Chapter 8 Appendix 3

PHOTON AND NEUTRON FLUENCE-TO-KERMA CONVERSION FACTORS FOR ICRP-1975 REFERENCE MAN USING IMPROVED ELEMENTAL COMPOSITIONS FOR BONE AND MARROW OF THE SKELETON

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Findings of a recent Oak Ridge National Laboratory (ORNL) review[1,2] and of other reviews, which have been discussed at the Late Effects Workshop on Dosimetry of Atomic Bomb Survivors, 29th Annual Meeting of the Radiation Research Society, Minneapolis, Minnesota, 31 May 1981,[3] and the Symposium on Reevaluations of Dosimetric Factors, Hiroshima and Nagasaki, US Department of Energy, Germantown, Maryland, 5 and 6 September 1981,[4] have clearly established a need to revise the dosimetry for the A-bomb survivors. This effort will involve several divisions at ORNL, several other national laboratories, and several consulting firms.

One of the main tasks of the Health and Safety Research Division at ORNL is to provide revised estimates of various organ-dose parameters related to a survivor's neutron and gamma-ray exposures. The objectives of the work summarized in this report were: (a) to better define the elemental composition of various skeletal components of ICRP-1975 Reference Man,[5] and (b) to investigate photon and neutron fluence-to-kerma conversion factors for various total-body and organ-tissue components of ICRP-1975 Reference Man as revised here. Scaled down mathematical descriptions of the volumes and shapes of the total body and internal organs of Reference Man will be used, of course, in the organ-dose calculations for A-bomb survivors (Chapter 8).[6–8]

Elemental Composition of Reference Man

Data on the elemental composition of Reference Man have evolved over a number of years.[5,6,9,10] A 12 elements approximation of Reference Man, as defined in the ICRP's 1975

Table 1. Composition of Reference Man for twelve elements

Element	Mass (g)			
	ICRP-revised	ICRP-1975	MIRD-1969	ICRP-1955
H	7,000[a]	7,000[b]	7,000[c]	7,000[d]
C	16,000	16,000	16,000	12,600
N	1,700	1,800	1,800	2,100
O	43,000	43,000	43,000	45,500
Na	100	100	110	105
Mg	19	19	20	35
P	580	580[e]	840	700
S	150	140	150	175
Cl	95	95	100	105
K	140	140	140	140
Ca	1,200	1,000	1,000	1,050
Fe	4.2	4.2	4.9	4

[a]This work.

[b]See Table 110 on page 327 in Publication 23, International Commission on Radiation Protection (Ref. 5).

[c]See Table 2 on page 9 in Phamphlet 5 of the Medical Internal Radiation Dose (MIRD) Committee (Ref. 6).

[d]See Table C.II on page 25 in Recommendations of the International Commission on Radiological Protection (Ref. 10).

[e]See Errata on page iii in Publication 30, Supplement to Part 1, International Commission on Radiological Protection (Ref. 12).

Report[5] and revised in this work (Table 1), was used to investigate particle fluence-to-kerma conversion factors for photons with energies between 1 keV and 20 MeV and neutrons with energies between 0.0253 eV and 20 MeV. Several recent revisions to ICRP-1975 Reference Man,[11,12] which have not been included in other kerma-factor calculations, are taken into account. For example, the ICRP has recommended that the total-body mass of phosphorus be reduced from 780 to 580 g and the skeletal mass be reduced from 700 to 500 g.[11] This revision suggests that the ICRP-1975 Reference Man Report[5] originally overestimated the mineral content of the skeleton or underestimated either the calcium content of bone (see page 288 of Reference 5) or the oxygen content of bone ash (see Table 106 of Reference 5). The mass fraction (or percent by weight) of oxygen in bone ash would need to be nearly 50% to account for this reduction of 200 g in the phosphorus content of the skeleton. It appears that the estimate of 1000 g of calcium in the skeleton of ICRP-1975 Reference Man is too low. Widdowson and Dickerson[13] estimate 1320 g for the skeletal calcium of Reference Man with a total-body mass of 70 kg, the data of Mitchell and co-workers[14–16] yield an average of 1090 g of calcium in the skeleton when normalized to the 10 kg skeletal mass of Reference Man, and an age-dependent model for skeletal calcium developed from the data of Mitchell and co-workers by Leggett, Eckerman, and Williams[17] yields a value of 1135 g when avergaged over 20 to 60 years of age. Thus, an increase in the calcium content of total

Table 2. Revision to Table 108 of ICRP-1975 Reference Man Report[a]

Organ/tissue	Quantity in organ or tissue (g)		
	Selenium	Silver	Sodium
92 Red marrow			
93 Yellow marrow		2.1E-6[b]	6.6E-1
94 Cartilage			6.0E+0
95 Periarticular tissue			4.9E+0
96 Skin		2.3E-5	6.7E+0
97 Epidermis			1.8E-1
98 Dermis			4.5E+0

[a]See Errata on page iii of Addendum to Ref. 11. The "organ or tissue" numbered 92 through 98 are misaligned with the data on Page 315 of Ref. 5.

[b]Read as 2.1×10^{-6}.

