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INCORPORATED
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January 20, 1972

AREA CODE 615
TELEPHONE 483-8411

Dear Jim,

I have taken too long in gathering up this material that we talked about on Tuesday, so I won't take up an additional day for having it typed by our secretarial pool. I hope you can interpret my typed thoughts!

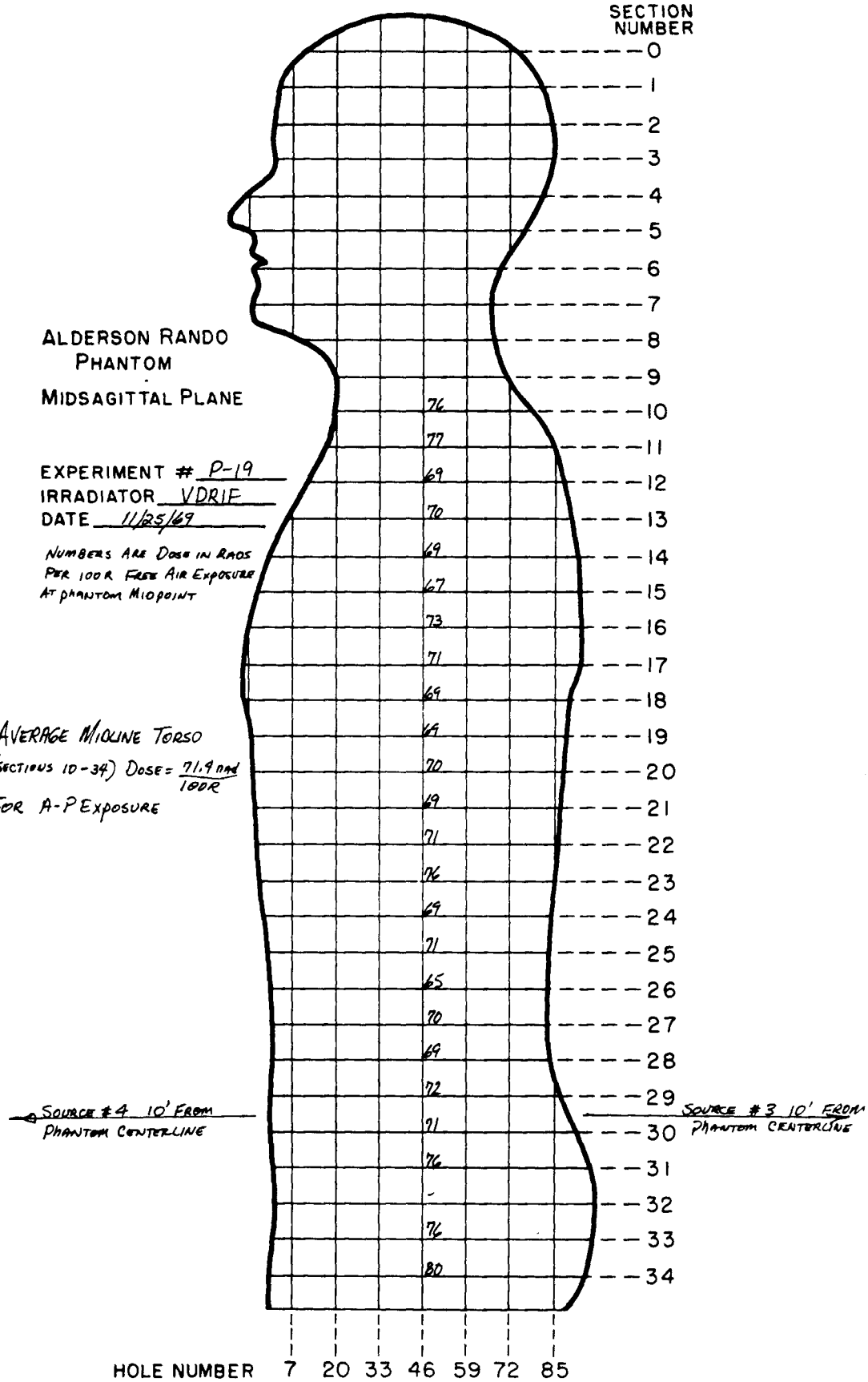
Enclosed are the proceedings of the total-body dosimetry conference you requested. This is really a short summary of the topics we discussed and if I can clarify or add to anything in the write up please give me a call.

I have also enclosed a copy of my last paper on the subject that is to be printed up in a conference proceedings soon. My main reason for enclosing it is because it contains a brief description and figures that illustrate the geometry and source configurations in the three total-body irradiators we are now using. Two of our irradiators use cobalt-60 but neither is 2-source bilateral as in your case. However, the VDRIF irradiator is bilateral in the sense that all sources are in a single plane and theoretical calculations indicate that 77% of the radiation is from the two sources that are perpendicular to the long axis of the body. Therefore I have enclosed our depth-dose data in the midline of the Alderson Rando phantom for both lateral and anterior-posterior exposures. These figures illustrate the importance of having the patient be exposed A-P if maximum uniformity of dose is desired, and all organ dose estimates in the reprint are for the phantom exposed on its side.

I hope this information is helpful, and I am sure much of it may need more explanation so give me a call anytime.

Yours sincerely,

Jack Cox



ALDERSON RANDO PHANTOM

MIDSAGITTAL PLANE

EXPERIMENT # P-19

IRRADIATOR VDRIF

DATE 11/25/69

NUMBERS ARE DOSE IN RADS PER 100R FREE AIR EXPOSURE AT PHANTOM MIDPOINT

AVERAGE MIDLINE TORSO (SECTIONS 10-34) DOSE = 71.9 RAD / 100R FOR A-P EXPOSURE

ALDERSON RANDO PHANTOM

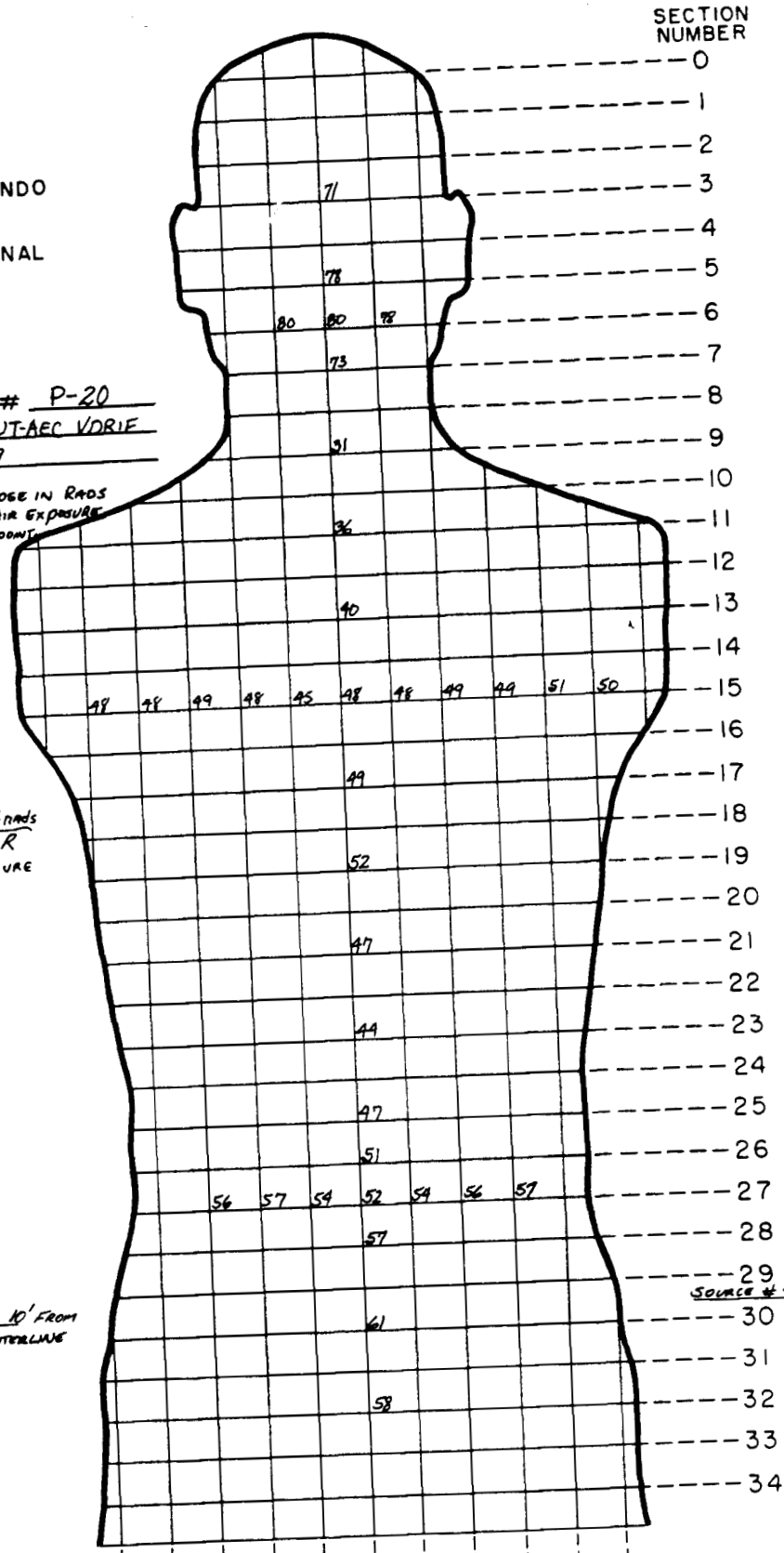
MIDLONGITUDINAL PLANE

EXPERIMENT # P-20
IRRADIATOR UT-AEC VDRIF
DATE 10/3/69

NUMBERS ARE DOSE IN RADS PER 100 R FREE AIR EXPOSURE AT PHANTOM MIDPOINT

AVERAGE MIDLINE TORSO* DOSE = 49.4 rads / 100 R
FOR LATERAL EXPOSURE

*SECTIONS 10-34



DOSIMETRY FOR RADIOBIOLOGICAL STUDIES OF THE HUMAN HEMATOPOIETIC SYSTEM[1]

W. L. Beck, T. R. Stokes, and C. C. Lushbaugh

Oak Ridge Associated Universities

INTRODUCTION

At present, physical measurements of radiation exposure field fluxes are considerably more accurate than retrospective biologic estimates of the radiation dose in any particular exposure incident. However, wide individual variation in clinical response to radiation exposure often creates an apparent disagreement between physical and biological dose estimates. This disparity is largely caused by biologic variations in radiosensitivity and systemic repair but is also the result of individually different depth-dose distributions owing to body size differences or orientation geometry occurring during otherwise equal exposures.

Medical appraisal of the range of human biological variation in hematologic responses is needed, but has not been made because dosimetric information about the real depth doses to the bone marrow of individual patients is not available. The wide spatial distribution of bone marrow in the human skeleton makes the determination of the total averaged dose or any local bone marrow dose difficult and at present requires an empirical approach. This study was performed to devise a system for estimating individual bone marrow doses in therapeutic radiation exposures of leukemic patients. These measurements are needed to make dose-response correlations and to study the effect of dose protraction on peripheral blood cell levels. Such correlations are basic to medical management of irradiated persons since the bone marrow is one of man's most important radiosensitive tissues; lethality within 60 days of acute exposures from 200 to about 1000 R usually results from hematopoietic failure. Some studies (refs. 1 and 2) have shown that in selected patient populations the human $LD_{50/60}$ may approach a low of 250 rads average body-dose, but confidence in these estimates is poor.

During extended space explorations there may be little risk of receiving such sizeable doses acutely but there is a real chance of accumulating doses to the marrow that may be biologically significant. True correlation and variation of human hematologic responses to total-body irradiation (TBI) are sorely needed to help in establishing workable limits for these occupational exposures during missions in outer space. While the studies we have made were primarily intended for clinical uses, the data obtained is applicable to some of the dosimetric and shielding problems of space medicine.

In the Oak Ridge Associated Universities (ORAU) Medical Division program of therapeutic TBI, three irradiators with different exposure rates are in use: the ORAU low-exposure-rate total-body irradiator (LETBI) and medium-exposure-rate total-body irradiator (METBI), and the University of Tennessee-AEC Variable Dose Rate Irradiation Facility (VDRIF). Each of these irradiators was specifically designed to produce a uniform field of high-energy-gamma radiation for total-body exposures of large animals and man.

[1]Research supported jointly by U.S. AEC and NASA.

THE IRRADIATORS

The LETBI facility consists of a large outer room (Fig. 1B) in which a smaller exposure room (Fig. 1A) is centrally positioned. Eight cobalt-60 sources of 16 Curies each are located in the outer room and they irradiate the treatment room from all sides. This arrangement provides a radiation field uniform to within ±10% in the living volume (16×16×8 ft) occupied by the patient. Treatments given at an average exposure rate of 1.5 R/hr have ranged from 3 to 8 days duration to provide total protracted exposures up to 250 R. During exposure the patient is free to move about the exposure room while being irradiated for 18 to 22 hr per day. This facility is described in more detail by Andrews, et al. (ref. 3).

A model of the METBI facility is shown in Fig. 2. The control room is connected by a curved hallway to the 8×8×8 foot treatment room. Eight cesium-137 sources of 500 Curies each, located in the walls, irradiate the centrally suspended treatment bed. The radiation field in the 2×2×6 foot volume occupied by the patient on the bed is uniform to within ±5% of the 1.5 R/min exposure rate in the volume center. Exposure times here range from a few minutes to a few hours for total exposures of 20 to 350 R. A complete description of this facility has been published by Brucer (ref. 4).

The floor plan of the third irradiator (VDRIF) used in this therapy program is shown in Fig 3. Six cobalt-60 sources of 7700 Curies each are arranged in a rectangular array with 20 ft between adjacent sources. Exposures are done with the patient lying on his side on a hospital stretcher in the center of the source array. During patient therapy five sources are used to provide exposure over the stretcher at a rate of 40 R/min ±5%. To minimize the radiation hazard to hospital attendants, who might be required to aid the patient in case of equipment failure, we do not use source No. 1, which is nearest the entrance to the exposure room. A more complete description of this irradiator is given by Checka, et al. (ref. 5).

The radiation characteristics and dimensions of these irradiators are summarized in Table 1.

THE PHANTOM

An Alderson Rando phantom (ref. 6) was used as a patient analogue. This standard-man-sized phantom is constructed of isocyanate rubber, equivalent to tissue in interactions with ionizing radiation. A human skeleton and density-adjusted lungs are contained within the otherwise solid phantom. The phantom is sliced into transverse sections 2.5 cm thick with holes of 5 mm diameter arranged in a 3×3-cm grid to provide positions for thermoluminescent dosimeters (TLD). When not in use as dosimeter sites, the holes are filled with removable plugs of tissue-equivalent material.

Each of the 137 dosimeter sites located within the bone-marrow loci, identified from radiographs of the 34 transverse sections of the phantom, contained an individually calibrated TLD during periods of irradiation similar to the exposure of the patients.

DOSIMETERS

Extruded lithium fluoride dosimeters[2] (1.4×1.4×7 mm) were used to make all measurements within the phantom. These dosimeters are well suited for this application because of their small size, energy independence, approximately tissue equivalence, sensitivity, reusability, and ease of handling. They have a linear response from 10^{-2} to 10^{3} rads and a slightly

[2]Dosimeter available from Harshaw Chemical Company, Cleveland, Ohio.

...ralinear response from 10^3 to about ...10^5 rads when radiation damage becomes a limiting factor. In our laboratory we found the response of freshly calibrated dosimeters to be reproducible with a standard deviation of the order of 1-2% when exposed under calibration conditions. Repeated measurements in the same position in the phantom rarely disagree by more than 5%. We have previously reported details for calibrating, annealing (processing for reuse), and analyzing these dosimeters (ref. 7).

MARROW DOSE CALCULATIONS

Since the active marrow is not uniformly distributed within the body in a simple, well-defined volume, it was necessary to know the spatial distribution of the marrow to determine average marrow dose. The distribution of active marrow for normal adults as estimated by Ellis (ref. 8) is expressed as the percent of the total amount located in a particular anatomical marrow compartment, e.g., the ribs or skull. The distribution of the dosimeters in the marrow compartments defined by Ellis was not proportionate to the amount of marrow therein. For example, 19% of the 137 dosimeters were located in ribs which contained only about 8% of the total active marrow. Therefore, average total dose to marrow had to be calculated by first determining the average dose for a specific compartment and then using its percentage of total marrow as a weighting factor. Table 2 lists the average compartment dose and its range per 100 R of exposure from each of the three irradiators. Table 3 summarizes the average marrow dose calculations.

