HEMATOPOIETIC BONE MARROW DOSE IN A ^{60}Co IRRADIATED TISSUE-EQUIVALENT HUMAN PHANTOM USING LITHIUM FLUORIDE DOSIMETRY

A dissertation submitted to the

Division of Graduate Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

1968

by

J. Winston Rogers, A.B.

University of Kentucky, 1958

ACKNOWLEDGEMENT

The task has not been easy--. To those who have guided me through the trying days of this thesis I offer my sincere appreciation. I especially thank Dr. James Kereiakes, my adviser, for all of his help throughout my entire Master's program. Thanks also go to Dr. Eugene L. Saenger, Dr. Ben I. Friedman, Dr. Gustave K. Bahr and all of the staff at the Kettering Laboratory. I appreciate the fact that it has not been easy.

TABLE OF CONTENTS

	Page
I Introduction	1
II Methods	
A. Equipment	2
B. Dosimeter Loading Procedure	2
C. Defining the Phantom Exposure	5
D. Calibration Procedures	5
III Results	
A. Counting Procedures and Conversion of Net Counts to Rads	12
B. Check Procedures	14
IV Interpretation of Data	14
V Conclusions	48
VI Bibliography	50

I INTRODUCTION

Partial and whole body irradiation delivered by a cobalt-60 (^{60}Co) teletherapy unit has been used in the therapy of certain cancers (1). This therapy is given as a single dose bilaterally. An unwanted side effect is an alteration in the blood picture. In the normal adult, the blood cells and their precursors are produced in "active" bone marrow. Large doses of radiation affect the "active" marrow to produce the unwanted side effects. Therefore, for a known midline ^{60}cobalt exposure, it is very important to know what the dose will be in the entire "active" marrow. This total dose is important for correlation with previously demonstrated changes in the blood pictures of irradiated patients. The measure of dose in only one section of the irradiated marrow gives no indication of the absorbed dose in an adjacent or far removed area because of differences in distance, scatter, overlying tissue, etc. Measurements in all irradiated sections of marrow would provide a better estimate of "active" marrow dose.

The purpose of this study is to experimentally determine "active" bone marrow dose under simulated whole body and partial body ^{60}cobalt exposure conditions.

II METHODS

Measurements in a human subject would provide the best indication of marrow dose, but the placement of dosimeters in the marrow spaces prior to irradiation and their subsequent removal after irradiation is not feasible at the present time. The next best approach would be to use a human tissue-equivalent phantom containing a human skeleton which would be easily accessible for dosimeter placement. The Rando phantom possessed by the Radiology Department of Cincinnati General Hospital is an ideal subject for these measurements (2).

A. Equipment

1. ^{60}Cobalt teletherapy unit. (Eldorado A, Atomic Energy of Canada).

2. Victoreen Condenser R Chambers calibrated for ^{60}cobalt gamma rays.

3. Lithium fluoride powder in a homogeneous form. (TLD-100, Harshaw Chemical Company, Cleveland, Ohio).

4. Lucite capsules. (for holding powder).

5. Lab Heat muffle furnace. (Blue M Electric Company, Blue Island, Illinois).

6. Laboratory glass drying oven.

7. Thermoluminescence radiation exposure meter (Madison Research, Development Laboratories, Inc., Madison, Wisconsin).

8. Rando human tissue-equivalent trunk phantom (Machlett Laboratories, Inc., Springdale, Connecticut).

9. Human articulated skeleton approximately the same size as the skeleton in the phantom.

B. Dosimeter Loading Procedures

The Rando phantom is divided into 36 sections (see figure 1). Sections 0 to 34 are 2.5 cm (≈ 1 inch) thick and cut parallel in a horizontal field.

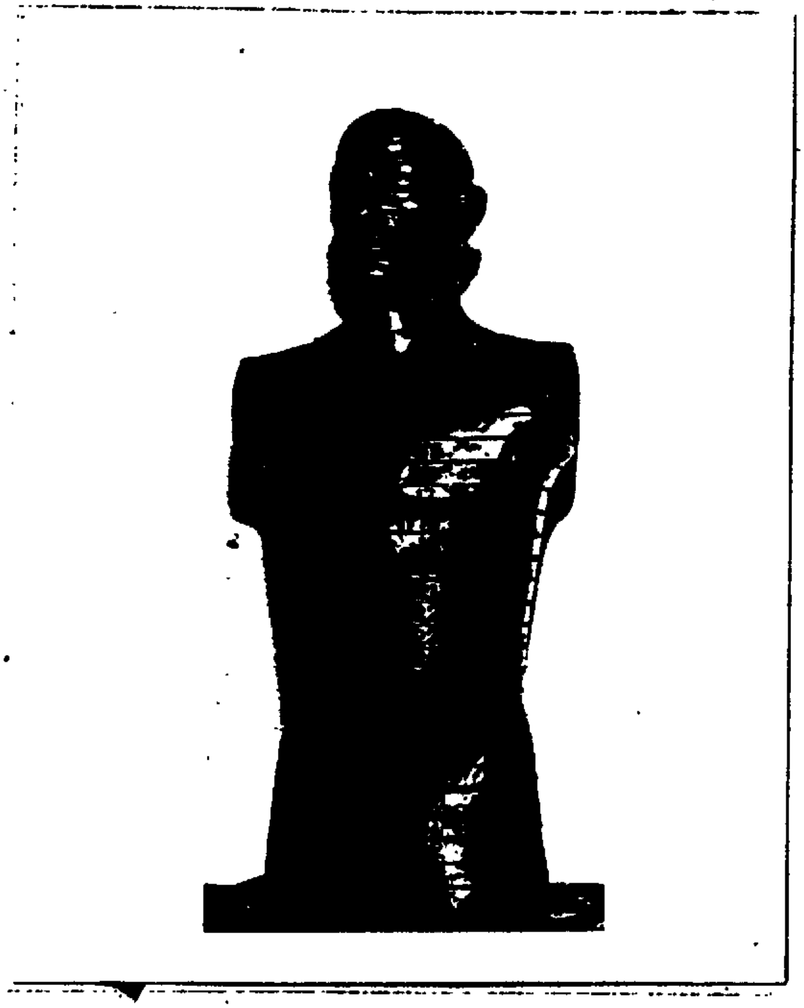


Figure 1. Sections of the Rando phantom

Sections 1 through 34 have a number of evenly spaced vertical holes with a 0.5 cm diameter. For each of these sections there is a companion full-size translucent line drawing which shows the exact locations of the predrilled holes. The holes accommodate lucite capsules 0.5 cm in diameter by 2.5 cm long. To measure radiation dose, the capsules are filled with lithium fluoride (TLD-100) and placed in the desired positions. Extra holes can be drilled where necessary.

To locate the bone structure in the phantom, radiographs of each of the sections one to thirty-four were taken (see

Figure 2). The evenly spaced predrilled holes and the bone structures are clearly delineated on the radiograph. The translucent line drawings of the sections were placed over the corresponding radiographs and the bone structures were traced on the paper as shown in Figure 3. The filled dosimeters were judiciously placed in the bone cavities as demonstrated by the radiographs and corresponding drawings. More than 200 capsules were loaded into the phantom for each of the three procedures described below. In most cases the capsules contained enough powder for two dose measurements.

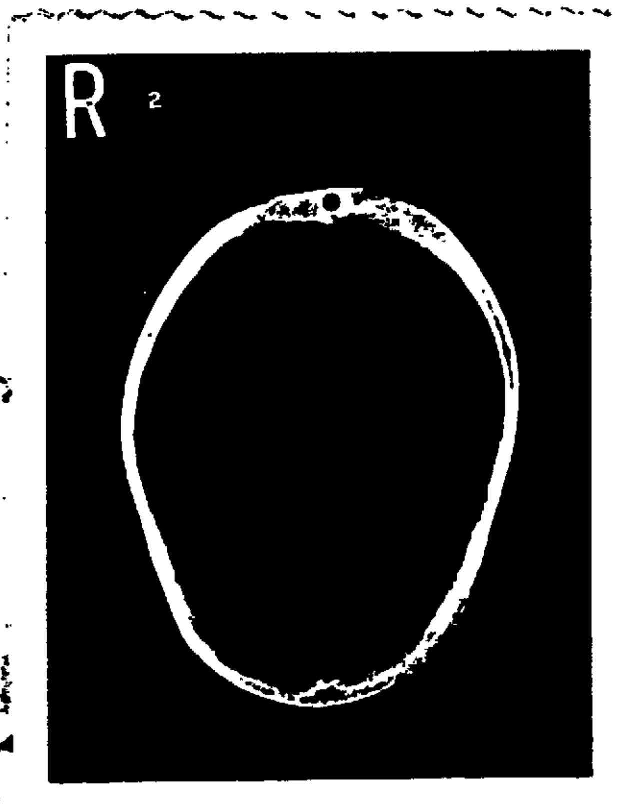


Figure 2. Radiograph of Rando phantom Section 2

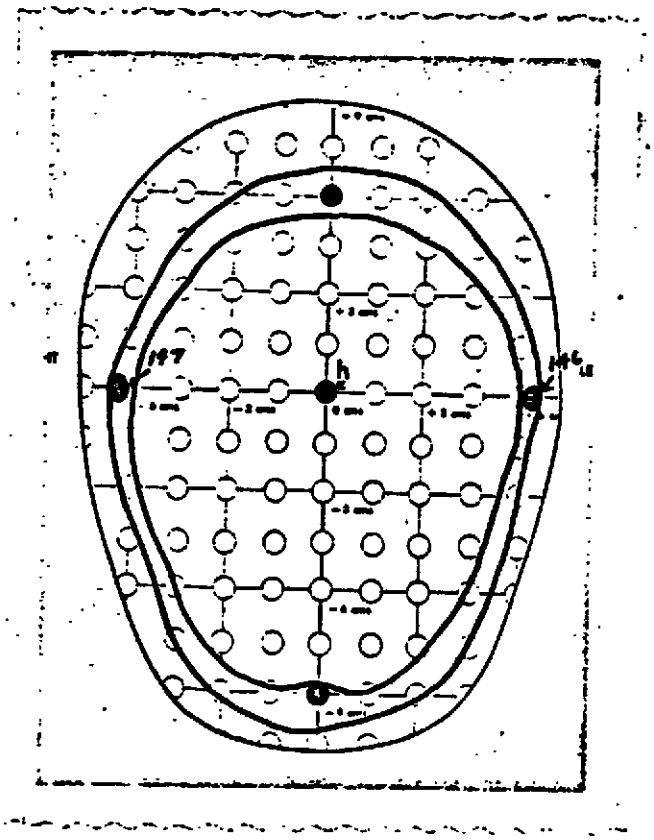


Figure 3. Line drawing of Section 2 with outline of bone structure

C. Defining the Phantom Exposure

It was decided at the outset that three sets of measurements would be taken. This was done to approximate the three different whole and partial body ^{60}co irradiation procedures presently used at Cincinnati General Hospital (see Figures 4,5 and 6).

D. Calibration Procedures

When lithium fluoride powder is properly pre-treated and subsequently exposed to radiation, some of the electrons are raised to higher energy levels and trapped inside crystal

WHOLE BODY

1. Source to wall distance = 338 cm.
2. Source to center of phantom = 282 cm.
3. Central axis of beam between sections 19 and 20.
4. Field size = 74 x 74 cm at 282 cm.
5. Time = 27.8 minutes left side.
   27.8 minutes right side.
6. Air exposure = 5.4 Roentgens/minute at 282 cm.
7. Total air exposure = 300 Roentgens at 282 cm.

