed dose to organs, other than active bone marrow, can be estimated from the T65D assignments for individual survivors or groups of survivors using values from Table 9 for the organ of interest.

ORGAN DOSE ESTIMATES FOR JUVENILE SURVIVORS

An elevated incidence of thyroid cancer and leukemia in survivors exposed as children compared to survivors exposed as adults has been of interest in the estimation of radiation risks.[22,42] Thus, doses to the active bone marrow and thyroid of juvenile survivors have been investigated using mathematical phantoms developed to represent a ten-year-old, five-year-old, one-year-old, and newborn infant.[a,43,44] Total body masses of these ICRP Reference Man-type phantoms are summarized in Table 10. Methods used to obtain doses to the thyroid and active bone marrow of the juvenile survivors were the same as those used in estimating organ doses for adult survivors. That is, a probability distribution of penetration depths, $p(\ell)d\ell$, for the active bone marrow and the thyroid were calculated for each of the juvenile phantoms, and the probability distributions for the thyroid were used to estimate mean penetration depths.[b] The mean

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[a]These juvenile phantoms were developed for use in pediatric nuclear medicine. A description of the ten-year-old ICRP Reference Man-type phantom used in this investigation has not been published.

[b]The thyroid of the juvenile phantoms was moved 1 cm closer to the neck surface for reasons noted in our calculations using the Japanese adult phantom.

penetration depths for the thyroid and the probability distributions for the active bone marrow were then combined with depth dose in cylindrical tissue phantoms matched in size to head and neck regions and torso regions of the juvenile phantoms.

Table 10. Total body mass of juvenile and adult phantoms

Phantom	Mass (kg)
Newborn	3.9
One-year-old	10
Five-year-old	20
Ten-year-old	32
Japanese adult	55
ICRP Reference Man	70

Figures 10 and 11 present results of these age-dependent investigations of dose in terms of the total body masses given in Table 10. The estimates of dose to the active bone marrow based on the 70-kg ICRP Reference Man phantom are from Jones,[21] and those based on the 55-kg Japanese adult phantom are from Kerr et al.[34] These results indicate that it is probably reasonable to apply any of the organ dose for an adult survivor in Table 9 to groupings of survivors with ages in excess of 10 years at the time of exposure. And, it is probably reasonable to apply organ dose estimates for a five-year-old survivor to groupings of survivors between the ages of 0 and 9 years.[22] Table 11 summarizes the estimates of dose to the thyroid and active bone marrow of survivors based on the 20-kg five-year-old and 55-kg Japanese adult phantoms.