Table 3. Summary of data on twelve-element composition for various skeletal components from Table 108 of ICRP-1975 Reference Man Report[a]

Element	Mass (g)							
	Skeleton	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow	Cartilage	Peri-articular
H	7.2E+2	1.9E+2	1.8E+2	4.3E+1	1.5E+2	1.7E+2	1.1E+2	8.8E+1
C	2.5E+3	7.4E+2	5.5E+2	1.3E+2	6.2E+2	9.5E+2	1.1E+2	8.2E+1
N	3.0E+2	2.1E+2	1.6E+2	3.8E+1	4.8E+1	9.6E+0	2.9E+1	2.2E+1
O	4.7E+3	2.1E+3	1.7E+3	2.6E+2	6.2E+2	3.4E+2	8.0E+2	6.6E+2
Na	3.2E+1					6.6E-1	6.0E+0	4.9E+0
Mg	1.1E+1		8.4E+0			2.6E-2		
P	5.0E+2	5.0E+2	4.0E+2	1.0E+2		2.1E-1		
S	1.7E+1		1.2E+1			1.1E+0	6.6E+0	5.4E+0
Cl	1.4E+1					1.6E+0	2.8E+0	2.3E+0
K	1.5E+1							
Ca	1.0E+3		8.0E+2			2.9E-2		
Fe	8.1E-1					3.2E-2		

[a]See pages 290 to 324 of Ref. 5 and Errata in Refs. 11 and 12.

bone in Reference Man from 1000 to 1200 g is consistent with the preceding information and also obviates any improper change in the oxygen content of bone ash or the total mineral content of the skeleton.

Another ICRP revision to the matrix of skeletal values (Reference 12) corrects a misalignment of data in Table 108 of the ICRP-1975 Reference Man Report (Table 2). Thus, no data are given on trace elements in red marrow of ICRP-1975 Reference Man (Table 3). Only the major elements are specified by using the assumption that red marrow is approximately

Table 4. Estimation of gross content and trace elements in red bone marrow of Reference Man[a]

Components	Mass (g)		
	Blood-erythrocytes	Adipose tissue-subcutaneous	Skeleton-red marrow
Total	2,400	7,500	1,500
Gross content			
Water	1,500	1,100	595
Ash	26	15	10
Fat	13	6,000	605
Protein	780	380	290
Trace element			
Na	0.57	3.8	0.56
Mg	0.13	0.15	0.056
P	1.6	1.2	0.62
S	7.9	5.5	3.0
K	8.3	2.4	2.8
Cl	4.2	9.0	2.2
Ca	0.012	0.17	0.021
Fe	2.4	0.18	0.77

[a]Assumes red marrow is approx. 50% (i.e., 750 g) red blood cells (i.e., erythrocytes) and 50% (i.e., 750 g) fat (i.e., subcutaneous adipose tissue) based on work of Roberts, Miles, and Woods (Ref. 19). Also see data of Aspden (Ref. 18).

60% hematopoietic tissue (i.e., erythrocytes) and 40% fat (i.e., subcutaneous adipose tissue). A more complete description of the elemental composition of red marrow has been given by Aspden[18] based on the work of Roberts et al.[19] Their work suggests that red marrow is approximately 50% hematopoietic tissue and 50% fat tissue. These data were used here to obtain a more realistic estimation of both the gross content and trace elements in red marrow of Reference Man (Table 4). One surprising result was that this approximation gives essentially the same values for the gross content of red marrow as Table 105 of the ICRP-1975 Reference Man Report (i.e., 600 g of water, 9 g of ash, 600 g of fat, and 300 g of protein). The only revision made in this work was to reduce the protein content in red marrow of ICRP-1975 Reference Man from 300 to 290 g. Addition of 6 g of potassium to the skeletal matrix of values for total bone (see page 287 of Reference 5) and 0.42 g of potassium to the yellow marrow, based on the trace-element content of subcutaneous adipose tissue (see page 96 and Table 108 of Reference 5), made it possible to better define the skeletal matrix of values for both marrow and bone (Table 5).

The ICRP-1975 Reference Man Report[5] defines two distinct types of mineralized bone (i.e., cortical and trabecular bone) and two distinct types of soft tissue in mineralized bone (i.e., red and yellow marrow). Cortical bone is the hard compact bone found on the exterior of bones, especially the shafts of the long bones (e.g., the femur and humerus). The cortical bone in an adult comprises about 80% (i.e., 400,g) of the total mineralized bone (i.e., 5000 g) of the skeleton. Trabecular bone, sometimes referred to as cancellous bone, is the soft spongy bone that is found in the interior of the flat bones (e.g., the skull and pelvis) and ends of the long bones of the body. The trabecular bone in an adult comprises about 20% (i.e., 1000 g) of the total mineralized bone in the skeleton. Yellow (fatty or inactive) marrow is contained

Table 5. Revisions to trace-element and mineral content of Reference Man[a]

Organ/tissue	Compo	Page	Original mass (g)	Revised mass (g)
1 Total body	Ca	296	1.0E+3	1.2E+3[b]
	P	310	5.8E+2[c]	5.8E+2[c]
	S	316	1.4E+2	1.5E+2[d]
62 Heart	Na	314	4.0E-1[e]	4.0E-1[e]
66 Liver	Na	314	1.8E?	1.8E+0
88 Skeleton	Ca	296	1.0E+3	1.2E+3[b]
	P	310	5.0E+2[c]	5.0E+2[c]
	S	316	1.7E+1	3.1E+1[f]
89 Skeleton-total bone	Ca	296		1.2E+3[b]
	Cl	298		5.0E+0[h]
	Mg	306		1.0E+1[i]
	P	310	5.0E+2[c]	5.0E+2[c]
	K	312		6.0E+0[j]
	Na	314		2.0E+1[h]
	S	316		1.5E+1[i]
90 Skeleton-cortical bone	Ca	296	8.0E+2	9.6E+2[k]
	Cl	298		4.0E+0[k]
	K	312		4.8E+0[k]
	Na	314		1.6E+1[k]
91 Skeleton-trabecular bone	Ca	296		2.4E+2[k]
	Cl	298		1.0E+0[k]
	Mg	306		2.1E+0[k]
	P	310	1.0E+2[c]	1.0E+2[c]
	K	312		1.2E+0[k]
	Na	314		4.0E+0[k]
	S	316		3.0E+0[i]
92 Skeleton-red marrow	Ca	296		2.1E-2[m]
	Cl	298		2.2E+0[m]
	Fe	304		7.7E-1[m]
	Mg	306		5.6E-2[m]
	P	310		6.2E-1[m]
	K	312		2.8E+0[m]
	Na	314		5.6E-1[m]
	S	316		3.0E+0[m]
93 Skeleton-yellow marrow	K	312		4.2E-1[n]

[a]See Table 108 on page 290 of Ref. 5.