The compartment dose estimates in Table 2 indicate that the marrow dose distribution is different in each of these irradiators. The most unexpected result is that the LETBI ^{60}Co gamma irradiator produces a smaller marrow dose than the METBI ^{137}Cs gamma irradiator. The other irradiator (VDRIF) produces the largest marrow dose as would be expected on the basis of relative penetrability of the gamma rays involved. This apparent paradox between the LETBI and METBI doses can be explained only on the basis of the distance the radiation travels in the body to the deep-seated marrow sites. In the VDRIF about 80% of the radiation is incident at 90° to the long axis of the body and passes through the body's least thickness, the anterior-posterior diameter. This geometry provides the minimum radiation-path length to all marrow sites and therefore the largest average depth dose.

In the METBI facility the ^{137}Cs gamma rays are incident on the body's long axis at angles from 78-90° and they penetrate the body at an angle of approximately 30° to its larger lateral (side to side) diameter. The average length of radiation path in this geometry, somewhat greater than in the VDRIF, and the lower energy radiation explain the smaller marrow dose from the METBI exposures. However, other depth dose studies (refs. 9 and 10) have shown a less than 5% difference in average marrow dose from ^{137}Cs and ^{60}Co gamma rays under equal exposure geometries.

In the LETBI the exposure geometry is complicated by the patient's freedom to move about the large exposure room. We have calculated the angle of incidence for two typical positions of the patient; when he is standing near the room center, the average angle of incidence is about 70°; lying on the bed, the average angle of incidence is only about 25°. If we make the assumption that the average angle of incidence is the average for these two positions, or about 45°, then by simple geometry the length of the radiation path is 40% greater in this geometry than it would be for radiation incident at 90°. Because of this geometry, the LETBI average marrow dose is the lowest of the three irradiators studied.

The large dependence of average marrow dose on the angle of incidence of radiation

is shown also by the study of Clifford (ref. 11), who measured this average dose in a rotating phantom first exposed at 90° and then at several angles down to 15° with the long axis of the body. Radiation energies of 60, 100, 212, and 660 keV were used. His results indicate that average dose to the marrow is reduced by a factor of two for exposures at 15° compared with 90° for all radiation energies. In addition, he also shows that marrow dose for 90° exposures varies by only about ±10% over the energy range from 60 to 660 keV and is maximum at about 100 keV.

Since the LETBI and METBI facilities produce essentially omnidirectional fields, we can compare the marrow dose estimates in LETBI of 0.59 and METBI of 0.64 rads/R with that predicted from Clifford's measurements (integrated over the angular region of 0° to 90°) of 0.62 rads/R. This agreement is surprisingly good considering that his estimates were based on measurements in only eight positions in his phantom and were primarily intended for evaluation of potential hazards of radiations from atomic weapons for civil defence planning.

The International Commission on Radiological Protection (ICRP) (ref. 12) has defined the active marrow dose as the appropriate radiation criterion for relating not only short-term hematopoietic effects but also certain late somatic biological effects to radiation exposures. To simplify its calculations to estimate marrow dose, the ICRP determined that the active marrow is located at an average depth of 5 cm. To test the validity of this simplification, we determined the average 5-cm dose to the phantom in each of the three irradiators. The circumferential 5-cm depth line was defined in each of the 34 phantom sections and divided by radii at every 30°. The depth dose at the intercepts of the radii and the 5-cm depth line was determined by interpolation of the depth-dose data obtained from dosimeters located in surrounding grid positions. These were averaged for each section and then weighted by the mass of the section to obtain the overall average 5-cm depth dose. The comparisons of these dose estimates with the average marrow doses are shown in Table 4.

These data indicate that the 5-cm dose approximates the average marrow dose quite closely in the ^{137}Cs gamma-ray field (METBI) and the high-flux ^{60}Co gamma-ray field (VDRIF) where the incident radiation is principally at right angles to the stationary body. The agreement, while adequate, is not as good for the low-exposure-rate cobalt irradiator (LETBI) where the incident radiation is from both above and below a standing patient and where the angles change as the patient sits down, reclines, or walks about, changing his geometric relationship to each source.

These results also suggest that a dosimeter, capable of indicating simultaneously dose rate and total accumulated dose, located in the center of a 5-cm radius sphere of tissue-equivalent material could be used to approximate the astronaut's average marrow dose received during space flight. The dose-rate signal from this dosimeter could also be used to indicate when maximum shielding from unidirectional exposures, such as solar flares, is needed and to indicate what vehicle orientation provides the maximum shielding.

This study also shows clearly that average dose to the marrow is strongly dependent on the length of the radiation path in the body. It is therefore obvious that for equal exposure conditions, a very large person will receive a relatively smaller dose to the marrow than a very small person. To determine how large this variation due to body size will be, we are extending these studies to determine body self-shielding factors for a particular individual rather than the idealized 70-kg man. The exposure rate from a small radioactive source is first measured in air and then at the center point of phantoms of different sizes by a high-sensitivity whole-body

counter containing an array of eight 5×4-in. sodium iodide crystals. The ratio of the counts from within the phantom to the counts in air can be used to indicate the body's self-shielding factor. The results of this study are still incomplete but the feasibility studies indicate that this experimental approach has merit. From these studies we should obtain correction curves relating average marrow dose to self-shielding factor for each of our irradiator geometries and type of source. The self-shielding factor for each individual or patient could then be obtained by having him swallow a less than 1.0-microcurie radioactive source, then counting him in the whole-body counter when the source is located at the center of the patient's body.

Accurate dosimetric information relevant to the biological effects under study are essential for improving the reliability of established human dose-response relations. This is particularly true when the effects considered are the changes in peripheral blood-cell levels. These studies are limited to medical exposures because changes in the blood-cell levels are related to the preirradiation levels. For these reasons, we are seeking to obtain truly adequate dosimetry information from which we can deduce dose-response relations which will aid in space mission planning, management of radiation accident victims, and will improve the usefulness of TBI therapy of disseminated diseases.

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TABLE 1

RADIATION CHARACTERISTICS AND DIMENSIONS OF THREE TOTAL-BODY IRRADIATORS

FACILITY	SOURCES	RADIATION (Gamma)	EXPOSURE VOLUME	EXPOSURE RATE TREATMENT VOLUME	MODE OF EXPOSURE	SOURCE TO CENTER EXPOSURE VOLUME
LETBI	8 ^{60}Co	1.25 MeV	16×16×8' (room)	1.5 R/hr (±10%)	Multilateral	19.5'
METBI	8 ^{137}Cs	0.662 MeV	6×2×1' (above bed)	1.5 R/min (±5%)	Multilateral	5.8'
VDRIF*	5† ^{60}Co	1.25 MeV	6×2×1' (above bed)	40 R/min (±5%)	Bilateral	10' (Sources 3,4) 22.5' (Sources 2,5,6)

*This irradiator belongs to the UT-AEC Agricultural Research Laboratory.
†VDRIF has 6 sources, but only 5 are used during therapy to patients.

TABLE 2

MARROW COMPARTMENT AVERAGE DOSE IN RADS/100 R

	IRRADIATORS					
	LETBI		METBI		VDRIF	
Marrow Compartment	Average Dose	Range	Average Dose	Range	Average Dose	Range
Head	82	73-89	78	71-85	68	61-74
Upper Limb Girdle	69	58-75	66	58-73	78	70-82
Sternum	75	73-77	69	65-71	77	74-77
Ribs	63	46-76	68	62-72	75	70-84
Vertebrae	58	47-75	65	59-80	70	63-78
Sacrum	45	41-46	54	50-56	75	67-83
Lower Limb Girdle	52	44-62	59	52-71	72	63-77

TABLE 3

CALCULATIONS OF AVERAGE BONE-MARROW DOSE IN RADS/100 R

Bone Marrow Compartment	Percent Active Bone Marrow	LETBI Average Dose	LETBI Weighted* Factor	METBI Average Dose	METBI Weighted* Factor	VDRIF Average Dose	VDRIF Weighted* Factor
Head	13.1	82	1074	78	1022	68	891
Upper Limb Girdle	6.4	69	442	66	422	78	499
Sternum	2.3	75	173	69	159	77	177
Ribs	7.9	63	498	68	537	75	593
Vertebrae	28.4	58	1647	65	1846	70	1988
Sacrum	13.9	45	626	54	751	75	1043
Lower Limb Girdle	26.1	52	1357	59	1570	72	1879
Totals	98.1†		5820		6277		7070
Average Weighted Dose‡		59		64		72	

* Weighted factor = average dose × percent bone marrow.
† Average weighted dose = Σ weighted factors ÷ total percent active bone marrow.
‡ Total percent is 98.1 because 1.9% of the marrow is located in the heads of the humeri where no measurements could be made.

TABLE 4

COMPARISON OF ESTIMATED DOSE TO BONE MARROW

WITH AVERAGE BODY DOSE AT 5-cm DEPTH

	Average Active Bone-Marrow Dose (in rads/100 R)	Average 5-cm Depth Dose (in rads/100 R)	Ratio $\frac{\text{5-cm Depth Dose}}{\text{Marrow Dose}}$
LETBI	59	68	1.15
METBI	64	66	1.03
VDRIF	72	73	1.01

LEGENDS

Figure 1.—Cutaway drawing of the low-exposure-rate total-body irradiation facility (LETBI) showing:

(A) Centrally positioned radiation exposure/living room.

(B) Concrete shielded radiation containment room.

(D) The remote control room for operation of the ^{60}Co sources (only sources No. 1,2,5,6,7, C and F are shown), radiation exposure level supervision, nursing and physiologic surveilance of the patient.

(E) The on-line and data processing room.

Figure 2.—Cutaway model of the medium-exposure-rate total-body irradiation facility (METBI).

Figure 3.—Floor plan of the University of Tennessee-Atomic Energy Commission (UT-AEC) Agricultural Research Laboratory Variable Dose Rate Irradiation Facility (VDRIF). Source positions are indicated by No. 1-6.

