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TECHNICAL NOTE 72-12
DREO TN 72-12

PROJECT NO.
DRB 16-01-39

MARCH 1972
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ABSTRACT

The dose at sites in the interior and on the surface of a human phantom was measured for broad-beam exposure to 0.66-MeV gamma rays and to 2.95-MeV neutrons. Measurements were made for a range of angles of radiation incidence. A comparison is presented between the surface dose at possible dosimeter locations on the chest, abdomen and groin and the corresponding absorbed dose to the bone-marrow system and to the abdomen. Unless the geometry of exposure is accurately known, it is shown that a chest dosimeter is a poor indicator of the absorbed dose. A dosimeter worn on the groin would be significantly better for both neutrons and gamma rays for a wide range of exposure geometries.

RÉSUMÉ

Les mesures de la dose ont été entreprises à l'interieur et à la surface d'un fantôme de forme humaine exposé totalement à des neutrons monoénergetiques de 2.95 MeV et aussi à des rayons gamma de 0.66 MeV. Les mesures ont été faites à differents angles d'incidence de la radiation. On donne une comparaison entre la dose de la surface localisée sur l'estomac, la poitrine et l'aine et la dose équivalente absorbée par la moelle osseuse et à l'interieur de l'abdomen. Un detecteur sur la poitrine est un pauvre indicateur de la dose absorbée, a moins que la géometrie de l'exposition soit connue avec exactitude. Si on considère les differents angles d'exposition soit aux neutrons soit aux rayons gamma un dosimetre porté à l'aine serait beaucoup plus significatif que celui sur la poitrine.

INTRODUCTION

A continuing problem in dosimetry is the relationship between the response of a dosimeter worn on the surface of the body and the corresponding hazard to the person that wore the dosimeter. It has long been recognized that this relationship depends on a great many factors. These include the nature of the incident radiations, eg. X-rays, γ-rays or neutrons, the energy of the radiations, the energy/fluence response of the dosimeter, the location of the dosimeter on the body, the geometry of the exposure and the definition of the hazard that is to be indicated by the dosimeter reading. For civilian and for peacetime applications it is usually sufficient to have the surface dosimeter give an indication of the maximum absorbed dose to the body. With the assumption that the absorbed dose is a useful criterion of the hazard, this provides a conservative indication of the radiation hazard for most circumstances. The simplest interpretaion of a dosimeter reading then is that the wearer of the dosimeter has not received an absorbed dose in any location that is greater than the value given by the dosimeter. For military applications where the dosimeters of a group of individuals are to be used to predict the incidence of casualties, a close correlation between dosimeter reading and the absorbed dose in relevant organs is desirable.

CHEST DOSIMETER

For a surface dosimeter worn high on the chest, the dosimeter reading usually will be close to the free-air exposure dose [midline dose (free-in-air)] that would be measured in the absence of the body. In turn the midline dose (free-in-air) is frequently used in shielding studies of the radiation protection afforded by shelters, vehicles or other radiation barriers. This usage tends to reinforce the concept that the exposure itself is a useful indicator of the hazard and that a surface dosimeter worn on the chest will be satisfactory if it can indicate the exposure environment.

Because of its built-in conservatism, the dosimetry approach described above could continue to be useful for peacetime add civilian exposures of non-radiation workers for whom long-term effects of small amounts of radiation might become significant. For war-time conditions or for accurate assessment of survival probability following a radiation exposure, the large errors inherent in this exposure-oriented interpretation of dosimetry should be recognized. When the continued operations of men or units could depend on their radiation history, it becomes imperative that dosimeter readings be interpreted as accurately as possible without distorting conservative factors. Generally the immediate requirement will be for the interpretation of the dosimeter reading in terms of the probable short-term or acute effects of the radiation exposure.

DESCRIPTION OF MEASUREMENTS

Dosimetry studies with human phantoms at this establishment have been directed to measurements of the absorbed dose to the red-bone-marrow system and to the upper abdominal region for a variety of exposure conditions (1, 2). The absorbed doses to these areas appear to be critical for acute or short-term lethalities in humans (3). The relationship of the dose to these critical regions and the corresponding free-air exposure dose has been studied for both gamma-ray and fast-neutron irradiations for a variety of exposure geometries. In addition, the surface doses have been obtained at a number of locations to examine the extent to which the reading on the surface dosimeters could be used to indicate the absorbed doses that could be important for acute effects.