[b]See discussion in text and Table 1 of this report.

[c]See Errata on page iii of Addendum to Ref. 12.

[d]Sum of revised values for sulfur content in the skeleton and total soft tissue.

[e]See Errata on page iii of Addendum to Ref. 11.

[f]Sum of revised values for sulfur content in the various components of the skeleton.

[h]Difference between values for mineral or trace-element content in skeleton and other components of the skeleton in Table 108 of Ref. 5.

[i]Based on mineral or trace-element content of cortical bone in Table 108 and on relative masses of cortical and trabecular bone in Table 105 of Ref. 5.

[j]See discussion on page 287 of Ref. 5.

[k]Based on mineral or trace-element content of total bone and on relative masses of cortical and trabecular bone.

[m]See Table 4 of this report.

[n]Based on trace-element content of subcutaneous adipose tissue in Table 108 of Ref. 5.

Table 6. Revisions to gross content of Reference Man[a]

Organ/tissue	Compo	Page	Original mass (g)	Revised mass (g)
1 Total body[b]	Carbo- hydrate	280		4.0E+2[c]
1a Total soft tissue	Carbo- hydrate	280		4.0E+2[c]
27 Central nervous system	Carbo- hydrate	280		1.4E+1[d]
28 Central nervous system-brain	Carbo- hydrate	280		1.4E+1[e]
29 Central nervous system-cerebrum	Carbo- hydrate	280		1.2E+1[d]
	Water	280	9.3E+2	9.4E+2[d]
30 Central nervous system-cerebellum	Carbo- hydrate	280		1.5E+0[d]
	Fat	280	1.3E+1	1.6E+1[d]
31 Central nervous system-brain stem	Carbo- hydrate	280		3.0E-1[d]
58 Lower large intestine-descending colon	Protein	282	3.8E+0	1.2E+1[f]
66 Liver	Carbo- hydrate	282		4.0E+1[h]
77 Muscle (skeletal)	Carbo- hydrate	284		3.0E+2[i]
80 Skeleton-bone	Protein	284	1.3E+3	1.2E+3[j]
92 Skeleton-red marrow	Protein	284	3.0E+2	2.9E+2[k]
95 Skeleton-periarticular tissue	Water	284	5.7E+2	7.0E+2[m]
103 Teeth-Dentin	Protein	284	1.6E-1	7.6E+0[n]

[a]See Table 105 on page 280 of Ref. 5.

[b]Glycogen, the chief carbohydrate storage material of the body, is produced in the liver and stored primarily in the liver and muscle tissue before being depolymerized to glucose and liberated as needed by the body (Ref. 21).

[c]See discussion on page 24 of Ref. 5.

[d]Based on gross content of "organ or tissue" numbered 28 (Brain) in Table 105 of Ref. 5.

[e]See discussion on page 214 of Ref. 5.

[f]Based on gross content of "organ or tissue" numbered 43 (Intestine) in Table 105 of Ref. 5.

[h]See table on pages 146 and 147 of Ref. 5.

[i]See discussion on pages 110 and 111 of Ref. 5.

[j]Value rounded down to 1.2E+3 g, rather than up to 1.3E+3 g, to make it more consistent with the values of 1.0E+3 g and 2.4E+2 g for cortical and trabecular bone and the value of 1.5E+3 g for the skeleton in Table 105 of Ref. 5.

[k]See Table 4 of this report.

[m]See table at top of page 79 in Ref. 5.

[n]Difference between values for "organ or tissue" numbered 101 (Teeth) and for other components numbered 102 (Teeth-Enamel) and 103 (Teeth-Pulp) in Table 105 of Ref. 5.

primarily within the shafts of the long bones, and red (active) marrow is contained primarily within the fragile network of trabecular-bone cavities in the flat bones and ends of the long bones. Since developing red blood cells (i.e., erythrocytes) are found in various stages of maturation throughout the red marrow, it is considered to be the critical target tissue with respect to leukemia induction.[20]

A BASIC computer program, RMCOMP, was written during the course of this work to calculate the major-element content (i.e., H, C, N, and O) of various organs or tissues from data given in Tables 105 and 106 of the ICRP-1975 Reference Man Report (Chapter 8 Appendix 3a and 3b). Values for the carbohydrate content of organs and tissues, which are not tabulated in Table 105 of the ICRP-1975 Reference Man Report, were obtained from discussions in the text of that report (Table 6). The RMCOMP/BAS computer program sums the major-element content with the mineral and trace-element content of an organ or tissue to obtain a calculated organ mass (or weight) and mass fraction (or percent by weight) for a total of 12 elements (i.e., H, C, N, O, Na, Mg, P, S, Cl, K, Ca, and Fe). Since some unexpected and rather large discrepancies were found between data from calculations for the skeleton and data on either the weight (i.e., mass) or the major-element content (i.e., H, C, N, and O) from Table 108 of the ICRP-1975 Reference Man Report (e.g., the mass of peri-articular tissue and the oxygen content of trabecular bone), the calculations were extended to all organ-tissue components of Reference Man (Tables 7 and 8). It was usually possible to resolve the various discrepancies by referring to either the text of the ICRP-1975 Reference Man Report,[5] a 1977 paper by White and Fitzgerald,[22] or the Errata published in 1979 and 1980 by the ICRP.[11,12]