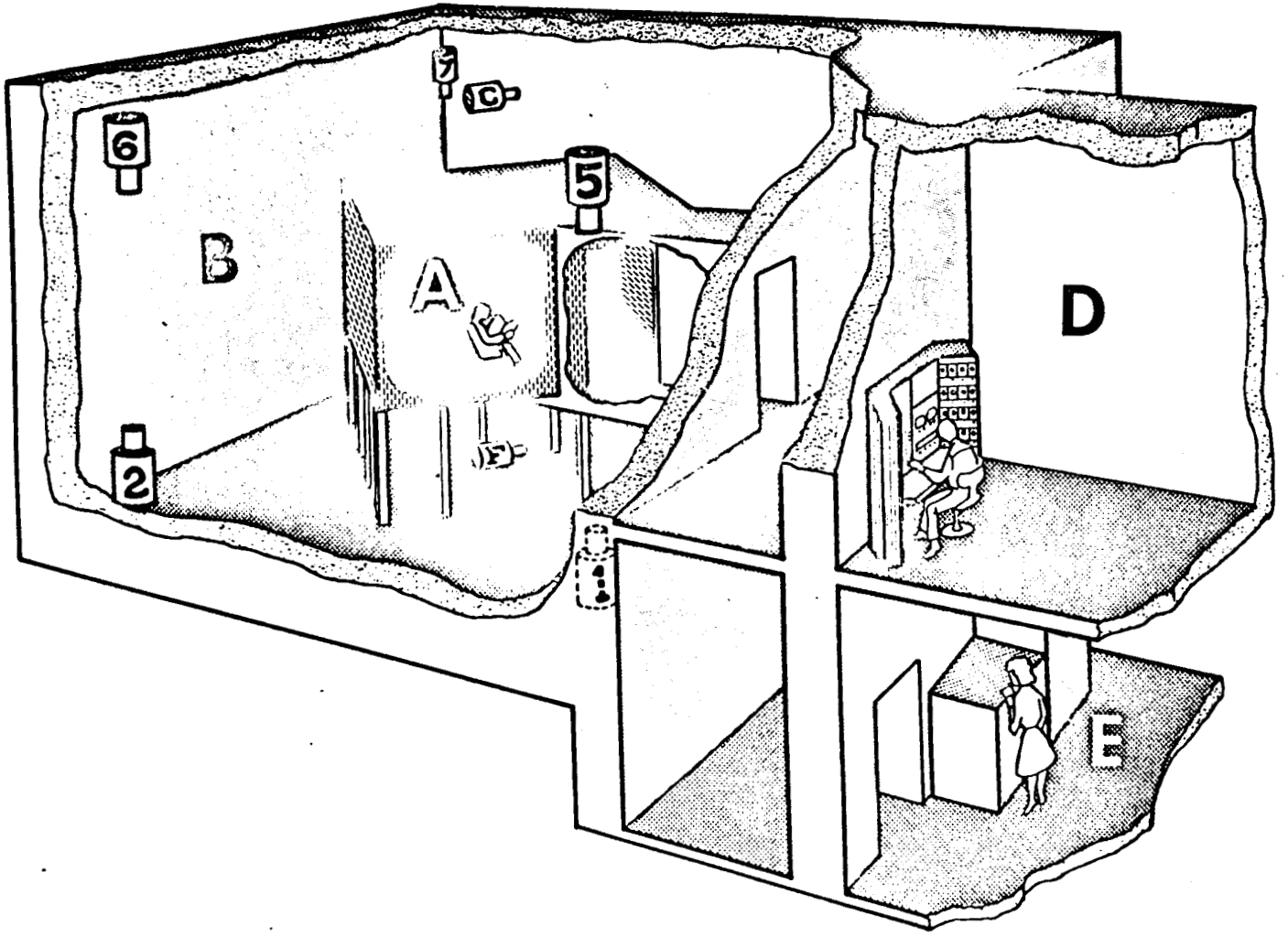


Fig. 1

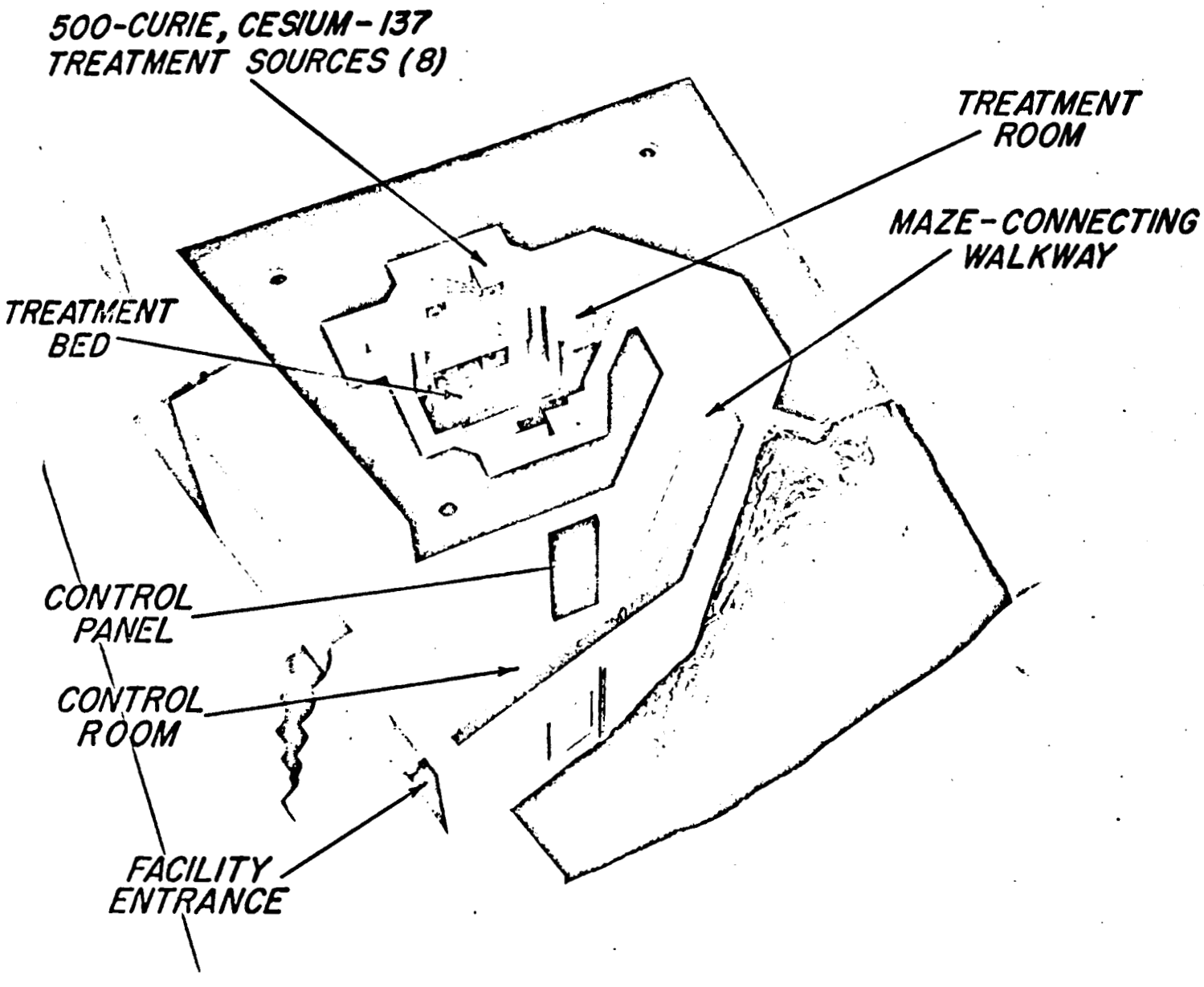
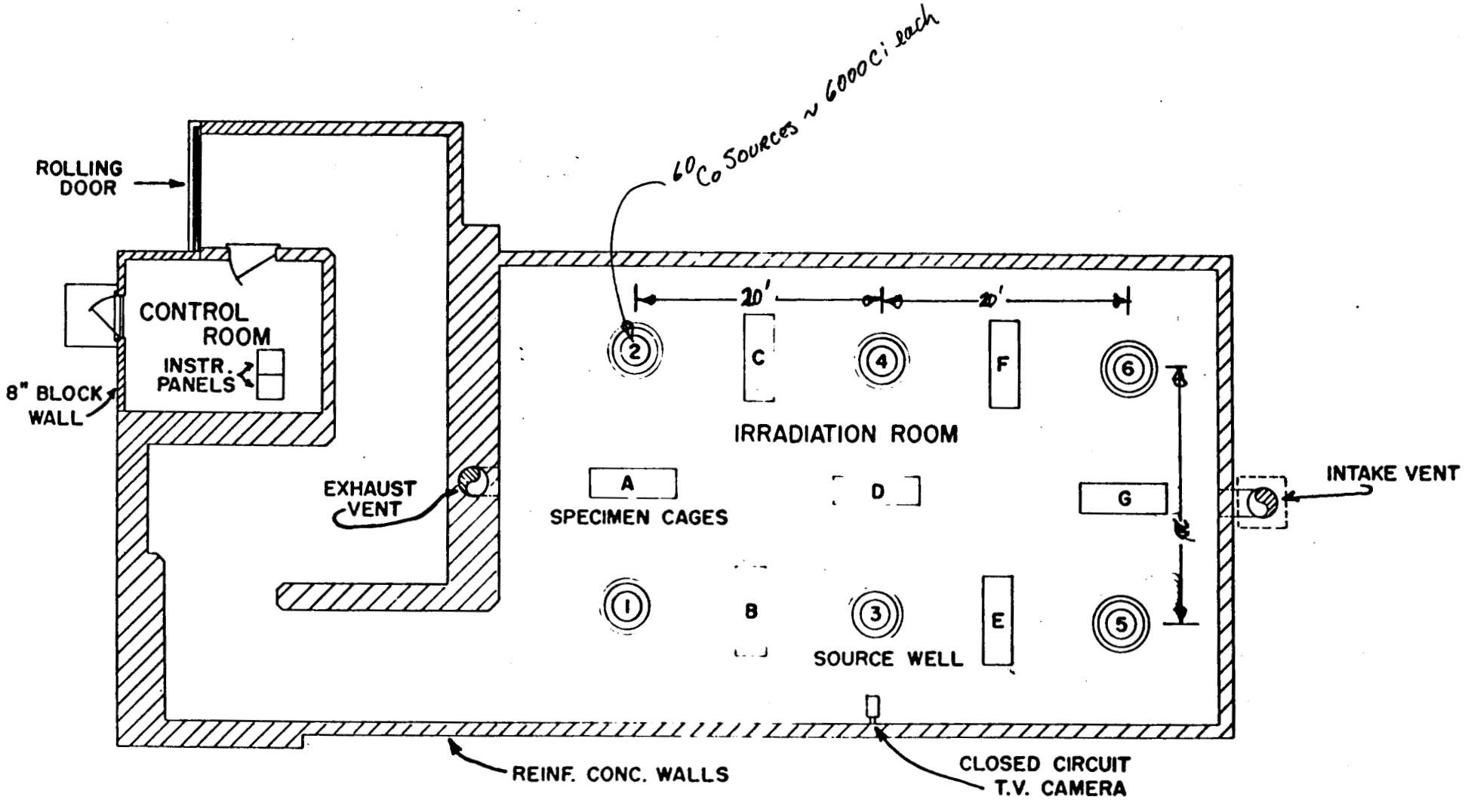

500-CURIE, CESIUM-137
TREATMENT SOURCES (8)
TREATMENT ROOM
MAZE-CONNECTING WALKWAY
TREATMENT BED
CONTROL PANEL
CONTROL ROOM
FACILITY ENTRANCE

Fig. 1



VARIABLE DOSE RATE FACILITY —— FLOOR PLAN

Fig. 3

Acupuncture Experience Proves 'Weird' To Westerner

Copley News Service

SAN DIEGO, Calif. — It sure is weird, getting punctured by an acupuncturist.

The doctor was "in," I could tell as soon as I came up the hedge-bordered walk leading from a busy main street in San Diego to his office. There were patients sitting everywhere in the waiting room — a young Chinese girl perched on a table, men and women of all ages on chairs, a middle-aged man with a hawk-like face massaging his swollen, arthritic joints, a black-haired, pretty woman who, I learned later, had multiple sclerosis complicated by bursitis.

All of them had come for the acupuncture treatments offered by Dr. Tomson Liang, an electronics engineer with a Ph.D. who studied acupuncture in Taiwan and who is a highly respected minister for the local Mandarin Church. Liang is thin and bespectacled, a man with a somber, sometimes smiling face who speaks broken English. He first learned acupuncture in China, before fleeing when the Communists swept into control.

Liang is one of a handful of accredited acupuncturists in the nation. There are hundreds, perhaps thousands of black market acupuncturists around now, but few who are as studied in this exotic science as Liang. People, lured by the new interest in acupuncture that is sweeping the country, come to visit him from all over the country, having heard about him from some mysterious grapevine.

("The nerve ends in your body carry current," Liang was to say, trying to calm your strung-out nerves as you thought of that inch-long needle being stuck into your body. "Sometimes your body is out of balance, the current is not carried correctly. My needle balances it again.")

Acupuncture is big news these days, with everyone

Copley Photo

The Theory And The Practice

. . . Dr. Tomson Liang demonstrates his ancient art

are cured and pain relieved by the insertion of needles into various parts of the body.

"Some people say it's very good," said David Adest, 57, who had come to Liang complaining of low back pains. "But I haven't seen any results yet. Of course, I've only had one treatment so far. I thought I had some relief for a while, but then it went away."

Adest's comment reminded you of what a Los Angeles acupuncture patient had said, "These people who go in for acupuncture are a bunch of health nuts.

"I'll come in a few more times, but if I don't have any help by then, I'm not coming back."

Liang is a surprise. You've heard of the black market acupuncturists around the country, the ones who know almost nothing about the science but who charge $50 a visit for sticking a few needles into you. But Liang charges nothing.

"I'd like to find a rich American," says Liang, smiling. "Someone who would put up enough money so I could set up a research institute to really study acupuncture."

Liang is an electronics engineer at the Hughes aircraft plant in Oceanside, Calif. He holds a degree in acupuncture from the Chinese Acupuncture and Moxabustion Society in Taiwan. He is calm, casual and professional at the same time.

"Will it hurt?" you ask.

Liang inserts the needle into the fleshy part of the skin between the thumb and the forefinger. There is no blood. Liang has massaged the area and this, it is said, moves the small blood vessels out of the way.

"This is called the Tiger's Mouth," Dr. Liang says. It is where the needle is inserted in people who have never had acupuncture before and must learn what such an insertion is like.

"This point can be used for numbing the mouth for dental work or for relieving headaches, says Liang, inserting the needle a little further. So far you have felt nothing.

Liang continues to insert the needle, centimeter by centimeter. You have felt nothing — and then, there is a small, dull ache in your hand.

"Ouch," you say, afraid that something vital has been hit.

"Ah," says Liang. "You feel something?"

"Yes," you say.

Evidently this is good. Liang smiles again and begins twirling the needle.

The ache continues and has a strange effect. You become exceptionally calm and relaxed and a little light-headed. The feeling will last for four hours.

The needle has gone an inch into your hand. Liang withdraws it. You leave, feeling humble before the mysterious art of acupuncture.

(YOU REMEMBER what Zsa Zsa Gabor had said after her acupuncture treatment. She'd fallen off a horse and her arm was paralyzed, so she went to a Los Angeles acupuncturist that actor Lorne Greene recommended.

("In two days I forgot which arm was sick," said Miss Gabor with a star-studded smile.)

Outside, in the waiting room, an elderly patient tells you how arthritis had so crippled him that he couldn't even crawl.

"After the first treatment," says Frederick Sosath, 82, in a deep German accent, "I could walk." Sosath seems very happy and confident. His swollen joints don't seem to bother him.

"He doesn't charge a fee," says Esster Barnhart, the wife of another patient. "But people usually donate. He (Sosath) gives $50 a treatment."

"My hearing was gone," says Tom Barnhart. "It was the result of nerve degeneration.

"I also had arthritis. I've had only one treatment, but I feel better.

"You'll do anything to get your hearing back."

Liang's patients are very defensive about him. They point out that he only sees patients on Sunday and sees only 20 to 30 patients on that day.

"He's a good man," they say.

You leave the waiting room and go outside into a brisk, blue clear California day.

YOU REALIZE that a lot of people have gotten results with acupuncture, and you feel good for them. You are glad that Liang will accept any patient, and they do not have to pay (though they must be referred by a physician so Liang will not get sued for practicing medicine without a license.)

You feel sorry for all those people who go to the black market acupuncturists and who pay a lot of money for this ancient, strange, powerful medicine and science that few American physicians are ready to accept or reject completely, the old Chinese art of acupuncture.

Movies Popular

BONN — In the past five years more than a million

Toll On Farms

CHICAGO (AP) — Accidents in 1971 killed more than 6500 farm and ranch

MEASUREMENT OF THE DOSE ABSORBED IN VARIOUS ORGANS AS A FUNCTION OF THE EXTERNAL GAMMA RAY EXPOSURE

A. R. JONES

ABSTRACT

An average man phantom, containing all bones of the head and trunk, was irradiated from in front, behind and rotationally with gamma rays of various energies.

The exposures at sites within and on the surface of the phantom were measured with lithium fluoride dosimeters. Also the exposures at the same points in space were similarly measured in the absence of a phantom. Among sites chosen were the gonads, representative points in the red bone marrow and the usual film badge positions.

From the measured ratio of the internal and external exposure the absorbed dose at important sites was computed as a function of external exposure for gamma rays of varying energy and direction.

Chalk River, Ontario

October 1964

AECL-2240

A.R. Jones, Title, AECL-2240 Chalk River, Ontario (1964)

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1. INTRODUCTION

In radiation protection of workers, the dose absorbed in various organs from external gamma rays is generally estimated from measurements of the exposure. The latter is measured either with a survey meter before a working area is occupied or by a dosimeter worn on the front surface of the trunk. When a dosimeter is worn, it measures both the incident exposure and additional radiation scattered by the body but, as the survey meter is normally held at arm's length, it measures the incident exposure only.

The absorbed dose, D_n, in any organ may be expressed in terms of the incident exposure, E, in the following way:-

$$D_n = S_n A_n a_n E$$

where S_n is a scattering factor,

where A_n is an attenuation factor,

where a_n is the rads/roentgen conversion factor. S_n and A_n depend upon the location and depth of the site at which the dose is absorbed and the energy and direction of the incident photons. The factor, a_n, depends upon the atomic composition of the tissue at the site and the energy of the photons passing through it.

In practice, the product $S_n A_n a_n$ is often assumed to be approximately one over a wide range of irradiation conditions for the organs referred to in the I.C.R.P. recommendations[1]. It is the purpose of the measurements reported here to assess the extent to which this approximation is justified and the size of the corrections needed. The quantity measured was the product $S_n A_n$ and the factor, a_n was taken from published sources[2,3].

Two previous measurements have been made of this factor for particular conditions of irradiation. Spiers and Overton[4] measured the attenuation and scattering in a water phantom which was irradiated omnidirectionally at three gamma ray energies (0.38, 0.8 and 2 MeV). Carruthers and Wilson[5] used a rotating phantom to measure the same quantity for sites in a thoracic vertebra and the sternum.

2. MEASUREMENT TECHNIQUE

In order to measure the product, $S_n A_n$, for a particular site and under chosen radiation conditions, the exposure was first measured in free space and then within, or on, the phantom at the chosen site. The product $S_n A_n$ was then equal to the ratio of the two measurements.

The dosimetric system, lithium fluoride, was chosen on the following grounds: (1) exposure as low as a few roentgens can be measured with adequate reprodubility; (2) the dosimeters are small enough (5 mm dia. x 19 mm long) to be inserted without interference with the photon flux; (3) the energy dependence is quite small.

The phantom, of commercial origin, is illustrated in Plate I. It satisfied the requirements of this series of measurements since its composition matches a muscle-fat mixture both with respect to effective atomic number and density. The lungs are similarly matched and a full set of bones for trunk and head are included. The phantom is sliced into thirty-four transverse slabs, 2.5 cm thick. The dosimeter sites are listed in Table I.

The distance from the source to the centre of the phantom was either 2 or 2.5 metres. The source was at the same height as the centre of the phantom (seventh thoracic vertebra) which was about 49 cm from the crown of the head. Square-law corrections were made for variations in the exposure rate at the phantom centre, and at the fifteen chosen sites.

Photon energies used, extended from 25 keV to 1.25 MeV and the energy and nature of each source is shown in Table II.

With each photon source, four irradiations were done. The phantom was irradiated from in front and behind and while rotating about the vertical axis. In addition, a calibration dosimeter was irradiated when mounted at the same point in space as that occupied by the centre of the phantom while under irradiation.

The product of the scattering and attenuation factors, $S_n A_n$, was computed from these results by dividing the dosimeter reading, at a particular site in the phantom, by the reading of the dosimeter in free air. The dosimeter readings were also divided by the reading of the dosimeter worn at the film badge site. Thus, the absorbed dose could be expressed either in terms of the exposure in free air or of the exposure to the film badge site. In order to calculate the average bone marrow dose, the doses at each bone marrow site listed in Table I were averaged by weighting them according to the marrow fraction located at each site[4,5].

It should be noted that, since square law corrections were made, the results are directly applicable to distant sources with no collimation. Since workers are generally clothed and sources may be both distant and thick, it was assumed, to be on the safe side, that no "skin sparing" occurs.