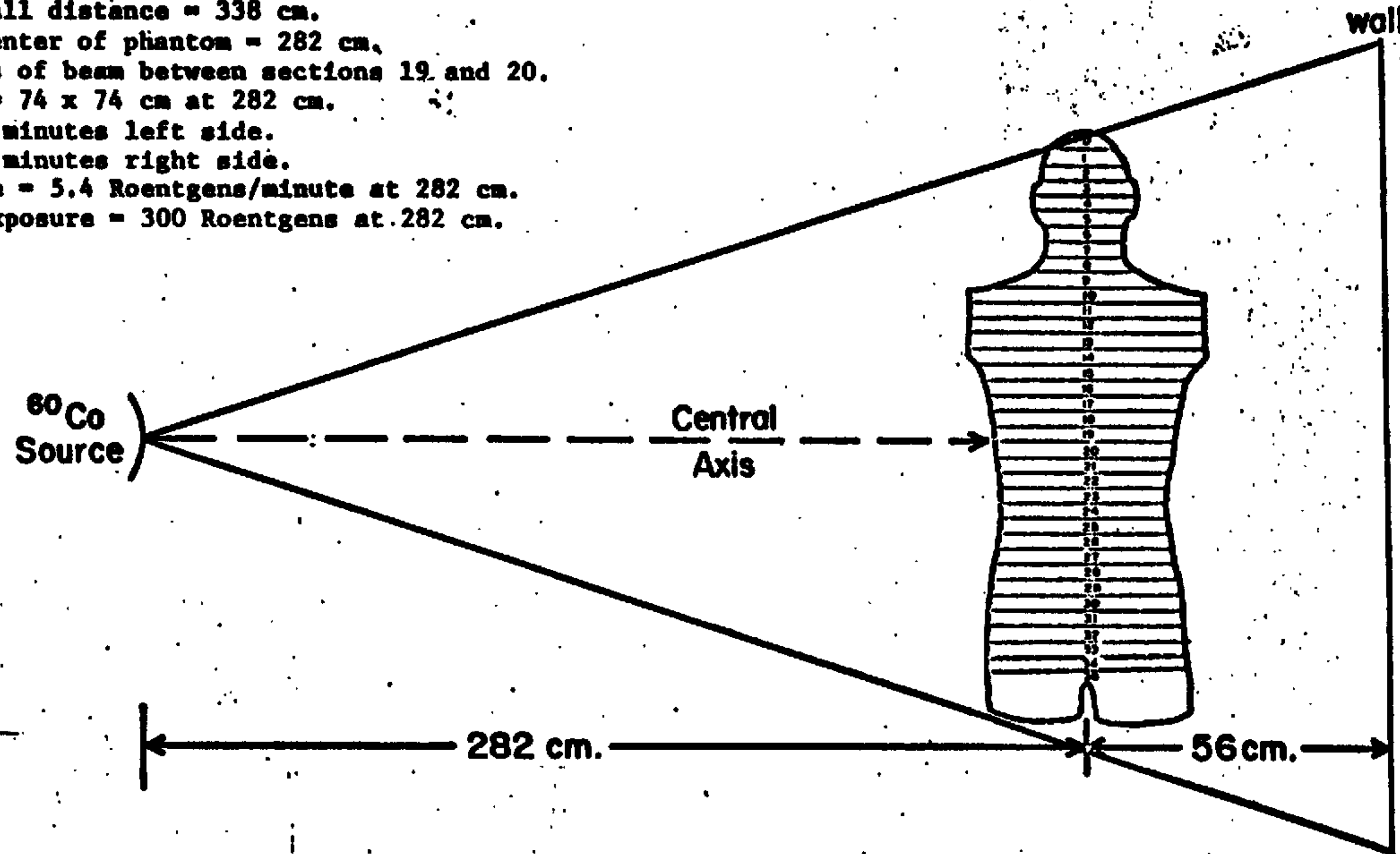


Figure 4. Procedure for whole body irradiation.

PARTIAL BODY (lower)

1. Source to wall distance = 338 cm.
2. Source to center of phantom = 282 cm.
3. Center axis beam at center of section 28.
4. Upper level of beam at lower portion of section 18.
5. Field size = 74 x 38 cm at 282 cm.
6. Exposure time = 27.8 minutes left side
   = 27.8 minutes right side
7. Air exposure = 5.4 Roentgens/minute at 282 cm.
8. Total air exposure = 300 R at 282 cm.

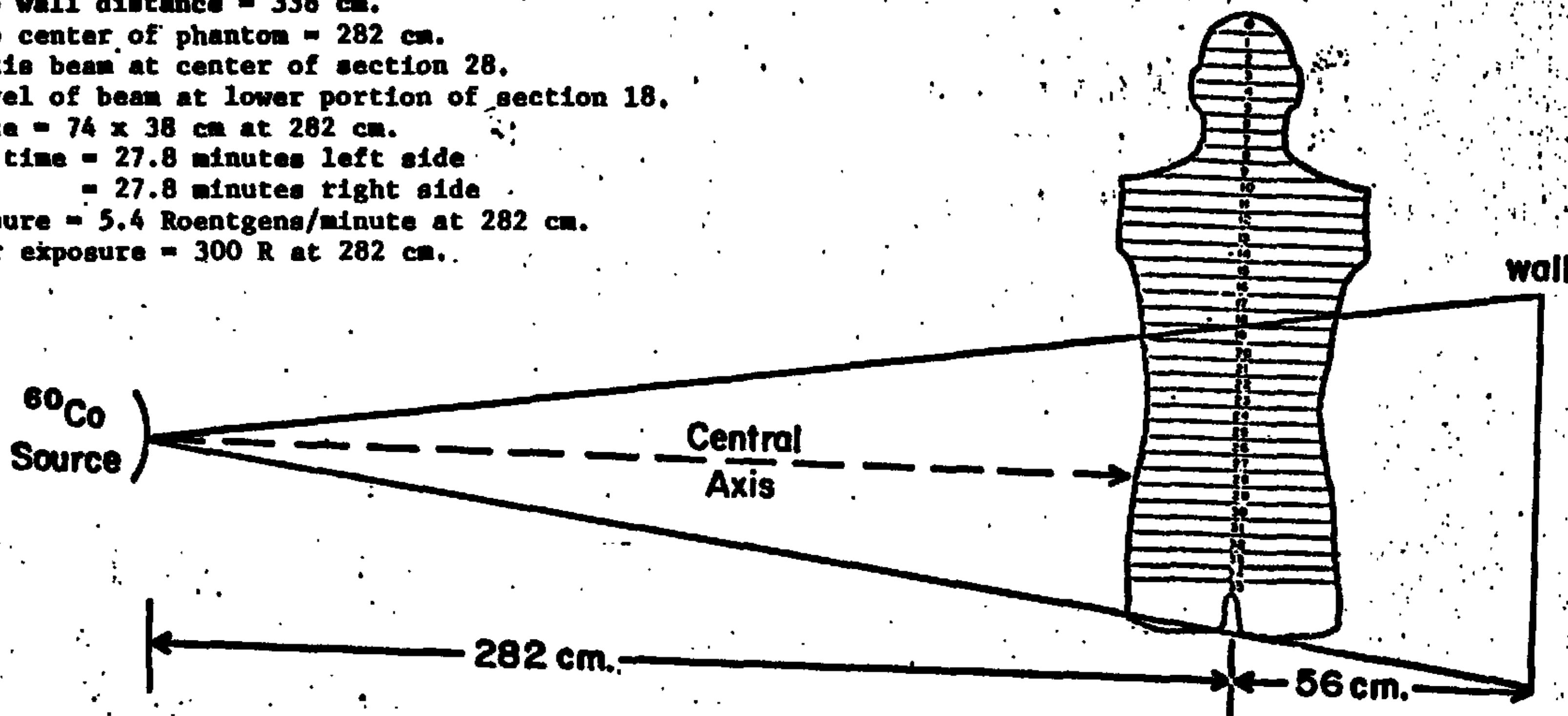
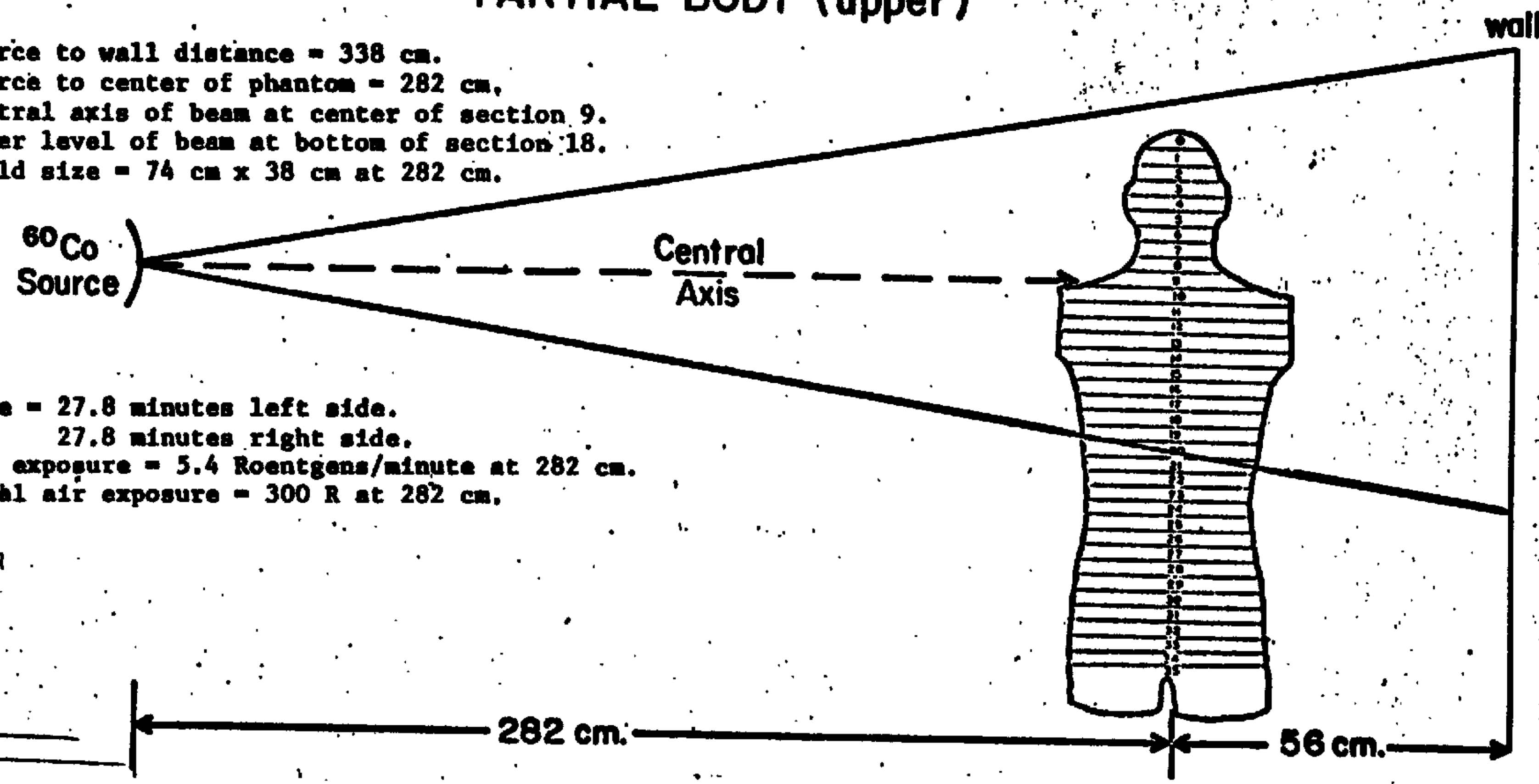


Figure 5. Procedure for partial body (lower) irradiation.

