

AFRRI_____TECHNICAL REPORT



**Phantom dosimetry for TRIGA
reactor irradiations in chair
and wheel arrays**

G. H. Zeman

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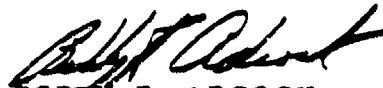
REVIEWED AND APPROVED



VINCENT L. McMANAMAN
CDR, MSC, USN
Chairman
Radiation Sciences Department



LAWRENCE S. MYERS, Ph.D.
Scientific Director



BOBBY R. ADCOCK
COL, MS, USA
Director

Research was conducted according to the principles enunciated in the
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Behavioral effects of reactor radiation on rhesus monkeys (<i>Macaca mulatta</i>) studied at AFRRI over the last 2 decades form an essential data base in development of combat casualty criteria for the armed forces of the United States and NATO. Through the course of the AFRRI studies, the irradiation techniques and the dose specification procedures differed, making difficult the complete intercomparability of results. A series of phantom dosimetry measurements completed in 1979-1980 have now been compiled to allow the interconversion of midhead and midthorax doses as well as free-in-air kerma at the midhead and midthorax locations. Included in the compilation are data for different reactor shield configurations and for both the visual discrimination task chair array and the physical activity wheel array. In addition to total-dose comparisons, the compilation includes data on neutron-to-gamma dose ratios free in air and at depth. Results of this work facilitate the more accurate retrospective analysis of AFRRI data on the behavioral effects of reactor radiations.				
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INTRODUCTION

This report compiles the phantom dosimetry measurements made at the Armed Forces Radiobiology Research Institute (AFRRI) TRIGA reactor during 1979 and 1980 for irradiations of the rhesus monkey (Macaca mulatta) in chair and wheel arrays. These two arrays have been used in a number of experiments evaluating behavioral effects of mixed gamma-neutron irradiation (1). Descriptions of the arrays appear in references 2 and 3.

Radiation doses delivered to experimental subjects have been expressed in four different ways, as follows:

- free-in-air kerma at midthorax
- free-in-air kerma at midhead
- depth dose at midhead
- depth dose at midthorax

In various experiments, any one or more of the above were measured and reported as the delivered dose. The purpose of the present report is to define the inter-relationship of the above four doses, i.e., to develop a set of conversion factors allowing the calculation of all four doses, given any one dose. This task is complicated by the facts that irradiations were performed at different distances from the reactor core, and only selected measurements were performed at each distance.

METHODS

Most data were compiled from unpublished measurements by K. Ferlie and E. Daxon recorded in AFRRI Laboratory Notebooks numbers SSD 5(a) through 5(d) and SSD 23(a) through 23(c), which were archived in the AFRRI library. Radiation dose rates at various distances and angles from the reactor core were taken from unpublished data obtained from K. Ferlie. Note that accurate replication of these dosimetry measurements was not feasible because the wooden walls and the wall coverings of gadolinium/cadmium in Exposure Room One were later replaced.

DEFINITIONS

The following terminology was used in the dosimetry measurements:

Dose: Neutron, gamma, or total kerma expressed in units of rad. (Gamma dose includes neutron-capture gamma rays.)

ICRU: International Commission on Radiation Units and Measurements

Tissue: ICRU muscle. Doses calculated for ICRU muscle (4) as material being irradiated. By weight, the composition of ICRU muscle is 10.2% H, 12.3% C, 3.5% N, 72.9% O, and 1.1% (Na + Mg + P + S + K + Ca).

Array: Entire collection of items brought into exposure room to irradiate an animal. For chair irradiations, array included a plywood box and testing apparatus, an acrylic restraint chair, and an animal. For wheel irradiations, array included an exercise wheel, an acrylic restraint box in which the animal was confined for irradiation, and the animal.

Depth Dose: Use of ionization chambers within tissue-equivalent phantoms to measure dose at depth. The entire experimental array was in place when depth doses were measured.