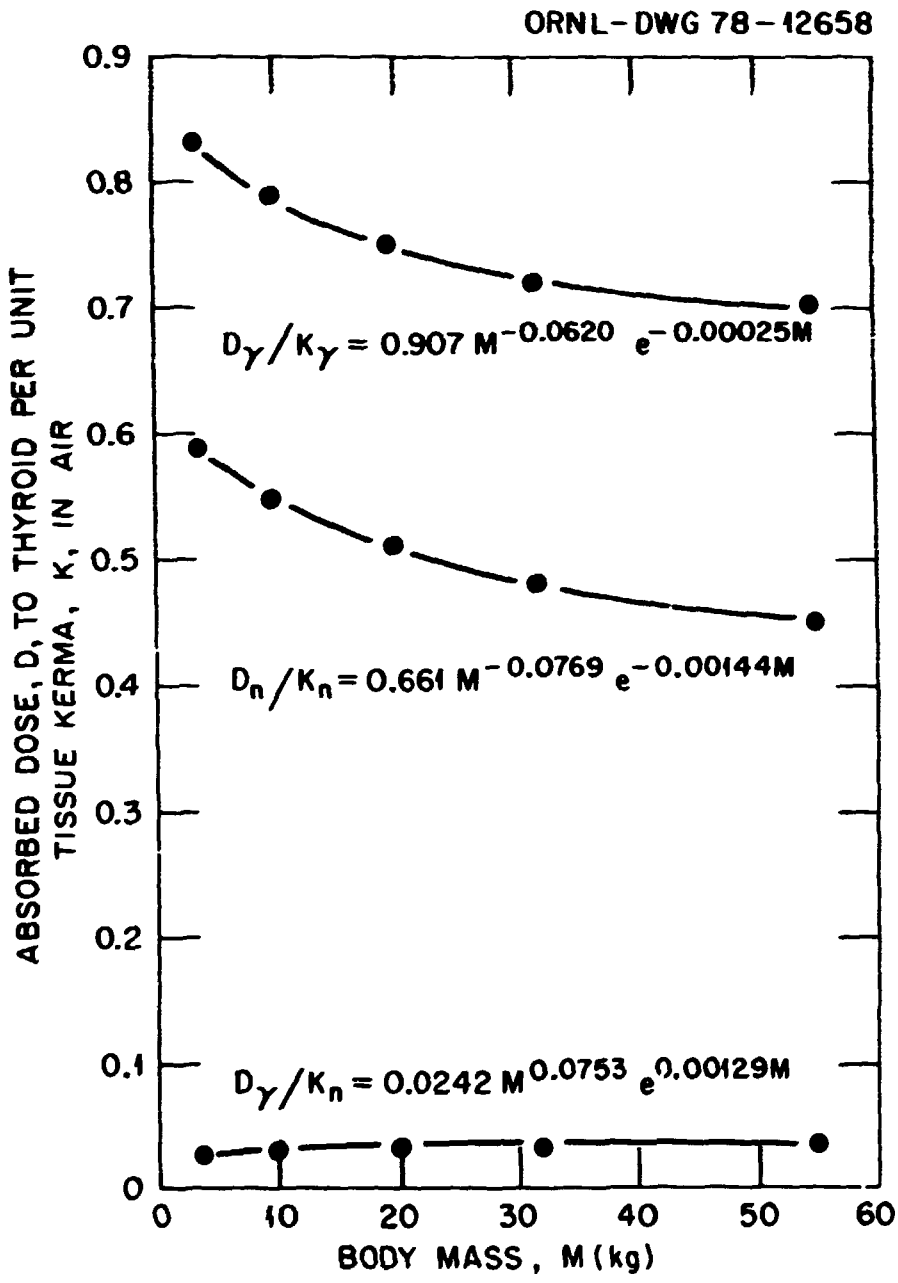

Fig. 10. Estimates of dose to the thyroid of atomic-bomb survivors.