PARTIAL BODY (upper)

1. Source to wall distance = 338 cm.
2. Source to center of phantom = 282 cm.
3. Central axis of beam at center of section 9.
4. Lower level of beam at bottom of section 18.
5. Field size = 74 cm x 38 cm at 282 cm.



6. Time = 27.8 minutes left side.
   27.8 minutes right side.
7. Air exposure = 5.4 Roentgens/minute at 282 cm.
8. Total air exposure = 300 R at 282 cm.

Figure 6. Procedure for partial body (upper) irradiation.

lattices. Post-irradiation heating causes these electrons to fall back to lower energy levels. The consequent emission of electromagnetic radiation in the visible light region is detected by a photomultiplier tube and recorded with a digital counter. The light output of the powder is directly proportional to the quantity of radiation. Lithium fluoride shows only a slight photon energy dependence and virtually no dose-rate dependence (3).

After irradiation of the phantom in the experiment, the lithium fluoride powder is loaded into a receiving bin (4) from which a single aliquot of the powder is delivered into a heating pan. The pan is passed between electrodes and is heated rapidly to about 300 degrees centigrade. During the heating of the lithium fluoride, the electron energy shift takes place and light is emitted. For a given radiation exposure to a properly treated batch of lithium fluoride, a given amount of light will result and can be measured. A properly recorded light output over a certain period of time is called a "glow curve". It is essential that the time of heating and the temperature are identical for each measurement for consistent results. Experimentally, under the best conditions, the standard deviation for reproducibility of readings is about ± 0.5 percent. The heating of the powder and recording of the light is often termed "read-out".

Before valid results can be obtained using LiF, a calibration curve must be run to determine the specific number of light counts for each Roentgen of exposure. In the calibration procedure two Victoreen Condenser R chambers and a 100 R high energy air equivalent chamber were used. The 100R high energy chamber had been calibrated for ^{60}Co irradiation; the correct reading is obtained by multiplying the observed reading by 0.97. For the higher exposure levels a 250 R medium energy chamber calibrated for ^{60}Co was used. The correction factor was 1.45.

For the first calibration curve, two exposures of the appropriate condenser R chamber were made at each of eight different exposure times. The measured Roentgen values at each exposure time were averaged. Enough of the LiF filled lucite capsules were similarly exposed for 14 to 16 readings. These measured light output values were averaged. For the second and third calibration curves there were similarly two exposures of the appropriate condenser R chambers for each radiation exposure time. Seven or eight aliquots of the powder were "read-out" at each of the different times.

All exposures were made at an 80 cm source-chamber distance and a 10 cm x 10 cm field size. The times used and the calculated doses are given in Table 1.

Table 1

Calibration Curve Data for Relating Absorbed Dose to Net Counts

Exposure Time (sec)	Curve #1		Curve #2		Curve #3	
	Net Cts.*	Net Rads**	Net Cts.*	Net Rads**	Net Cts.*	Net Rads**
15	115	11.2256	126	10.8748	79	10.8748
30	250	24.4683	279	25.0822	152	25.0822
60	535	52.6200	606	53.1462	338	53.1462
90	846	78.9300	884	80.5963	516	80.5963
120	1173	110.3266	1260	112.2560	703	112.2560
180	1745	167.1562	1873	169.2610	1064	169.2610
240	2385	224.5997	2536	227.1430	1479	227.1430
300	3185	279.4122	3141	285.0250	1852	285.0250

* The net counts indicate the emitted light readings of the powder minus the counts of unexposed powder.

** The net Roentgen readings (as measured with the ion chambers) are converted to rads by multiplying by 0.877 rad/Roentgen.

To secure the "best fit" lines for the data, least square analyses were performed on all three sets (see Figures 7,8 and 9). The curves are defined by the equation $Y = b_o + b_1X$ where X is the net emitted light counts and Y is rads. b_o is the Y intercept and b_1 is the slope of the line. The 95 percent confidence bands for the lines are shown in the three graphs (6). The three curves were run in succession. The sensitivity of the powder (counts/rad) in calibration curve #2 is slightly greater than in curve #1. The sensitivity then drops in curve #3. The powder was fresh before curve #1 was run. Cameron et. al. (7) report that LiF powder can be reused and its sensitivity at first increases. Karzmark et. al. (8) indicate that the sensitivity is reduced by repeated exposure and reprocessing. This fact was very much in evidence after the third annealing procedure.

III RESULTS

A. Counting Procedures -- Conversion of Net Counts to Rads

The phantom was loaded and irradiated in the same manner for each of the three different exposures. The lucite capsules containing the LiF powder were removed and "read-out" 24 to 72 hours later. Check exposures were made on a subsequent date and the capsules were "read-out" 24 to 72 hours later.

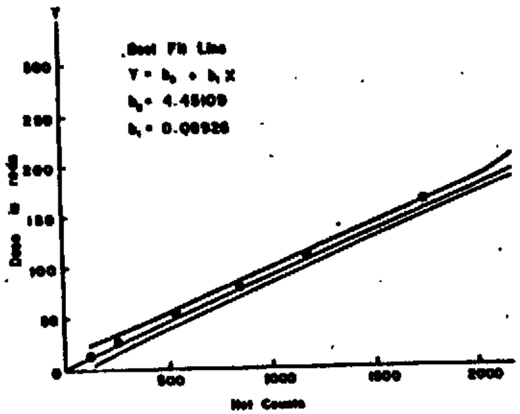


Fig.7. CALIBRATION CURVE #1
rads vs. Net Counts
[For whole body irradiation]

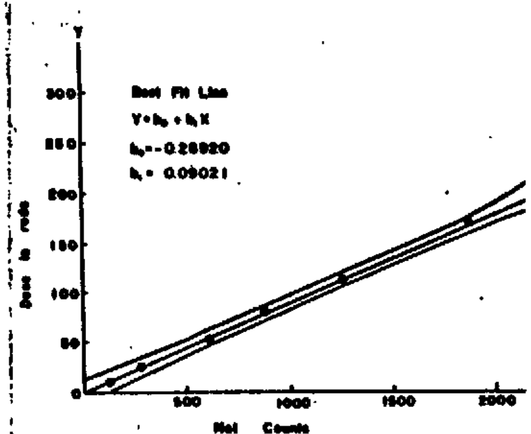


Fig.8. CALIBRATION CURVE #2
rads vs. Net Counts
[For partial body irradiation (lower)]

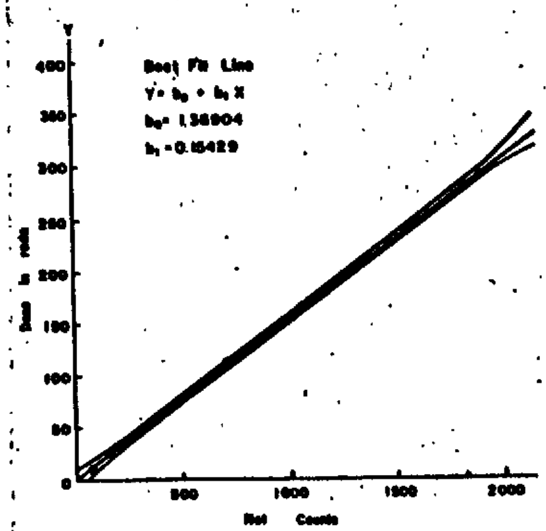


Fig.9. CALIBRATION CURVE #3
rads vs. Net Counts
[For partial body irradiation (upper)]

In nearly every instance a minimum of two aliquots of the LiF powder was contained in each capsule. Where only one aliquot was available, the reading was accepted. In all other instances the two readings were averaged. The net counts and corresponding net rads are indicated in Table 2 for the three different types of exposure. The dosimeter numbers define the dosimeter positions in the phantom.

B. Check Procedures

In order to substantiate the data, check measurements were made for each of the three different types of exposure. Dosimeters were placed randomly in the phantom and the exposures were duplicated. Tables 3,4, and 5 show the results of the check procedures for the three exposure conditions. Net counts are given for the first exposure and its check in each instance. The percent difference is shown and an average percent difference for all the dosimeters is calculated. The range of percent differences is also given.

IV INTERPRETATION OF THE DATA

The data collected by Mechanik (9) is the most complete treatise available on the weights of marrow in the bone of

Table 2. Doses as measured using lithium fluoride

Dosimeter Number	Whole Body Net Counts	Whole Body Rads	(Lower) Partial Body Net Counts	(Lower) Partial Body Rads	(Upper) Partial Body Net Counts	(Upper) Partial Body Rads
1	912	85.86	1998	179.95	16	3.84
2	867	81.84	1759	158.39	10	2.91
3	945	88.80	1901	171.20	21	4.61
4	937	88.09	1781	160.37	11	3.07
5	900	84.79	1761	158.57	16	3.84
6	998	93.53	2217	199.71	15	3.68
7	1060	99.07	2212	199.26	28	5.69
8	1172	109.06	2032	183.02	14	3.53
9	1160	108.00	2110	190.05	14	3.53
10	1063	99.33	2030	182.84	9	2.76
11	1356	125.49	2258	203.40	19	4.30
12	1352	125.13	2158	194.38	16	3.84
13	1288	119.42	2203	198.44	15	3.68
14	1323	122.54	2070	186.45	20	4.45
15	1240	115.13	2032	183.02	23	4.92
16	1527	140.75	2185	196.85	21	4.61
17	1581	145.57	2338	210.62	15	3.68
18	1584	145.84	2315	208.55	15	3.68
19	1521	140.22	2213	199.35	23	4.92
20	1454	134.24	2245	202.23	22	4.76
21	1540	141.91	2271	204.58	17	3.99
22	1534	141.38	2202	198.35	22	4.76
23	1786	163.87	2345	211.25	11	3.07
24	1602	147.45	2258	203.40	19	4.30
25	1681	154.50	2225	200.43	10	2.91
26	1644	151.19	2205	198.62	20	4.45
27	1613	148.43	2131	191.95	16	3.84
28	1603	147.53	2260	203.59	14	3.53
29	1664	152.98	2327	209.63	15	3.68
30	1660	152.62	2309	208.01	16	3.84
31	1641	150.93	2272	204.67	18	4.15
32	1735	159.32	2233	201.15	15	3.68
33	1710	157.09	2220	199.98	14	3.53
34	1702	156.37	2226	200.52	20	4.45
35	1785	163.78	2343	211.07	21	4.61
36	1776	162.98	2276	205.03	18	4.15
37	1796	164.76	2483	223.70	24	5.07
38	1794	164.58	2355	212.16	23	4.92
39	1901	174.13	2455	221.18	47	8.62
40	1893	173.42	2364	212.97	42	7.85
41	1862	171.10	2463	221.90	30	6.00
42	1925	176.28	2427	218.65	41	7.69
43	1792	164.41	2303	207.46	29	5.84
44	1712	157.26	2294	206.65	29	5.84
45	1903	174.32	2330	209.90	51	9.24
46	1955	178.95	2434	219.28	37	7.08
47	1836	168.33	—		46	8.47
48	1847	169.31	2310	208.10	51	9.24
49	1901	174.13	2306	207.74	53	9.55
50	1840	168.70	2216	199.62	34	6.61
51	1795	164.67	2199	198.08	31	6.15
52	1886	172.80	2207	198.80	41	7.69
53	2122	193.86	1437	129.34	59	10.47

Table 2. (continued)

