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The Influence of Exposure Geometry on the Pattern of Radiation Dose Delivered to Large Animal Phantoms[1, 2]

V. P. BOND, E. P. CRONKITE, C. A. SONDHAUS, G. IMIRIE, J. S. ROBERTSON AND D. C. BORG

Medical Department, Brookhaven National Laboratory, Upton, New York, and The Naval Medical Research Institute, Bethesda, Maryland

INTRODUCTION

In attempts to make quantitative comparisons of the effects of fallout γ-radiation exposure received by the Marshallese with those of previous human and large animal exposure (*1*), it became necessary to consider the influence of exposure geometry on the tissue dose and on the pattern of dose deposition. It became evident that, for the same dose expressed as roentgens measured free in air, in terms of which exposures and LD_{50} values have been generally reported in the literature, the tissue dose could vary by as much as a factor of 2 or more. In the present work, the influence of exposure geometry on the depth-dose pattern in a large animal phantom was investigated systematically, under the several exposure conditions frequently encountered in situations where large animals or man have been exposed to penetrating radiations. A more detailed treatment of the problem may be found in a current Naval Medical Research Institute report (*2*).

It will be apparent that the biological effects of penetrating radiation must depend on the dose "absorbed" in the tissues (*3*), not on the exposure received by the ambient air. Thus, much of the confusion that results from expressing large animal exposures in terms of air dose could be alleviated by using tissue dose to characterize an exposure. The necessity of using tissue dose has been recognized for many years by radiologists and is set forth in the 1937 and 1953 recommendations of the International Commission on Radiological Units (*4*) and in the 1940 Technical Bulletin of the Radiological Society of North America Standardization Committee (*5*). This practice has cleared up much of the confusion in clinical radio-

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[2] Presented as part of a symposium at the Radiation Research Society Meeting, Chicago, Ill., May 17–19, 1956.

therapy, and the recent trend toward following these recommendations has aided in eliminating apparent discrepancies in quantitative comparisons of small animal radiation data. With large animals and man, however, added problems enter that make the situation more difficult. In the first place, under many practical exposure conditions, *only the monitored air dose will be available or readily calculable at the time*. Thus, in monitored exposures or in radiation accidents around reactors or other nuclear machines, or after exposures to the initial or to fallout γ-radiations from an atomic bomb, only the dose measured in air will be available. Second, since the dose delivered to different tissues with "whole-body" exposures of large animals can vary quite markedly under some conditions of exposure, as will be seen, it is frequently not possible to characterize an exposure with *a single* tissue dose. Unlike the situation of relatively uniform dose distribution in small animal exposures, it becomes very difficult to decide what is the locus of prime interest in the large animal exposure situation, and which of the myriad possible "tissue doses" to use. Similar considerations enter in the sterilization of bulky foodstuffs with ionizing radiations (*6*). For these reasons it appeared useful to investigate the depth-dose patterns under the various exposure geometries, and to compare the several dose distributions with large animal exposure data as obtained from the published literature.

Terms used in this report conform to the recommendations of national and international committees (*4*, *5*). Dose and exposure are used interchangeably. "Free air dose" or "air dose" indicates the dose measured free in air in the absence of animal, phantom, or exposure equipment. Unless otherwise specified, this refers to the dose as it has been conventionally measured at a point in space corresponding to the proximal skin surface (the side nearest the radiation source) of the animal or phantom when it is later put in place for irradiation. This is termed more explicitly the "entrance air dose" and is expressed in roentgens. Air doses at other points in space are easily approximated under most circumstances by use of the inverse square law. Dose measured with the dosimeter embedded at any position within the animal or phantom in place for irradiation is termed "tissue dose," also expressed in roentgens; thus, "entrance tissue dose," "midline tissue dose," "exit tissue dose." Tissue doses are not converted to absorbed dose (*4*), expressed in "rads,"[3] because of the uncertainty of the conversion factor for tissue dose under some conditions discussed, and because of the considerable variation of the conversion factor with different tissues (*7*, *8*).

[3] See references *4*, *7*, and *8*. Tissue dose refers only to the ionization measured by the detector embedded in the material being irradiated and usually does not indicate accurately the absorbed dose, i.e., the energy per unit mass deposited in the irradiated material, here tissue or unit density material. Over much of the range of radiation energies usually of interest in large animal work, from 250 kvp to 1.5 Mev or higher, the tissue dose will be equal to the absorbed dose in lean tissue, expressed as rads (100 ergs/gm), to within 10% or better. Much larger discrepancies occur in bone.

A word should be said initially regarding the possible application to the problem of the vast amount of dosimetry data that has been published in connection with clinical radiation therapy. Most clinical radiotherapy exposures differ fundamentally from the "total-body" exposures considered here in that the object of the one is to obtain localized, circumscribed partial-body irradiation of a diseased area, whereas the object of the other usually is to obtain the same degree of exposures to *all* tissues of the body. The one usually attempts to narrow the beam by collimation or by the use of ports; the other requires a beam sufficiently broad to expose the entire irradiated object. Thus, the numerous depth-dose figures published for radiotherapists (*9*) usually cannot be carried directly to the "total-body" exposure situation, although the curves obtained with very large area ports apply approximately in some situations. Since the depth-dose pattern with "total-body" irradiation is highly dependent on the precise conditions of exposure, it is not practical to compile complete tables of depth-dose values for reference. The patterns to be presented here obviously apply strictly only to the specific conditions employed.