TABLE I

Site Number	Description	Distance from front surface	Distance from back surface
1	Brain	3 cm	16 cm 5-20
2	Eye (lens)	0.5 cm	18
3	Cranium (occipital pole) Marrow 1	18	2
4	Sternum Marrow 2	2	20
5	Scapula Marrow 3	12	4
6	Sixth Thoracic Vertebra Marrow 4	15	7
7	2nd Lumbar Vertebra Marrow 5	13	8
8	Gut Mucosal Layer	3 cm	18 cm
9	Sacrum Marrow 6	15	7
10	Iliac Crest Marrow 7	8	12
11	Ovaries	10 cm	11 cm
12	Testes	2 cm	indeterminate
13	Skin (Forehead)	0	20
14	Skin, chest front at height of seventh Thoracic Vertebra.	0	22
15	Skin, chest back at height of seventh Thoracic Vertebra.	22	0

Marrow

TABLE II

PHOTON SOURCES

Effective Energy	Nature of Source
1.24 MeV	Co^{60} γ Source. Two close energies.
660 keV	Cs^{137} γ Source. Single energy.
400 keV	Ir^{192} γ Source. Many energies mostly between 300 and 500 keV.
240 keV	Filtered Bremsstrahlung. Narrow Band of energies.
165	Filtered Bremsstrahlung. Narrow Band of energies.
125	Filtered Bremsstrahlung. Narrow Band of energies.
100	Filtered Bremsstrahlung and characteristic X-rays from Uranium. Narrow Band of Energies.
75	Filtered Bremsstrahlung and characteristic X-rays from Lead. Narrow Band of Energies.
63	Filtered Bremsstrahlung and characteristic X-rays from Tantalum. Narrow Band of Energies.
38	Filtered Bremsstrahlung and characteristic X-rays from Neodymium. Narrow Band of Energies.
27	Filtered Bremsstrahlung and characteristic X-rays from Tin. Narrow Band of Energies.

3. DISCUSSION OF THE RESULTS

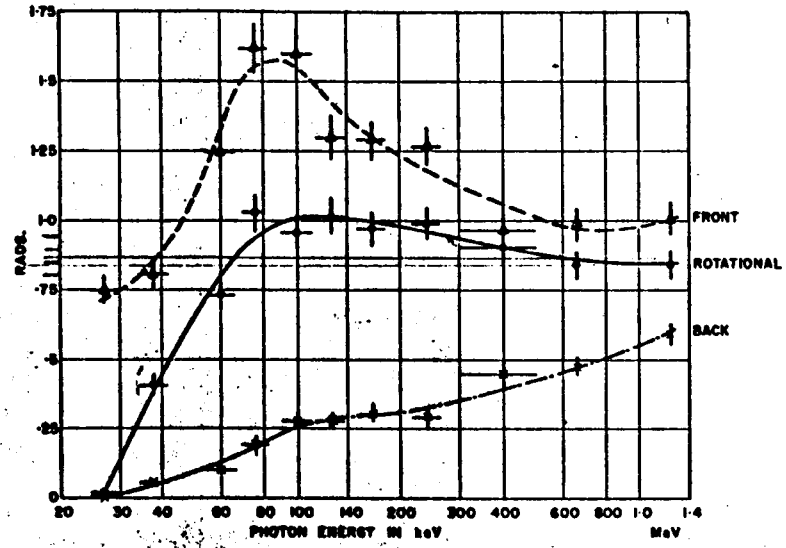
The results, in the form of dose exposure ratios, (exposure measured both in free air and at the front of the chest) for nine points or regions in the phantom, under various irradiation conditions, are tabulated in the appendix. In addition, the more important of these results are illustrated in Figures 1-11. Figures 1-6 show the absorbed dose, as a function of external exposure for the eye (lens), skin (front of chest), gut mucosa, testes, ovaries and bone marrow. Figures 7-11 show the dose absorbed in the eye (lens), skin (back of chest), testes, ovaries and bone marrow as a function of the exposure at the film badge site.

Considering first the absorbed doses as a function of free air exposure (Figures 1-6), the following general characteristics can be noted. Between 0.1 and 1.25 MeV the dose/exposure ratio does not vary by more than 2:1 for any direction of irradiation. The highest values of absorbed dose (0.5 - 1.0 rads/roentgen) occur at higher energies and at about 0.1 MeV, where the build-up due to scattering often more than compensates for attenuation. The lowest doses are absorbed at low energies below 50 keV and, generally, at an intermediate energy between 200 and 700 keV. The dose absorbed in rotational irradiation is usually intermediate between that for front or back irradiation. However, this is not true for the ovaries (Figure 5), presumably because they are located near the centre line of the trunk where it is wider than it is deep.

The largest dose is that absorbed in the gut mucosa (Figure 3) when irradiated from the front at about 80 keV. It is about twice the external exposure or the dose absorbed in the bone marrow. The average dose (about 0.8 rads/roentgen) absorbed in the bone marrow is not critically dependent on direction or the energy of X-rays for energies above 0.1 MeV.

Considering next the absorbed dose as a function of exposure to the film badge site, the following can be observed. The dose absorbed in tissue near the front surface is close to the exposure at the film badge site regardless of the direction or energy of the γ-rays for energies above 60 keV, (e.g. the dose to the lens of the eye is within 50 per cent of the film badge exposure for these conditions). This is certainly not the case for deep sites, e.g. the film badge exposure underestimated the marrow dose (Figure 11) for back irradiation by a factor of six at 80 keV and overestimated it by two for front irradiation. These factors are even larger for doses absorbed in the skin of the back (Figure 8). The dose/exposure ratios for all sites and energies above 0.11 MeV are between 0.6 and 1.1 rads/roentgen when the phantom is rotationally irradiated.

FIG. 1
DOSE ABSORBED IN THE EYE LENS
FOR ONE ROENTGEN OF FREE AIR EXPOSURE



87 1/2
84 1/2

FIG. 2
DOSE ABSORBED IN SKIN (CHEST, FRONT)
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

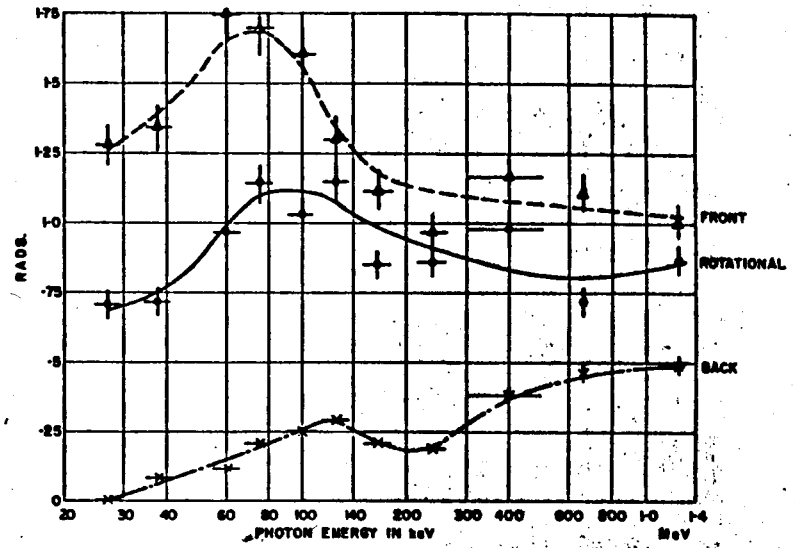


FIG. 3
DOSE ABSORBED IN GUT MUCOSA
FOR ONE ROENTGEN OF FREE-AIR EXPOSURE

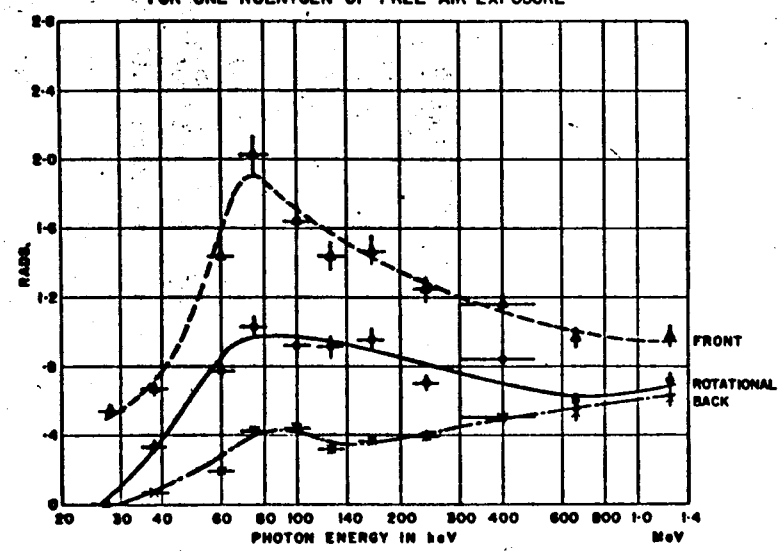


FIG. 4
DOSE ABSORBED IN TESTES
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

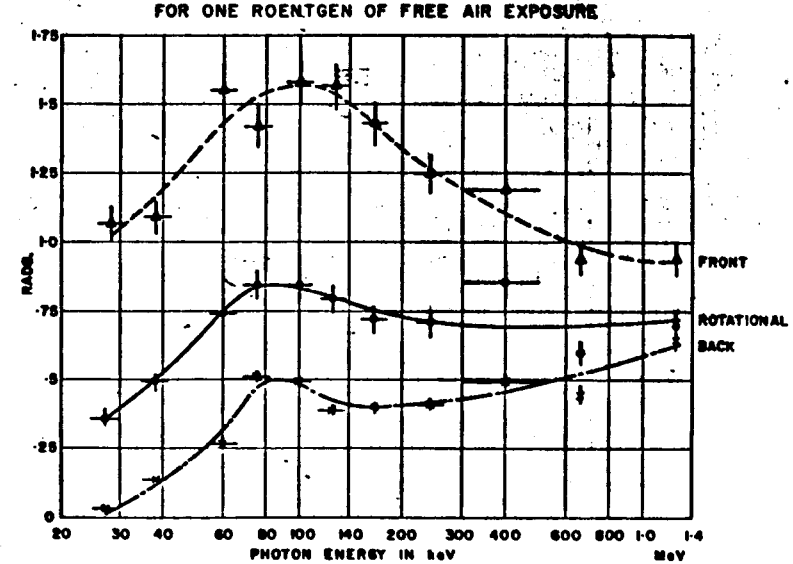


FIG. 1
DOSE ABSORBED IN THE EYE LENS
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

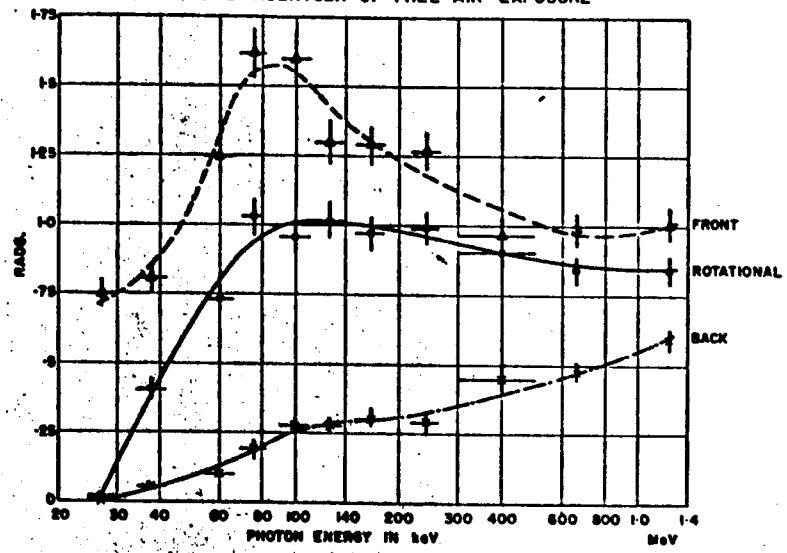


FIG. 2
DOSE ABSORBED IN SKIN (CHEST, FRONT)
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

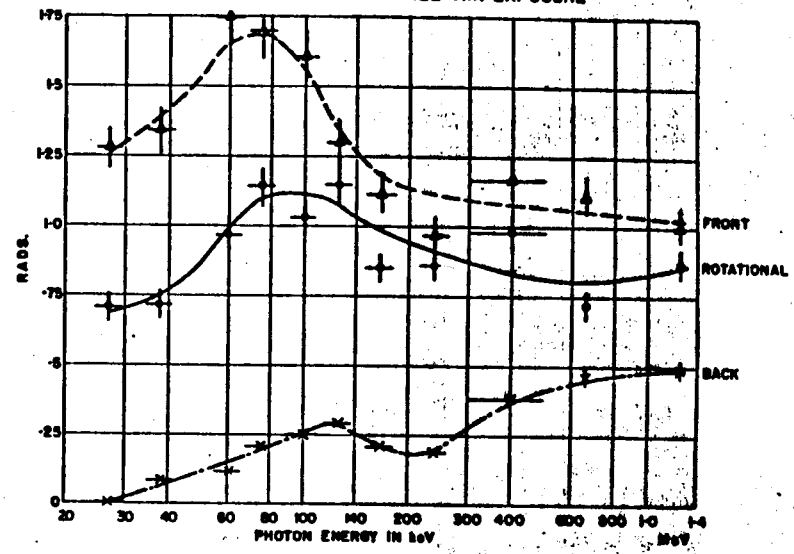


FIG. 3
DOSE ABSORBED IN GUT MUCOSA
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

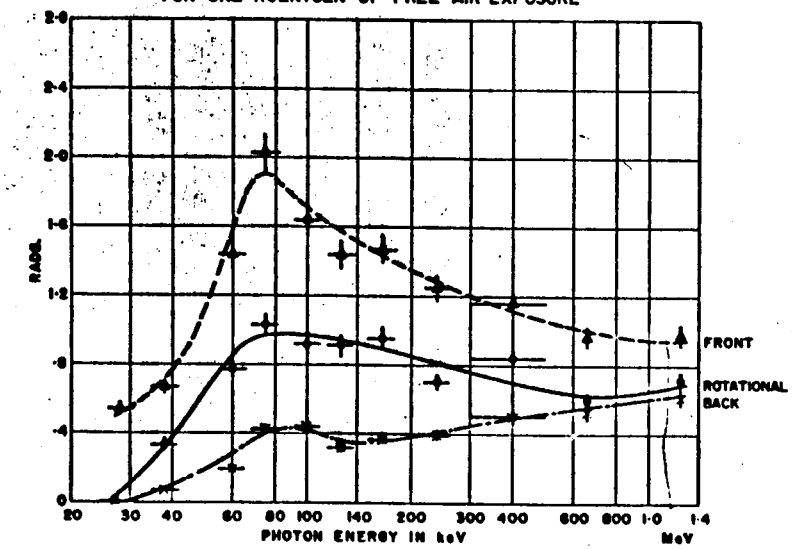


FIG. 4
DOSE ABSORBED IN TESTES
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

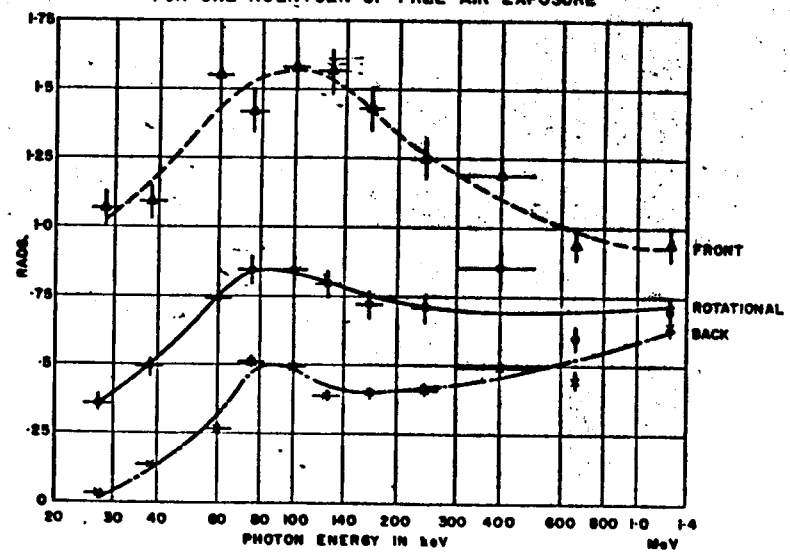


FIG. 5
DOSE ABSORBED IN OVARIES
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