Dosimeter Number	Whole Body Net Counts	Whole Body Rads	(Lower) Partial Body Net Counts	(Lower) Partial Body Rads	(Upper) Partial Body Net Counts	(Upper) Partial Body Rads
54	2034	186.01	1497	134.76	73	12.63
55	1974	180.65	1485	133.67	72	12.48
56	1938	177.44	1478	133.04	71	12.32
57	1734	159.23	1320	188.79	52	9.39
58	1655	152.18	1348	121.31	55	9.85
59	1635	150.39	1372	123.48	48	8.77
60	1829	167.71	1422	127.99	62	10.94
61	2109	192.70	313	27.95	85	14.48
62	2324	211.89	344	30.74	83	14.18
63	2322	211.71	473	42.38	91	15.41
64	1977	180.92	361	32.28	82	14.02
65	1786	163.87	364	32.55	83	14.18
66	1738	159.58	379	33.90	88	14.95
67	1823	167.17	362	32.37	78	13.40
68	1900	174.05	355	31.74	82	14.02
69	1993	182.35	149	13.15	477	74.97
70	2047	187.17	147	12.97	458	72.03
71	1919	175.74	161	14.23	413	65.09
72	1809	165.92	139	12.25	363	57.38
73	1727	158.60	140	12.34	368	58.15
74	1688	155.12	147	12.97	374	59.07
75	1592	146.55	130	11.44	378	59.69
76	1725	158.42	136	11.98	349	55.22
77	2165	197.70	113	9.90	940	146.40
78	1858	170.30	88	7.65	1124	174.79
79	1547	142.54	100	8.73	728	113.69
80	1797	164.85	62	5.30	1175	182.66
81	1819	166.82	70	6.03	964	150.10
82	1755	161.10	68	5.85	979	152.42
83	1809	165.92	92	8.01	1042	162.14
84	1903	174.31	73	6.30	1023	159.21
85	1587	146.11	70	6.03	840	130.97
86	1596	146.91	55	4.67	853	132.98
87	1438	132.81	61	5.21	776	121.10
88	1543	142.18	71	6.12	861	134.21
89	1249	115.94	—		—	
90	1225	113.79	53	4.49	925	144.09
91	1293	119.86	51	4.31	855	133.29
92	1750	160.66	54	4.58	1009	157.05
93	1613	148.43	69	5.94	906	141.16
94	1557	143.43	56	4.76	873	136.06
95	1738	159.58	53	4.49	—	
96	1715	160.66	55	4.67	967	150.57
97	1415	130.75	62	5.30	814	126.96
98	1701	156.28	48	4.04	943	146.86
99	1391	128.61	42	3.50	1285	199.63
100	1608	147.98	46	3.86	1076	167.39
101	1499	138.25	44	3.68	1027	159.82
102	1178	109.60	43	3.59	777	121.25
103	1231	114.33	—		809	126.19
104	1605	147.71	47	3.95	961	149.64
105	1693	155.57	53	4.49	1055	164.14

Table 2 (continued)

Dosimeter Number	Whole Body Net Counts	Whole Body Rads	(Lower) Partial Body Net Counts	(Lower) Partial Body Rads	(Upper) Partial Body Net Counts	(Upper) Partial Body Rads
106	1414	130.66	40	3.32	840	130.97
107	1377	127.36	57	4.85	841	131.13
108	1222	113.53	49	4.13	805	125.57
109	1537	141.64	50	4.22	999	155.50
110	1482	136.73	48	4.04	1023	159.21
111	1318	122.10	a 43	3.60	a 1024	159.36
			b 71	6.12	b 995	154.89
112	2209	201.63	40	3.32	1499	232.65
113	2038	186.36	26	2.96	1498	232.50
114	1307	121.11	44	3.68	—	
115	--		32	2.60	1104	171.70
116	1422	131.38	39	3.23	1085	168.77
117	1453	134.15	53	4.49	1069	166.31
118	1345	124.51	40	3.32	1085	168.77
119	1388	128.34	29	2.33	1061	165.07
120	1784	163.69	38	3.14	1162	180.65
121	1932	176.90	31	2.51	1309	203.33
122	2077	189.84	44	3.68	1475	228.95
123	1873	171.64	50	4.22	1615	250.55
124	1912	175.12	62	5.30	1516	235.27
125	1958	179.22	52	4.40	1540	238.98
126	1502	138.52	31	2.51	1481	229.87
127	1434	132.45	66	5.66	1465	227.40
128	1432	132.27	35	2.87	1457	226.17
129	1149	103.01	50	4.22	1475	228.95
130	1157	107.72	44	3.68	1478	229.41
131	1168	108.71	38	3.14	1513	234.85
132	1107	103.26	22	1.70	1444	224.16
133	1131	105.40	27	2.15	1345	208.89
134	1124	104.78	26	2.06	1359	211.05
135	1199	111.47	30	2.42	1482	230.03
136	762	72.47	21	1.61	1387	215.37
137	770	73.18	12	0.79	1402	217.68
138	788	74.79	19	1.42	1336	207.50
139	784	74.43	31	2,51	1312	203.80
140	926	87.11	31	2.51	1511	234.50
141	456	45.15	31	2.51	1468	227.87
142	468	46.22	20	1.52	1250	194.23
143	458	45.33	23	1.79	1218	189.29
144	567	55.06	14	0.97	1354	210.28
145	209	23.11	23	1.79	1255	195.00
146	247	26.50	24	1.88	1188	184.67
147	243	26.14	23	1.79	1185	184.20
148	279	29.35	35	2.87	1265	196.55
149	150	17.84	07	0.34	823	128.35
150	159	18.64	15	1.06	839	130.82
151	152	18.02	20	1.52	822	128.20
152	158	18.55	16	1.15	859	133.90

Table 2. (continued)

Dosimeter Number	Whole Body Net Counts	Whole Body Rads	(Lower) Partial Body Net Counts	(Lower) Partial Body Rads	(Upper) Partial Body Net Counts	(Upper) Partial Body Rads
A = 34	909	85.59	1752	157.76	7	2.45
B = 33	1086	101.39	2079	187.26	14	3.53
C = 32	1246	115.67	2023	182.21	13	3.37
D = 31	1514	139.59	2237	201.51	14	3.53
E = 30	1673	153.78	2255	203.13	26	5.38
F = 29	1647	151.46	2113	190.32	19	4.30
G = 28	1712	157.26	2251	202.77	19	4.30
H = 27	1756	161.19	2150	193.66	16	3.84
I = 26	1839	168.60	2397	215.94	24	5.07
J = 25	1853	169.85	2315	208.55	28	5.69
K = 24	1807	165.74	2303	207.46	39	7.39
L = 23	1839	168.60	—	—	41	7.69
M = 22	1900	174.05	1923	173.18	56	10.01
N = 21	1910	174.94	1524	137.19	72	12.48
O = 20	2198	200.64	965	86.76	87	14.79
P = 19	2223	202.88	453	40.58	96	16.18
Q = 18	2144	195.82	270	24.07	116	19.27
R = 17	2114	193.15	209	18.56	224	35.93
S = 16	2006	183.51	168	14.87	399	62.93
T = 15	1746	160.30	122	10.72	661	103.35
U = 14	1680	154.41	97	8.46	864	134.68
V = 13	1626	149.59	66	5.66	929	144.70
W = 12	1493	137.72	52	4.40	856	133.44
X = 11	1324	122.63	42	3.50	836	130.36
Y = 10	1191	110.76	31	2.51	993	134.68
Z = 9	1865	170.92	33	2.69	1379	214.13
a = 8	2134	194.93	46	3.86	1452	225.40
b = 7	1921	175.92	44	3.68	1510	234.35
c = 6	1387	128.25	35	2.87	1465	227.40
d = 5	1142	106.39	31	2.51	1406	218.30
e = 4	792	75.15	37	3.05	1337	207.65
f = 3	465	45.96	23	1.79	1230	191.15
g						
h = 2	266	28.19	21	1.61	1167	181.43
i = 1	147	17.57	28	2.24	840	130.97

Table 2. (continued)

Dosimeter Number		Whole Body Net Counts	Whole Body Rads	(Lower) Partial Body Net Counts	(Lower) Partial Body Rads	(Upper) Partial Body Net Counts	(Upper) Partial Body Rads
13 LL		1637	150.57	79	6.84	827	128.97
13 RL		1635	150.39	83	7.20	905	141.00
16 LL	Lungs	1978	181.01	160	14.14	442	69.57
16 RL		1992	182.26	157	13.87	435	68.49
19 LL		2282	208.14	390	34.89	95	16.02
19 RL		2189	199.84	390	34.89	98	16.49
21 La		1961	179.49	1498	134.85	70	12.17
21 Lb		1927	176.46	1494	134.48	57	10.16
21 Lc		1957	179.13	1427	128.44	71	12.32
23 La	Liver	1782	163.51	2409	217.03	42	7.85
23 La		1749	160.57	2298	207.01	47	8.62
24 La		1868	171.19	2479	223.34	80	6.00
24 Lb		1883	172.53	2512	226.32	31	6.15
25 La		1877	171.99	2413	217.39	33	6.46
25 Lb		1908	174.76	2449	220.64	27	5.53
20 Spl	Spleen	2198	200.64	947	85.14	73	12.63
21 Spl		1940	177.62	1526	137.37	59	10.47
23 L Kid		1835	168.24	2286	205.93	38	7.23
23 R Kid		1741	159.85	2271	204.58	41	7.69
24 L Kid		1761	161.64	2341	210.89	39	7.39
24 R Kid		1881	172.35	2424	218.38	40	7.54
25 L Kid	Kidneys	1846	169.23	2324	209.36	23	4.92
25 R Kid		1804	165.48	2378	214.23	47	8.62
26 L Kid		1822	167.08	2450	220.73	27	5.53
26 R Kid		1800	165.12	2338	210.62	19	4.30
13 13 L	Humeral Heads and Necks	—		80	6.93	1040	161.83
13 13 R		—		77	6.66	1025	159.52
16 Misc L		2056	187.97	141	12.43	354	55.99
16 Misc R		2127	194.31	144	12.70	349	55.22
31 L Ov		1636	150.48	2289	206.20	27	5.53
31 R Ov	Ovaries	1595	146.82	2272	204.67	25	5.22
32 L Ov		1456	134.41	2302	207.37	12	3.22
32 R Ov		1369	126.65	2178	196.19	32	6.31
31 Uterus	Uterus	1590	146.37	2306	207.74	15	3.68
32 Uterus		1285	119.15	2062	185.72	16	3.83

Table 3

Lithium Fluoride Measurements (Check) for Whole Body Exposure

Dosimeter #	Net Counts	Check Net Counts	% Difference
A	909	917	+ 0.9
D	1514	1519	+ 0.3
23	1786	1655	- 7.3
24	1602	1621	+ 1.2
G	1712	1664	- 2.8
J	1853	1720	- 4.5
39	1901	1925	+ 1.3
M	1900	1786	- 6.0
R	2114	2008	- 5.0
R MISC	2127	2134	+ 0.4
L MISC	2056	2013	- 2.1
X	1324	1347	+ 1.7
100	1608	1574	- 2.1
105	1693	1716	+ 1.4
120	1784	1794	+ 0.6
a	2134	2042	- 4.3
123	1873	1811	- 3.3
d	1142	1109	- 2.9
135	1199	1205	+ 0.5
149	150	147	- 2.0
152	158	153	- 3.2
i	147	155	+ 5.4

Average difference = -1.45%

Range - 7.3% to + 5.4%

Table 4

Lithium Fluoride Measurements (Check) for Partial Body (Lower) Exposure

Dosimeter Number	Net Counts	Check Net Counts	% Difference
M	1923	1855	- 3.5
45	2230	2284	- 1.9
46	2434	2328	- 4.3
39	2455	2418	- 1.5
40	2364	2343	- 0.9
41	2463	2394	- 2.8
42	2427	2448	+ 0.9
J	2315	2302	- 0.6
34	2226	2305	+ 3.5
G	2251	2244	- 0.3
30	2345	2328	- 0.7
24	2258	2308	+ 2.2
31 L Ovary	2289	2293	+ 0.2
D	2237	2194	- 1.9
A	1752	1783	+ 1.8

Average difference = -0.65%

Range = - 3.5% to + 3.5%

Table 5

Lithium Fluoride Measurements (Check) for Partial Body (Upper) Exposure

Dosimeter Number	Net Counts	Check Net Counts	% Difference
1	840	723	-13.9
142	1250	1208	- 3.4
130	1478	1371	- 7.2
135	1482	1364	- 8.0
123	1615	1534	- 6.3
a	1452	1444	- 0.6
120	1162	1196	+ 2.9
x	836	804	- 3.8
80	1175	1152	- 2.0
85	840	840	0.0
13 L	1040	1012	- 2.7
T	661	662	+ 2.2
S	399	444	+11.3
R	224	258	+15.2

Average difference = - 1.31%

Range = -13.9% to + 15.2%

humans. Woodard & Holodny (10) have summarized the data of Mechanik. Mechanik dissected thirteen cadavers including six men and seven women. The ages ranged from 16 to 86 years and the causes of death were as follows:

1) Senile marasmus - 4
2) Pneumonia - 3
3) Tuberculosis - 3
4) Heart disease - 2
5) Malaria - 1

Mechanik removed the fresh bones and weighed them. The marrow was then removed and the bones reweighed, the difference representing the marrow weight. In the case of opposite side duplication, only the right side marrow was considered.