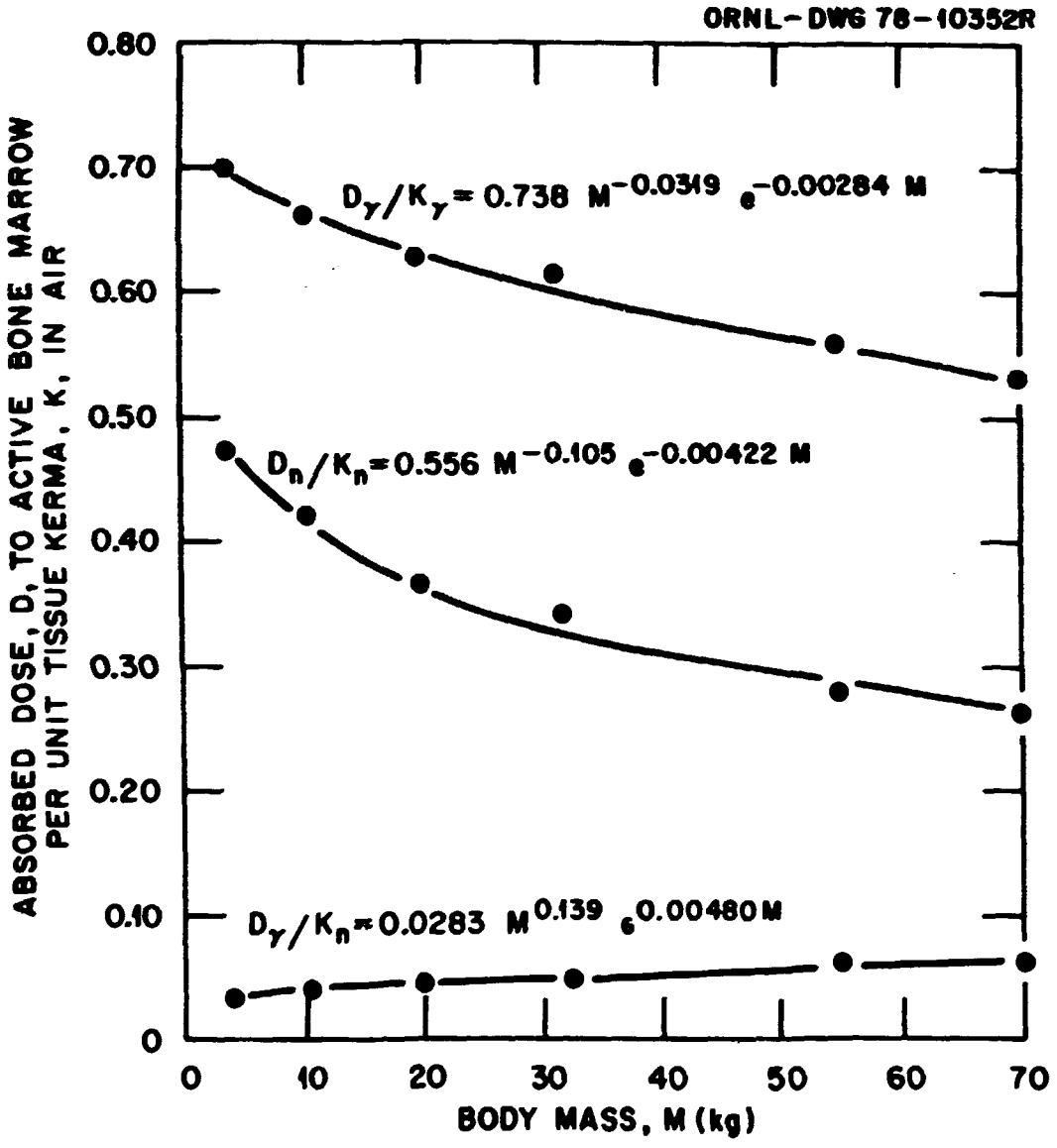

Fig. 11. Estimates of dose to active bone marrow of atomic-bomb survivors.

Table 11. Estimates of mean absorbed dose to the thyroid and active bone marrow of a five-year-old and an adult Japanese atomic-bomb survivor

Absorbed dose/tissue kerma in air	Five-year-old survivor	Adult survivor
Thyroid:		
D_γ/K_γ	0.75	0.70
D_n/K_n	0.51	0.45
D_γ/K_n	0.031	0.035
Active bone marrow:		
D_γ/K_γ	0.64	0.56
D_n/K_n	0.37	0.28
D_γ/K_n	0.047	0.067

Linear regression analysis and so-called Hoerl's special functions[45] were used to obtain the dose vs body-mass equations given in Figs. 10 and 11. These equations and anatomical data from the 1930s and 1940s indicate that adjustments in dose to body masses more like those of the survivors in 1945 are very small. For example, data from the 1930s in *Tabulae Biologicae*[46] on growth in weight of Japanese males and females and other data[29-31] from the 1940s suggest mean total body masses of about 10 kg for a one-year-old, 15 kg for a five-year-old, 25 kg for a ten-year-old, 45 kg for a female adult, and 50 kg for an adult male survivor. These data and the equations in Figs. 10 and 11 predict values of D_γ/K_γ, D_n/K_n, and D_γ/K_n for an adult male or female survivor and for a five-year-old survivor that differ about 10 percent or less from the estimates of dose in Table 11 based on the 55-kg Japanese adult and 20-kg five-year-old phantoms. Negligibly small adjustments in the dose estimates

of Figs. 10 and 11 for other aged juvenile survivors also are indicated by anatomical data from the 1930s and 1940s.