EXPERIMENTAL PROCEDURE

The exposure geometries considered, all described more fully below, include unilateral, bilateral, multiport, rotational, ring, and 4π exposures in the laboratory, and exposure to immediate and fallout γ-radiations in the field. A cylindrical Masonite phantom 26 cm long and 26 cm in diameter, corresponding to a 32-inch waist, was exposed under each of the laboratory conditions listed. The density of the Masonite was 1.05. This phantom obviously does not represent exactly the essentially oval configuration of man in cross section in the region of the trunk, but it was felt to be a sufficiently close approximation. A diagram of the exposure conditions for a "point" source is shown in Fig. 1 for reference purposes. A target-to-"skin" distance (TSD) of 100 cm was used for all exposures unless otherwise indicated. Studies showed that lengthening the cylindrical phantom beyond the

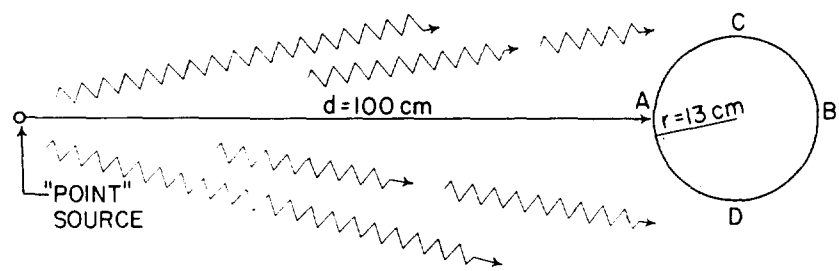

FIG. 1. Schematic diagram showing method of exposure of a Masonite phantom to a "point" source of X- or γ-radiation.

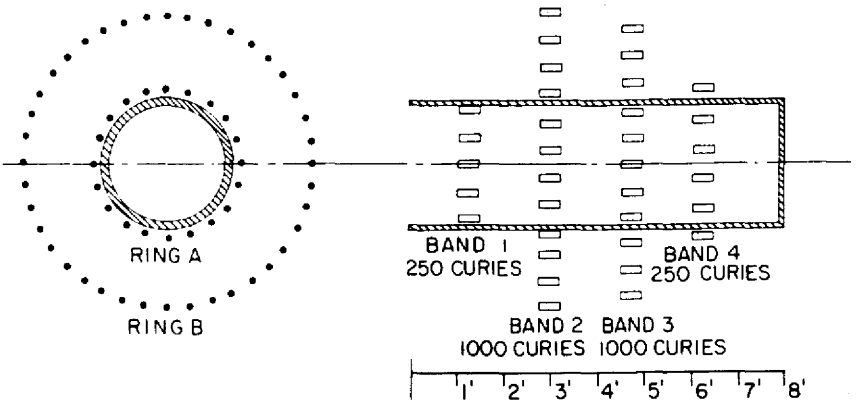

FIG. 2. Cobalt source for 4π geometry exposures, located at the Naval Medical Research Institute, Bethesda, Maryland.

26 cm did not alter the depth-dose curves detectably. The laboratory radiation for most of the exposures was Co^{60} γ-rays. As will be seen, high voltage (250 to 2000 kvp) would have served as well for most exposures; however, the use of Co^{60} allowed more direct comparison of the geometry effect with some exposures not attainable with X-rays (ring, 4π, and field exposures). A diagram of the cobalt generator used for bilateral, crossfire, ring, and 4π exposures is shown in Fig. 2.[4] (See reference *10* for a description of the apparatus.)

For essentially all laboratory dosimetry, the same 100-r-capacity Victoreen thimble chamber and charger-reader were employed. For a few low dose-rate exposures with the bilateral and ring exposures, a 10-r-capacity Victoreen thimble chamber, intercalibrated with the 100-r chamber, was used. The chambers were embedded in a thin, close-fitting plastic shell which was, in turn, inserted into closely machined holes drilled in the Masonite phantom. Thus, the phantom was essentially solid during exposure. The same observer took all laboratory measurements. The phantom measurements in the field were made with thin-walled Sievert-type ionization chambers embedded throughout the thickness of the phantom. For measurement of γ-radiation in the fallout field, the chambers were enclosed in sufficient copper to exclude β-radiation. The thimble chamber measurements did not allow accurate characterization of the depth-dose pattern at the surface and just beneath the surface of the phantom. Since only relative measurements were used in the phantom measurements, absolute calibration of the chambers used was not necessary. Curves were not corrected for inverse square falloff, since

[4] The authors are indebted to Capt. W. E. Kellum, former Commanding Officer of the Naval Medical Research Institute, and Capt. O. E. Van der Aue, present Commanding Officer, for their cooperation in making available the cobalt irradiator for these studies.