Free-In-Air (FIA) Dose: Use of ionization chambers to measure tissue kerma at a point in space in absence of animal and in absence of experimental array. Ion chambers were positioned at same point in space as for depth-dose measurement.

Tissue-Air Ratio (TAR): Ratio of depth dose to FIA dose

CLCL: Distance from centerline to centerline. Used to express horizontal distance from center of reactor core to point at which dose was measured. Animals were assumed to sit up straight, with all points along their midline at the same CLCL distance.

Midthorax: Point at trunk midline of animal or phantom. In all arrays considered in this report, midthorax is positioned at the same height from the floor as the center of the reactor core, or 120 cm in Exposure Room One (ER 1) and 92 cm in Exposure Room Two (ER 2).

Midhead: Geometric midpoint of animal's head, which is assumed to be vertically above midthorax

Ion Chamber: Device for measuring radiation dose. Two 50-cc ion chambers were used for all FIA measurements. Two 0.5-cc ion chambers were used for depth-dose measurements. See more detailed description below.

Phantom: Plastic and liquid device that approximates shape of a rhesus monkey. Used for all depth-dose measurements, as described below.

RESULTS

Phantoms

Phantoms were constructed to approximate the dimensions of rhesus monkeys. Figure 1 is a diagram of a phantom. The trunk portion of each phantom was a hollow lucite cylinder filled with tissue-equivalent (TE) liquid (4). Cylinders of 4- and 5-inch diameters were used to model juvenile rhesus monkeys, and cylinders of 6-inch diameter were used to model mature subjects. These sizes were based on actual measurements of a

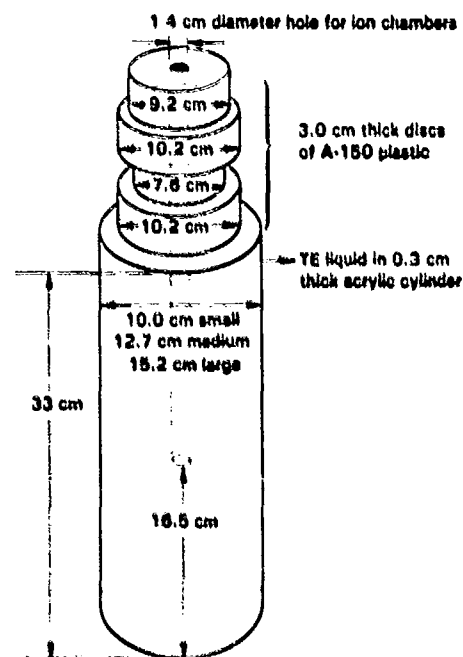


Figure 1. Simple monkey phantom used for dosimetry measurements in chair array

number of experimental animals. Lucite tubes containing the ionization chambers were suspended in the TE liquid for depth-dose measurements. The head and neck sections of the phantom were made of A-150 tissue-equivalent plastic with a hole at the center of the midhead for positioning the ionization chambers. The midhead-to-midthorax distance in the phantom was varied between 18 and 25 cm during the course of the measurements.

To simulate subjects irradiated in the chair configuration, the phantom was placed in the chair so that the vertical centerline of the phantom was at the specified CLCL distance. Legs were not included in the phantom for chair irradiations because the subject's legs extend away from the body in this configuration. For irradiations in the wheel configuration, the subjects were in a crouched position, so it was appropriate to include legs in the phantom, as shown in Figure 2. (Note that Figure 2 shows an anterior view of the phantom, but irradiations were done with posterior incidence.)

