CALCULATION OF SURFACE DOSE AND INTERNAL ORGAN DOSE FOR HUMAN EXPOSURE TO WEAPON NEUTRONS

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Abstract

A method is described of calculating internal organ dose for humans by computer. Any type of neutron spectrum may be used for input. The method is illustrated by the use of a typical neutron energy angular distribution prepared for civil defense purposes.

Introduction

Dose relationships for fast neutrons are of particular importance in criticality accident dosimetry, and for so-called "disaster dosimetry". The latter includes casualty prediction for civil defense and military applications. After allowance for the large differences in the applicable quality factors, the same relationships also could be useful for fast neutron therapy.

A theoretical model would be concerned with dose to the internal organs of the body. This internal organ dose or doses then would be related by the model to dose on selected areas of the surface of the body where a surface dosimeter might be worn, and also to an external reference such as the midline tissue dose, free-in-air. Dose to the bone marrow system and to the intestines were of interest to this study.

Previous Work

A previous approach to the problem of dose prediction in the body was that of Mechali[1, 2]. His method was to create a theoretical, elliptical cylindrical phantom of homogeneous tissue, and to locate point representations of bone marrow at reasonable depths within it. He then applied the slab calculations of Handbook 63[3] to derive dose and dose-equivalent components at these points.

Mechali made the assumption that the chest dosimeter was on the most exposed region (even for bilaterally incident radiation), and that maximum internal absorbed dose or RBE-dose could be taken as the surface dosimeter reading. The problem of the most suitable location for a surface dosimeter for prediction of absorbed dose is of interest and it is worth noting that experimental phantom irradiations with monoenergetic sources of photons[4] or neutrons[5] have favoured locations on the torso lower than the chest. One aim is to relate internal organ dose in a theoretical model to the readings of various surface dosimeters, as well as to midline tissue dose, free-in-air.

Method

Input spectrum

For the first calculations, for a man exposed to neutrons from a nuclear weapon, the spectrum chosen was that recommended for shielding calculations for civil defense purposes for the Committee on Civil Defense of the U.S. National Academy of Sciences[6]. This spectrum, which will be referred to as the "civil defense spectrum" was for a typical thermonuclear weapon of intermediate yield at a slant range of 1200 m in infinite air. It is recognized that the thermal and blast environments could be quite unsupportable at such a location, but here we are concerned only with the method.

The civil defense spectrum used presents relative neutron fluences as a function of angle of incidence and of neutron energy. The spectrum is normalized to unit incident dose, although in the original work of Straker and Gritzner[7], the normalization was per source neutron.

The use of a spectrum, calculated in terms of incident dose seemed appropriate to our purposes. The civil defense spectrum[6] is specifically intended for use with shielding calculations for buildings. There is an analogy between the calculation of dose ratios inside and outside a blockhouse, and the calculation of similar ratios inside and outside the human body. A further advantage of the 1200 m spectrum is that the spectrum from a thermonuclear source varies only slowly with range for ranges greater than 600 m[6].

The normalization of the results occurs automatically with this form of the spectrum. The use of the ORNL cylindrical phantom depth-dose data[8], as described later, provides factors which are dimensionally the same as fluence-to-dose conversion factors. The application of these factors to the civil defense spectrum produces quantities that are thus automatically in units of dose per incident dose. This is numerically the same as ratios of internal dose to external free-in-air dose, continuing the analogy between the blockhouse and the human body. However, because for some internal locations the depth-dose calculations of Auxier, Snyder and Jones[8] for the cylindrical phantom lie above the fluence-to-dose conversion factors of Henderson recommended[6] for use with the civil defense spectrum, the analogy starts to break down. At some locations, the internal dose can apparently exceed the exposure by more than 40%, owing to this inconsistency in the two sets of calculations. If the fluence-to-kerma factors of Ritts et al.[9] are used this is reduced in the worst case to less than 30%.

Phantoms

The depth dose was determined in two steps, using two theoretical "phantoms". The first of these, called the DREO phantom, consisted of a series of horizontal cross-sectional drawings of the human body at a number of heights in an erect individual. Each drawing showed realistic locations of all bones, and effective centres were chosen for the bone marrow in each bone. The lungs were also included and an intestinal location was shown. Lines were drawn in the horizontal plane through each effective centre parallel to the directions of the incident radiation, and measurements made of the penetration distances from the irradiated surface. Six equally spaced horizontal directions were considered, but only 4 needed to be calculated. Penetration distances were corrected for passage through lung or bone. Two representative sections of the DREO phantom are shown in Figs. 1 and 2.