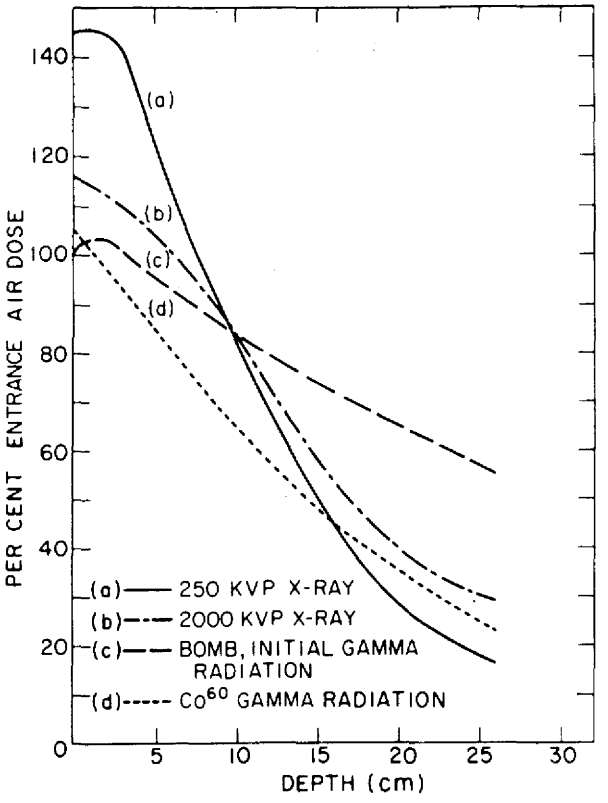

FIG. 3. Unilateral exposure depth-dose curves in a Masonite phantom for different energy radiations; depth dose expressed as per cent of entrance air dose.

it was desired to present depth-dose patterns as actually observed and since inverse square corrections can be applied by the reader, if desired.

RESULTS

The depth-dose curves obtained for the various exposure conditions are shown in Figs. 3 and 4. In these figures, the tissue dose is expressed as per cent of the entrance air dose. Additional theoretical and analytical treatment of the several exposure situations is given in reference *2*.

Unilateral exposure. In Fig. 3, the depth-dose patterns obtained with 250- and 2000-kvp X-rays, Co^{60}, and the initial bomb γ-radiations are shown for comparison. In all cases the total dose is delivered in a single exposure from one side of the phantom.[5] It is apparent from the figure that marked nonuniformity of

[5] The term "unilateral" is applied for convenience to the exposure to the initial γ-radiation from the atomic bomb, even though an appreciable component of the total dose undoubtedly is received from the lateral and distal aspects of the phantom.

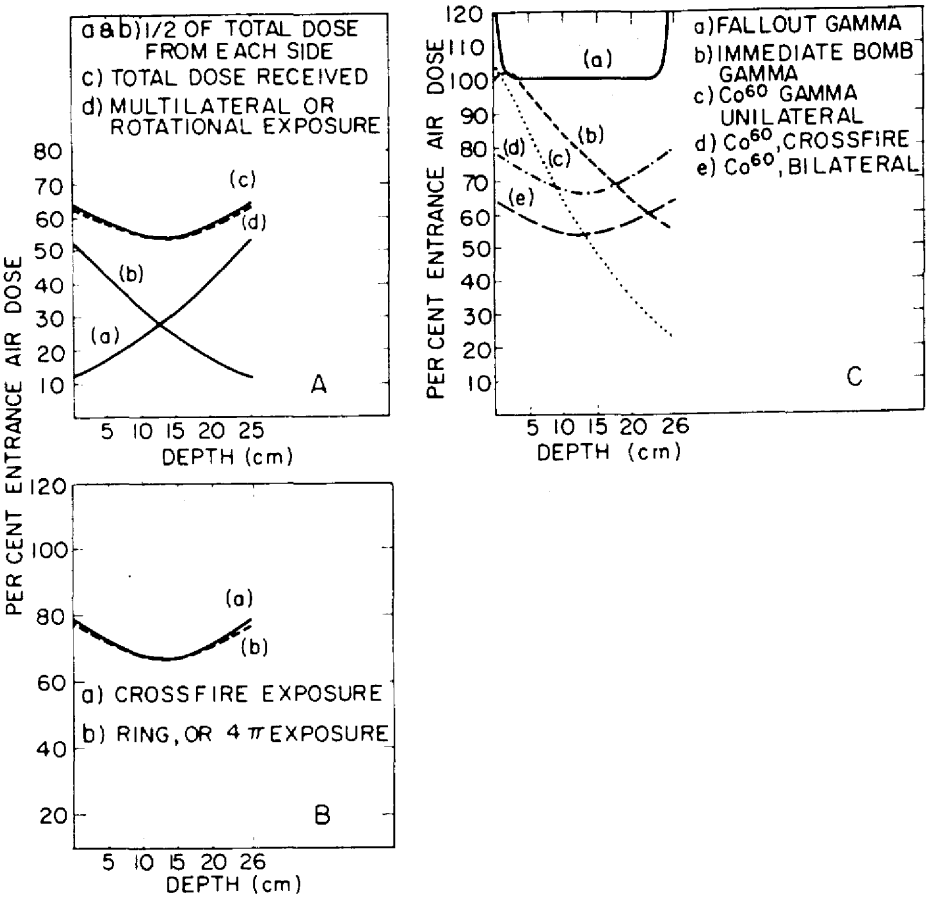

FIG. 4. Depth-dose curves for Co^{60} γ-radiation in Masonite phantom material for several exposure geometries; depth dose expressed as per cent of entrance air dose.