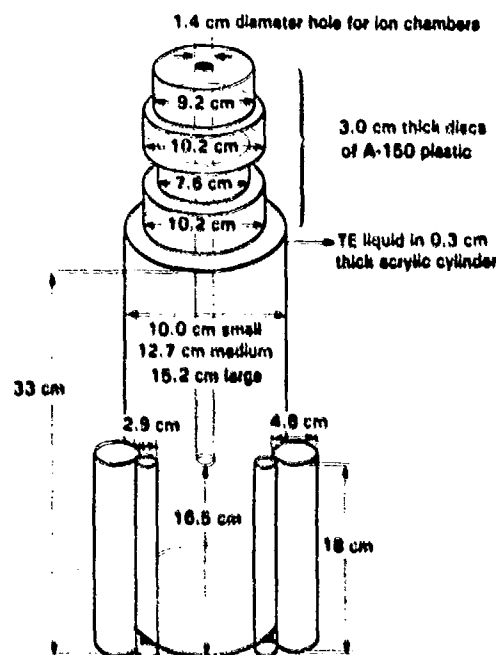


Figure 2. Monkey phantom with legs in crouched position used for dosimetry measurements in wheel array

Ionization Chambers

AFRRI 50-cc paired ionization chambers were used for all FIA-dose measurements. These ion chambers have been used at AFRRI for calibration purposes since about 1968, and were the model for subsequent development of commercially available spherical chambers. A diagram of the chambers appears in reference 5. AFRRI 0.5-cc paired-ion chambers were used for all depth-dose measurements; these have been described in reference 6.

The paired-ion chamber constants used for all dose measurements are defined by the following equations:

$$DN = a T - b U$$

$$DG = -c T + d U$$

where T is the response of a tissue-equivalent ion chamber filled with tissue-equivalent gas and U is the response of a 50-cc graphite ion chamber filled with CO₂, or the response of a 0.5-cc magnesium chamber filled with argon normalized by the cobalt-60 roentgen calibration factor for each chamber. DN is the neutron kerma for tissue, and DG is the gamma kerma for tissue. The four constants of concern are a, b, c, and d. Values of these constants used for all dosimetry calculations are listed in Table 1.

Table 1. Paired Ionization Chamber Constants for Evaluation of Gamma-Neutron Doses

Constant	50-cc Chambers	0.5-cc Chambers
a	1.22	1.061
b	1.22	1.061
c	0.094	0.024
d	1.05	0.961

Tissue-To-Air Ratios

Table 2 lists the measured dose rates collated by array and reactor shield. Table 3 summarizes the TAR values for small, medium, and large phantoms. Since midhead TAR values were nearly identical for phantoms of different sizes, the average value is given for each configuration.

Table 2. Free-in-Air and Phantom Midline Dose Rates* for Reactor Chair and Wheel Configurations

Configuration	Midthorax	Midhead	Midthorax/Midhead
<u>Room 2, No shield, Chair 125 cm</u>			
FIA	27.0	23.4	1.15
Large [†]	18.6	18.2	1.02
Medium	19.4	18.1	1.07
Small	20.5	18.4	1.11
<u>Room 1, 2" Pb, Chair 90 cm</u>			
FIA	14.9	12.7	1.17
Large	8.88	8.90	1.00
Medium	10.2	9.16	1.11
Small	11.2	9.04	1.24
<u>Room 1, 6" Pb, Chair 100 cm</u>			
FIA	6.85	5.64	1.21
Large	3.26	3.55	0.94
Medium	3.67	3.51	1.05
Small	4.31	3.49	1.23
<u>Room 1, No shield, Chair 100 cm</u>			
FIA	35.2	31.8	1.11
Large	25.0	25.3	0.99
Medium	27.6	25.8	1.07
Small	29.1	24.7	1.19
<u>Room 1, 5" H₂O, Chair 100 cm</u>			
FIA	13.5	12.2	1.11
Large	9.91	9.91	1.00
Medium	10.0	10.0	1.00
Small	11.3	10.1	1.12
<u>Room 1, 2" Pb, Wheel 90 cm</u>			
FIA	14.9	12.7	1.17
Large	8.28	9.13	0.91
Medium	9.75	9.26	1.05
Small	11.33	10.7	1.06

* Rad/kilowatt-min

[†] Small, medium, and large phantoms were 4", 5", and 6" in diameter, respectively.