Ellis (11) further reviewed the literature on the distribution of active marrow. Using Mechanik's data and the works of Piney (12), Huggins and Blocksom (13), and Custer (14), Ellis arrived at the conclusion that the "active" marrow in the adult is contained in the skull, clavicles, scapulae, sternum, ribs, vertebrae, pelvis, and proximal extremities. Custer's work shows the percent of the marrow which is "active" at certain ages. Ellis used the figures for age 40 and averaged the weights of the marrow for twelve of the thirteen cadavers. He removed from consideration a 15 year old boy because of his obvious emaciation. The summary of Ellis' work is shown in Table 6. This will serve as a reference point for all of our considerations in calculating "active" bone marrow doses.

Many of the dosimeter positions could be identified for correlation with Table 6, but many of the bones pass through more than one of the parallel sections of the phantom. In order to determine more closely dosimeter positions, a skeleton of approximately the same size as that in the phantom was secured. The skeleton was carefully measured into 35 parallel sections which were as identical to the 35 phantom sections as possible. The sections were then marked off with a very thin plastic tape. (see Figure 10).

The previously mentioned radiographs of each section were then compared with the sections as marked on the skeleton. Numbered markers were placed as close to the exact locations of the lucite dosimeters as was possible. By this method the bones and specific locations were determined for all of the dosimeters (see Figure 11).

The average rad dose to each section of the marrow could be determined by using the data in Table 6, and the dosimeter placement just described.

Table 6

Marrow Distribution of the Adult

	Marrow wt. (g)	Fraction red marrow age 40	Red marrow wt. age 40 (g)		% Total red marrow
Head				136.6	13.1
Cranium	165.8	0.75	124.3		
Mandible	16.4	0.75	12.3		
Upper Limb Girdle				86.7	8.3
2 Humerus, head			20.0		
and neck	26.5	0.75	50.5		
2 Scapulae	67.4	0.75	16.2		
2 Clavicles	21.6	0.75	~~[illegible]~~	23.4	2.3
Sternum	39.0	0.6	25.[illegible]	82.6	7.9
Ribs			4.1		
1 pair	10.2	All 0.4	5.0		
2	12.6		6.4		
3	16.0		7.4		
4	18.6		9.5		
5	23.8		9.4		
6	23.6		10.0		
7	25.0		9.6		
8	24.0		8.5		
9	21.2		6.4		
10	16.0		4.5		
11	11.2		1.8		
12	4.6			35.8	3.4
Vertebrae (Cervical)			5.0		
1	6.6	All 0.75	6.3		
2	8.4		4.1		
3	5.4		4.3		
4	5.7		4.4		
5	5.8		5.3		
6	7.0		6.4		
7	8.5			147.9	14.1
Vertebrae (Thoracic)			8.1		
1	10.8	All 0.75	8.8		
2	11.7		8.5		
3	11.4		9.1		
4	12.2		10.1		
5	13.4		11.5		
6	15.3		12.1		
7	16.1		13.9		
8	18.5		14.8		
9	19.7		15.9		
10	21.2		16.3		
11	21.7		18.8		
12	25.0			114.1	10.9
Vertebrae (Lumbar)			20.8		
1	27.8	All 0.75	21.8		
2	29.1		23.8		
3	31.8		24.1		
4	32.1		23.6		
5	31.4		145.6	145.6	13.9
Sacrum	194.0	0.75		273.0	26.1
Lower Limb Girdle			233.0		
2 Os coxae	310.6	0.75			
2 Femoral heads and necks	53.0	0.75	40.0		
Total	1497.7		1045.7	1045.7	100.0

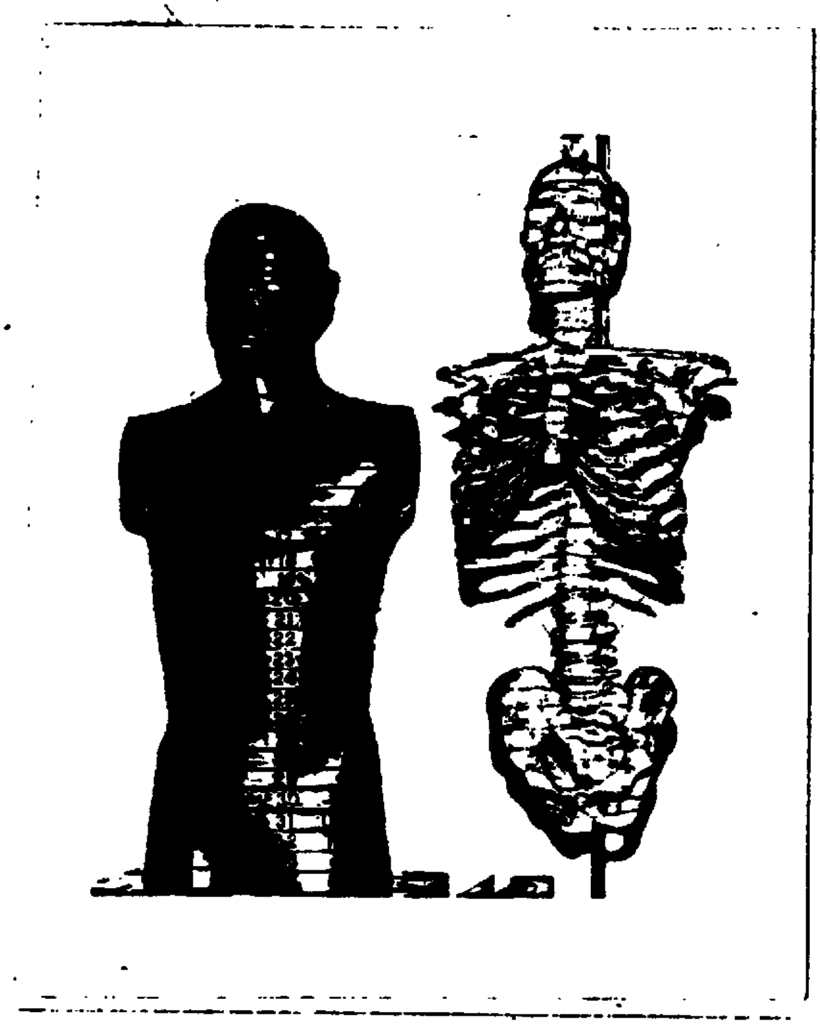


Fig. 10. Comparison of skeleton sections with phantom sections.

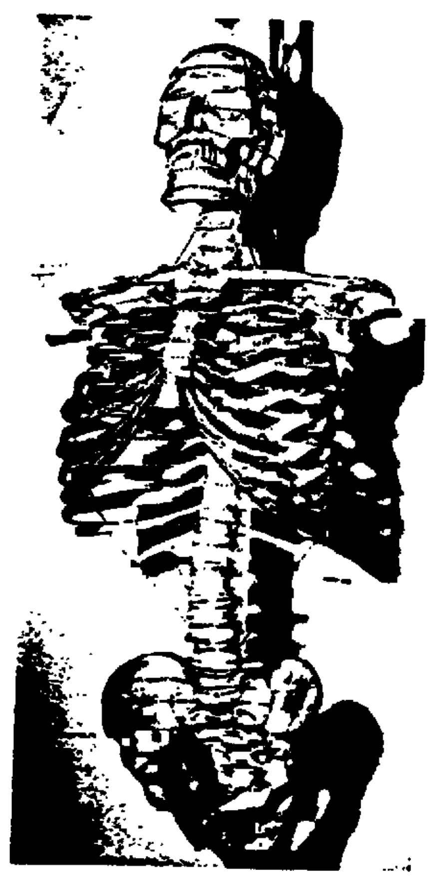


Fig. 11. Location of dosimeters in the skeleton

The anatomical positions listed in Table 6 will be followed in order, and the average doses in rads will be determined.

A. Ribs (see Figure 12)

The methods of determining the dose in rads for each of the rib pairs are as follows:

1. The values used are the averages of the right side and the left side values.
2. When there are two or three values for a particular individual rib, the values are averaged.
3. When there is no measurement for a particular rib, the value used is an interpolation between its superior and inferior member.

The dose to each pair of ribs is shown in Table 7.

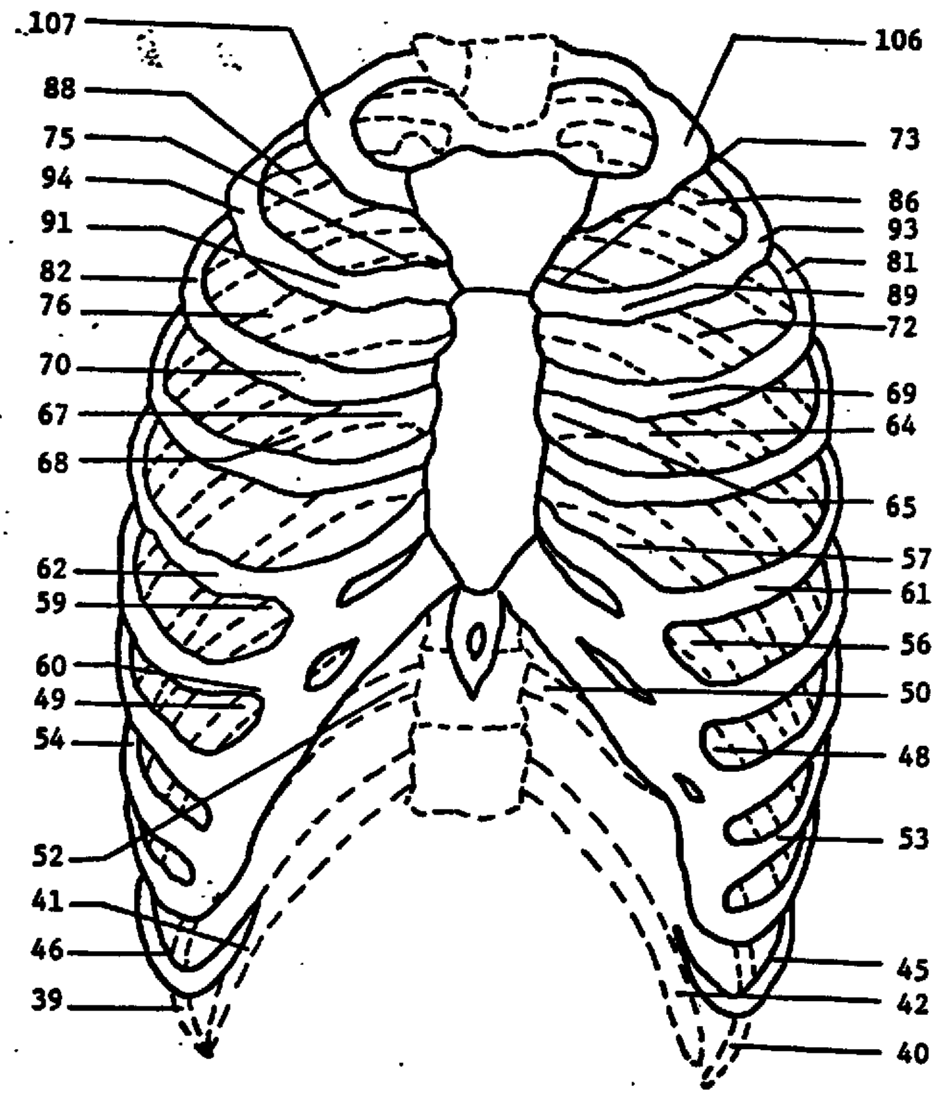


Figure 12. Dosimeter placement in the ribs.