dose deposition results even with highly energetic radiations, and that with this type of "total-body" exposure the distal surface may receive only a very small percentage of the "dose" that the phantom or animal, by convention, is said to have received. The marked falloff in dose results both from absorption in the phantom and from the inverse square effect. (By inverse square effect alone, the dose at the distal side, *B* (Fig. 1), is 63 % of the entrance air dose (see reference *2*).)

Bilateral exposure. In an effort to overcome the marked lack of uniformity of depth dose obtained with unilateral exposure, a number of investigators have

employed the "bilateral exposure" technique (see the excellent work of Tullis, *11*). This procedure is identical to the unilateral exposure, except that one-half of the "total dose" is administered from each side. Thus, if a total of "300 r" is to be given, 150 r as measured free in air at the proximal skin surface is given from side *A* (Fig. 1). The remaining 150 r is then administered from side *B*. The depth-dose pattern for each separate exposure to Co^{60} γ-rays and the total obtained by combining the values obtained with each separate exposure are shown in Fig. 4*A*.

It can be seen from the curve that the tissue dose throughout the phantom is remarkably uniform when contrasted with that obtained with unilateral exposure, and that a maximum variation of only 7% is obtained in traversing the phantom. *Of equal importance, however, is the fact that the tissue dose at no point in the phantom exceeds 62% of the entrance air dose, the dose that the phantom, by convention, is said to have received.* The reason for this discrepancy lies mainly in the fact that, during each half-exposure, the distal side of the phantom is receiving only a very small percentage of the dose received by the proximal side, and, on adding the half-exposures, the total falls far short of the dose said to have been given (see under "crossfire" exposure below for additional reasons).

If the midline air dose, instead of the entrance air dose, is taken as the total exposure, the resulting curve retains the shape noted above, but becomes 70% (instead of 55%) at the midline. This applies to unilateral irradiation as well. Thus it is seen that use of the midline rather than the entrance air dose tends to equalize the tissue dose and the total air dose, but does not accomplish this fully.

Multilateral exposure. In an effort further to improve the pattern of dose deposition, or in some stated instances to simulate fallout γ-radiation, several investigators have utilized more complicated exposure procedures, such as multilateral, rotational, ring, crossfire, or 4π geometries. By multilateral is meant "total-body" exposure as with bilateral exposure, except that smaller equal fractions of the "total dose" are delivered from more than two "sides." For example, one-fourth of the total dose is delivered to each of four 90-degree intervals around the body axis.

The depth-dose pattern obtained (four equal exposures) is shown as curve *d*, Fig. 4*A*. It is seen that this is no improvement over bilateral exposure. The basic difficulty of bilateral exposure is not corrected, since with each fractional exposure, the distal side always receives a very small per cent of the entrance air exposure dose. It can be shown easily that, independent of the number of exposures carried out in this fashion, and as a result of symmetry, the midline dose remains the same. The dose at *A* and *B* (Fig. 1) decreases less than 2% in going from bilateral to multilateral (any number of exposures) geometry. Similarly, the dose at intermediate points such as *C* and *D* (Fig. 1) changes only by a very few per cent as the number of fractional exposures is increased.

Rotational exposure.[6] This type of exposure in which the source is fixed and the phantom is allowed to rotate on its vertical axis can be regarded as the limiting case of multilateral exposure, and the curve essentially superimposes on that for multilateral exposure (curve *d*, Fig. 4*A*). Thus, there is no advantage of this type of exposure over the bilateral or multiport geometries. Identical results are obtained if the phantom is held constant and the source is allowed to revolve about the phantom at a constant TSD of 100 cm.

Crossfire technique. With the crossfire technique, only a *single* exposure from two opposing "point" sources energized simultaneously is used, as opposed to the bilateral technique in which two exposures, first one side and then the other, are made with a single source. The resulting dose pattern is shown as curve *a*, Fig. 4*B*. It is apparent that the shape of the curve is negligibly different from that obtained with bilateral, multilateral, or rotational techniques, and that the tissue dose is still considerably below the air exposure dose that the phantom is said to have received.

The reason for the low tissue dose relative to air dose may not be immediately apparent, since with crossfire technique the air dose throughout the exposure volume is essentially constant. It is easily seen, however, if one considers that as soon as the animal or phantom is introduced the "skin" dose at either side (and throughout the phantom) immediately drops considerably because of absorption in the tissue or phantom. Thus, the entire curve is well below the entrance air dose.