Table 7. Summary of organ-tissue masses of Reference Man[a] calculated by using RMCOMP/BAS computer program

Organ/tissue		Standard mass (g)	Percent difference[b]	
			Original values	Revised values
1	Total body	70,000	+1.6[c]	+0.78[d]
1a	Total soft tissue	60,000	+1.5	+0.80
2	Adipose tissue	15,000	-0.53	-0.53
3	Subcutaneous	7,500	+0.07	+0.07
4	Other separable	5,000	-0.20	-0.20
5	Interstitial	1,000	-0.08	-0.08
7	Adrenals	14	+1.3	+1.3
8	Aorta	100	+1.5	+1.5
9	Contents (Blood)	190	+1.9	+1.9
10	Blood (Whole)	5,500	+0.82	+0.82
11	Plasma	3,100	-1.7	-1.7
12	Erythrocytes	2,400	+4.1	+4.1
13	Blood vessels	200	+1.5	+1.5
14	Contents (Blood)	3,000	+0.80	+0.80
22	Connective tissue (CT)	3,400	+0.95	+0.95
23	Separable CT	1,600	-0.74	-0.74
27	Central nervous system	1,430	+3.1	+2.1
28	Brain	1,400	+1.8	+0.76
29	Cerebrum	1,200	+2.5	+0.88
30	Cerebellum	150[e]	+2.5	-0.51
31	Brain stem	30	+3.1	+2.1
32	Contents (Fluid)	120	-0.99	-0.99
35	Eye lenses	0.4	-3.8	-3.8
36	Gall bladder[f]	10		
37	GI tract	1,200	+1.0	+1.0
40	Esophagus	40		
41	Stomach	150	+6.8	+6.8
43	Intestines	1,000	+1.5	+1.5
45	Small intestine	640	+0.73	+0.73
47	Duodenum	60	+2.1	+2.1

Table 7 (cont'd.)

	Organ/tissue	Standard mass (g)	Percent difference[b]	
			Original values	Revised values
48	Jejunum	280	+2.1	+2.1
49	Ileum	300	+0.34	+0.34
50	Large intestine (LI)	370	+2.2[c]	+2.2[d]
52	Upper LI	210	−0.41	−0.41
54	Ascending colon	90	+1.3	+1.3
55	Transverse colon	120	+1.0	+1.0
56	Lower LI	160	−0.85	−0.85
58	Descending colon	90	−10.2	−1.2
59	Sigmoid colon	50	−0.49	−0.49
60	Rectum	20	−0.66	−0.66
61	Hair	20	−4.0	−4.0
62	Heart	330	+0.10	+0.10
63	Contents (Blood)	500	+0.99	+0.99
64	Kidneys	310	−0.16	−0.16
66	Liver	1,800	+2.5	+0.33
67	Lungs	1,000	+2.7	+2.7
68	Parenchyma	570	+5.0	+5.0
69	Content (Blood)	430	−0.49	−0.49
73	Lymph nodes	250		
77	Muscle (Skeletal)	28,000	+1.5	+0.45
79	Pancreas	100	+7.5	+7.5
82	Pituitary	0.6		
83	Prostate	16	+2.3	+2.3
88	Skeleton	10,000	+2.7	+0.54
89	Bone	5,000	+24.9	+1.8
90	Cortical bone	4,000	+7.0	+2.4
91	Trabecular bone	1,000	+22.5	−2.6
92	Red marrow	1,500	+0.40	+0.38
93	Yellow marrow	1,500	+0.50	+0.48
94	Cartilage	1,100	+3.1	+3.1
95	Periarticular tissue	900	+18.7	+4.2
96	Skin	2,600	−0.55	−0.55
97	Epidermis	100		
98	Dermis	2,500		
100	Spleen	180	+0.53[c]	+0.53[d]
101	Teeth	46	+1.2	+1.2
102	Enamel	10[e]	+5.3	+5.3
103	Dentin	35[e]	+19.9	−0.97
105	Testes	35	+4.2	+4.2
106	Thymus	20		
107	Thyroid	20	+0.64	+0.64
108	Tongue	70	−3.2	−3.2
110	Trachea	10		
113	Urinary bladder	45		
114	Contents (urine)	102	+0.15	+0.15

[a]Based on calculations using values from Tables 105, 106, and 108 of Ref. 5.

[b]100 x (standard mass − calculated mass)/standard mass.

[c]Includes revised values from Errata in Refs. 11 and 12.

[d]Includes revised values from Tables 5 and 6 of this report.

[e]See White and Fitzgerald (Ref. 22) and Errata in Ref. 11.

[f]Gross contents (i.e., water, fat, and protein) of the gall bladder and some other organs are not completely defined in Ref. 5.

A summary of all revisions to either the gross content or the elemental content of various organs or tissues of ICRP-1975 Reference Man are listed in Tables 6 and 8. The revisions in Table 8 are only those values from calculations using the RMCOMP/BAS computer program (Chapter 8 Appendix 3a) that did not round up or down to the value given in Table 108 of the ICRP-1975 Reference Man Report.[5] One of the original objectives of this work was to

Table 8. Summary of revisions to Table 108 of ICRP-1975 Reference Man Report[a]