DISCUSSION

Experimental measurements of depth dose from fission neutrons transported through large distances of air have been made by Bond et al.[47] and Aceto et al.[48] These measurements were made in phantoms exposed in the open during Operation Plumbbob and Operation BREN at the Nevada Test Site. During Operation BREN, the HPRR was attached to the hoist platform of a tower and operated at elevations of up to 460 m. Typical results of Operation BREN measurements made 1 m above ground level in phantoms located at distances of 460 to 1380 m from the tower's based are shown in Fig. 12.[a] These results of Aceto et al.,[48] which are only relative measurements of the magnitude and shape of various dose distributions within the phantom, have been normalized to an absorbed dose from recoil ions per unit tissue kerma in air of unity at the phantom's front surface. This normalization gives an absorbed dose from recoil ions per unit tissue kerma in air of about 0.6 at the phantom's back surface facing away from the source, and these values are in good agreement with other recoil-ion-dose measurements made on the surface of a phantom in air-transported fields of the HPRR.[49]

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[a]The high LET-absorbed dose component from our previous calculations of depth dose from neutrons in a small torso (see Fig. 2) has been broken down into a fast-neutron or recoil-ion component and a thermal-neutron or $^{14}N(n,p)^{14}C$ component. The depth doses of Aceto et al. are those measured along a 20-cm minor axis of an ellipitcal phantom with a 36-cm major axis and a 60-cm torso length.