The crossfire curve is higher than the bilateral curve because of what might be regarded as an artifact of dosimetry resulting from the manner in which *air dose* is measured with the two techniques. This can be seen as follows: With the bilateral technique, the total air "dose" administered is the sum of two *entrance* air doses from the two half-exposures. With the crossfire technique, the total air "dose" given is the sum of the *entrance* air dose from one machine and the *exit* air dose from the opposite machine (less by inverse square). Thus the total air "dose" with crossfire measured at either surface of the exposure volume (*A* or *B*, Fig. 1), is *less* than with bilateral, and the tissue dose, in terms of the per cent of air "dose," is correspondingly *greater*. It should be noted that exposure with crossfire for one half the *total time* for both half-exposures with bilateral (two tubes on simultaneously with crossfire) yields a tissue-dose curve that superimposes on the bilateral curve. Since, as noted, the air dose for the same total time is less with crossfire, however, the exposure time with crossfire for the same total air "dose" is *longer*

[6] This method of exposure should be clearly differentiated from the multiple-port or rotational exposure used in radiotherapy of tumors. In the clinic, a collimated beam is employed which at any given time exposes, in theory, only the tumor mass and a small volume of overlying skin and tissue at any instant. Thus, with multiple-port or rotational therapy, the deep tumor, always in the field, receives a maximum dose and any given portion of overlying skin receives a minimum dose.

than one-half the total time for bilateral, and the depth-dose curve is thus above that for bilateral.

Thus, the difference noted is seen to result from the inverse square effect. It is important, however, to note that, although the crossfire technique has taken into account to a degree the inverse square effect, it has not, of course, in any sense eliminated the effect. It has averaged the entrance and exit exposure doses, and thus has raised the depth-dose curve, somewhat as might result if inverse square were negligible. An identical superimposed curve is obtained if, with bilateral, the average of the entrance and exit doses is used as the "air dose," instead of the entrance air dose with each half-exposure. If the midline air dose is used with bilateral exposure, the curve is essentially identical in shape to the crossfire curve, but is placed a short distance above it. Of importance later in considering the curve for fallout radiation, if the half-exposure curves for bilateral radiation are corrected for inverse square falloff before addition, the resulting curve, although placed at approximately the level of the crossfire curve, is considerably flatter than the crossfire curve (70.5% at the edges, 69.0% at the midline).

Ring and 4π exposures. With ring geometry, the phantom is at the center of a concentric ring of fixed sources (any of the "bands" shown in Fig. 2). The phantom placed in the geometric center of the γ-ray generator shown in Fig. 2 is exposed under conditions closely approaching a 4π geometry. The depth-dose pattern for both exposures is shown as curve *b*, Fig. 4*B*. They are essentially identical and are negligibly different from those obtained with the crossfire technique. These types of exposure can be considered to bear a similar relationship to crossfire exposure, as does multilateral or rotational exposure to the bilateral technique. Inverse square is taken into account to a degree, but is not corrected for or eliminated.

Bomb, initial γ-radiation. The measured depth-dose curve in phantom material exposed to the initial γ-radiation from a nuclear device is shown as curve *c*, Fig. 3, and as curve *b*, Fig. 4*C*. The phantom employed was a cylinder measuring 25 cm in diameter, and measurements were taken approximately 3 feet above the ground. It is apparent that, although the rate of falloff of dose in tissue is still appreciable in a thickness of tissue approximating man, the exit dose of approximately 55% is well above the value of approximately 20% for Co^{60} γ-radiation in the laboratory. This is consistent with theory (*12*, *13*) and other observations (*14*). The linear absorption coefficient for bomb immediate γ-radiation observed at distances of biological interest (quoted on page 97 of reference *14*) can be converted to the mass absorption coefficient that will apply to the phantom material by correcting for the small difference in electron density and for inverse square (no detectable falloff through the 26-cm phantom). Application of the absorption coefficient thus derived yields a depth-dose curve essentially identical to that observed. A similar, more approximate result is obtained by using the good geometry coefficient for γ-rays of several Mev and applying the appropriate build-up

factors, in accordance with the theories of Spencer and Fano (*13*, *15*), as extended and applied by others (*15*; also Loevinger *et al.* in reference *8*).

Bomb, fallout γ-radiation. The depth-dose curve obtained for exposure in a γ-ray field from fallout is shown as curve *a* in Fig. 4C (the curve is truncated and does not indicate the skin dose). This curve was measured in a fallout field (*1*), and the air dose is that measured by Sievert ionization chambers enclosed in sufficient copper to exclude β-radiation. The phantom actually used was 25 cm in diameter; the curve was flat throughout the phantom as measured with thin-walled Sievert chambers that measured γ-radiation, as well as energetic β-radiation if present. The flat central portion of the curve is, of course, due to γ-radiation only. The relatively high doses at the edges (as high on the surface as fifty times the midline dose) resulted from addition of γ-radiation and β- or very low energy γ-radiation, not measured by the γ-ray survey instruments used to determine air dose. It is apparent from the curve that the γ-radiation dose throughout the phantom is essentially constant, except at the skin surface.