The second phantom was the ORNL circular cylindrical phantom of 30 cm diameter, used in the calculations of Auxier, Snyder and Jones[8]. The corrected penetration distances were transferred onto the ORNL phantom so that the various effective marrow centres now fell into various volume elements of the middle section (layer number three of Ref. 8) of the cylindrical mass of tissue. Because of the variable radius of curvature of the irradiated surface of a real body, the organs in the DREO phantom were classified as either midline-located (e.g. the vertebrae for frontal irradiation) or side-located (e.g. the ribs). The midline organs fell on the midline of the ORNL phantom, while the side-located organs were plotted at reasonable displacements towards the side of the ORNL phantom. The DREO phantom contained fixed organs, but was freely rotatable to any chosen angle with respect to the incident radiation. The ORNL phantom was rigidly fixed with respect to the direction of incident radiation, but it contained equivalent organs, whose positions formed a changing pattern whenever the DREO phantom changed its orientation in the radiation field.

Determination of depth dose

For each of the 20 volume elements of layer three of the ORNL phantom,

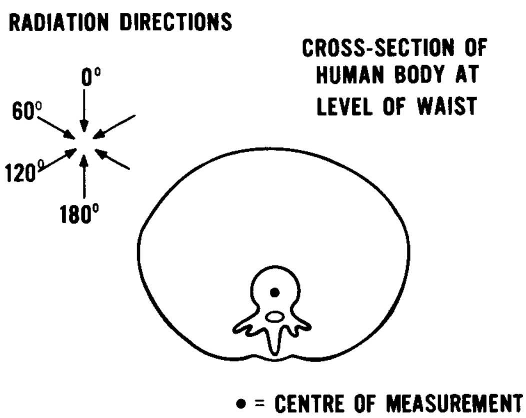

Fig. 1

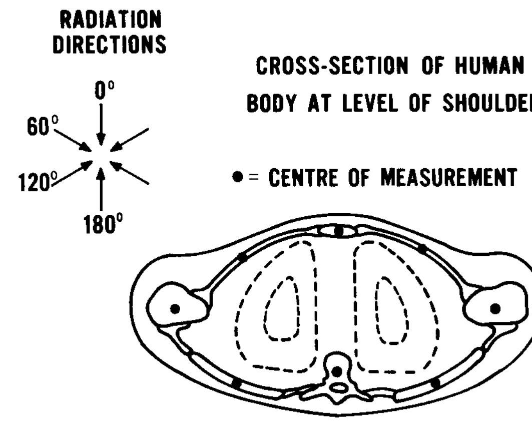

Fig. 2

and two supplementary surface elements, obtained by extrapolation, dose-versus-energy graphs were plotted using the data of Ref. 8. The dose-energy graphs were read off for each volume element at the mid-point of the 22 energy bins of the civil defense spectrum[6]. This provided the input data in units of rad cm^2 $neutron^{-1}$ at 22 energies for 22 volume elements, to be used for the determination of the depth dose.

Angular constraint

Ultimately a useful theoretical model should be able to apply various angular spectra to a three-dimensional set of penetration distances to take maximum advantage of the large amount of angular information implicit in such spectra. It is already well demonstrated[4,5] that the case of normally incident radiation, is over-conservative and unrealistic, when it is applied to prediction of the dose to the bone marrow or to points in the intestinal tract for the cases of off-angle (elevated angle of incidence), or semi-isotropic incidence. This is due to the effects of body self-shielding for the organs in question.

In the present program there was a severe angular constraint on the three-dimensional spectral data. The fluences in each angle bin of the input spectrum were regrouped into six wide angle bins, and these six bins were then constrained to lie in the horizontal plane. Thus all the neutrons of the civil defense spectrum were presumed to be incident upon the phantom horizontally. This unavoidably overestimated the internal dose to our organs of interest. It must be emphasized that the concern of the present paper with normally incident radiation in no way implies any belief that this is an adequate approach to what is really a three-dimensional problem. Until we are able to complete our set of three-dimensional measurements, a two-dimensional approach has to suffice.

Program

After reading-in the spectrum and the depth dose data, and calculating their product, the program performed the summations over energy to produce an array of partial doses in each volume element of the ORNL phantom for each of our six angles of incidence. This was done by applying the six angular fluences, one at a time, to the front irradiated surface of the ORNL phantom. The rest of the program consisted of a system of keeping track of the internal organs or the surface dosimeters with respect to their constantly changing locations in the ORNL volume elements, and of summing up their accumulated doses with respect to angle. This produced an integrated dose for each location. In the case of the bone-marrow system, the calculated partial dose at each effective centre of a bone, was weighted by the local percentage of red marrow for that bone or group of bones according to the data of Ellis[10]. This gave an array of dose contributions for each of the 22 bones or bone groups, and this was then summed to give mean bone marrow dose.