Organ/tissue	Compo	Page	Original mass (g)	Revised mass (g)
1 Total body	Ca	296	1.0E+3	1.2E+3
	N	310	1.8E+3	1.7E+3
	P	310	5.8E+2[b]	5.8E+2
	S	316	1.4E+2	1.5E+2
1a Total soft tissue	N	310	1.5E+3	1.4E+3
7 Adrenals	O	310	8.2E+0	8.0E+0
9 Aorta-blood content	H	302	2.0E+1	1.9E+1
12 Blood-erythrocytes	H	302	2.1E+2	2.2E+2
	O	310	1.4E+3	1.5E+3
13 Blood vessels	C	296		2.0E+1
	H	302		2.5E+1
	N	310		7.7E+0
	O	310		1.4E+2
33 Central nervous system-fluid content	N	310	5.4E-3	4.8E-3
43 GI Tract-intestine	C	296	9.4E+1	1.2E+2
	O	310	7.7E+2	7.4E+2
60 Lower large intestine-rectum	H	302	1.2E+0	2.1E+0
61 Hair	O	310	6.0E+0	5.7E+0
62 Heart	Na	314	4.0E-1[c]	4.0E-1
66 Liver	C	296	2.6E+2	2.8E+2
	Na	314	1.8E?	1.8E+0
83 Prostate	H	302	1.5E+0	1.6E+0
88 Skeleton	Ca	296	1.0E+3	1.2E+3
	P	310	5.0E+3[b]	5.0E+3
	S	316	1.7E+1	3.1E+1
89 Skeleton-total bone	Ca	296		1.2E+3
	C	296	7.4E+2	6.6E+2
	Cl	298		5.0E+0
	Mg	306		1.0E+1
	N	310	2.1E+2	1.9E+2
	P	310	5.0E+2[b]	5.0E+2
	K	312		6.0E+0
	Na	314		2.0E+1
	S	316		1.5E+1
90 Skeleton-cortical bone	Ca	296	8.0E+2	9.6E+2
	Cl	298		4.0E+0
	H	302	1.8E+2	1.4E+2
	K	312		4.8E+0
	Na	314		1.6E+1
91 Skeleton-trabecular bone	Ca	296		2.4E+2
	Cl	298		1.0E+0
	Mg	306		2.1E+0
	O	310	2.6E+2	4.6E+2
	P	310	1.0E+2[b]	1.0E+2
	K	312		1.2E+0
	Na	314		4.0E+0
	S	316		3.0E+0
92 Skeleton-red marrow	Ca	296		2.1E-2
	Cl	298		2.2E+0
	Fe	304		7.7E-1
	Mg	306		5.6E-2
	N	310	4.8E+1	4.6E+1
	O	310	6.2E+2	6.7E+2
	P	310		6.2E-1
92 Skeleton-red marrow	K	312		2.8E+0
	Na	314		5.6E-1
	S	316		3.0E+0
93 Skeleton-yellow marrow	O	310	3.4E+2	3.5E+2
	K	312		4.2E-1

Table 8 (cont'd.)

Organ/tissue	Compo	Page	Original mass (g)	Revised mass (g)
102 Teeth-Enamel	C	296	1.0E-1[c]	6.2E-2
	H	302	4.0E-2[c]	4.0E-2
	N	310	1.0E-1[c]	1.9E-2
103 Teeth-Dentin	C	296	4.2E+0[c]	4.0E+0
	H	302	9.6E-1[c]	9.6E-1
	N	310	1.2E+0[c]	1.2E+0
	O	310	1.4E+1	1.5E+1
107 Thyroid	C	296	2.1E+0	3.0E+0
114 Urinary bladder-contents	C	296	3.4E-1	3.2E+0
	O	310	9.0E+1	8.6E+1

[a]See pages 290 to 324 of Ref. 5.

[b]See Errata on page iii of Addendum to Ref. 12.

[c]See Errata on page iii of Addendum to Ref. 11.

Table 9. Summary of revised data on twelve-element composition for various skeletal components of Reference Man[a]

Element	Mass (g)							
	Skeleton	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow	Cartilage	Peri-articular
H	7.2E+2	1.9E+2	1.4E+2	4.3E+1	1.5E+2	1.7E+2	1.1E+2	8.8E+1
C	2.5E+3	6.6E+2	5.5E+2	1.3E+2	6.2E+2	9.3E+2	1.1E+2	8.2E+1
N	3.0E+2	1.9E+2	1.6E+2	3.8E+1	4.8E+1	9.6E+0	2.9E+1	2.2E+1
O	4.7E+3	2.1E+3	1.7E+3	4.6E+2	6.7E+2	3.5E+2	8.0E+2	6.6E+2
Na	3.2E+1	2.0E+1	1.6E+1	4.0E+0	5.6E-1	6.6E-1	6.0E+0	4.9E+0
Mg	1.1E+1	1.0E+1	8.4E+0	2.1E+0	5.6E-2	2.6E-2		
P	5.0E+2	5.0E+2	4.0E+2	1.0E+2	6.2E-1	2.1E-1		
S	3.1E+1	1.5E+1	1.2E+1	3.0E+0	3.0E+0	1.1E+0	6.6E+0	5.4E+0
Cl	1.4E+1	5.0E+0	4.0E+0	1.0E+0	2.2E+0	1.6E+0	2.8E+0	2.3E+0
K	1.5E+1	6.0E+0	4.8E+0	1.2E+0	2.8E+0	4.2E-1		
Ca	1.2E+3	1.2E+3	9.6E+2	2.4E+2	2.1E-2	2.9E-2		
Fe	8.1E-1				7.7E-1	3.2E-2		

[a]See Tables 3, 4, 5, and 8 of this report.

better define the elemental composition of various skeletal components of Reference Man (Table 3). Thus, the revisions relating directly to this objective are listed separately in Table 9.

Twelve-element Approximation

Various approximations to the elemental composition of Reference Man have been used in calculations of particle fluence-to-kerma conversion factors for photons and neutrons. Some calculations have considered as few as the four major elements of the body,[23,24] and others as many as 15 elements[25] or more.[22] However, most of the calculations have used either 11 or 12 of the most abundant elements in the body.[26–29] A 12 elements approximation was selected for use in this work. It includes the 11 most abundant elements in the total body (i.e., skeleton and total soft tissue) of the ICRP-1975 Reference Man (see Table 110 of Reference 5) and iron, which is one of the most abundant trace elements in some organs or tissues of interest such as the lungs (see Table 2 of Reference 6) and red bone marrow (Table 9).