It is possible to construct very approximately the depth-dose curve to be expected in the semi-infinite plane fallout situation, using a source spectrum for the fallout field (*1*), approximate build-up factors (*2*) calculated from the theories of Spencer and Fano (*13*, *16*), and the geometrical considerations developed in the present paper. The resulting curve is essentially flat as in the experimental curve; however, the midline tissue dose with the calculated curve is approximately 75% of the entrance air dose. The explanation for this difference between the calculated and observed curve is not apparent.

It is pointed out that with both initial and fallout γ-ray exposures the dose is essentially uniform as one goes from one end of the phantom to the other. This is in contrast to all the laboratory geometries described and is approached only with 4π exposure.

DISCUSSION

Comparison of depth-dose patterns. In the preceding results, the marked differences in tissue dose, obtained with different exposure geometries for the same air dose as conventionally expressed, have been stressed. The large discrepancies possible must be kept in mind when only the air dose is quoted or is available. It is seen that no laboratory radiations as they have been employed quantitatively simulate the initial or fallout γ-radiations from the atomic bomb. Perhaps more striking than the differences, however, is the marked *similarity* of the depth-dose patterns for most of the exposure situations, and their essential *identity* if the artifact of expressing dose in terms of that received by the air rather than the tissues could be abandoned. The geometries fall into two basic categories—unilateral exposure, and a second to include all the other types considered. With the exception of unilateral

exposure, all those considered yield reasonably flat or uniform depth-dose patterns (*11*, *17*).

The relationship of the midline tissue dose to the entrance air dose, for any exposure geometry, will vary considerably with beam energy, target-to-skin distance, and animal thickness. The *shape* of the depth-dose curves (essentially flat) for all geometries except unilateral exposure is remarkably insensitive to these factors for radiations and exposure conditions commonly used for large animal irradiations (200- to 2000-kvp X-rays, Co^{60} γ-rays). As the beam energy becomes low (practically at about 100 kvp), or with animals of very large diameter (as with burros), the midline tissue dose becomes vanishingly small compared to the entrance air or entrance tissue doses, and the depth-dose curve is far from flat. This type of "energy dependence" of biological effect has been investigated quantitatively (*17–19*). It should be noted that, although fallout γ-radiation has been termed "soft," only a very small percentage of the primary beam is below 100 to 200 kev under most practical circumstances (*1*). Thus the fallout γ-radiation must be considered quite penetrating in terms of biological effectiveness.

Correlation of depth-dose patterns with biological effect. From the depth-dose considerations outlined above, wide variations in the dose required for a given biological effect, expressed as air dose, would be expected with different exposure conditions. A glance at Tables I and II, in which large animal mortality data from the literature are collected, shows this to be true. The LD_{50} values for dogs and swine are given in the tables in terms of entrance air dose, as well as in terms of the entrance, midline, and exit tissue doses.

A better correlation between dose and effect would be expected if tissue dose is used unless (1) marked differences in the *shape* of the depth-dose pattern exist, (2) a true energy dependence of biological effect is present, or (3) strain differences in the degree of biological effect exist. If the LD_{50} values are considered for bilateral X-irradiation, in which the depth-dose curves are flat, the several LD_{50} values obtained are remarkably close in terms of the midline tissue doses for both dogs and swine. Since the determinations were made by several investigators under different conditions, this indicates a marked lack of sensitivity of the LD_{50} value on X-ray beam energy (over the range employed), TSD, animal strain used, or small variations in the essentially flat depth-dose patterns employed. Appreciable differences in LD_{50}, expressed as midline dose, occur only when the depth-dose pattern is altered markedly (as with unilateral exposure), or when Co^{60} γ-irradiation is used.

Unilateral exposure yields higher LD_{50} values in the laboratory, as might be expected in considering the relatively little-exposed tissues on the distal side (see studies on the effect of spleen and bone marrow shielding in references *27* and *28*). Expressing the LD_{50} as midline tissue dose does not bring the values for unilateral exposures under different laboratory conditions into agreement, nor does it allow