Table 7

Total Gram-rads to the Active Marrow of the Ribs

Rib Number	Active Marrow Wt. at Age 40 (gm.)	Whole Body		Partial Body (Lower)		Partial Body (Upper)	
		rads	gm-rads	rads	gm-rads	rads	gm-rads
1	4.1	129.01	528.941	4.09	16.769	131.05	537.305
2	5.0	156.92	784.600	4.83	24.150	135.95	679.750
3	6.4	164.42	1052.288	8.13	52.032	119.45	764.480
4	7.4	168.39	1246.086	12.96	95.904	81.32	601.768
Totals	22.9		3611.915		188.855		2583.303
5	9.5	172.35	1637.325	17.78	168.910	43.18	410.210
6	9.4	171.93	1616.142	25.01	235.094	28.55	268.370
7	10.0	171.50	1715.000	32.24	322.400	13.91	139.100
8	9.6	189.94	1823.424	132.05	1267.680	11.56	110.976
Totals	38.5		6791.891		1994.084		928.656
9	8.5	163.69	1391.365	125.83	1069.555	10.36	88.060
10	6.4	174.18	1114.752	211.26	1352.064	8.78	56.192
11	4.5	172.24	775.080	208.14	936.630	7.69	34.605
12	1.8	173.69	312.642	220.28	396.504	6.85	12.330
Totals	21.2		3593.839		3754.753		191.187

B. Cranium (see Figure 13)

Figure 13 shows the position of all the dosimeters placed in the skull and mandible. Arbitrarily the heavy black line divides the cranium into two halves. The contribution of each half is to be 50% of the total dose. The data are shown in Table 8.

C. Mandible (see Figure 13)

The mandible is divided arbitrarily into two halves as was the cranium. The dose values are shown in Table 9.

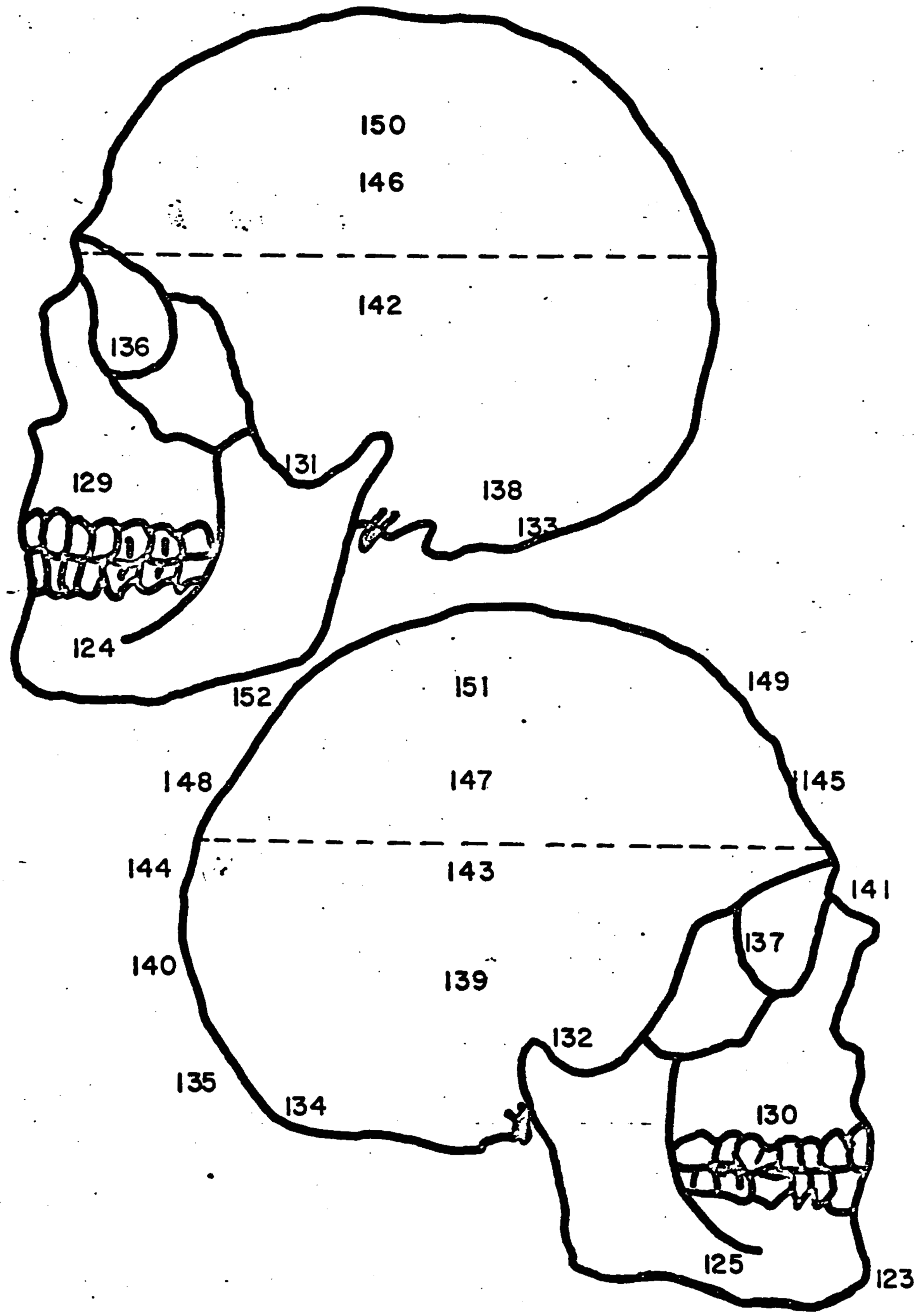


Figure 13. Dosimeter placement in the cranium and mandible.

Table 8. Dose to the cranium

Dosimeter Number		Whole Body rads	Partial Body (Lower) rads	Partial Body (Upper) rads
152		18.55	1.15	133.90
151		18.02	1.52	128.20
149		17.84	0.34	128.35
150	50%	18.64	1.06	130.82
148		29.35	2.87	196.55
147		26.14	1.79	184.20
145		23.11	1.79	195.00
146		26.50	1.88	184.67
Rads to upper one-half of cranium	=	8/178.15 = 22.27	8/12.40 = 1.55	8/1281.69 = 160.21
141		45.15	2.51	227.87
137		73.18	0.79	217.68
143		45.33	1.79	189.29
144		55.06	0.97	210.28
136		72.47	1.61	215.37
142		46.22	1.52	194.23
130		107.72	3.68	229.41
132		103.26	1.70	224.16
139	50%	74.43	2.51	203.80
140		87.11	2.51	234.50
134		104.78	2.06	211.05
135		111.47	2.42	230.03
129		107.01	4.22	228.95
131		108.71	3.14	234.81
138		74.79	1.42	207.50
133		105.40	2.15	208.89
Rads to lower one-half of cranium	=	16/1322.09 = 82.63	= 16/35.00 = 2.19	= 16/3467.82 = 216.74
Net rads to cranium	=	2/22.27 + 82.63	= 2/1.55 + 2.19	= 2/160.21 + 216.74
	=	52.45	= 1.87	= 188.48

Table 9. Dose to the mandible

Dosimeter Number	Whole Body rads	Partial Body (lower) rads	Partial Body (upper) rads
131	108.71	3.14	234.81
132 50%	103.26	1.70	224.16
rads to upper	= 2/211.07	= 2/4.84	= 2/458.97
one-half of mandible	= 105.54	= 2.42	= 229.49
124	175.12	5.30	235.27
123 50%	171.64	4.22	250.55
125	179.22	4.40	238.98
rads to lower one-half of	= 3/525.98	= 3/13.92	= 3/724.80
mandible	= 175.33	= 4.64	= 241.60
net rads to	= 2/105.54 + 175.33	= 2/2.42 + 4.64	= 2/229.49 + 241.60
mandible	= 140.44	= 3.53	= 235.55

D. Scapulae and Humeral Heads and Necks (see Figure 14)

The scapulae were again arbitrarily divided by the dotted lines as shown in Figure 14 with each section contributing 50% to the total dose. The dose values for the humeral heads and necks are represented by dosimeters 13L and 13R (see Table 10).

E. Clavicles (see Figure 15)

The three measured dose values were averaged to arrive at the number of rads to each clavicle. The right and left clavicle rads were then averaged. The results are shown below in Table 11.

F. Sternum (see Figure 15)

The rad values for the dosimeters shown in Figure 15 were averaged. The results are shown in Table 11.

Table 11. Dose to the clavicles and sternum.

Skeletal Anatomy	Whole Body rads	Partial Body (Lower) rads	Partial Body (Upper) rads
Clavicles	149.89	3.89	184.07
Sternum	155.44	6.31	163.00