A summary of data on the percent by weight (i.e., mass fraction) of the 12 elements (i.e., H, C, N, O, Na, Mg, P, S, Cl, K, Ca, and Fe) in various total-body, soft-tissue, and skeletal components of ICRP-1975 Reference Man as revised in this work are listed in Tables 10 to 12, respectively. The formulations for total body and skeleton in Table 10 and for the bone and red-marrow components of the skeleton in Table 11 are significantly different compared to those for ICRP-1975 Reference Man , and therefore, are designated as ICRP-revised values (Tables 13 and 14). All other formulations, including those for total soft tissue in Table 10 and for various soft-tissue components in Table 12, which are based primarily on data in Tables 105 and 108 of the ICRP-1975 Reference Man Report[5] and the Errata published in 1979 and 1980 by the ICRP,[11,12] are designated simply as ICRP-1975 values (Tables 13 to 15).

Additional comparisons with other formulations[18,30–33] for compact bone, red marrow, and muscle tissue are given in Tables 13 to 15, respectively. In the past, a variety of soft tissues of the body have been approximated by the use of muscle tissue or so-called typical soft tissue. The formulations for muscle tissue (i.e., typical soft tissue) and compact bone (i.e., wet cortical bone) from the ICRU's 1964 Report,[30] which have been widely used in dosimetric calculations for soft tissue in bone[34–36] are of special interest. It has been suggested by White and Fitzgerald[22] that consideration should be given to the abandonment of the ICRU bone formulation, as the newer ICRP data for cortical bone and for red and yellow marrow provide much better alternatives.

Table 10. Elemental composition for various total-body components of Reference Man calculated by using EHCOMP/BAS computer program

Element	Percent by weight		
	Total body	Skeleton	Total soft tissue
H	10.052	7.279	10.514
C	22.922	24.644	22.631
N	2.442	3.057	2.339
O	61.289	46.884	63.686
Na	0.144	0.322	0.114
Mg	0.027	0.111	0.013
P	0.835	5.027	0.134
S	0.216	0.312	0.202
Cl	0.137	0.141	0.136
K	0.202	0.151	0.202
Ca	1.728	12.065	0.024
Fe	0.006	0.008	0.006

Table 11. Elemental composition for various skeletal components of Reference Man calculated by using RMCOMP/BAS computer program

Element	Percent by weight				
	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow
H	3.735	3.605	4.218	10.594	11.622
C	13.485	14.104	12.908	41.011	63.984
N	3.908	4.097	3.741	3.105	0.643
O	43.110	42.210	44.910	44.618	23.478
Na	0.407	0.410	0.390	0.037	0.044
Mg	0.224	0.215	0.205	0.004	0.002
P	10.177	10.243	9.742	0.041	0.014
S	0.305	0.307	0.292	0.201	0.074
Cl	0.102	0.102	0.097	0.147	0.107
K	0.122	0.123	0.117	0.187	0.028
Ca	24.425	24.583	23.380	0.001	0.002
Fe				0.052	0.002

Table 12. Elemental composition for various soft-tissue components of Reference Man calculated by using RMCOMP/BAS computer program

Element	Percent by weight				
	Skin	Muscle	Brain	Lungs	Intestine
H	9.934	10.218	10.620	10.212	10.499
C	22.576	11.119	12.854	10.241	11.707
N	4.590	2.755	1.267	2.910	2.111
O	62.161	75.006	74.000	75.630	75.093
Na	0.180	0.075	0.180	0.185	0.102
Mg	0.006	0.019	0.015	0.007	0.013
P	0.033	0.179	0.345	0.080	0.086
S	0.157	0.240	0.173	0.226	0.112
Cl	0.264	0.079	0.230	0.267	0.142
K	0.084	0.301	0.302	0.195	0.122
Ca	0.015	0.003	0.009	0.009	0.010
Fe	0.001	0.004	0.005	0.037	0.002

Kerma

Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a small volume element of a specified material divided by the mass of material in that volume element.[37–39] It is a useful quantity in dosimetry when charged particle equilibrium exists at the position and in the material of interest, and bremsstrahlung losses by the charged particles are negligible. In this case, kerma and

Table 13. Comparison of data on elemental composition for compact bone[a]

Element	Percent by Weight					
	ICRP-revised	ICRP-1975	Kim-1974	Tipton-1969	ICRU-1964	Woodard-1962
H	3.6[b]	3.8[b]	5.6[c]	4.1[d]	6.4[e]	3.39[f]
C	14.1	14.8	9.3	16	27.8	15.5
N	4.1	4.3	3.3	4.3	2.7	3.97
O	42.2	44.3	39.4	43	41.0	44.1
Na	0.41		0.4	0.62		0.06
Mg	0.22	0.23	0.4	0.22	0.2	0.21
P	10.2	10.8	13.4	10	7.0	10.2
S	0.31	0.32		0.31	0.2	0.31
Cl	0.10					
K	0.12		0.2			
Ca	24.6	21.5	28.0	21	14.7	22.2

[a]Assumed to be wet cortical bone.

[b]Calculated by using RMCOMP/BAS computer program (see Appendix A).

[c]See Kim (Ref. 31).

[d]See Tipton (Ref. 32).

[e]See International Commission on Radiological Units and Measurements (Ref. 30).

[f]See Woodard (Ref. 33).