TABLE 1

LD_{50} DOSES FOR DOGS EXPOSED UNDER DIFFERENT GEOMETRY CONDITIONS

Method of exposure	*Radiation used*	*Radiation factors*					LD_{50} *dose*				*Reference*
		Filter (mm)	*HVL (mm)*	*TSD (cm)*	*Dose rate (r/min)*	*Ma*	*Entrance air*	*Entrance tissue*	*Midline tissue*	*Exit tissue*	
Unilateral (from above)	250-kvp X-ray (Picker)	14.2 Al Parabolic 0.5 Cu	2.15 Cu	102	9	15	450	562	332	160	Michaelson,[a] Rochester
Unilateral (from above)	1000-kvp X-ray (G.E., transmitted beam)	12.7 Pb	5.6 Pb	274	10	3	450	495	360	202	Michaelson,[a] Rochester
Unilateral	Bomb γ	None		1000 yd	High, variable	—	271	271	255	210	(*14*)
Bilateral	200-kvp X-ray (G.E.)	0.5 Cu	0.98 Cu	100	6	15	360[b]		260[b]		Presser *et al.* Argonne (*20*)
Bilateral	250-kvp X-ray (G.E., radial beam)	0.5 Cu 1.0 Al		100	15	15	281	252	252	252	Bond *et al.*, USNRDL (*17*)
Bilateral	1000-kvp X-ray (G.E., radial beam)	(Inherent)	2.0 Pb	110	27	3	304	250	255	250	Bond *et al.*, USNRDL (*17*)
Bilateral	2000-kvp X-ray (G.E., radial beam)	6.3 Fe (inherent)	4.3 Pb	200	15	1.5	312	265	265	265	Cronkite and Brecher NMRI (*21*)
Bilateral	2000 kvp	6.3 Fe	4.3 Pb	200	15	1.5	316	262	262	262	Gleiser, NMRI (*22*)
Bilateral	1000 kvp	Not given in report					335		258[a]		Boche and Bishop, Rochester (*23*)
Bilateral	Co^{60} γ	None	10.5 Pb	115	7	—			334		Shiveley *et al.*[a]

[a] S. Michaelson, J. N. Shiveley, and J. Howland, personal communication.

[b] Calculated or estimated; value not given in reference cited.

TABLE II

LD_{50} Doses for Swine Exposed under Different Geometry Conditions

Method of exposure	Radiation used	Radiation factors					LD_{50} dose				Reference
		Filter (mm)	HVL (mm)	TSD (cm)	Dose rate (r/min)	Ma	Entrance air	Entrance tissue	Midline tissue	Exit tissue	
Unilateral	2000-kvp X-ray (G.E., radial beam)	6.3 Fe (inherent)	4.3 Pb	200	15	1.5	500	380	311	130	Tullis *et al.*, NMRI (*11*)
Unilateral	Bomb γ	None	—	1000 yd.	High, variable	—	225	225	191	145	Tullis *et al.*, NMRI (*24*)
Bilateral	1000-kvp X-ray (G.E., radial beam)	(Inherent only)		100	30	3	510	357	252	357	Tullis *et al.*, NMRI (*11*)
Bilateral	1000-kvp X-ray (G.E., radial beam)	(Inherent only)	2.0 Pb	110	27	3	425	302	255	302	Bond, NRDL (*25*)
Bilateral	2000-kvp X-ray (G.E., radial beam)	6.3 Fe (inherent)	4.3 Pb	200	15	1.5	388	279	242	279	Tullis *et al.*, NMRI (*11*)
Multisource field	Co^{60} γ	None	46.2 Al	Variable	About 0.85	—	618		300		Rust *et al.*, Oak Ridge (*26*)

quantitative comparison with bilateral exposures. Evidence from small animal data has been presented indicating that the *exit* tissue dose might be the best single parameter in terms of which to express unilateral exposure (*29*, *30*). The small amount of data available are not sufficient to evaluate this relationship in large animals. Although with bilateral and the more complicated exposure geometries use of the midline tissue dose appears to normalize the LD_{50} values, no clear-cut single parameter appears to exist for unilateral exposure.

It has been suggested that integral dose or gram roentgens might be a suitable measure of dose for comparing "total-body" exposures. Grahn and Sacher (*18*) investigated this possibility using rabbits and mice exposed to different energy radiations and found that integral dose did not normalize the LD_{50} values. These results, together with data from partial-body irradiation (*31*), indicate that the concept of gram roentgens or integral dose is not useful in acute irradiation LD_{50} studies.

"Unilateral" exposure to the atomic bomb immediate γ-radiation appeared to be more effective than unilateral, and perhaps more effective than bilateral irradiation in the laboratory (bomb γ-rays were found to be equally effective as laboratory X-radiation in mice; see reference *32*). The explanation for this may lie in unevaluated geometry or energy factors, or it may lie in biological factors. A neutron contribution cannot be excluded definitely. The LD_{50} values were obtained in a single exposure with relatively few animals. The swine used were much smaller than those used in the laboratory (*24*).

From the dog and swine data in Tables I and II, an intrinsic energy dependence in going from high-energy X-radiation to undegraded Co^{60} γ-radiation appears to exist. The higher LD_{50} for swine exposed to Co^{60} γ-radiation at Oak Ridge could be largely explained on the basis of the low dose rate employed (*33*, *34*); however, no such explanation applies to the Co^{60} data obtained on dogs at Rochester. There are considerable data indicating a possible low effectiveness of Co^{60} and other γ-radiations compared to high-energy X-radiation (*35–40*). The data are not sufficient to indicate to what degree the apparent difference results from a true energy dependence, and how much is explicable on dosimetric or other grounds. At any rate, the difference probably does not exceed 10 or 15%, much less than can result from exposure geometry differences.

The discrepancies among air-dose LD_{50} values is considerably larger for swine than for dogs (Tables I and II), and the differences in LD_{50} values for unilateral radiation, however expressed, appear to be greater for swine than for dogs. This would be expected, since energy and geometry factors become more pronounced as animal size is increased. Thus, even dogs are not sufficiently large to allow direct quantitative comparisons with man, and animals the size of adult human beings should be used for this purpose.