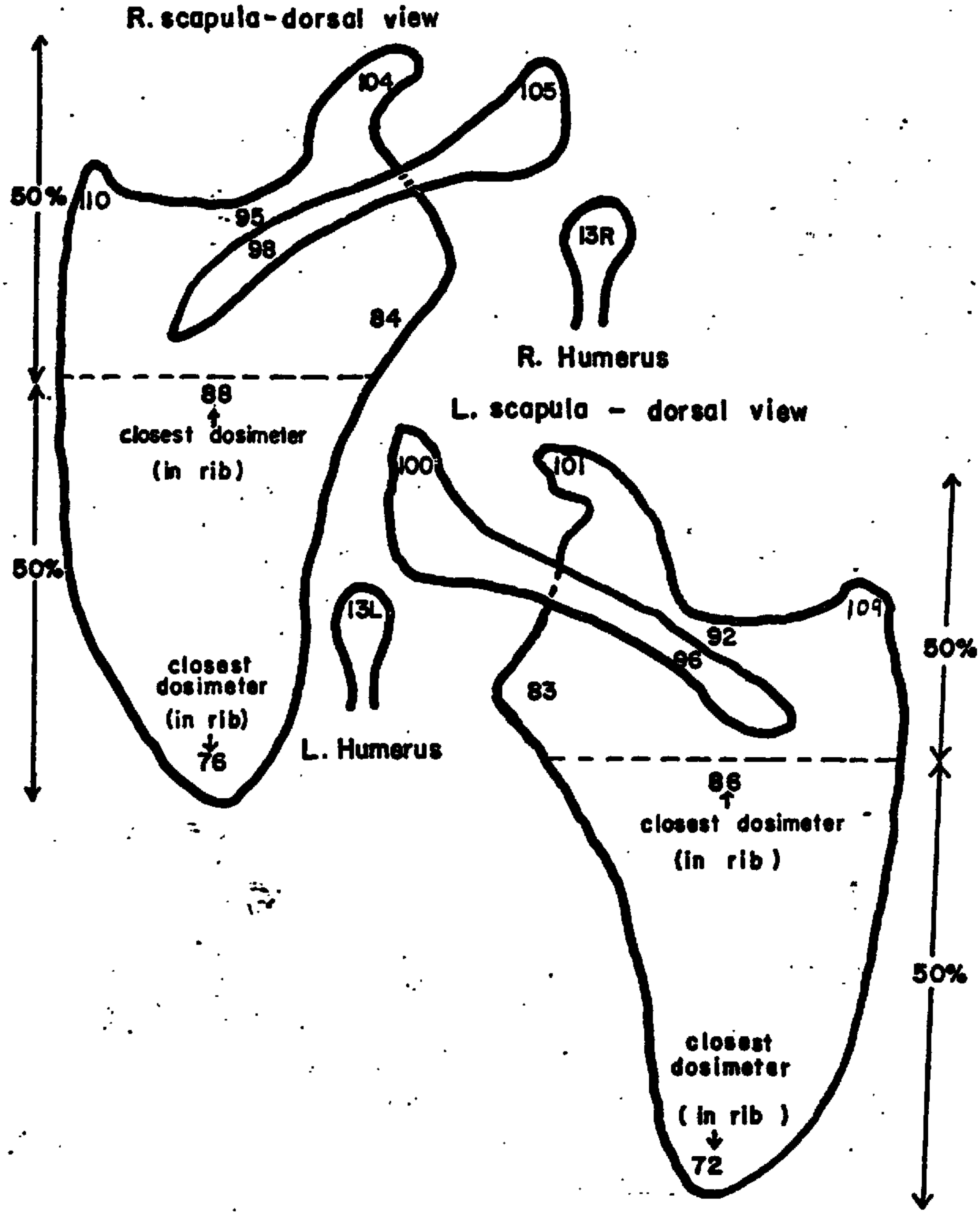


Figure 14. Dosimeter placement in the scapulae and humeral heads and necks.

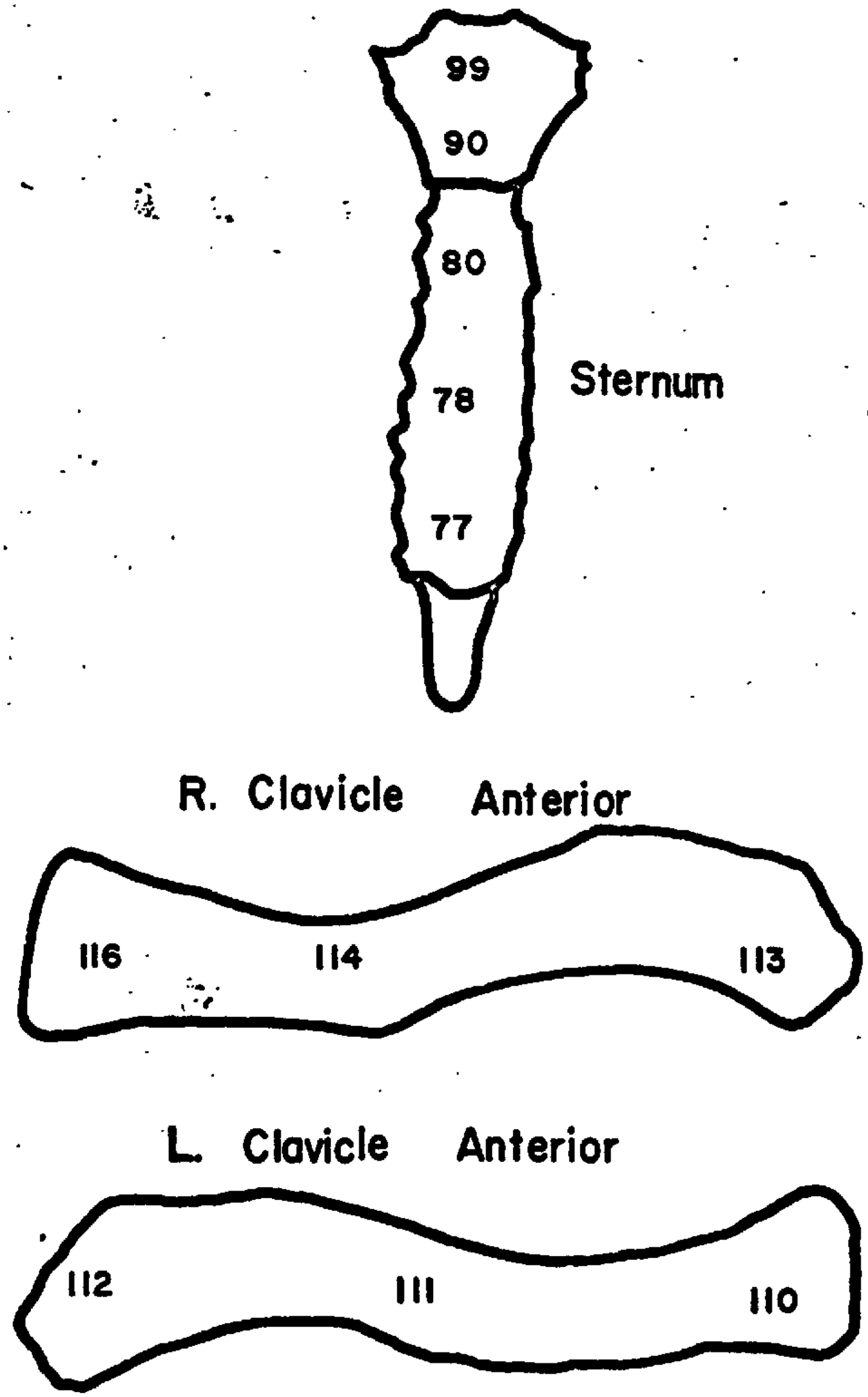


Figure 15. Dosimeter placement in the clavicles and sternum.

Table 10

Total Gram-rads to the Active Marrow of the Scapulae and Humerae

Skeletal Anatomy	Active Marrow Wt. at Age 40 (gm.)	Whole Body		Partial Body (Lower)		Partial Body (Upper)	
		rads	gm-rads	rads	gm rads	rads	gm rads
R and L Scapulae	50.5	153.57	7755.285	6.73	339.865	126.17	6371.585
R and L Humerae	20.0	147.22	2944.400	6.78	135.600	160.68	3213.600
Totals	70.5		10699.685		475.465		9585.185

Table 11

Total gram-rads to the active marrow of the cranium, mandible, clavicles and sternum

Skeletal Anatomy	Active Marrow Wt. at Age 40 (gm.)	Whole Body		Partial Body (Lower)		Partial Body (Upper)	
		rads	gm-rads	rads	gm-rads	rads	gm-rads
Cranium	124.3	52.45	6519.54	1.87	232.44	188.48	23428.06
Mandible	12.3	140.44	1727.41	3.53	43.42	235.55	2897.27
Clavicles	16.2	149.89	2428.22	3.89	63.02	184.07	2981.93
Sternum	23.4	155.44	3637.30	6.31	147.65	163.00	3814.20

G. Pelvic Area (see Figure 16)

The pelvic area was given a total rad dose in the following manner.

1. The sacrum was divided into three sections and each section rad dose counted one-third. The division lines are shown in Figure 16. The averaged value is the value of the net rads for the sacrum.

2. The values for the right os coxae and left os coxae were figured separately and then averaged.

3. The values for the right and left heads and necks of the femora were figured separately and then averaged.

Dose values are listed in Table 12.

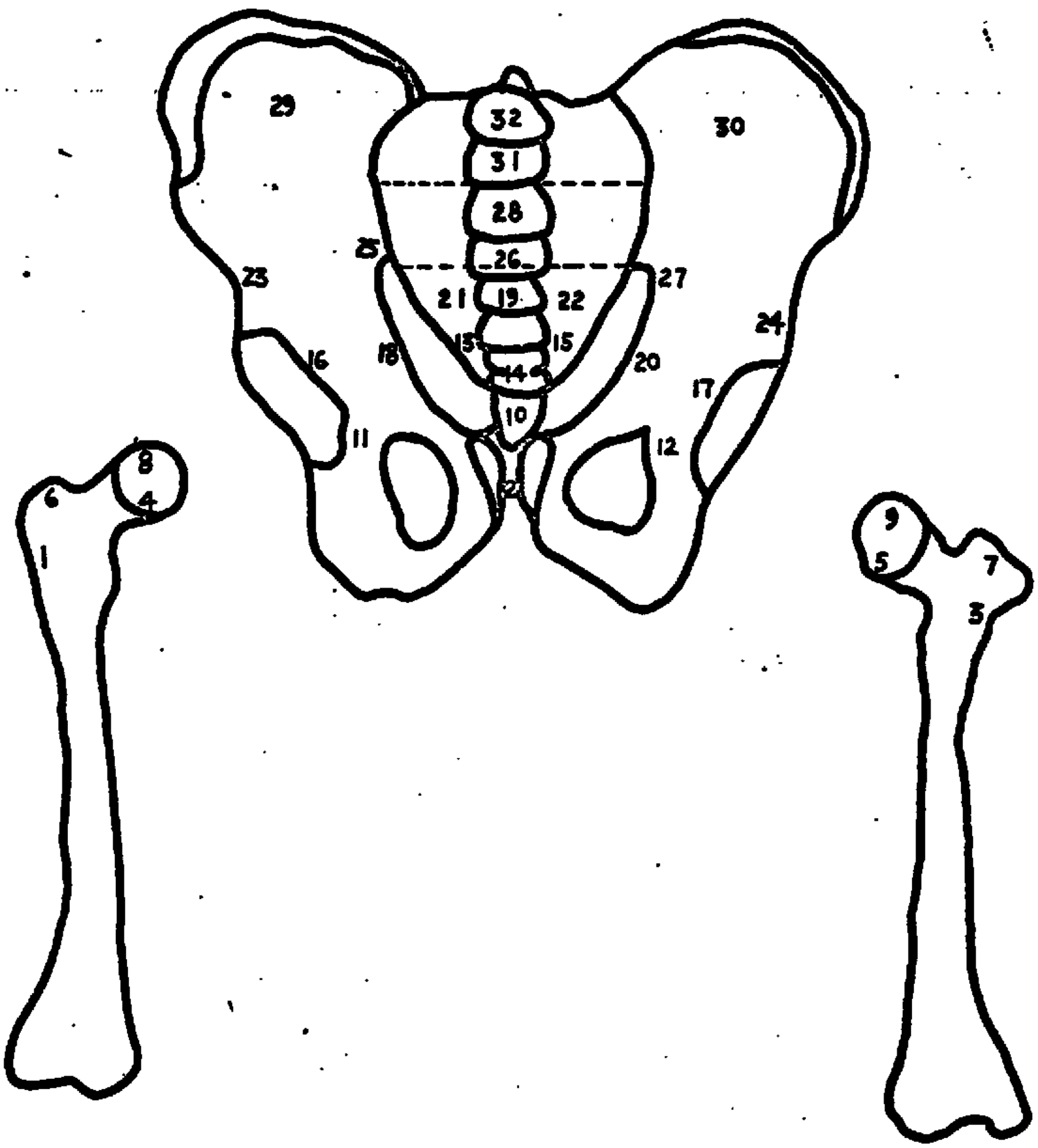


Figure 16. Dosimeter placement in the pelvis and femoral heads and necks.