Table 3. Phantom Tissue-Air Ratios*

Room	Shield	CLCL (cm)	Array	Midthorax			Midhead
				Small	Medium	Large	
2	None	125	Chair	0.76	0.72	0.69	0.78
1	None	100	Chair	0.83	0.78	0.71	0.81
1	2" Pb	90	Chair	0.75	0.69	0.60	0.71
1	2" Pb	90	Wheel	0.76	0.66	0.56	0.73
1	6" Pb	100	Chair	0.63	0.54	0.48	0.62
1	5" H ₂ O	100	Chair	0.84	0.74	0.73	0.82

* Ratio of total (neutron plus gamma) dose measured within phantom to total kerma measured at same point in space, but in absence of phantom and array

The precision of the TAR measurements was probably better than $\pm 5\%$ (2 standard deviations) based on the fact that all but a few of the measurements were done in duplicate. If the results were not within $\pm 5\%$, a third measurement was made. Also, for all measurements, the readings of monitor chambers were recorded, and data were corrected if monitor chambers showed reactor output variations of more than 1%.

The above data did not cover all CLCL distances of concern at the time. By definition of the TAR, the same values may be used for other CLCL distances, as long as the radiation field is the same. The fields do indeed change with distance: capture-gamma radiation and scattered low-energy components are more significant at greater distances. However, it can be argued that most of the scattered radiation affecting the TAR is scattered radiation caused by the array itself, with walls and floor exerting only a secondary effect because of their greater distance from the phantom.

Neutron-to-Gamma Ratios

Neutron-to-gamma ratios were also compiled from the available data. They are listed in Table 4. The midhead neutron-gamma ratios listed in Table 4 are averages of values measured for trunks of three different sizes.

Table 4. Neutron-to-Gamma Ratios for Phantom Irradiations

Room	Shield	CLCL (cm)	Array	Midthorax				Midhead	
				FIA	Small	Medium	Large	FIA	All
2	None	125	Chair	0.57	0.28	0.27	0.19	0.42	0.25
1	None	100	Chair	0.57	0.30	0.26	0.21	0.44	0.30
1	2" Pb	90	Chair	3.80	1.70	1.40	1.00	3.80	1.70
1	2" Pb	90	Wheel	3.80	1.40	1.20	0.83	3.80	1.60
1	6" Pb	100	Chair	17	2.70	2.10	1.20	12	2.50
1	5' H ₂ O	100	Chair	0.20	0.16	0.06	0.01	0.16	0.10

Different Distances

The ratio of midthorax-FIA to midhead-FIA doses is needed to complete the four-way comparisons discussed in the Introduction. These ratios are shown in Table 5 for the arrays/shields for which they were measured. For the unshielded reactor, other CLCL distances were used for some irradiations: from 85 to 150 cm in ER 1, and from 80 to 260 cm in ER 2. Two factors affect the relative midthorax-FIA and midhead-FIA radiation dose rates at these distances. First, the slant distance from reactor core to midhead is greater than to midthorax. Second, the reactor output at an angle (toward midhead) is reduced compared to the output along the horizontal (toward midthorax). These two effects have been characterized separately in the past, as shown in Figures 3 and 4. These data were used to estimate free-in-air doses at midhead and midthorax positions for various CLCL distances. The estimated ratios shown in Table 5 agree within 3% with the measured ratios in the two configurations for which measurements were available.