On printout, a man could be considered as facing into the radiation from the weapon, or at angles of 60°, 120° or 180° from it. Tables are printed of the dose contributions at all the sites due to the fluence reaching him from one of the 60° angle bins in the horizontal plane. This procedure is repeated for the six angles. At each of the six orientations, dose due to total fluence as well as the partial angular fluences is obtained.

A variant of the program was written to perform calculations for mono-energetic, monodirectional neutrons at the mid-points of the upper 13 energy groups used previously. This gave a number of irregularly-spaced energies lying between 330 keV and 13.6 MeV. The program and the types of output obtained were similar to that just described.

Results

Because of uncertainties due to the imposed angular constraints, it would be unwarranted to attach much significance to the absolute values predicted. However, the relative dose values are less sensitive to error. Figs. 3 to 6 are histograms showing relative dose contributions, in the case of a man facing the weapon, for neutrons arriving from various angles. Fig. 3 shows mean bone marrow dose. Fig. 4 shows intestinal dose at a representative location. As one would expect the intestines are more heavily dosed than the bone marrow, and their dose is much more dependent upon the fraction of the neutrons arriving from the direction of the source. Fig. 5 shows the dose to a front surface dosimeter, located on the midline at the waist. This is even more directionally dependent when the man is facing the source. Fig. 6 shows dose to a similar waist dosimeter worn at the back. In this case, the largest dose contribution is received from neutrons entering the bins at 120° and 240°. In the case of a man facing 180° away from the weapon, Figs. 5 and 6 would simply be reversed for the two waist dosimeters.

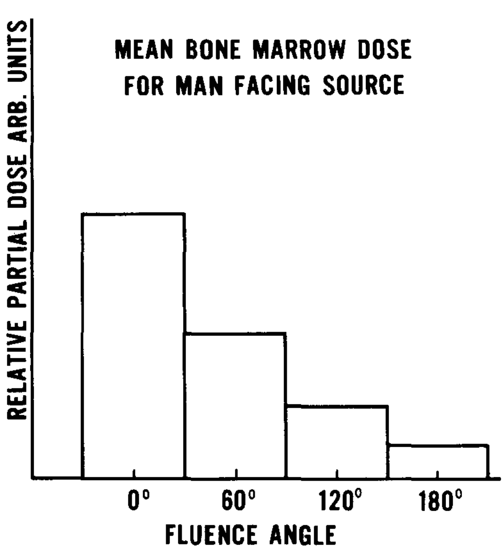

Fig. 3

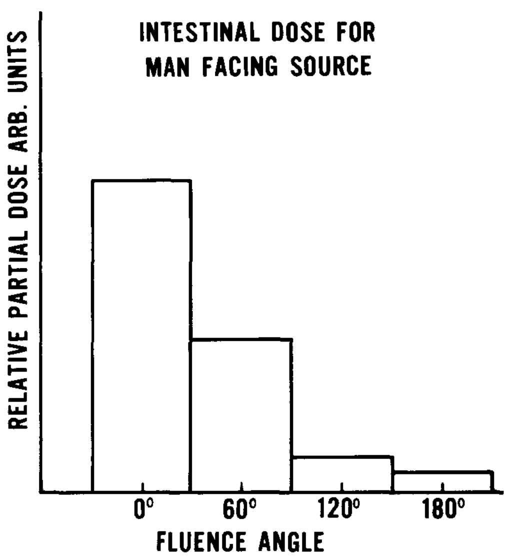

Fig. 4

Fig. 7 shows a table of dose ratios for a man standing in four different orientations in the field, from face-on to the source (0°) to back-on (180°). The top line shows intestinal dose over the reading of a front waist dosimeter. The ratio is about 0.5 to 0.7, and is not very sensitive to orientation. The second line shows the ratios for intestinal dose over a back waist dosimeter. The body shielding of the dosimeter in this location raises the 0° ratio to 0.8, and the directional dependence now changes the ratio by a factor of about 2 as the man turns to the back-on position. The bottom line shows the ratio of the intestinal dose to the free-in-air tissue dose. There is little directionality,