Table 12

Total Gram-rads to the Active Marrow of the Pelvic Area

Skeletal Anatomy	Active Marrow Wt. at Age 40 (gm.)	Whole Body		Partial Body (Lower)		Partial Body (Upper)	
		rads	gm-rads	rads	gm rads	rads	gm-rads
Sacrum	145.6	143.40	20879.040	199.10	28988.960	4.04	588.224
R and L Os Coxae	233.0	94.65	22053.450	180.27	42002.910	3.97	925.010
R and L Femoras	40.0	135.76	5430.400	206.38	8255.200	3.74	149.600
Totals	418.6		48362.890		79247.070		1662.834

H. Vertebrae (see Figure 17)

The active marrow weights of the vertebrae were shown in Table 6. The dose values of all the vertebrae dosimeters were averaged for each vertebra. Where there was no dosimeter, the value assigned was an interpolation between its superior and inferior member. The dose values are shown in Table 14.

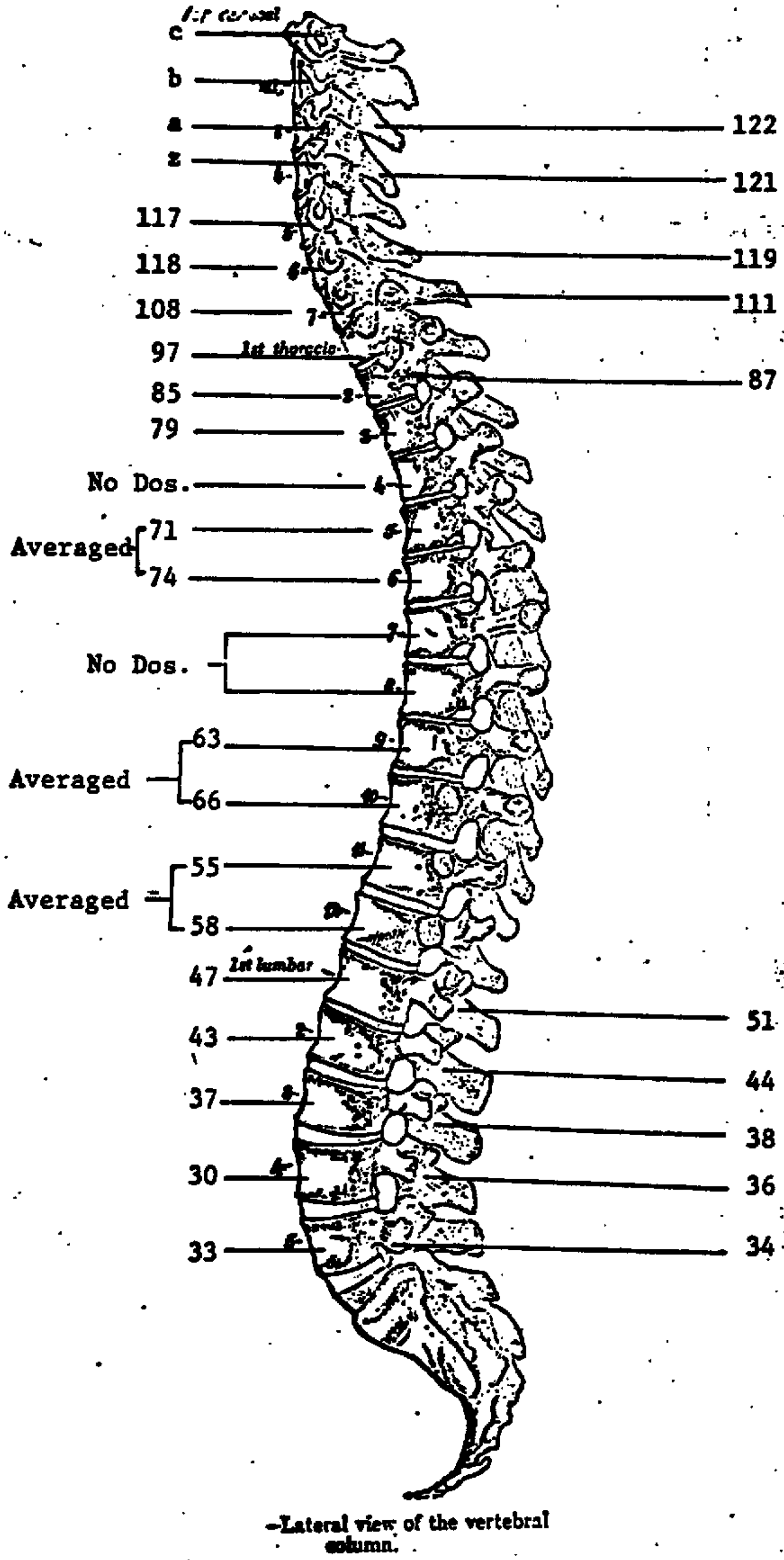


Figure 17. Dosimeter placement in the vertebrae.

Table 14

Total gram-rads to the active marrow of the vertebrae

Cervical Vertebra #	Active Marrow Wt. Age 40 (gm)	Whole Body		Partial Body (Lower)		Partial Body (Upper)	
		rads	gm-rads	rads	gm-rads	rads	gm-rads
1	5.0	128.25	641.25	2.87	14.350	227.40	1137.00
2	6.3	175.92	1108.296	3.68	23.184	234.35	1476.405
3	4.1	192.39	788.799	3.77	15.457	227.18	931.438
4	4.3	173.91	747.813	2.60	11.180	208.73	897.539
5	4.4	134.15	590.260	4.49	19.756	166.31	731.764
6	5.3	126.43	670.079	2.83	14.999	166.92	884.676
7	6.4	124.60	797.440	3.87	24.768	142.47	911.808
Totals	35.8		5343.937		123.694		6970.630
Thoracic Vertebra #							
1	8.1	130.75	1059.075	5.30	42.93	126.96	1028.376
2	8.8	139.46	1227.248	5.62	49.456	126.04	1109.152
3	8.5	142.54	1211.590	8.73	74.205	113.69	966.365
4	9.1	153.99	1401.309	11.14	101.374	87.89	799.799
5	10.1	165.43	1670.843	13.55	136.855	62.08	627.008
6	11.5	165.43	1902.445	13.55	155.825	62.08	713.920
7	12.1	175.54	2124.034	25.85	312.285	38.63	467.423
8	13.9	175.54	2440.006	25.85	359.315	38.63	536.957
9	14.8	185.15	2747.620	38.14	564.472	15.18	224.664
10	15.9	185.65	2951.835	38.14	606.426	15.18	241.362
11	16.3	166.42	2712.646	127.49	2078.087	11.17	182.071
12	18.8	166.42	3128.696	127.49	2396.812	11.17	209.996
Totals	147.9		24577.347		6878.542		7107.093
Lumbar Vertebra #							
1	20.8	166.50	3463.200	198.08	4120.064	7.31	152.048
2	21.8	160.84	3506.312	207.06	4513.908	5.84	127.312
3	23.8	164.67	3919.146	217.93	5186.734	5.00	199.000
4	24.1	163.38	3937.458	208.05	5014.005	4.38	105.558
5	23.6	156.73	3698.828	200.25	4725.900	3.99	94.164
Totals	114.1		18524.944		23560.611		598.082

The dose values for the cranium, mandible, clavicles and sternum were given in Tables 8, 9 and 11. The total gram-rads for each of these sections is given in Table 15.

Table 15

Total gram-rads to the whole body active marrow

Skeletal Anatomy	Whole Body (gm-rads)	Partial Body (Lower) (gm-rads)	Partial Body (Upper) (gm-rads)
Ribs 1-4	3611.9	188.9	2583.3
Ribs 5-8	6791.9	1994.1	928.7
Ribs 9-12	3593.8	3754.8	191.2
Cranium	6519.5	232.4	23428.1
Mandible	1727.4	43.4	2897.3
R and L Scapulae Human Heads and Necks	10699.7	475.5	9585.2
Clavicles	2428.2	63.0	2981.5
Sternum	3637.3	147.7	3814.2
Pelvic Region	48362.9	79247.1	1662.8
Cervicle Vertebra	5343.9	123.7	6970.6
Thoracic Vertebra	24577.3	6878.5	7107.1
Lumbar Vertebra	18524.9	23560.6	598.1
Totals	135818.7	116709.7	62748.1

CONCLUSIONS

Mechanik and Ellis have together provided the average weight of "active" bone marrow in the forty year old male by examination of total marrow weights in twelve carefully dissected cadavers. The fact that these were severely diseased individuals limits the absolute acceptance of the marrow weight; however, these data are the best currently available. Until exhaustive microscopic studies of the total marrow in undiseased human cadavers is undertaken, the values listed in Table 6 will have to suffice.

It has been possible by the use of a tissue-equivalent phantom and thermoluminescence dosimetry (lithium fluoride powder) to obtain the "active" bone marrow dose in ^{60}cobalt bilateral radiation exposure. The rad dose to each of the active components is indicated. The gram-rads or integral dose to each compartment has been calculated, and these integral dose data are summarized in Table 15. For bilateral ^{60}cobalt exposure, partial body (lower) irradiation results in a considerably higher "active" bone marrow dose than does partial body (upper) irradiation (the lower border of the sternum serving to delineate the upper body and lower body irradiation procedures). These data serve as a basis for possible correlation of the hematologic findings observed for whole body irradiation and for partial body irradiation (upper or lower body) in humans with the "active" bone marrow dose. Interpretations may follow concerning the importance of shielding certain portions of "active" bone marrow.

Bibliography

1) Saenger, E.L., Friedman, B.I., Kereiakes, J.G., Perry, H.: Metabolic changes in humans following total body irradiation. DASA - 1844. University of Cincinnati College of Medicine, Cincinnati, Ohio. September 1, 1966.

2) Rando Phantom Systems: The Machlett Laboratories, Inc., Springdale, Connecticut 06879.

3) Cameron, J.R., Zimmerman, D., Kenney, G., Buch, R., Bland, R. and Grant, R.: Thermoluminescent radiation dosimetry utilizing LiF. Health Physics 10: January 1964, pp. 25-29.

4) Madison Research, Inc.: Using the thermoluminescent radiation dosimeter system. Middleton, Wisconsin.

5) Johns, H.: The physics of radiology. Second Edition. Springfield, Illinois, Charles C. Thomas Co. 1964, p. 280.

6) Natrella, M.G.: Experimental Statistics. National Bureau of Standards Handbook 91. August 1963, p. 5-36.

7) Saenger, E.L., Friedman, B.I., Kereiakes, J.G., Perry, H.: Metabolic changes in humans following total body irradiation. DASA - 1844. University of Cincinnati College of Medicine, Cincinnati, Ohio. September 1, 1966.

8) Karzmark, J.: Phys. Med. Biol. 9: 1964, p. 273.

9) Mechanik, N.: Untersuchungen uberdas Gewicht des Knochennarkes des Menschen. ges Anat. Z ges Anat. November 1925, pp. 58-99.

10) Woodard, H., and Holodny, E.: A summary of the data of Mechanik on the distribution of human bone marrow. Phys. Med. Biol 5: 1957, p. 57.

11) Ellis, R.: The distribution of active bone marrow in the adult. Phys. Med. Biol.: 1961, p. 255.

12) Piney, A.: Brit. Med. J. 2: 1922, p. 792.

13) Huggins, C. and Blocksom, B.H.: J. Exp. Med. 64: 1936, p. 253.

14) Custer, R.P.: Atlas of blood and bone marrow. W.R. Saunders Co. 1949, p. 29.

15) Epp, E.R., Weiss, H., Laughlin, J.S.: Measurements of bone marrow and gonadal dose from the chest x-ray examination as a function of field size, field alignment, tube kilovoltage and added filtration. Brit. J. of Radiol. 34: 1961, p. 85.