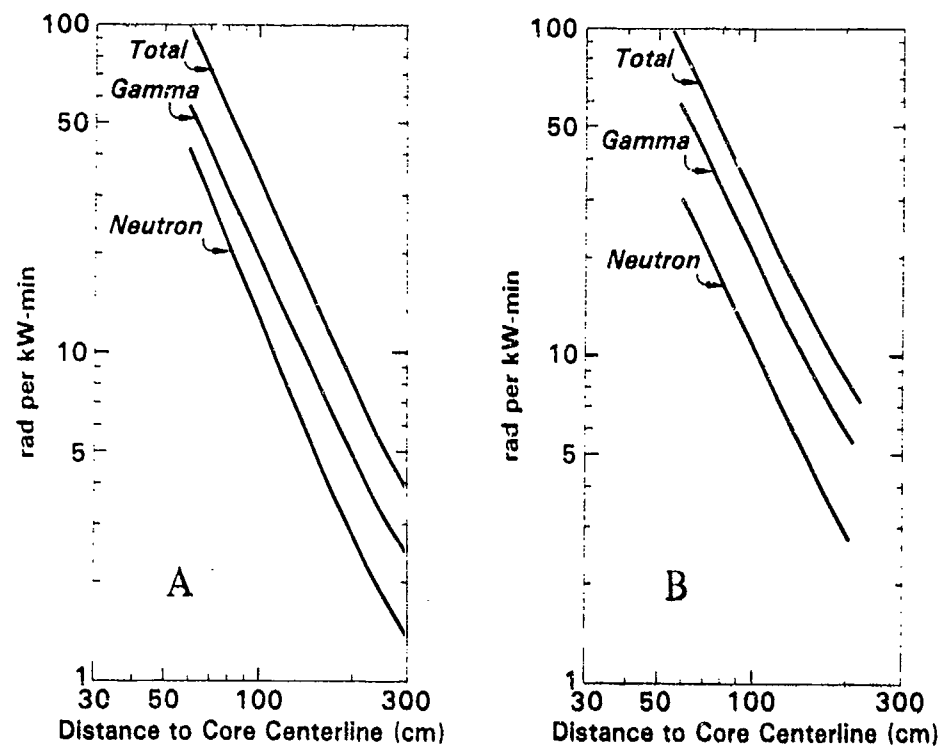


Figure 3. Radiation output at different distances from AFRRI TRIGA reactor in Exposure Room One (A) and Two (B)

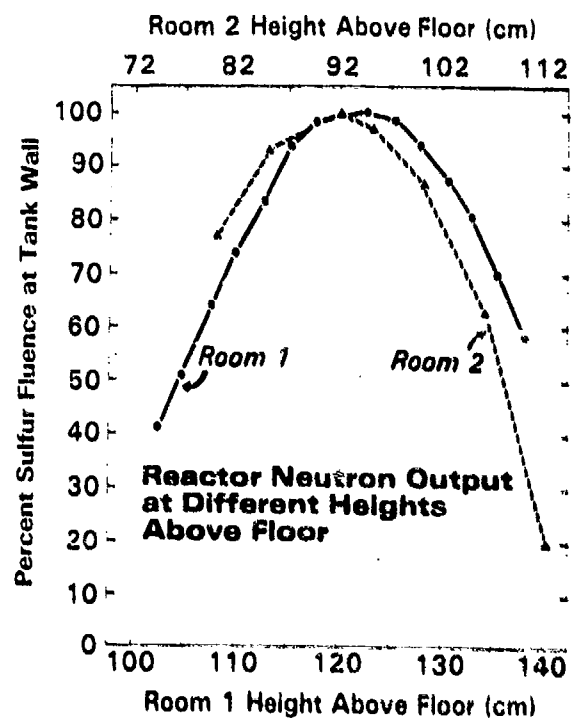


Figure 4. Radiation output from AFRRI TRIGA reactor at different heights in Exposure Rooms One and Two

Table 5. Ratios of Midthorax-to-Midhead Free-in-Air Doses

Room	Shield	CLCL (cm)	Measured	Estimated
1	2" Pb	90	1.17	-
1	6" Pb	100	1.21	-
1	5" H ₂ O	100	1.11	-
2	None	80	-	1.29
		125	1.15	1.12
		200	-	1.05
		260	-	1.03
1	None	85	-	1.14
		90	-	1.12
		100	1.09	1.11
		150	-	1.03

Dose Conversion Factors

From the results compiled above, a dose conversion-factor chart was constructed (see Table 6). The chart gives the total doses appearing at depth in midthorax or in air at midhead or midthorax for an irradiation delivering a depth dose of 1000 rads at the midhead position. Based on this chart, complete inter-comparison of the experimental dosimetry results specified for the four sites (in air, at depth, midhead, and midthorax) can be achieved.