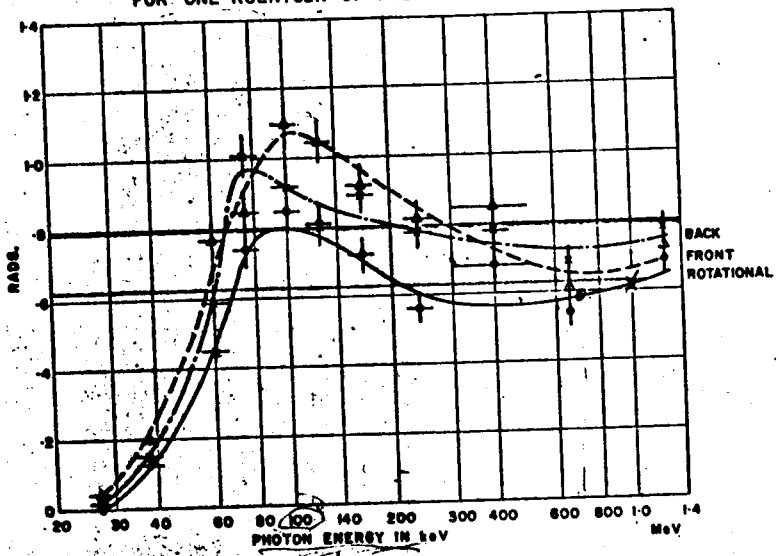


FIG. 6
DOSE ABSORBED IN BONE MARROW
FOR ONE ROENTGEN OF FREE AIR EXPOSURE

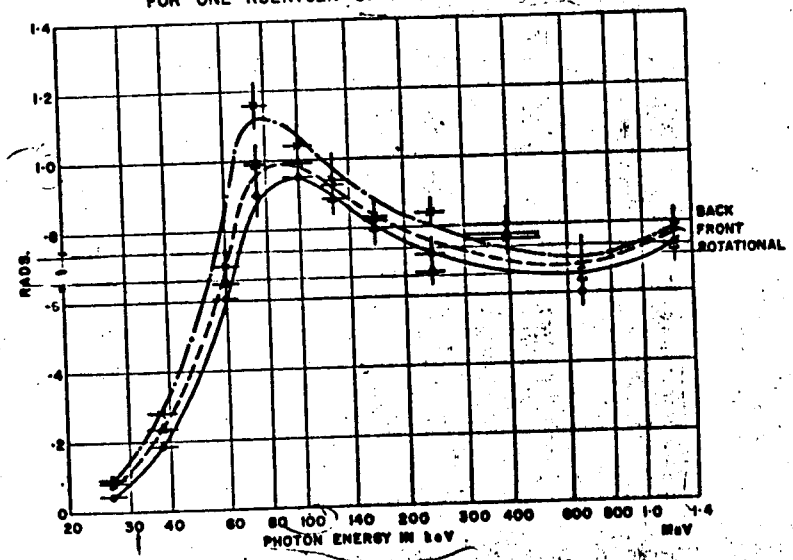


FIG. 7
DOSE ABSORBED IN THE EYE LENS
FOR ONE ROENTGEN EXPOSURE TO FILM BADGE

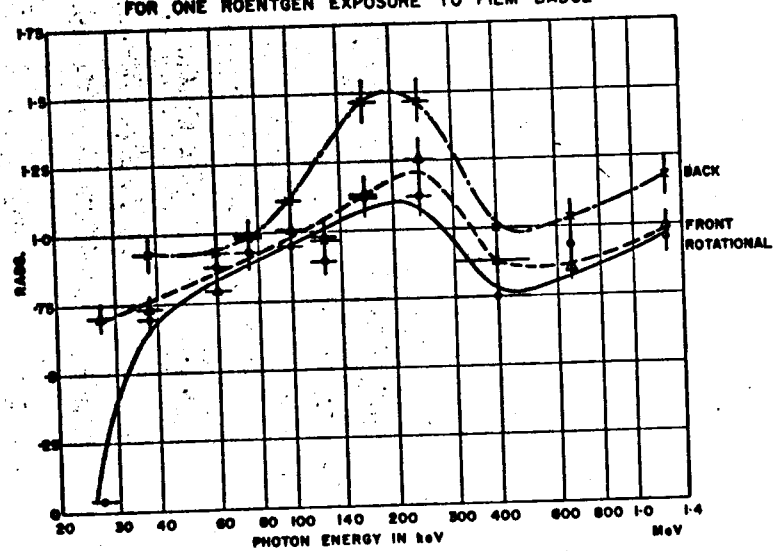


FIG. 8
DOSE ABSORBED IN THE SKIN OF THE BACK
FOR ONE ROENTGEN EXPOSURE TO FILM BADGE

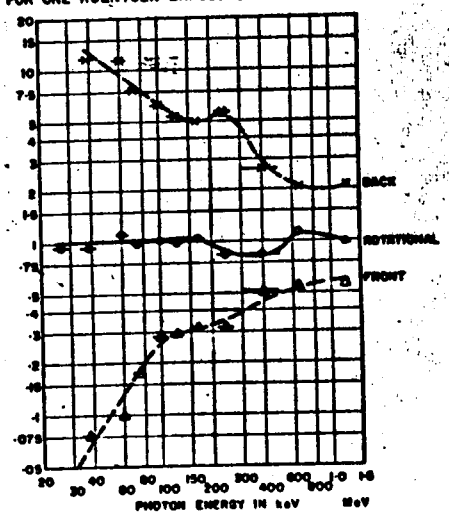


FIG. 9
DOSE ABSORBED IN TESTES
FOR ONE ROENTGEN EXPOSURE TO FILM BADGE

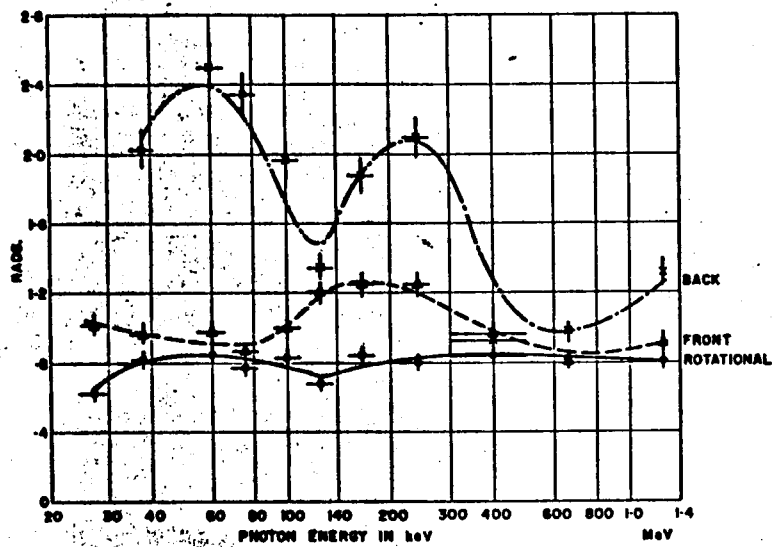


FIG. 10
DOSE ABSORBED IN GUT MUCOSA
FOR ONE ROENTGEN EXPOSURE TO FILM BADGE

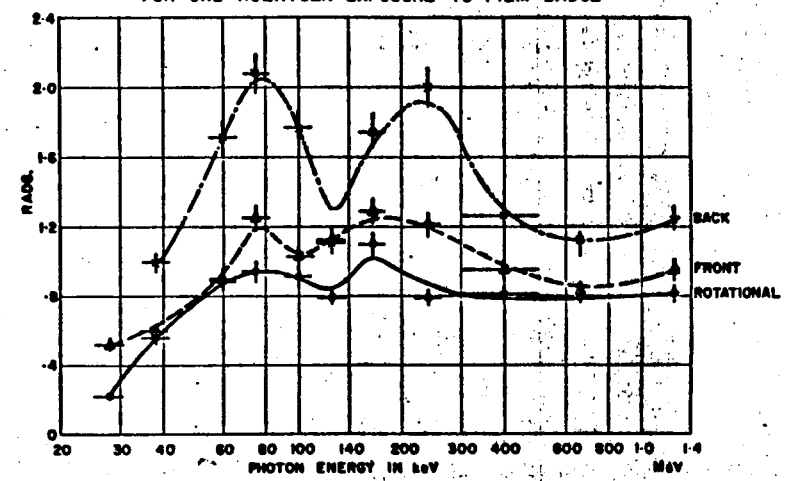
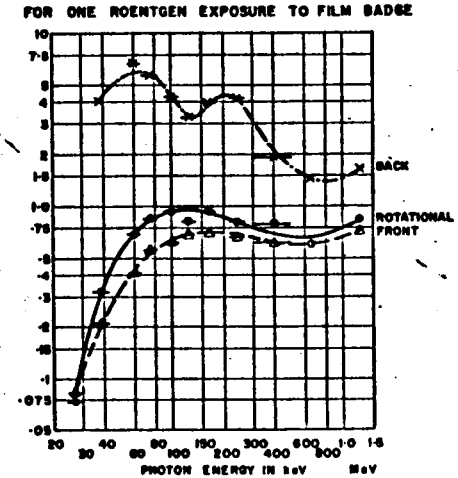


FIG. 11
DOSE ABSORBED IN BONE MARROW
FOR ONE ROENTGEN EXPOSURE TO FILM BADGE



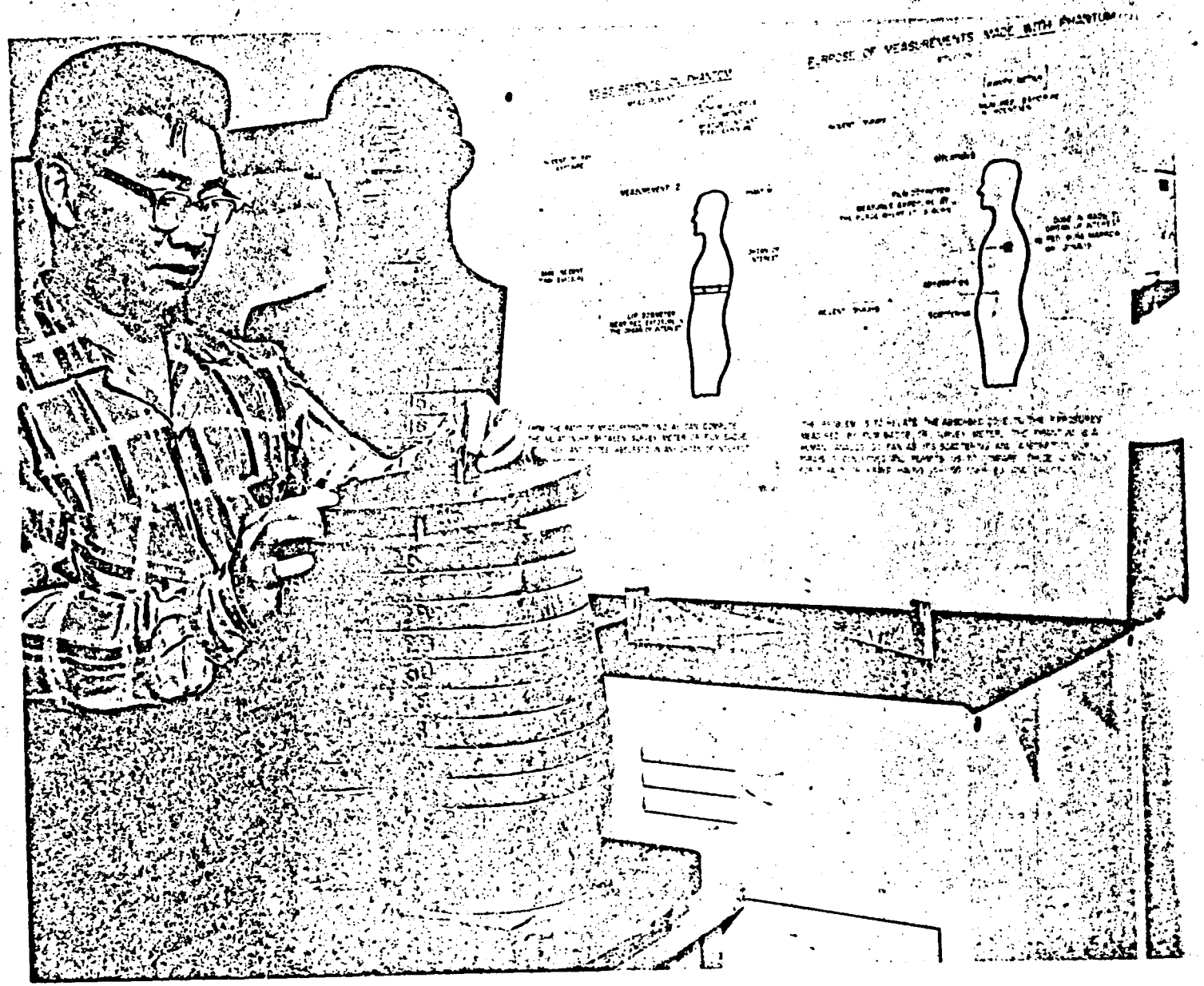


Plate I A Lithium Fluoride Dosimeter being inserted into the Phantom.

APPLICATION

The results may be used to estimate the dose absorbed in various organs and sites of the body if the exposure and conditions of exposure are known. The exposure can be measured either with a survey meter in free air or by a dosimeter worn at the usual film badge site. The direction(s) and energy(ies) of the γ-rays must be known.

Measurements were made of the dose to the skin of the forehead and at the back of the chest (see appendix). By dividing the dosimeter readings obtained at these two sites into those obtained at others, the dose in various organs can be expressed in terms of the exposure to a film badge worn at either the forehead or the back of the chest. It is clear that wearing dosimeters at more than one site could provide information about the direction of the incident γ or X-rays. Any device which gave some estimate of the energy of the radiation would also improve the precision of dose estimation.

Specialized dosimeters, calibrated in absorbed dose in a particular site, when exposed in free air could, in principle, be designed. For example, in a disaster situation where the main interest is survival, it would be useful to have a dosimeter calibrated directly in terms of dose to the blood forming organs (i.e. red marrow). This is a case (see Figure 6) where the dose/exposure ratio is nearly independent of direction and it would therefore be relatively easy to simulate in a detector. In the case of dosimeters designed to measure the genetic dose to populations from the environment, the appropriate curve would be a composite one of that for the ovaries (Figure 5) and testes (Figure 4), suitably modified for the smaller dimensions of children. Averaged over a long period, the exposure could be thought of as rotational.

In the design of film badges, or other personal dosimeters, the objective is a response independent of energy and direction and numerically equal to the exposure. However, the ICRP recommendations[1] refer to the dose equivalent in specified organs. Since the measurements reported have shown that the exposure to the film badge site is not generally numerically equal to the absorbed dose in the organs of interest, it is questionable whether the design objective is the correct one.

ACKNOWLEDGEMENTS

I wish to thank Mr. G. Cowper for his encouragement and support of the work reported here. Also, I wish to thank Mr. A. Ohno for carrying out a tedious and exacting set of measurements and for his assistance in the computations.

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APPENDIX I

Dose absorbed at various sites as a function of the free-air exposure in rads/roentgen.