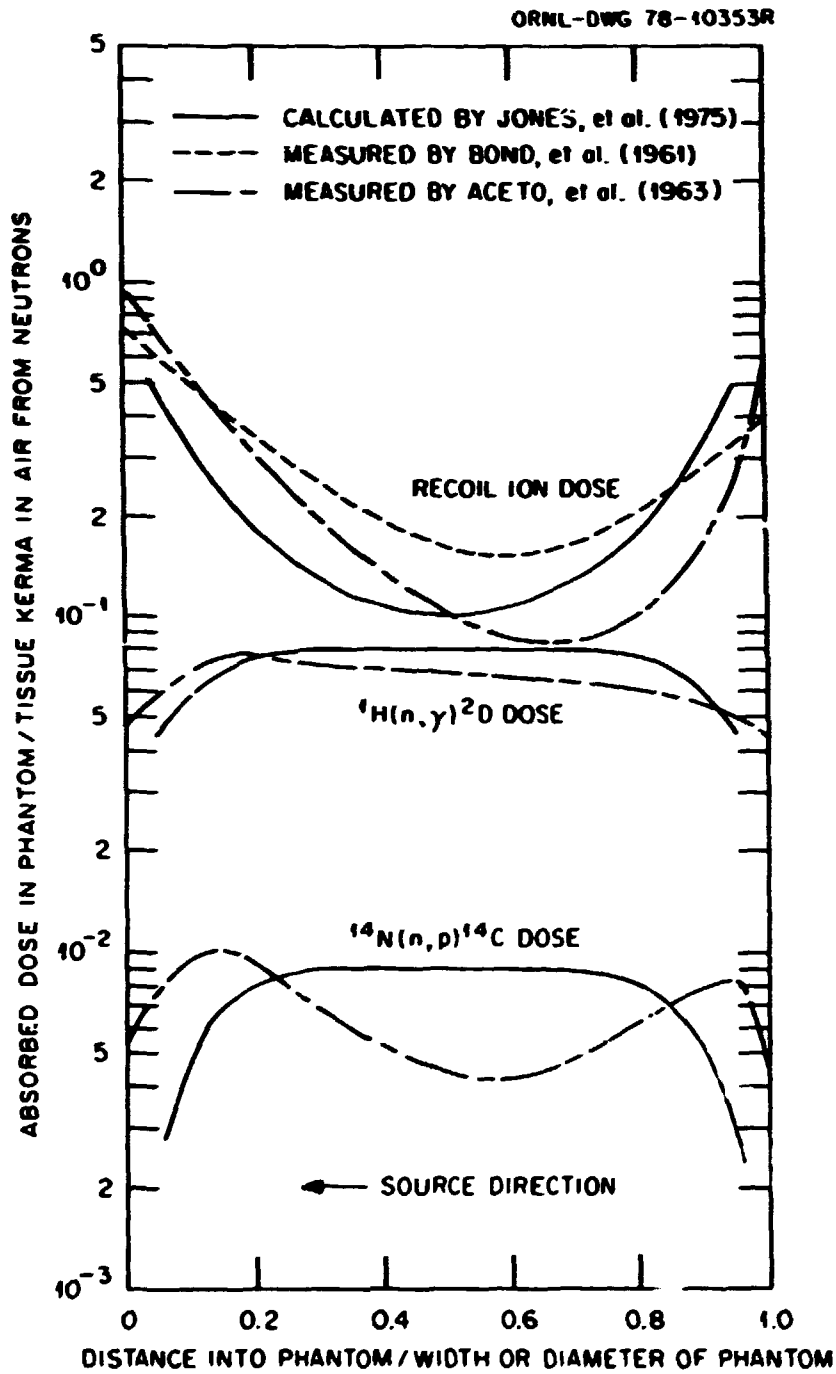

Fig. 12. Depth dose from fission neutrons transported through large distances of air.

The recoil-ion doses of Aceto et al. in Fig. 12 were obtained from measurements of the energy fluence of fast neutrons made with a tissue-equivalent proportional counter.[46] In coverting these measurements to dose, Aceto et al. assumed that the average energy of the fast neutrons remained constant as they penetrated the phantom. That is, the scattering cross sections of tissue at the average energy of fast neutrons incident on the phantom were used to convert energy-fluence measurements to recoil-ion doses. These data should be regarded, therefore, as only approximations to the depth dose from recoil ions.[48] A BF_3 counter and indium foils provided better measurements of the thermal-neutron fluence within the phantom, and thereby, better data on the $^{14}N(n,p)^{14}C$ and $^{1}H(n,\gamma)^{2}D$ dose distributions. These experimental results of Aceto et al. are in good agreement with our calculations of the low LET-absorbed dose from neutron-capture gamma rays.

The measurements of Bond et al.[47] provide more reliable data on the high LET-absorbed dose from air transported neutrons. Their results shown in Fig. 12 were obtained from ORNL-type TDU measurements made in 28-cm-diam. by 32-cm-long cylindrical phantoms and TDU measurements made in air at the phantom exposure sites.[a] These data of Bond et al.[47] show less attenuation in depth dose from recoil ions than our calculations. For example, the absorbed dose from recoil ions at the center of the phantom is about 10% of the tissue kerma in air from neutrons in our calculations, and about 15% of the tissue kerma in air from neutrons in their measurements. These differences may be due in part to the angular distribution

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[a]The in-air measurements of "tissue kerma" are referred to as "incident dose" in the report by Bond et al.[47]

of neutrons in their measurements and our calculations (in the open vs inside a lightly shielding structure) and in part to the lengths of the phantoms (32 cm vs 60 cm). Neutrons incident on the ends of the 60-cm-long phantoms used in our calculations make a negligible contribution to the recoil-ion dose near the phantom's center compared to neutrons incident on the ends of the 32-cm-long phantoms used in their measurements. Other measurements were made during Operation Plumbbob in phantoms with longer lengths, and these results contained in a classified version of the report by Bond et al.[47] are in better agreement with our calculations.[a]

While our calculations and the neutron measurements of Bond et al. are in good agreement, their gamma measurements and our calculations are not. There are differences in the angular distribution of gamma rays in our calculations and their measurements (inside a lightly shielding structure vs in the open), but typical results of their measurements with gamma-sensitive films and other devices have a shape more like the depth dose from a broad unilateral beam of gamma rays (see Fig. 1), than the depth dose expected from Ritchie and Hurst's in-air measurements of angular distributions of gamma rays from fission weapons.[10] One would expect the depth dose from in-air gammas to exhibit a minimum value in the interior of the phantom. These gammas are, however, not the only contributor to response of a film or other gamma measuring device exposed within the phantoms. Also included in the responses are contributions from capture gammas produced by neutrons