Biological data for multiport, rotational, and crossfire exposure are available

for rabbits or monkeys only (*18*, *41–44*). These data, though meager, are in agreement with what must follow from geometrical considerations (*2*). No data were available for ring or 4π exposures. If exposures are expressed as midline tissue doses and possible intrinsic energy dependence is neglected, all such complicated laboratory sources and fallout γ-radiation must yield essentially identical results.

LD_{50} for man. The consideration of the geometry of exposure and beam energy bear heavily on the LD_{50} value for man. This value has been assumed to be in the range of 400 to 500 r (*45*); however, the figure is of course an estimate, and the conditions of exposure are not specified. It will be evident from the present paper that any value assigned is meaningless unless the conditions of exposure and the exact method of expressing dose are specified.

There are no adequate sources of human data from which the LD_{50} for man can be satisfactorily estimated. Neither biological nor physical dose data[7] from the bombings of Hiroshima and Nagasaki are sufficient to allow more than an order-of-magnitude estimate (*46–48*). Data from human exposures in laboratory accidents (*49–51*) are not sufficient to bear heavily on the problem. Total-body exposure of patients in cancer therapy[8] indicates that very severe hematologic depression results from doses of 150 and 175 r (midline tissue dose, bilateral exposure). This would place the LD_{50} value below 300 r. From the sublethal blood changes of the Marshall Islanders (*1*), the LD_{50} for man exposed to fallout γ-radiation was estimated to be approximately 350 r, midline tissue dose. The possible error in this estimation is very large. The LD_{50} values for dogs and swine (midline tissue dose, bilateral exposure) are of the order of 250 r; that for the monkey may be as high as 500 r. It is thus apparent that the LD_{50} value for man cannot be accurately fixed at present. The problem may be further complicated in that the bulk of acute mortality in most laboratory animals occurs within 30 days of exposure, whereas many deaths in man occur between the thirtieth and sixtieth days. It would thus appear that a 60-day mortality value rather than a 30-day value should be used for description of the LD_{50} in man.

SUMMARY AND CONCLUSIONS

The influence of the geometry of exposure and of beam energy on the depth-dose pattern obtained in tissue-equivalent material simulating a large animal or man was determined for a variety of exposure techniques used in the laboratory, and for the initial and fallout γ-radiations from the atomic bomb. The available LD_{50} values for large animals obtained under various conditions of exposure have been compared to those predicted from considerations of exposure geometry and beam spectrum. LD_{50} values are given in terms of air dose, as well as tissue dose, since

[7] The falloff in tissue of a flux of high-energy neutrons is rapid under laboratory conditions (17, 52), and the considerations of geometry outlined in this paper must be taken into account in considering their contribution to the total biological effect from nuclear devices.

[8] J. J. Nickson and H. E. Bane, personal communication.

under many practical conditions only air dose is available, and since LD_{50} values have conventionally been expressed as entrance air dose. The following conclusions are drawn:

1. The tissue dose and thus the biological response, for a given exposure as expressed conventionally in terms of entrance air dose, can differ by a factor of greater than 2, depending on the geometry of exposure. It is recommended that tissue dose be used whenever possible.

2. With unilateral exposures, the tissue-dose distribution is markedly nonhomogeneous even with the most penetrating laboratory radiations. Laboratory radiation sources have not been used in a way to simulate the measured dose distribution from the initial γ-rays of the atomic bomb.

3. Bilateral radiation with 250-kvp X-rays yields essentially uniform tissue-dose distribution, and no appreciable increase in uniformity is obtained with the more expensive higher-energy machines, or with more complicated techniques such as multiport, rotational, crossfire, ring, or 4π exposures. In all such exposures, the depth-dose curve is essentially flat throughout the phantom; however, in all instances the tissue dose is less by an appreciable degree than is the entrance air dose. Use of the midline tissue dose to characterize these exposures is recommended. The pattern of dose distribution from fallout γ-radiation can be simulated satisfactorily with bilateral exposure, with the exception of the first few millimeters of tissue.

4. There appears to be no satisfactory method of comparing quantitatively unilateral exposure with exposures yielding more uniform dose distribution. Use of gram roentgens, or integral dose, is of little value in this regard.

5. For large animals there appears to be no detectable intrinsic energy dependence of response for X-rays over the range of 250 to 2000 kvp, and for the initial or fallout bomb γ-radiations. Reports indicate that undegraded laboratory γ-ray sources may be less effective than lower-energy X-radiations.

6. The application of the considerations set forth in the present paper to the LD_{50} for man is discussed. There do not appear at present to be sufficient data to allow a better estimate of the LD_{50} for man than the currently accepted 400 to 500 r (geometry or energy not specified). Present considerations indicate that the LD_{50}, expressed as midline tissue dose, may be lower than this for most types of exposure.

7. The relationships of geometry and energy to dose received, discussed in reference to animal mortality, applies also to the practical problem of sterilizing large volumes of food.

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