Uncertainties in the above dosimetry conversion scheme lie in the precision of the basic data set (estimated to be better than $\pm 5\%$, 2σ) and in the use of estimated parameters for angular output of the unshielded reactor. The latter uncertainties appear to be no worse than $\pm 3\%$ for CLCL distances beyond 100 cm, but may be larger than $\pm 5\%$ at closer distances.

Table 6. Doses Resulting From 1000-Rad Midhead Dose

Room	Shield	Array	CLCL (cm)	FIA Midhead	FIA Midthorax	Midthorax		
						Large	Medium	Small
1	2" Pb	Wheel	90	1310	1540	850	1010	1170
1	2" Pb	Chair	90	1410	1650	980	1130	1240
1	6" Pb	Chair	100	1600	1950	930	1040	1230
1	5" H ₂ O	Chair	100	1220	1350	990	1000	1130
1	None	Chair	85*	1260	1430	1020	1120	1180
			90*	1260	1400	1000	1100	1160
			100	1260	1390	990	1090	1150
			150*	1260	1290	920	1010	1070
2	None	Chair	80*	1280	1700	1170	1220	1290
			125	1280	1480	1020	1060	1120
			200*	1280	1390	960	1000	1050
			260*	1280	1360	940	980	1030

* These entries are based on estimates of free-in-air dose ratios at midhead to midthorax position. All other entries are based on direct experimental measurements.

DISCUSSION

The data compiled in this report allow intercomparison of dosimetry results for irradiations of rhesus monkeys (*Macaca mulatta*) conducted in different experiments using the chair and wheel arrays. The data also serve as a body of baseline reference information on reactor output and neutron-to-gamma ratios both free in air and at depth within cylindrical phantoms of different sizes.

The dosimetry conversion factor chart resulting from the data compiled in this report demonstrates the importance of proper site specification for dosimetry measurements. The chart shows that free-in-air doses were 22% to 95% higher than midhead doses. Also, for a midhead depth dose of 1000 rads, the dose delivered at depth in midthorax ranged from 850 to 1290 rads, depending on size of phantom and irradiation array/shield. For many arrays/shields, the midthorax and midhead depth doses were approximately equal ($\pm 5\%$), but universal application of this generality is definitely contraindicated, particularly for the small phantom (4" diameter).

For all sizes of phantom, the neutron-to-gamma-dose ratios at depth were significantly different from the free-in-air values. Even for the enhanced neutron field (6" Pb shield) the gamma component ranged from one quarter to almost one half of the total midthorax dose in the three phantoms. This finding indicates the futility of attempts to further reduce the gamma contamination of the reactor field, since neutron-capture photons dominate the gamma dose at depth. This finding also suggests that all dosimetry results should be measured and specified within phantoms instead of in air. The specification of in-air total kerma and neutron-to-gamma ratios may bear little resemblance to the actual dose and the dose ratios appearing at depth in a phantom.

Measurement of depth-dose distribution was beyond the scope of the present study. For further information on neutron and gamma dose distributions, the original work by Dowling (7) should be consulted. That study examined dose distributions in rhesus monkey cadavers irradiated with pulsed gamma-neutron fields from the unshielded TRIGA reactor. More recently, Zeman et al. (8) reported depth-dose measurements in cadavers and phantoms irradiated with a 15-cm-lead-shielded TRIGA reactor. Finally, references 3 and 9 report doses and energy spectra determined by means of Monte Carlo calculations at selected points and averages over selected regions in monkey-like phantoms.

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