Table 14. Comparison of data on elemental composition for red bone marrow

Element	Percent by weight		
	ICRP-revised	ICRP-1975	Aspden-1972
H	10.6[a]	10.6[a]	10.18[b]
C	41.0	41.4	47.48
N	3.1	3.2	2.18
O	44.6	44.8	36.04
Na	0.037		0.008
Mg	0.004		0.0024
P	0.041		0.028
S	0.20		0.154
Cl	0.15		0.100
K	0.19		0.174
Ca	0.001		0.0004
Fe	0.032		0.010
Others			3.64[c]

[a]Calculated by using RMCOMP/BAS computer program (see Appendix A).

[b]See Aspden (Ref. 18).

[c]Treated as oxygen in kerma calculations.

Table 15. Comparison of data on elemental composition for muscle tissue

Element	Percent by weight			
	ICRP-1975	Kim-1974	Tipton-1969	ICRU-1964
H	10.2[a]	10.3[b]	10[c]	10.2[d]
C	11.1	9.9	11	12.3
N	2.8	3.2	2.6	3.5
O	75.0	75.7	75	72.9
Na	0.075	0.1	0.075	0.08
Mg	0.019		0.019	0.02
P	0.18	0.2	0.18	0.2
S	0.24	0.3	0.23	0.5
Cl	0.079	0.1	0.078	
K	0.30	0.3	0.30	0.3
Ca	0.003		0.0031	0.007
Fe	0.004			

[a]Calculated by using the RMCOMP/BAS computer program (see Appendix A).

[b]See Kim (Ref. 31).

[c]See Tipton (Ref. 32).

[d]See International Commission on Radiological Units and Measurements (Ref. 30).

absorbed dose can be equated.[37–39] Absorbed dose is the energy imparted by charged particles in the small volume element of the specified material divided by the mass of the material within that volume element. Units of absorbed dose and kerma can be either rad or gray.[39] One rad is equal to 100 erg g^{-1} of the specified material, and 1 gray (Gy) is equal to one joule per kilogram of the specified material (or 100 rad).

The material volume of interest in a practical situation may be located in a medium of similar composition or in a medium of different composition. For example, the intensity of a radiation field incident on the body may be specified in terms of tissue kerma in air. If the tissue volume is so small that it does not appreciably disturb the radiation field, then the in-air tissue kerma in rad units and the exposure in roentgen (or R) units will be nearly equal in magnitude (i.e., 1 R is approximately equal to 0.95 rad).[30] Exposure is the sum of all positive or negative ions produced by photons in a small air-volume element divided by the mass of the air in that volume element (i.e., 1 R equals 2.58×10^{-4} coulomb per kilogram of air).[39] Thus, exposure is applicable only in the case of photons, while in-air tissue kerma can be applied in the case of both photons and neutrons.

Some recently published factors for in-air tissue kerma from neutrons and gamma rays use the ICRP-1975 formulation for either total body or total soft tissue of Reference Man. The ICRP-1975 formulation for total soft tissue of Reference Man is recommended over that for the total body. Since the total body is a combination of the skeleton and total soft tissue, its use as a typical soft tissue of the body is inappropriate, especially in the case of low-energy photons. The ICRP-1975 formulation for total soft tissue of Reference Man gives conversion factors that are more consistent with the ICRU-1964 and A-150 (or Shonka) formulations for muscle tissue[34,40] and muscle equivalent plastic,[40,41] respectively, which have been widely used as a typical soft tissue in both theoretical calculations and experimental measurements of in-air tissue kerma.

The kerma factors given here are the kerma in the specified material of interest per unit particle fluence of either photons or neutrons with a specified energy. If the particle fluence involves a broad spectrum of photon or neutron energies, then an appropriately weighted mean value must be used for the kerma factor.[38,39] Of course, the mean value would be weighted by the particle spectrum in air if the quantity of interest is in-air tissue kerma and by the particle spectrum in the body if the quantity of interest is an organ dose. The particle spectrum within the organ of interest can be calculated, for example, by using Monte Carlo radiation transport codes such as MORSE.[42,43]

Bremsstrahlung losses by the charged particles are negligible for the biological materials of concern here, and charged particle equilibrium exists for all practical purposes at the interfaces between the various soft tissues. Thus, kerma and absorbed dose can be equated in the case of most soft tissue in the body once the self shielding by overlying body tissues is taken into account. In the case of the skeleton, only the soft tissue, and not the bone itself, are considered to be at risk.[20,44] The red marrow is considered to be the critical target tissue for leukemia induction, and the osteogenic cells, especially those on the endosteal surfaces of bone, are considered to be the critical target tissue with respect to bone cancer induction. The osteogenic cells are the precursors of the cells involved in the formation of new bone (i.e., the osteoblasts) and the resorption of old bone (i.e., the osteoclasts). However, kerma and absorbed dose to soft tissues in bone cannot be equated since charged particle equilibrium may not exist near a soft tissue-bone interface.[35,36] The calculation of absorbed dose to soft tissues in the skeleton, which will be discussed later, is a more difficult problem than the calculation of absorbed dose to soft-tissue organs, such as the breasts, thyroid, lungs, and GI tract, which are critical target tissues for cancer induction, and the gonads, which are the critical target tissue for genetic effects.[44–46]

Kerma Factors for Photons

The kerma factor for photons in a specified tissue (or organ) is calculated by summing the products of the mass fraction of an element in the tissue, the photon energy, and the mass energy-transfer coefficient of the element for photons of that energy.[38,39,47] If the unit of photon energy is MeV, and the units of the mass energy-transfer coefficients are square centimeters per gram, then the above sum can be multiplied by 1.602×10^{-8} to obtain a kerma factor with units of rad per photon per square centimeter or 1.602×10^{-10} to obtain a kerma factor with units of gray per photon per square centimeter. The mass energy-transfer coefficients for photons from a 1968 report by Evans[47] and a 1969 report by Hubbell[48] have become the standard for use in kerma-factor calculations for the biological materials of interest here. These data have been updated recently by Hubbell,[49] and his newer cross-section tabulations for photons with energies between 1 keV and 20 MeV were used in this work. Differences between the newer cross-section tabulations of Hubbell[49,50] and the older cross-section tabulations of both Hubbell[48] and Storm and Israel[51] are of the order of 1%

or less over most of the element-energy range of the data, but in some cases are as much as 5%.