Measurements of the gamma dose were made with thermoluminescent dosimeters that were small enough for insertion into cavities in representative portions of the red-marrow-containing bones of a human skeleton (4). The skeletons of the phantoms were "fleshed out" with solid or liquid tissue-equivalent material to the approximate dimensions of the standard man. Additional gamma-dose measurements also were made with small BD-11 ionization chambers and with a "Phil" detector which is a miniature, shielded, energy-compensated geiger counter (5). For neutron irradiations, the recoil proton dose component of the fast-neutron dose was measured with small proportional counters and the associated gamma dose produced by (n, γ) interactions in the irradiated phantom was measured with the detectors described above. All irradiations were made under "broad-beam" whole-body conditions. Dose measurements were made at a number of fixed exposure angles of elevation for a range of rotation angles of the phantom. These could be combined to simulate the exposure, the absorbed dose in a critical area and the corresponding surface dose for a variety of exposure geometries.

RESULTS

Tables I to IV present the relationships between the exposure dose that would be observed with the phantom away, the absorbed doses to the red marrow and to the upper abdominal regions, and the surface doses at the chest, abdomen and groin for two general exposure geometries. The first geometry considers whole-body exposure face on to a broad beam of gamma radiation of 0.66 MeV (Table I), which is close to the average energy of the gamma rays from fission products, and to a broad beam of fast neutrons of 2.95 MeV (Table II), for different angles of radiation incidence as measured from the horizon for an upright phantom. The second geometry of exposure (Tables III and IV) presents the corresponding values for a ring source, ie. exposure incident from all sides, for similar energies and angles of radiation incidence. In all tables the surface dose and the absorbed dose in the critical regions are expressed as fractions of the dose due to the incident radiation. For the gamma rays the incident dose is the exposure expressed in roentgens and the absorbed dose values are in rads (tissue). For the fast neutrons the fluence-to-kerma value for tissue was used to express the reference dose in rads (tissue)*. Also, for the fast-neutron exposures, the recoil proton dose component and the associated gamma dose component produced by (n, γ) interactions in the irradiated phantom are expressed as separate fractions of the incident dose produced by the neutrons when the phantom was removed. These components of the total neutron dose also have been combined with a Quality Factor (QF) of one to give the ratio of the total dose due to neutron exposure. It is recognized that the particular values shown in the tables depend on the detailed dimensions of the human phantoms used in the measurements. However they should be representative of the general relationships between surface and absorbed doses. Further details of these measurements and additional dose-to-exposure values at other gamma-ray energies are described elsewhere (1, 2, 4).

TABLE I

Face-On Whole-Body Exposure to 0.66-MeV Gamma Rays

Angle of Incidence (elevation)	Absorbed Dose/Exposure (rad/R)				
	Bone Marrow	Upper Abdomen	Surface Chest	Surface Abdomen (front)	Surface Groin
-30°	0.49	0.65	1.02	1.05	1.04
0	0.58	0.73	0.97	1.02	0.96
30	0.58	0.65	0.96	1.06	0.50
45	0.55	0.53	1.03	1.05	0.40
60	0.44	0.34	1.03	0.98	0.21
75	0.24	0.17	1.03	0.96	0.16

* This gives essentially the midline dose (free-in-air) which is defined as the dose absorbed in a small sample of tissue suspended in air at the position of the midline of the body with the body absent.

TABLE II

Face-On Whole-Body Exposure to 2.95-MeV Neutrons

Region	Angle of Incidence (elevation)	Absorbed Dose/Midline dose (free-in-air)		
		Recoil Proton	Associated Gamma	Total (for QF = 1)
Bone Marrow*	0°	0.41	0.12	0.53
	30	0.36	0.14	0.50
	60	0.07	0.07	0.14
Upper Abdomen (midline)	0°	0.48	0.13	0.61
	30	0.37	0.11	0.48
	60	0.09	0.05	0.14
Surface Chest	0°	1.10	0.08	1.18
	30	1.13	0.07	1.20
	60	1.00	0.06	1.06
Surface Abdomen (front)	0°	1.14	0.09	1.23
	30	1.18	0.08	1.26
	60	1.07	0.05	1.12
Surface Groin	0°	0.93	0.09	1.02
	30	0.36	0.04	0.40
	60	0.09	0.02	0.11

* The recoil proton dose component to the bone marrow shown in the table was measured only at the surface of the lumbar vertebrae and is therefore representative only of the dose to a particular region that contains a significant portion of the red marrow. The associated gamma dose shown is the average value to the entire red marrow system.