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[a]The results of our calculations of the low LET-absorbed dose from neutrons are also in good agreement with the phantom measurements of Bond et al.[47] They concluded, for example, that the low LET-absorbed dose from capture gamma was negligible compared to the high LET-absorbed dose from recoil ions near the surface of the phantoms, and that the two components of absorbed dose from neutrons were approximately equal near the center of the phantoms.

from the weapon. The shape of the depth-dose curves measured by Bond et al.[47] appears to result from a combination of these two gamma components: the depth dose from neutron-capture gammas, which is at a minimum at the surface and a maximum in the phantom's interior, and the depth dose from in-air gammas, which is at a maximum at the surface and a minimum in the phantom's interior. Data in a classified version of the report by Bond et al.[47] and a recently declassified version of the report by Ritchie and Hurst[10] indicate that tissue kermas in air from gamma rays and neutrons were of about the same magnitude at the phantom exposure sites. A D_γ/K_γ of 0.90 for the active bone marrow of a survivor estimated by Rossi and Mays[50] from these phantom measurements is unreasonably high for reasons discussed above.

Some other experimental studies that need to be mentioned are those of Hashizume et al.[51-54] of the NIRS in Japan. They first measured depth doses from beams of radiation incident at oblique or slant angles on the torso of a realistic man phantom, and then summed these slant-beam measurements of depth dose to represent the angular distribution of radiation from a fission weapon. Their slant-beam method of estimating organ doses, and their use of 12-MV x-rays from a betatron to simulate the energy spectrum of gamma rays from a fission weapon have been investigated due to large discrepancies between NIRS and ORNL estimates of fetal dose.[20] The ORNL and NIRS estimates of dose for a first trimester fetus are shown in Table 12.[a]

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[a]Other sets of values for a second and third trimester fetus have been given by Hashizume et al.,[51,53] but these NIRS values are estimates of dose to the head of a fetus[51] and are not comparable to the ORNL estimates of mean fetal dose.[20]

Table 12. Estimates of absorbed dose to a first trimester fetus in terms of tissue kerma in air

Absorbed dose/tissue kerma	ORNL[a]	NIRS[b]
D_γ/K_γ	0.42	0.62-0.70
D_n/K_n	0.14	0.12-0.16[c]
D_γ/K_n	0.077	0.095-0.11

[a]G. D. Kerr, ORNL/TM-4830 (1975).

[b]Range of values covers differences in shielding, orientation of survivor, and distances from the hypocenters considered in the slant-beam estimation of dose to a fetus by T. Hashizume et al., *J. Radiat. Res.* 14(4), 346 (1973) and T. Hashizume and T. Maruyama, *J. Radiat. Res.* 16, Suppl., p. 12 (1975).

[c]Recoil-ion dose plus $^{14}N(n,p)^{14}C$ dose from neutrons.

Results of NIRS measurements of depth dose in the abdominal region of a realistic man phantom from normal and slant beams of 12-MV x-rays incident on the front of the phantom[51,52] are shown in Figs. 13 and 14.[a] Also shown in these figures are depth doses from normal and slant beams of gamma rays with the same Straker-Gritzner spectrum of energies used in our previous dose calculations for survivors shielded by Japanese houses.[12] The differences in depth dose from the two spectra are too small to explain the large discrepancies between ORNL and NIRS estimates of fetal dose from gamma rays, and the large discrepancies were traced to the slant-beam method of estimating organ doses. Our investigations indicate that, while the slant-beam method gives reasonable estimates of dose to superfical organs, it can grossly over-estimate the dose to deeply seated organs of the body. The degree of over-estimation, which depends to some extent on

[a]The angle of slant incidence, θ, in Fig. 14 corresponds to $(90°-\theta)$ in Tables 2, 3, and 4 of Hashizume et al.[51]