Energy 1.24 MeV (Co^{60} X-rays)

Site	Direction of Irradiation: Front	Back	Rotational
Brain (Front)	.89	.62	.80
Eye (Lens)	1.01	.59	.84
Skin (Front of Chest)	1.01	.49	.87
Skin (Back of Chest)	.59	1.06	.87
Skin (Forehead)	1.02	.56	.93
Gut Mucosa	.97	.62	.71
Ovaries	.73	.78	.68
Testes	.94	.65	.71
Average Bone Marrow	.73	.79	.74

Energy 660 keV (Cs^{137} X-rays)

Site	Direction of Irradiation: Front	Back	Rotational
Brain (Front)	.77	.49	.58
Eye (Lens)	.99	.48	.84
Skin (Front of Chest)	1.11	.46	.72
Skin (Back of Chest)	.62	1.00	.83
Skin (Forehead)	1.01	.39	.72
Gut Mucoas	.96	.52	.59
Ovaries	.62	.69	.54
Testes	.94	.45	.60
Average Bone Marrow	.65	.68	.60

Energy 400 keV (Iridium^{192} X-rays)

Site	Direction of Irradiation: Front	Back	Rotational
Brain (Front)	.90	.415	.80
Eye (Lens)	.97	.45	.91
Skin (Front of Chest)	1.17	.38	.98
Skin (Back of Chest)	.63	1.06	.86
Skin (Forehead)	1.19	.42	.87
Gut Mucosa	1.16	.50	.84
Ovaries	.85	.78	.68
Testes	1.19	.49	.86
Average Bone Marrow	.77	.76	.80

Energy 240 keV (Filtered Bremsstrahlung)

Site	Direction of Irradiation Front	Back	Rotational
Brain (Front)	1.13	.44	.99
Eye (Lens)	1.27	.29	.99
Skin (Front of Chest)	.97	.19	.86
Skin (Back of Chest)	.34	1.12	.74
Skin (Forehead)	1.30	.17	.90
Gut Mucosa	1.25	.39	.70
Ovaries	.82	.78	.56
Testes	1.25	.41	.71
Average Bone Marrow	.67	.84	.72

Energy 165 keV (Filtered Bremsstrahlung)

Site	Direction of Irradiation Front	Back	Rotational
Brain (Front)	1.07	.38	.93
Eye (Lens)	1.29	.31	.97
Skin (Front of Chest)	1.12	.205	.85
Skin (Back of Chest)	.38	1.07	.91
Skin (Forehead)	1.29	.16	1.06
Gut Mucosa	1.47	.37	.95
Ovaries	.92	.87	.72
Testes	1.43	.40	.72
Average Bone Marrow	.80	.83	.82

Energy 125 keV (Filtered Bremsstrahlung)

Site	Direction of Irradiation Front	Back	Rotational
Brain (Front)	1.27	.33	.91
Eye (Lens)	1.30	.28	1.02
Skin (Front of Chest)	1.30	.29	1.15
Skin (Back of Chest)	.38	1.50	1.14
Skin (Forehead)	1.54	.20	1.02
Gut Mucosa	1.44	.32	.91
Ovaries	1.05	.80	.81
Testes	1.57	.39	.79
Average Bone Marrow	.89	.94	.93

Energy 38 keV (Bremsstrahlung filtered with Neodymium)

Site	Direction of Irradiation Front	Back	Rotational
Brain (Front)	.40	.088	.215
Eye (Lens)	.81	.064	.41
Skin (Front of Chest)	1.34	.084	.72
Skin (Back of Chest)	.086	.98	.55
Skin (Forehead)	1.07	.086	.65
Gut Mucosa	.67	.068	.33
Ovaries	.205	.155	.125
Testes	1.09	.14	.49
Average Bone Marrow	.235	.28	.185

Energy 27 keV (Bremsstrahlung filtered with Tin)

Site	Direction of Irradiation Front	Back	Rotational
Brain (Front)	.079	.014	.03
Eye (Lens)	.75	.012	.022
Skin (Front of Chest)	1.28	undetectable	.71
Skin (Back of Chest)	.023	1.44	.54
Skin (Forehead)	1.18	.007	.47
Gut Mucosa	.54	.002	.013
Ovaries	.047	.017	.008
Testes	1.07	.033	.36
Average Bone Marrow	.089	.082	.043

CONF-670219

Conference on Dosimetry of Total-Body Irradiation by External Photon Beams

Oak Ridge, Tennessee
February 23-24, 1967

United States Atomic Energy Commission
Division of Technical Information

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CONF - 670219
HEALTH AND SAFETY
(TID - 4500)

Conference on Dosimetry of Total-Body Irradiation by External Photon Beams

by
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F. O'Foghludha
F. V. Comas

Oak Ridge Associated Universities
Oak Ridge, Tennessee

DOSIMETRY OF TOTAL-BODY IRRADIATION BY EXTERNAL PHOTON BEAMS

R. J. Cloutier, F. O'Foghludha and F. V. Comas

Introduction

A conference on total-body dosimetry, attended by physicists, radiobiologists, and clinicians* was held at Oak Ridge Associated Universities (ORAU) on February 23 and 24, 1967, under the auspices of the National Aeronautics and Space Administration (NASA)† and ORAU.‡ Its purpose was to review work on total-body irradiation, and if possible to arrive at a consensus on a uniform way of reporting the doses delivered. Discussion was restricted to photon irradiation, with emphasis on the physical rather than on the biological aspects.

Although much of the work had appeared in the open literature, some of it first came to light during the conference. The meetings were informal and as much time was allotted to discussion as to presentation of papers. The authors of the present paper were the organizers and also served as rapporteurs. What follows is their view of what took place; it does not follow exactly the order in which the talks were given. Instead the topics are divided into two groups: I. Methods of irradiation; and II. Measurement and calculation of dose.

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* Appendix I gives the participants and the program.

† The retrospective evaluation was supported conjointly by the USAEC and the Manned Spaceflight Medical Division of the National Aeronautics and Space Administration, NASA Order R-104, Task No. 9 (Interagency Agreement 40-35-64).

‡ Medical Division, Oak Ridge Associated Universities, Oak Ridge, Tennessee, under contract with the United States Atomic Energy Commission.

PART I: METHODS OF IRRADIATION

After a welcome by Andrews and introductory remarks by Cloutier, Lushbaugh stated that the aim of the ORAU survey, undertaken on behalf of NASA, is to establish a quantitative relation between radiation dose and a number of biological responses in man. Retrospective studies on the case histories of all known patients exposed to total-body irradiation, both in the United States and abroad, are under way and future studies are in prospect. Lushbaugh expressed the hope that some uniform method of reporting the dose received by irradiated patients would be agreed upon as a result of the present meeting, and that the method would be widely used in future studies. He described the methods used in seeking out information for the ORAU-NASA survey and stressed that considerable difficulty arose in interpreting records, particularly if the work reported on had been carried out many years ago. No two institutions used the same system of reporting, and many vital items in both dosimetric and medical histories, originally thought to be unimportant, were now irretrievably lost.

He reported that the average dose and the exposure at the midline in the absence of the subject were most frequently used to describe the patient's total-body irradiation. Several other radiation units were also used; the one Lushbaugh favored was what he called "epigastric dose"; that is, the number of rads delivered to the upper abdominal compartment. He pointed out that this quantity was the variable with which the severity of systemic symptoms seemed to be most readily correlated. In replying to a question by Focht, Lushbaugh stated that at ^{137}Cs energies the number of rads delivered to the epigastrium is, in persons of normal size, approximately 0.66 times the exposure (R) that would have existed at the position of the epigastrium if the patient's body were removed.

Another objective of the present study is to change the rather widely held concept that a specified dose level invariably brings about a certain physiological response. Thus, the statement that 200 R would invariably induce vomiting should be replaced by a statement of the probability that 200 R would cause vomiting. Lushbaugh then outlined the system of probit analysis used at ORAU to correlate "go, no-go" phenomena, such as vomiting or diarrhea, with the dose that would induce these effects with a certain probability.

From initial analyses of a limited number of cases, which give remarkably consistent results, it is possible to estimate for any effect E, the dose ED_x that causes the effect to occur with a probability of x percent.

Beck then summarized the material available for analysis. It now consists of about 1800 cases located at 38 institutions (Table I). For the NASA study any number of irradiations given on the same day were considered as one treatment. One or more irradiations given in a period of one week constitute an intermediate group. Multiple irradiations extending beyond one week are considered as a fractionated treatment, and irradiations separated by six weeks or more are considered as separate treatment series. The collaborating institutions, on the other hand, used quite different conventions.

Questions from Shonka and others brought out that most of the ORAU patients had suffered from leukemia or lymphomas but patients from other institutions generally had epithelial neoplasms. It also emerged that some patients had been exposed to more than 1000 R in a single day, although in the vast majority the exposure had been much less.

Typical Total-Body Irradiators

Beck then described the radiation equipment used at collaborating institutions. As a general rule, the older work was done with X-ray equipment not specifically designed for total-body irradiation, whereas the more recent equipment tended to be custom-built and relied predominantly on gamma rays. Only fragmentary dose data existed for patients treated in the 1930's, whereas dosimetric information for patients irradiated in recent years was generally in more detail.

As typical arrangements, Beck chose to describe those at ORAU, Peter Bent Brigham, Mary Imogene Bassett, and City of Hope Hospitals. In the ORAU installation, the early work was done with a ^{60}Co source enclosed in a spherical shield. Most of the patients, however, have been treated in a later irradiator (*1*) with multiple ^{137}Cs sources, providing remarkably uniform exposure over the treatment area (*2*). Exposure rates available were between 0.7 and 2.0 R/min. Results were recorded as midline air exposure, average abdominal dose, or total-body average dose. The City of Hope Hospital in Duarte, California, also has a specially-built installation with eight ^{137}Cs sources. The exposure rates were between 0.02 and 4.7 R/min. Results were given

as "average midplane, midbody dose" (*3*). At the Peter Bent Brigham Hospital, in Boston, Massachusetts, multiple portals were used to cover the whole body. A 250-kV machine was used with an exposure rate of 5.5 R/min; the midbody depth dose was recorded (*4*). The irradiator at the Mary Imogene Bassett Hospital, Cooperstown, New York, consists of two ^{60}Co sources with the patient in between. Exposure rates ranged from 6 to 25 R/min. Both exposure and depth dose at the center of the body were given (*5*).

In the first invited paper, Shalek described the 250-kV X-ray facility used at the M. D. Anderson Hospital during the 1950's for the irradiation of 263 patients. The half-value thickness (HVT) was 3 mm Cu. The patients were placed 275 cm from the X-ray target and irradiated laterally while in a crouched position. The "edges" of the beam (taken to coincide with the 50% isoexposure line in air) enclosed an area of 1200 cm^2, which was large enough to accommodate the crouching patient. After one-half of the exposure had been given, the patient was turned and irradiated from the opposite side. The dose within the patient varied ±20% with the minimum dose at the patient's center. The exposure rate was 3.8 R/min. Both the exposure at midline and the average dose, calculated by one of Mayneord's formulas were reported for all patients (*6*).

At Baylor University in Dallas, West reported that the initial irradiations had been performed with a 220-kV X-ray machine while the patient lay on a stretcher. Half the exposure was given AP and the other half PA. The surface dose was taken as 100% (*7*). The exposure rate was 5 R/min. Later, X rays from a 2-MeV accelerator were used with the patient sitting up in a rotating chair. The dose at the center of the body was calculated to be 68 to 72% of the air exposure. Integral doses were also calculated by Mayneord's equations, correcting for nonuniformity of the beam (*8*).

Hayes presented details of dose measurements carried out at the ORAU irradiator with three anthropomorphic phantoms corresponding to three typical body sizes: a small child, an adolescent, and an adult. The complete isodose distribution (Fig. 1) within the phantom was determined with an ionization probe. In addition, chemical dosimetry was used to measure the average dose to the whole body and for separate body compartments. The integral dose calculated graphically from the isodose lines differed by less than 5% from the values obtained with the chemical dosimeter.

A comparison was also made, with the same phantoms and chemical system, of the average dose in various body

compartments when exposed to radiation from two temporary ^{60}Co irradiators used at ORAU during the early total-body irradiation studies. There was less variation in average dose from one compartment to the other with the eight ^{137}Cs-source facility than with the bilateral ^{60}Co radiation setup (*9*).

Kereiakes reported that the irradiator at the Cincinnati General Hospital consisted of a single ^{60}Co source housed in a teletherapy head. The patient was placed in a sitting position, the lower extremities were raised, and the head was tilted forward. In this way the patient was made to fit within the 50% isoexposure line of the beam. The distance from source to the patient's center was 282 cm. One-half the dose was administered from one side, the patient was rotated, and the remaining dose was given. The exposure rate was 3.5 to 6 R/min at the center of the body, in the absence of the patient. Skin doses were calculated and verified by means of ionization chambers and lithium fluoride dosimeters. Depth-dose measurements in a masonite phantom indicated that dose variation in the trunk of a typical patient was only ±8%. Dosage was expressed as rads at the patient's midline (*10*). More recently, integral doses have been calculated by Mayneord's method. For a given midline dose, the integral dose varies depending upon the patient's lateral dimensions.

Campbell reported that the total-body irradiator at the Manitoba Cancer Treatment and Research Foundation, Winnipeg, Canada, provides a uniform exposure rate (±2.4%) within a cylindrical treatment volume 6 feet high with a base diameter of 8 feet. The uniformity becomes ±4% if the base diameter is increased to 10 feet. The uniform field is produced by six ^{60}Co sources; four of them, positioned at the midplane of the irradiation volume, provide 99% of the exposure; two small sources one above and one below the treatment volume provide the remaining 1% of exposure. The exposure rate is about 0.5 R/min. The facility has not been placed in routine use for patients. Depth-dose measurements in phantoms have not been done (*11*).

Focht described the irradiator that Heublein and Craver used in the 1930's at Memorial Hospital, New York. Since dosimetry was not then very advanced, accurate dose estimates could not be made. Dosage was given at that time in erythema units. On the basis of available information about the X-ray machines (kilovoltage, milliamperage, etc.), Focht has estimated the doses in rads that the patients had received. Although it is difficult to assess the accuracy of the estimates, the data are unique in that they represent

observations for low exposure rates and low-energy radiation, whereas most other work was carried out at higher exposure rates and at higher energies.

Comments

The preceding presentations, together with data from other institutions that were not represented at the meeting, may allow a few generalizations.

1. Several techniques of total-body irradiation have been used. The most common one has been to irradiate the patient with a single beam of X rays generated at about 250 kV. The patient was usually two or three meters from the X-ray tube. The exposure was given AP-PA or from each lateral side of the patient. Dose uniformity within the body was from ±15 to ±30%.

2. Several investigators used the same technique but with ^{60}Co gamma rays or 2000-kV X rays. Dose uniformity within the body was between ±8 and ±15%.

3. Special facilities using eight ^{137}Cs sources gave a dose uniformity within the body comparable to that obtained with opposing beams at about 1-MeV.

4. The exposure rates were generally between 1 and 6 R/min.

5. Dose has been reported in a variety of ways, and many institutions use more than one expression. Exposure (usually at the patient's midline) is by far the most common figure given. Dose estimates in use are (a) midtrunk dose; (b) integral dose; (c) average dose; (d) midplane, midbody dose; (e) skin dose; and (f) epigastric dose.

Evaluation of Reported Dose

Comas, Beck, and Cloutier explained how they attempted to unify the dosimetry of all patients treated with total-body irradiation in the 38 institutions of Table I. The first step was to select dose expressions that would be common to all patients.

Of the available choices, the average total-body dose appeared to be open to the fewest objections and was calculated when sufficient data were available from the

patients' records. Lushbaugh is using this dose expression in current attempts to correlate dose and response.

The midbody dose was also calculated but has the objection that it represents the dose to only a small fraction of the body tissues (see Fig. 1).

Target-organ dose, although an appealing concept, has the drawback that the identity of the organ responsible for a specific biological effect is generally not known and, if known, the organ's dose is difficult to calculate. On the assumption that the prodomal syndrome is related to the dose absorbed in the upper abdomen, "epigastric doses" were computed for those patients on whom enough information was available. Lushbaugh used this dose estimate in his early attempt to correlate dose and response.

Exposure and integral doses were also calculated if data were available. Objections to these dose expressions had been well explained in the report of Sinclair and Cole (*6*): "It is evident that we cannot accurately compare the effects produced in animals and humans, or even in different human beings, by means of either the air dose or the integral dose . . . We would not, for instance, consider that a very large man, placed at the point where 200 R might be measured in air, experiences a much greater effect because the integral dose to his body is much greater than that of a man only half his weight."

In this connection Robinson argued that the average total-body dose could also be misleading. For example, suppose that several kilorads were given to only the foot. Here the average total-body dose might still be hundreds of rads; however, the systemic response would clearly not correlate with the average total-body dose. Others pointed out that concepts applicable in partial-body irradiation were not necessarily transferable to total-body irradiation. O'Foghludha indicated that it would not avoid the issue to give a complete description of the doses at different parts of the body. He said that the phantom studies of Hayes, Oddie, and Brucer (*9*) were as complete as one might wish, yet the information contained in the isodose plots was not readily usable for the purpose of relating biological response to radiation dose; for this, one needed a single dose value.