TABLE III

Rotational Whole-Body Exposure to 0.66-MeV Gamma Rays

Angle of Incidence (elevation)	Absorbed Dose/Exposure (rad/R)				
	Bone Marrow	Upper Abdomen	Surface Chest	Surface Abdomen (front)	Surface Groin
-30°	0.60	0.63	0.67	0.73	0.80
0	0.71	0.67	0.71	0.80	0.84
30	0.68	0.59	0.77	0.74	0.50
45	0.62	0.49	0.83	0.70	0.42
60	0.45	0.32	0.83	0.55	0.27
75	0.28	0.22	0.81	0.47	0.14

TABLE IV

Rotational Whole-Body Exposure to 2.95-MeV Neutrons

Region	Angle of Incidence (elevation)	Absorbed Dose/Midline dose (free-in-air)		
		Recoil Proton	Associated Gamma	Total (for QF = 1)
Bone Marrow*	0°	0.33	0.09	0.42
	30	0.23	0.12	0.34
	60	0.07	0.06	0.13
Upper Abdomen (midline)	0°	0.32	0.10	0.42
	30	0.23	0.09	0.32
	60	0.06	0.04	0.10
Surface Chest	0°	0.70	0.05	0.75
	30	0.77	0.05	0.81
	60	0.79	0.04	0.82
Surface Abdomen (front)	0°	0.66	0.07	0.73
	30	0.71	0.07	0.78
	60	0.53	0.04	0.57
Surface Groin	0°	0.59	0.06	0.65
	30	0.28	0.05	0.33
	60	0.10	0.02	0.12

* The recoil proton dose component to the bone marrow shown in the table was measured only at the surface of the lumbar vertebrae and is therefore representative only of the dose to a particular region that contains a significant portion of the red marrow. The associated gamma dose shown is the average value to the entire red marrow system.

SUMMARY

Tables I to IV show that there can be large variations of the dose values with changing angles of incidence for both the neutron and gamma-ray exposures. Consideration of the effects of self shielding on the absorbed dose in the critical areas compared to the surface dose supports the following conclusions:

1. The ratio of the absorbed dose in a critical region to the midline dose (free-in-air) is highly dependent on the angle of incidence of the radiation.

2. The response of a surface dosimeter worn on the chest is relatively independent of the angle of incidence of the radiation and hence a chest dosimeter is a poor indicator of the absorbed dose to a critical region.

3. A dosimeter worn on the belt would have a greater probability of indicating a critical dose due to gamma irradiation than would a dosimeter worn on the chest.

4. A surface dosimeter worn on the groin would be a significantly better indicator of the dose to regions that are critical for acute effects for both gamma rays and fast neutrons.

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DOCUMENT CONTROL DATA – R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATING ACTIVITY 02040 Defence Research Establishment Ottawa, National Defence Headquarters, Ottawa, Canada ONT 0204b K1A 0Z4 (CAN)	2a. DOCUMENT SECURITY CLASSIFICATION Unclassified 2b. GROUP n/a

3. DOCUMENT TITLE

040 RELATIONSHIPS BETWEEN DOSIMETER RESPONSE AND ABSORBED DOSE FOR 0.66-VeV GAMMA RAYS AND 2.95-MeV NEUTRONS (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Note

5. AUTHOR(S) (Last name, first name, middle initial)

1101 1102

Clifford, Charles E. and Facey, Robert A.

6. DOCUMENT DATE 46 March, 1972	7a. TOTAL NO. OF PAGES 0901 9	7b. NO. OF REFS 0902 6
8a. PROJECT OR GRANT NO. 35D 16-01-39	9a. ORIGINATOR'S DOCUMENT NUMBER(S) 0203 DREO Technical Note No. 72-12	
8b. CONTRACT NO.	9b. OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)	

10. DISTRIBUTION STATEMENT

Unclassified, no restriction

11. SUPPLEMENTARY NOTES	12. SPONSORING ACTIVITY

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Phantom

Dosimeter

Neutron dose

Gamma dose

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