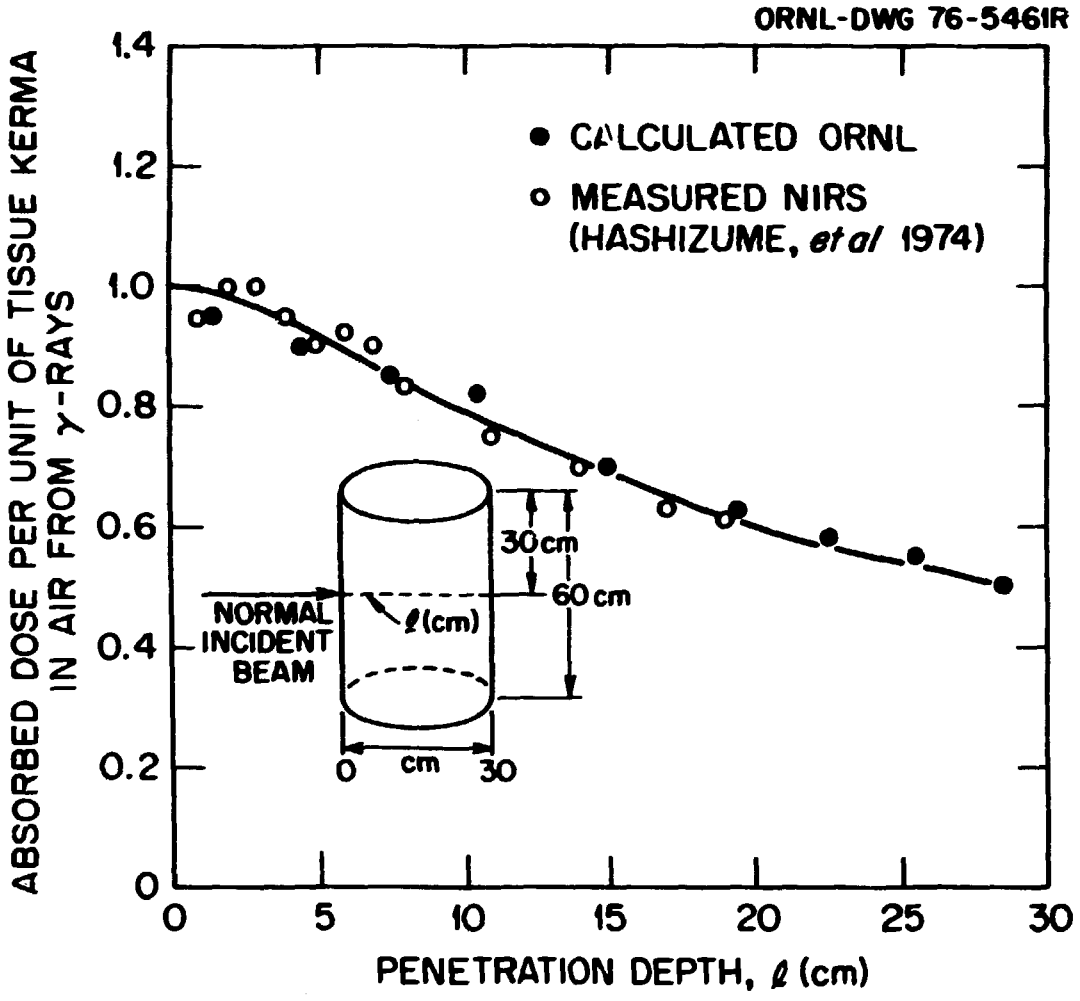

Fig. 13. Depth dose from gamma-rays at normal incidence with an energy distribution typical of a fission weapon.