The ORAU speakers went on to describe how they converted the doses, as given by the participating institutions, to average total-body dose. They indicated that this study was still in progress and that data from only 21 of the 38

reporting institutions had been analyzed. Of the 757 treatments reviewed, exposures have been calculated for 724 and average doses have been calculated (or measured in phantoms) in 504. Table II gives the distribution of patients according to exposure and total-body average dose. About 5% of the patients could not be given any kind of dose estimate for lack of sufficient data.

Beck explained that the average total-body dose for ORAU patients was obtained by multiplying the patient's exposure by a conversion factor (Table III) derived from the phantom measurements of Hayes *et al.* (*9*). This factor is the ratio of the average number of rads per roentgen of exposure and is sensitive to patient size and weight. For the ^{60}Co opposing-field technique, the average dose changes more rapidly with patient weight than for the 8-source ^{137}Cs facility.

Average doses for the Cincinnati General Hospital patients were estimated by using the ORAU conversion factors for the temporary ^{60}Co unit in the third column, Table III. This was justifiable because the irradiation techniques at both institutions were almost identical (bilateral ^{60}Co radiation in both cases; treatment distances of 282 cm at Cincinnati, 275 to 285 cm at ORAU). Furthermore, a comparison of measured central-axis depth-dose data showed that the radiation distribution inside a phantom was the same at both facilities (Fig. 2). The data from Mary Imogene Bassett Hospital were treated in the same way although a comparison of central-axis depth-dose curves could not be made.

The City of Hope Hospital reported their doses as "average midplane, midbody dose" (*3*). This dose is the arithmetic mean of point values in the midcoronal plane of the trunk. For the NASA study, the reported values were converted to average total-body doses by means of the conversion factors of Table III. Justification for using the factors in Table III, which were determined for the 8-source ORAU irradiator, was the similarity of the ORAU and City of Hope facilities. A comparison of the radiation distribution measured in phantoms at ORAU and City of Hope showed that the dose at similar points was almost identical.

Whereas in gamma-irradiated patients dosimetry had been based on experimentally determined data, the same approach could not be followed for the far greater number of patients treated with X rays. The irradiation conditions varied so that phantom studies designed to reproduce all combinations of radiation energy, distance, and HVT would have been

impractical. Instead, Cloutier explained, average doses were calculated by means of Mayneord's equations (*12*, *13*, *14*), which give average dose as the product of the mean skin dose and certain tabulated factors. The skin dose usually had to be calculated from the midline air exposure; this was straightforward except for some uncertainty about the proper choice of backscatter factors.

Mayneord's calculations require a knowledge of the radiation quality and the trunk dimensions. In those cases where the HVT of the beam was not recorded, no estimate of average dose could be obtained; when the trunk dimensions were unknown, it was assumed that the correct AP trunk thickness was given by the expression (*15*):

$$\text{AP (cm)} = \sqrt{\frac{\text{weight (g)}}{\text{height (cm)}}}$$

It was also assumed that the lateral dimension was 1.5 times the AP thickness.

As a check on the validity of Mayneord's method of calculation, three phantoms were irradiated with 250-kV X rays (HVT 1.8 mm Cu) and average doses were measured with a ferrous sulfate dosimeter. The agreement between measured values and those obtained by Mayneord's method is good for the adolescent phantom, only fair for the adult, and poor for the child (Table IV). This may be a result of the failure of the theory when applied to conditions very different from those assumed in deriving it, incorrect choice of constants, or a combination of both factors.

The measured average total-body dose, for one roentgen exposure in air at the midbody position, is higher for this radiation quality than for a similar opposing-beam treatment using ^{60}Co radiation. The radiation distribution inside the phantom, however, is presumably less uniform, although this was not investigated.

PART II: MEASUREMENT AND CALCULATION OF DOSE

The second group of papers dealt with various practical and theoretical aspects of dose determination.

Ion Chamber Materials

Shonka described the tissue-equivalent plastics and gases he had developed and their application for the construction of ionization chambers. He demonstrated how a simple molecule such as O_2 might be simulated by combining nitrogen and fluorine in certain proportions so that the photon absorption coefficient of the combination in the energy range of interest was equivalent to that of the O_2 molecule. By extension of these ideas, a "molecule of muscle" (*16*), could be simulated by combining carbon, polyethylene, mylar, and calcium fluoride in the proper proportions. Carbon makes the mixture electrically conducting while calcium fluoride raises the effective atomic number, which would otherwise be too small at the lower energies.

Shonka described in detail the automatic mixing equipment used in the manufacture of the plastics. One of the solids made in this way has an absorption coefficient equal to that of tissue at 30 keV, while at 10 keV and several MeV the discrepancies do not exceed 9.5% and 12% respectively. An important characteristic of chambers made from these plastics is that an all-welded construction is possible, permitting fabrication of very complex shapes and providing absolute uniformity of composition at all places, including joints. Tissue-equivalent gas mixtures are also available for use in sealed tissue-equivalent chambers.

As an example of construction methods, Shonka described the ICRU transfer chambers (*17*). They are extraordinarily stable and give easily reproducible results - so reproducible in fact, that they may, in combination with a radium standard, eventually serve as secondary standards.

In answer to a question by Robinson, Shonka said that the carbon particles in the solid plastics have diameters of about 29 mμ, and make up about 18% by weight of the mixture. The electrical conductivity is a function of blending time, decreasing at first as blending begins but later increasing slightly as mixing progresses.

Integral Absorbed Dose

O'Foghludha then gave a summary of the development and present status of the integral-dose concept. The integral dose or total absorbed energy is defined by

$$\Sigma = \int_M D \, dm$$

where D is the absorbed dose in a mass element dm, and the integral is taken over the entire mass M of the irradiated body. The integral dose (Σ) has the dimensions of energy [(energy/mass) x mass] and its value should be given in energy units (ergs, joules) rather than in mixed units such as gram-rads. The integral dose receives scant attention today, largely because no satisfactory correlation between its magnitude and the severity of any systemic symptoms has been established, in spite of the promising early work of Bush (*18*). Although it is unlikely that further experiments will reveal Σ to be decisively important, it should be pointed out that the Σ data on which past clinical correlations had been based were so inaccurate as to be valueless as evidence for or against the biological significance of Σ.

The importance of Σ in the present discussion arises (a) because it gives a convenient single-number description of complex irradiations and (b) because determination of it is an essential, though frequently unrecognized, first step in finding the average dose (D_{av}). Contrary to popular belief, the average dose cannot always be obtained by simply averaging the local doses at a few points within the body, but involves an integration over the entire body volume and subsequent division by the body mass.

$$D_{av} = \frac{\int_M D \, dm}{\int_M dm} = \frac{\Sigma}{M}$$

Chemical dosimetry uses this method of determining D_{av}. In a chemical system, the change at any point in the system is proportional to the dose at that point and the total change in the system is proportional to Σ. Thus, D_{av} is measured when a sample is taken from a well-mixed system since the sample is representative of $\frac{\Sigma}{M}$ where M is the total mass of the system.

Both theoretical and experimental dosimetry studies are available for total-body irradiation. Mayneord (*12-14*) had calculated and also measured Σ for anthropomorphic phantoms composed of a number of homogeneous elliptical cylinders. His calculations assumed that the isodose lines within the body were normal to the direction of radiation incidence, which coincided with one of the axes of the elliptical cross-sections. He also assumed that the dose decreased either linearly or exponentially with depth. Experimental work and Snyder's calculations, reported during this conference, show that the assumption of linear fall-off is in fact reasonable. The integral dose was calculated by integrating the chosen depth-dependent function over the various elliptical cross-sections. This operation gave Σ as a function of the apparent linear coefficient μ, a quantity that takes account of both geometrical and absorptive attenuation (*14*). Here μ was treated as an adjustable constant whose value at any one energy and geometry was chosen to make the calculated and measured Σ's agree. To check theory, measurements were made with a solid multiple-slab man-like phantom in which some 70 ion chambers were embedded. The phantom was irradiated with a wide variety of radiation qualities (0.04 mm to 16 mm Cu HVT). It was assumed that the ion chamber dose was representative of the small section of the body in which it was located. The integral and average doses were found by summing the total energy deposition per segment. Although it was not unduly difficult to carry out the experiment with different radiations, adjustment of phantom dimensions was very inconvenient; therefore it was assumed that agreement between theory and experiment, which had been forced by suitable choice of μ in a phantom of given size, would be equally good for other dimensions. Under this assumption, Σ or D_{av} could be calculated for any geometry and any energy at which μ had been determined. The results were presented as tabulations of Σ in terms of μ and the body dimensions.

Monte-Carlo Techniques

Snyder next gave an account of Monte-Carlo calculations (*19*) in which a computer calculates the case histories of photons emitted by a point source situated near a homogeneous

phantom whose mass and shape approximate those of the standard man (*20*). The point of impact of a randomly chosen photon is calculated and the history of the quantum is then followed through various interactions until complete absorption or escape from the phantom occurs. The distances between successive collision sites, the nature of each interaction, the scattering angle, the energy deposition per collision, and so forth are chosen on a probability basis from the various possibilities that theory allows.

The energy deposited by large numbers (40,000 to 100,000) of incident photons is calculated in each of many small segments of the body giving the local dose in rads per incident photon. Computations are carried out for a variety of photon energies between 0.07 and 1.0 MeV; the sources are assumed to be points situated at either one or two meters from the body surface and level with either the shoulders or the midpoint of the chest. Because of the large number of photon histories studied, the standard deviation of the calculated dose never exceeds 20% and is usually much smaller.

In a sagittal direction, the Snyder method predicts an almost linear decrease in dose with depth for unilateral irradiation, confirming the validity of one of the assumptions underlying Mayneord's method of total-body calculation. It is interesting that the average dose is proportional to the dose at the center of gravity (*14*); this result may have a bearing on the usefulness of Lushbaugh's "epigastric dose" since the center of gravity of the human body is in the epigastric region (*21*) and the epigastric dose should therefore be proportional to D_{av}.

Snyder's method permits the theoretical calculation of dose in various parts of the body. However Σ and D_{av} can be found by summing the dose in all parts of the phantom (average compartment dose x compartment mass). This refinement has not yet been carried out.

The Monte-Carlo method is versatile and the validity of dose estimates obtained by it depends only on the accuracy with which the interaction cross sections of the phantom materials are known and the number of incident-photon histories followed. In principle it is applicable to any photon beam whose energy spectrum is known.

The present computer code gives entrance and exit doses that differ from the experimental results of Jones (*22*). This may be because the computer "phantom" is homogeneous while Jones used a phantom containing bone and air spaces.

Measurement of D_{av}

O'Foghludha next described methods of measuring D_{av}. He first referred to the chemical dosimetric studies of Sinclair (*23*), and of Hayes *et al.* (*9*).

Although chemical methods were thoroughly understood, it is curious (and regrettable) that they were so little used in studying the total-body problem. It is further to be regretted that they have not been employed to check the validity of various energy-absorption theories. The chemical technique demands large doses, requires considerable care, and is inflexible as far as changing phantom dimensions is concerned; but this disadvantage is shared with most other methods, among which are Grimmett's "celluloid man" approach (*24*), Rossi's cross-sectional chamber (*25*), and dose mapping with ionization chambers (*13*).

Conceptually, the most fundamental method was Carlsson's (*26*) in which both source and irradiated body were placed in the hollow interior of an ionization chamber made in the form of a large spherical shell. The inner and outer surfaces of the shell acted as the chamber electrodes. The outward energy flow was measured in terms of ionization current, first when the target body was inside the spherical enclosure, and later when it had been removed; the difference between the two energy fluxes was a measure of Σ. The method had yet to be tried, although Zieler (*27*) had attempted a measurement that relied on the same principle.

In Grimmett's "celluloid man" studies, a man-like phantom of plastic material, containing a number of very thin slab-like ionization chambers, was exposed to radiation and the sum of the currents in all chambers was taken as a measure of Σ; by making the individual chambers very thin but very large in area, the dose was sampled at a large number of points simultaneously, without serious perturbation of the photon flux by the thin layers of air. Rossi's cross-sectional chamber (*25*) is a simpler version of the same idea.

Mayneord, in the experiments on which his tables of Σ's were based, mapped dose distribution either with single movable chambers or with an array of stationary ones. Oddie, as Hayes reported at this meeting, had carried out similar experiments at ORAU (see Fig. 1).

A less tedious method of calculating Σ is based on the radiation reciprocity principle, first stated by King (*28*). According to the principle, the energy increment in a body

exposed to an external source is proportional to the exposure rate E which would be observed at the source position, if the source were removed and the body uniformly filled with radiating material. Mayneord used the principle at radium-gamma energies to investigate the dependence of Σ and of D_{av} on the source-skin distance and on source orientation with respect to the phantom (*29*). In Mayneord's "reciprocal" (or conjugate) simulation of external-beam radium irradiation, multiple point sources were inserted in a full-sized model of the patient. The exposure rate (E) at the position that the external sources would occupy was taken as a measure of Σ or of D_{av} in the phantom. To-and-fro and angular displacements of the detector enabled the dependence of Σ on source-skin distance and on source orientation to be found quickly. The experiments gave relative Σ values only, since the constant of proportionality between Σ and E is not easy to evaluate, either theoretically or experimentally. Changes in E thus correctly reflect variations in Σ, but absolute value of the energy increment remain unknown.

A flaw in the early experiments was failure to verify that the reciprocity principle is valid when Compton effect is the predominant energy-transfer mechanism. This point has since been checked experimentally by O'Foghludha* who has found that the principle is applicable with accuracy (±3%) over the range of energies and geometries normally used in therapy (*30*).

Complex irradiation patterns can be studied by this method; for example, the dose to an astronaut in a spacecraft bombarded by an omnidirectional flux of charged particles. Use of the reciprocity principle avoids the necessity of expensive and hazardous irradiation mock-ups. Instead, a low-activity radioactive analog of the astronaut is constructed and the exposure rate is integrated over the surface of a sphere centered on the model. According to the reciprocity theorem, the integrated exposure is proportional to the total energy that would be deposited in the astronaut if radiation of the same type as that emitted from the model were liberated uniformly from the walls surrounding the pilot. To apply the method when the energy spectrum of the incident radiation is continuous, as in Bremsstrahlung generated by electron impact, a series of conjugate simulations are necessary, each using a different monoenergetic emitter. The results that would have been obtained for a

* Supported by the National Aeronautics and Space Administration (Grant NGR 47-002-004)

continuous distribution can be inferred by suitably combining the results obtained at the various discrete energies.

If the flux within the capsule is anisotropic, conjugate simulation is carried out by weighting the residence time of the integrating detector so that, in any given orientation, the dwell-time is proportional to the intensity of the radiation incident from that direction. O'Foghludha described a number of methods by which the necessary measurements can be made, including a unit designed specifically for such measurements. To date, much of the work using this principle has been concerned with the measurement of photon spectra.

Snyder commented that the principle could not hold exactly in the Compton region. O'Foghludha, agreeing, stated that experiments had nevertheless shown the ratio Σ/E to be acceptably constant ($\pm 3\%$) in the range of energy and geometry of interest, and he suggested that the approximate validity of the principle should be further exploited in studying total-body dose.

A Radiobiological Approach

Robinson applied an interesting radiobiological concept to the definition of what he called the "equivalent uniform dose" for the bone marrow. The definition is based on the fact that the mammalian hemopoietic system behaves, at least to a first approximation, as if it were a single homogeneous organ. In particular, its capacity to function after irradiation seems to depend mainly on the number of stem cells surviving the insult. Even when the dose pattern in the body is grossly nonuniform, the equivalent uniform marrow dose may be defined as that dose which, if distributed uniformly in the marrow, would spare the same number of cells as does the nonuniform radiation actually used.

The equivalent dose will generally differ from the average dose in the marrow, since cell survival is an exponential rather than a linear function of dose. The difference between the average and equivalent doses depends on the shape of the cell-survival curves, on the nonuniformity of dose distribution, and on the average dose. As an example, the average marrow dose for 50% lethality in dogs nonuniformly irradiated with a unilateral field is about 350 rads, whereas for bilateral (and hence approximately uniform) irradiation the average marrow dose for 50% lethality is about 270 rads. In these circumstances, 270 rads is then considered the equivalent uniform dose that corresponds

with 350 rads delivered nonuniformly. The equivalence arises because 350 rads delivered unilaterally spares the same number of stem cells as 270 rads delivered bilaterally.