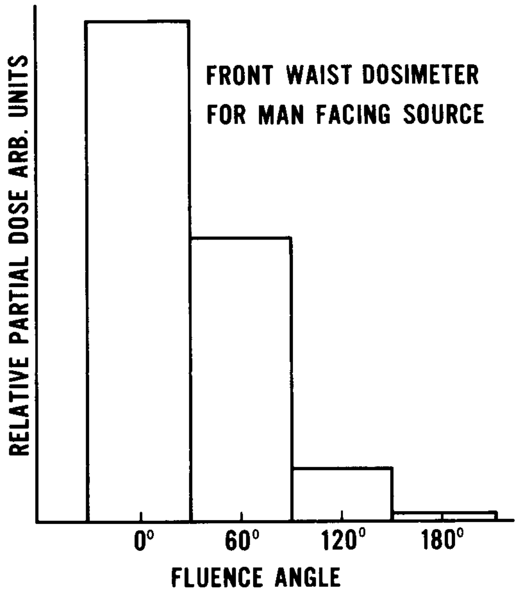

Fig. 5

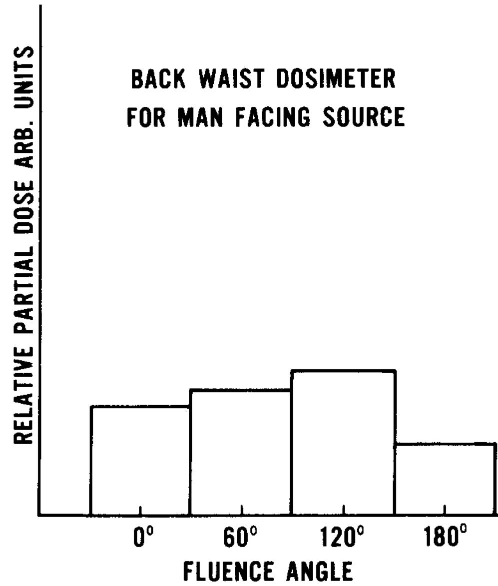

Fig. 6

but the ratio is around 0.45. This supports the view[4,5] that the free-in-air dose, unless weighted by ratios like this, is a poor indicator of dose to deeply located organs such as the intestines, or the pelvic bone marrow.

Fig. 8 illustrates the results of the monoenergetic calculations for a human exposed face-on to the source. The ordinate gives total mean bone marrow dose (recoil ion plus gamma components), and the abscissa gives neutron energy. The present work is higher in dose than the calculation of Mechali[1], particularly at 3.5 MeV, where the difference is around 25%. When the monoenergetic calculations at 2.74 MeV were compared with the DREO experimental human phantom measurements at 2.95 MeV[5] the results agreed within 20% for the intestinal location and for the front surface-waist for both face-on and back-on orientations.

INTESTINAL DOSE RATIOS

INTESTINAL DOSE RELATIVE TO DOSE AT		ORIENTATION OF MAN IN FIELD (DEGREES OFF FACE-ON) 0°	60°	120°	180°
SURFACE WAIST	FRONT	.53	.55	.60	.66
SURFACE WAIST	BACK	.81	.67	.49	.43
	FREE-IN-AIR	.50	.49	.43	.40

Fig. 7

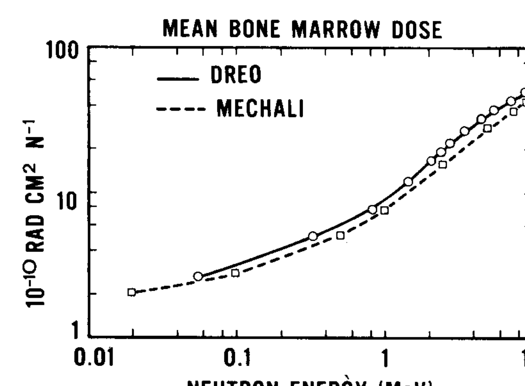

Fig. 8

Conclusions

This method can provide a rapid and versatile approach to problems of dose prediction. The approach is particularly powerful in the amount of angular information that can be made available, both with respect to neutron angle and to angle of orientation of the man. A complete breakdown of all bone-marrow components is also always available. The demands on computer time and memory are insignificant.

It appears that the calculations support the view that a dosimeter located on the surface of the body facing the unscattered radiation in a semi-isotropic field overestimates the dose to deep internal organs by a factor of around 2, while a detector on the far side may not. This is in line with the view previously expressed[4, 5] that a partially shielded dosimeter location such as the groin may be an improved location for a detector for disaster or criticality dosimetry.

It is felt that future work should involve a method to handle the three-dimensional case, without any angular constraint on the incident fluence.

Acknowledgements

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