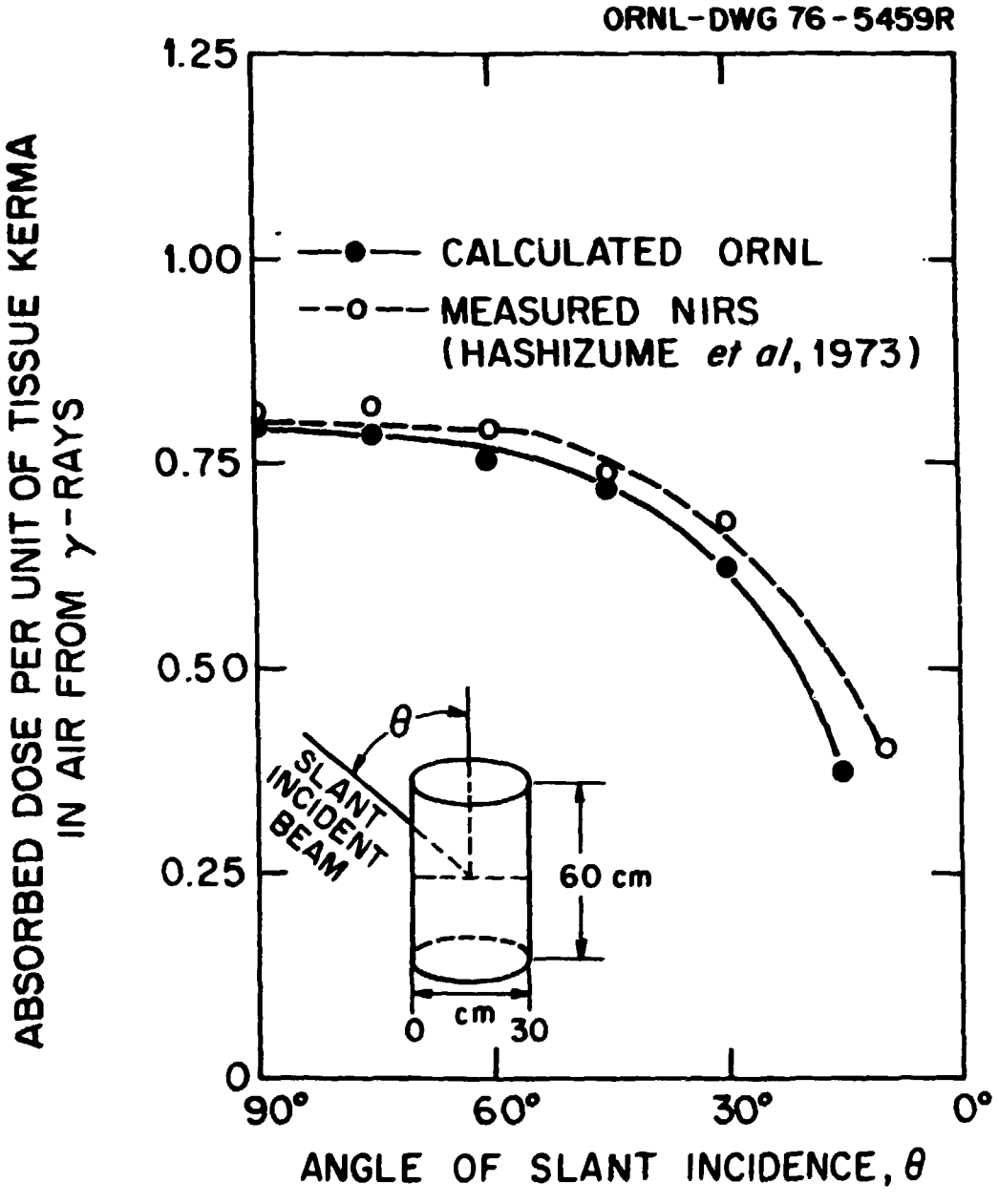

Fig. 14. Absorbed dose from fission-weapon gamma rays at a penetration depth, ℓ, of 9.5 cm as a function of angle of slant incidence, θ.

the energy spectrum of the gamma rays and neutrons, can be as much as a factor of two. A report is now being prepared that will review the slant-beam method of estimating organ doses and some other organ-dose studies relevant to the dosimetry for the atomic-bomb survivors.

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