CONCLUSIONS

How should Dose be Reported?

All participants agreed that specification of the radiation field alone was insufficient to describe the irradiation completely. For example, a statement of the exposure in roentgens, although forming an essential part of the record, is not enough. An attempt should always be made to specify the energy deposition or dose. If details of the method and results of dose measurements as well as the exposure are quoted, later recalculation is possible and intercomparison with the results of others is simplified.

In specifying the dose a choice must be made between the maximum, minimum, modal, integral, or average doses (*31*). The physical arguments for and against the various specifications have already been given. The choice depends to some extent on the response that is clinically interesting or important. Langham cited the possibility of erythema in an astronaut exposed to low-energy radiation. In this circumstance the skin dose is of critical importance. On the other hand if lethality is the response under study, the dose to the bone marrow is most important since the marrow appears to be the target organ, at least when the dose is of the same order of magnitude as the $ED_{50/60}$. In some situations, of course, the target organ is unknown as in the prodromal syndrome where the means by which anorexia, nausea, and vomiting are induced remain obscure. Since the onset of these symptoms is unlikely to be related to irradiation of the extremities, a specification of the average dose to the trunk - or possibly the upper abdomen alone - is of value. Where the physiologically important organ cannot be localized even to this degree of accuracy, the average dose to the whole body is the most appropriate value to quote.

The average dose has the advantage that it can be calculated with fair accuracy in most cases if the properties of the radiation field are known. Whether D_{av} is required for a single organ or for the entire body, its determination involves measurement or calculation of the integral dose Σ,

either explicity or conceptually. For this reason it may be advantageous to state D_{av} not in rads but in the dimensionally equivalent form "gram-rad per gram"; such a statement, though clumsy, draws attention to the way in which D_{av} was actually obtained.

The extremes between which values of the local dose vary should be reported as an indication of the degree of nonuniformity. If the frequency distribution about the mean were normal, the standard deviation could be used; but it is usually most appropriate to indicate the spread by quoting the highest and lowest doses in the region of interest.

National and international organizations have recommended standards for dose recording in portal therapy. Until similar standards are set up for total-body irradiation, it is suggested that:

1.) The characteristics of the radiation field used should be stated.

2.) The average dose D_{av} in the target organ and the method of calculation or measurement should be given. If the target organ is unknown, D_{av} for the entire body should be stated.

3.) The maximum and minimum doses in the region of interest or some other indication of the degree of nonuniformity should be reported.

Whatever method of dose specification is used, a single number is unlikely to provide a firm basis for the prediction of biological response. The more data one quotes, the more complete is the information, though the additional data may appear irrelevant or even confusing. Past experience proves that information once thought to be unimportant is later vital. Therefore, as much information as possible should be recorded to permit later evaluation in the light of new identification of target organs.

At the present time Mayneord's analytical technique and Snyder's computer study of individual photon histories offer powerful tools for the calculation of radiation dose. However, additional experimental corroboration of these theoretical methods is urgently needed for various phantoms and for a range of photon energies. The participants at this meeting expressed the hope that the next few years would see a rapid advance in the science of whole-body dosimetry.

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TABLE I

JANUARY 1967 AUDIT OF RETROSPECTIVE AEC/NASA STUDY OF HUMAN TOTAL-BODY IRRADIATION

Hospital or Institution	Anticipated Treatments	Retrieved Treatments	Treatment Types <Day	>Day but <8 Days	>8 Days	No. of Treatments Reviewed for Dose Estimation
Albert Einstein Medical Center	1	1	1			1
Baylor University	113	111	67	15	29	74
Bowman Gray	7					
Burge Protestant Hospital	5	5	1	2	2	
Cincinnati General	32	32	29	1	2	30
City of Hope Medical Center	53	58	36	8	14	43
Charity Hospital	80	98	3	18	77	
Colorado General	1	1			1	
Ellis Fischel State Cancer Center	77	84	2	9	73	
Franklin Hospital	85	85			85	
Jefferson Medical College	10	11	11			4
Long Beach Community Hospital	1	1	1			1
Los Alamos Hospital	9	9	9			1
Mary Imogene Bassett	22	27	15	11	1	19
Massachusetts General (McGovern)	6	7	7			7
Massachusetts General (Robbins, L.)	200					
M. D. Anderson Hospital & Tumor Institute	293	292	286	1	5	287
Medical College of Virginia	5	5	5			5
New York Memorial (Craver--Heublein)	144	188		112	76	108
New York Memorial (Nickson)	46	48	35	6	7	23
Oak Ridge Associated Universities-ORINS	138	138	134	1	3	123
Penrose Cancer Clinic	54	68			68	
Peter Bent Brigham	10	11	2	8	1	10
Philadelphia Children's	3					
Providence Hospital	45	288	236	3	49	
Rhode Island Accident	1	1	1			
Temple University	26	29	15	5	9	7
Thomas M. Fitzgerald Mercy	4	4	4			4
U. S. Naval Hospital	11	11	7		4	7
U. of Calif. Medical School, S. F.	163					
University of Michigan	128	128			128	
University of Pennsylvania	10					
V. A. Hospital at Denver	12	25	2		23	
V. A. Hospital at Long Beach	10	2	2			2
V. A. Hospital at New Orleans	24	57	5	16	36	
V. A. Hospital at Wood, Wisconsin	1					
Winnipeg General	7					
White Memorial Medical Center	2	2	2			2
Totals 38 Institutions	1839	1814	904	216	648	757

TABLE II

DISTRIBUTION OF PATIENTS
ACCORDING TO EXPOSURE AND TOTAL-BODY AVERAGE DOSE

Exposure (R)	Number of Patients	Total-Body Average Dose (rads)	Number of Patients
0-25	155	0-25	149
26-50	152	26-50	108
51-75	51	51-75	90
76-100	127	76-100	19
101-125	47	101-125	17
126-150	37	126-150	36
151-200	60	151-200	19
201-250	16	201-250	26
251-300	22	251-300	4
301-400	16	301-400	15
401-500	11	401-500	7
501-700	13	501-700	7
701-900	5	701-900	2
901-1100	6	901-1100	3
1101-1300	3	1101-1300	2
1301-1600	3	1301-1600	0
	724		504

January, 1967

TABLE III

ORAU WEIGHT-CORRECTED
CONVERSION FACTORS

Patient's Weight (Pounds)	AVERAGE TOTAL-BODY RAD/R	
	^{137}Cs TBI Facility	Temporary ^{60}Co Unit
35-45	0.75	0.77
45-55	0.75	0.74
55-65	0.75	0.71
65-75	0.75	0.69
75-85	0.74	0.67
85-95	0.74	0.65
95-105	0.74	0.64
105-115	0.73	0.63
115-125	0.72	0.62
125-135	0.72	0.61
135-145	0.71	0.61
145-155	0.70	0.61
155-165	0.70	0.61
165-175	0.69	0.61
175-185	0.69	0.60
185-195	0.68	0.60
195-205	0.68	0.60

TABLE IV

COMPARISON OF MEASURED AND CALCULATED AVERAGE DOSES

Phantom	Thickness	SSD	Average dose/R exposure		% Difference
			Measured	Calculated	
Adult	29 cm	285 cm	0.67	0.73	9
Adolescent	23 cm	200 cm	0.78	0.80	3
Child	16 cm	200 cm	0.79	0.93	18

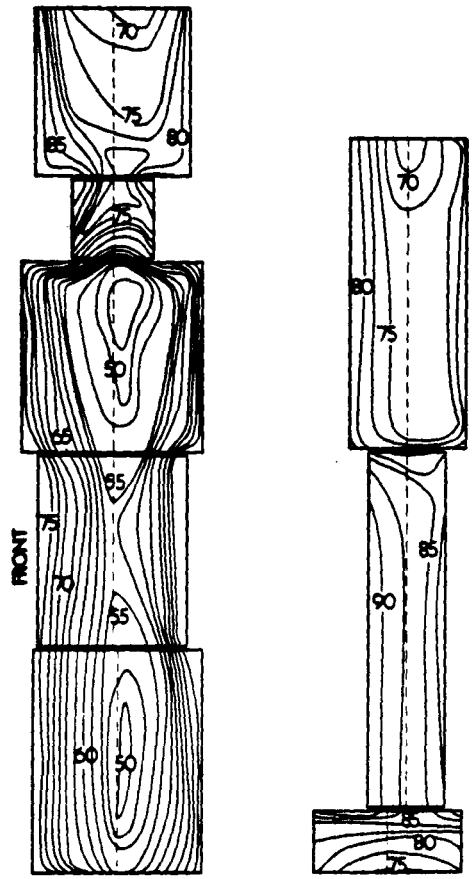

Figure 1. Isodose lines in an "adult" phantom, irradiated with eight converging ^{137}Cs radiation beams. ORAU total-body irradiation facility. Isodose lines normalized to 100-R exposure at the center of the phantom.

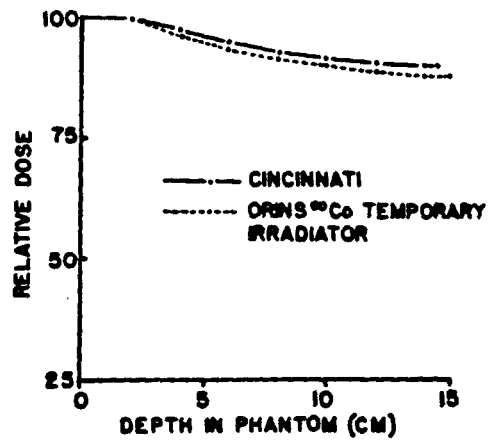

Figure 2. Central-axis depth-dose curves in the "trunk" of phantoms irradiated with opposing ^{60}Co radiation beams. Depth doses normalized to 100 at the phantom's surface.

Appendix I

WORK CONFERENCE

List of Participants
Program

WORK CONFERENCE

DOSIMETRY IN TOTAL BODY PHOTON IRRADIATION OF MAN

February 23-24, 1967

List of Participants

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WORK CONFERENCE

DOSIMETRY IN TOTAL BODY PHOTON IRRADIATION OF MAN

CO-CHAIRMEN
R. J. Cloutier
F. T. O'Foghludha
F. V. Comas

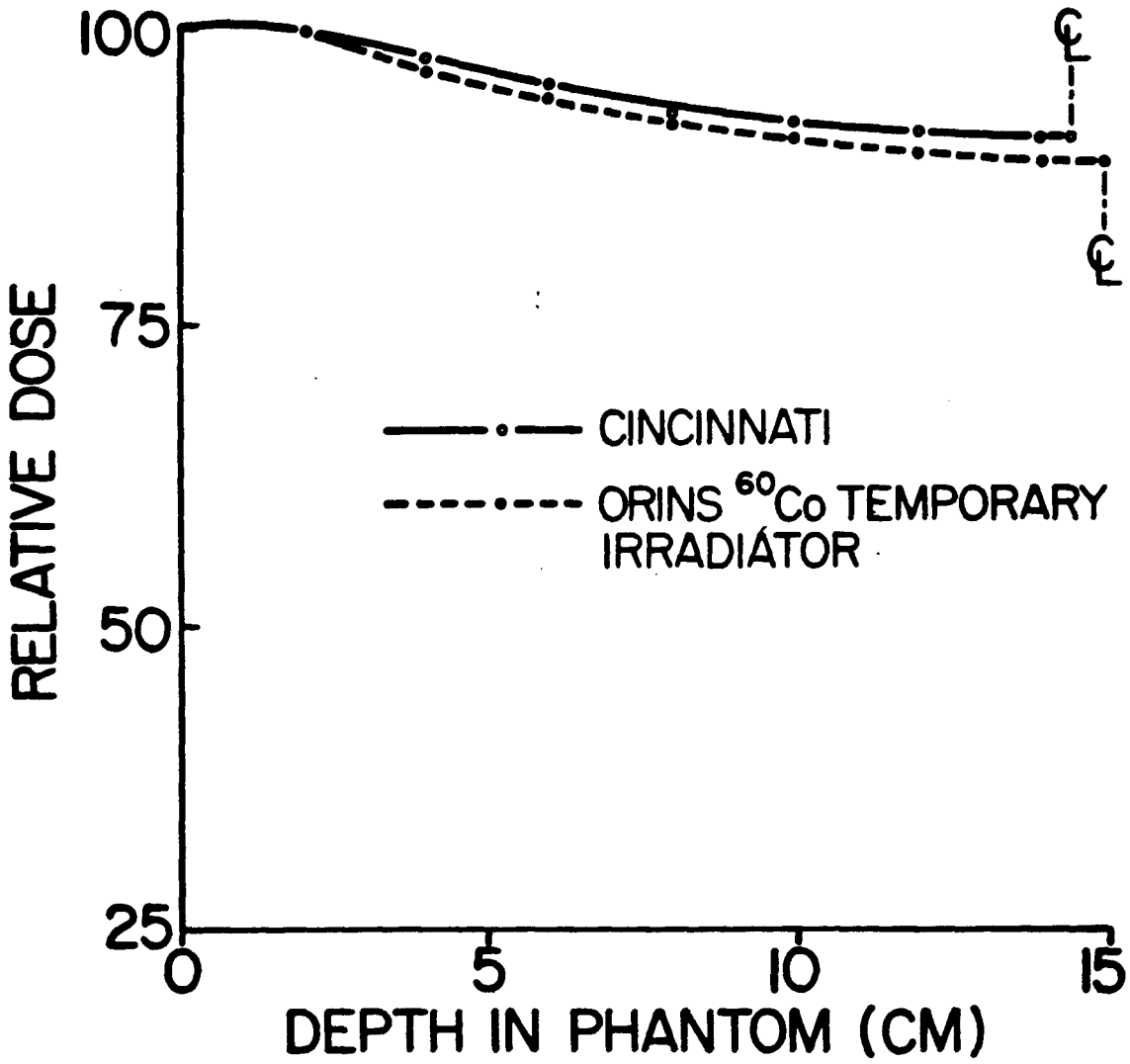
Thursday, February 23, 1967

8:30 A. M.	Welcome	Andrews, G. A.
	Purpose of meeting	Cloutier, R. J.
9:00	NASA study	Lushbaugh, C. C.
9:15	Types of facilities and reported exposures	Beck, W. L.
9:45	Coffee break	
10:00-12:00	APPROACHES TO TOTAL BODY DOSIMETRY	Cloutier, R. J. (Chairman)
10:00	Integral dose review	O'Foghludha, F. T.
10:45	Discussion	
11:00	Bone marrow dose	Robinson, C. V.
11:20	Discussion	
11:30	Tissue-equivalent chambers	Shonka, F. R.
11:50	Discussion	
12:00	Lunch	
1:30-4:30	PHYSICAL DOSIMETRY: Methods and results	Comas, F. V. (Chairman)
1:30	ORINS medium-exposure total-body irradiator	Hayes, R. L.
1:50	Winnipeg total-body irradiator	Campbell, E. M.
2:10	M. D. Anderson Hospital irradiator	Shalek, R. J.
2:30	Baylor Hospital irradiator	West, W.

2:50	Cincinnati General Hospital irradiator	Kereiakes, J. G.
3:10	Discussion	
3:45	Coffee break	
4:00	Heublein irradiation and dosimetry	Focht, E. F.
5:00	Social hour	
6:30	Dinner	

Friday, February 24, 1967

8:30 A. M.	HANDLING OF NASA DATA	Comas, F. V. Beck, W. L. Cloutier, R. J.
9:15	Discussion	
9:30-10:30	OTHER APPROACHES TO TOTAL BODY DOSIMETRY	O'Foghludha, F. T. (Chairman)
9:30	Computer Calculation of dose	Snyder, W. S.
9:50	Discussion	
10:00	Reciprocal dose: theory and results	O'Foghludha, F. T.
10:20	Discussion	
10:30	Coffee break	
10:45	PANEL DISCUSSION: What is the best way for reporting whole body exposure or dose?	Comas, F. V. Cloutier, R. J. O'Foghludha, F. T.
12:00	END	


100
75
50
25
RELATIVE DOSE
0
5
10
15
DEPTH IN PHANTOM (CM)
CINCINNATI
ORINS 60Co TEMPORARY IRRADIATOR

OAK RIDGE ASSOCIATED
UNIVERSITIES, INC.

711377-1

fig 4