Mass fractions for the total-body, skeletal, and soft-tissue components given in Tables 10 to 12 were used to obtain the kerma factors for photons listed in Tables 16 to 18. Note that the kerma factors for photons in all of these various organ-tissue components are essentially the same in the energy regions dominated by Compton scattering (i.e., several hundred keV to several MeV) and pair production (i.e., several MeV or more) (see Figure 1 of Reference 47). The kerma factors, however, are quite different in the energy region dominated by photoelectric absorption (i.e., several hundred keV or less). Adipose tissue and other soft tissues with a high fat content, such as the yellow marrow (80% fat) and red marrow (50% fat), yield the smallest kerma factors.[22] However, the kerma factors for 30-keV photons in all soft tissues of the body are nearly an order of magnitude smaller than in bone due to differences in the abundance of higher atomic-number elements such as phosphorus (Z = 15) and calcium (Z = 20). The greater photoelectric absorption of low-energy photons in the higher Z elements of bone is extremely important since it enhances the absorbed dose to soft tissues in the skeleton.

Table 16. Kerma factors for photons in various total-body components of Reference Man[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)		
	Total body	Skeleton	Total soft tissue
1.0E-3	5.64E-10	5.55E-10	5.66E-10
1.5E-3	2.84E-10	2.83E-10	2.84E-10
2.0E-3	1.68E-10	1.69E-10	1.68E-10
3.0E-3	8.34E-11	1.05E-10	7.98E-11
4.0E-3	4.87E-11	6.24E-11	4.63E-11
5.0E-3	3.78E-11	8.61E-11	2.98E-11
6.0E-3	2.66E-11	6.32E-11	2.05E-11
8.0E-3	1.52E-11	3.82E-11	1.14E-11
1.0E-2	9.71E-12	2.55E-11	7.09E-12
1.5E-2	4.24E-12	1.18E-11	2.98E-12
2.0E-2	2.33E-12	6.75E-12	1.60E-12
3.0E-2	1.02E-12	3.01E-12	6.87E-13
4.0E-2	5.98E-13	1.71E-12	4.15E-13
5.0E-2	4.35E-13	1.13E-12	3.21E-13
6.0E-2	3.73E-13	8.43E-13	2.95E-13
8.0E-2	3.67E-13	6.17E-13	3.26E-13
1.0E-1	4.28E-13	5.80E-13	4.03E-13
1.5E-1	6.68E-13	7.19E-13	6.60E-13
2.0E-1	9.47E-13	9.59E-13	9.45E-13
3.0E-1	1.52E-12	1.50E-12	1.53E-12
4.0E-1	2.08E-12	2.04E-12	2.09E-12
5.0E-1	2.62E-12	2.56E-12	2.63E-12
6.0E-1	3.13E-12	3.05E-12	3.14E-12
8.0E-1	4.07E-12	3.97E-12	4.09E-12
1.0E+0	4.93E-12	4.80E-12	4.95E-12
1.5E+0	6.78E-12	6.60E-12	6.81E-12
2.0E+0	8.30E-12	8.10E-12	8.33E-12
3.0E+0	1.09E-11	1.07E-11	1.10E-11
4.0E+0	1.33E-11	1.31E-11	1.33E-11
5.0E+0	1.54E-11	1.54E-11	1.54E-11
6.0E+0	1.75E-11	1.77E-11	1.75E-11
8.0E+0	2.16E-11	2.21E-11	2.15E-11
1.0E+1	2.57E-11	2.67E-11	2.55E-11
1.5E+1	3.62E-11	3.86E-11	3.58E-11
2.0E+1	4.71E-11	5.12E-11	4.65E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions from Table 10 of this report.

Table 17. Kerma factors for photons in various skeletal components of Reference Man[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^{2})				
	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow
1.0E-3	5.97E-10	5.95E-10	5.98E-10	4.95E-10	4.05E-10
1.5E-3	3.09E-10	3.08E-10	3.10E-10	2.44E-10	1.94E-10
2.0E-3	1.87E-10	1.86E-10	1.87E-10	1.44E-10	1.14E-10
3.0E-3	1.38E-10	1.38E-10	1.36E-10	6.79E-11	5.25E-11
4.0E-3	8.35E-11	8.35E-11	8.20E-11	3.93E-11	2.97E-11
5.0E-3	1.47E-10	1.48E-10	1.42E-10	2.52E-11	1.88E-11
6.0E-3	1.09E-10	1.10E-10	1.05E-10	1.73E-11	1.29E-11
8.0E-3	6.68E-11	6.71E-11	6.45E-11	9.68E-12	7.04E-12
1.0E-2	4.51E-11	4.53E-11	4.35E-11	6.04E-12	4.35E-12
1.5E-2	2.12E-11	2.13E-11	2.04E-11	2.54E-12	1.80E-12
2.0E-2	1.22E-11	1.23E-11	1.17E-11	1.37E-12	9.64E-13
3.0E-2	5.44E-12	5.47E-12	5.24E-12	5.95E-13	4.26E-13
4.0E-2	3.06E-12	3.08E-12	2.95E-12	3.68E-13	2.78E-13
5.0E-2	1.98E-12	1.99E-12	1.91E-12	2.93E-13	2.38E-13
6.0E-2	1.42E-12	1.42E-12	1.37E-12	2.77E-13	2.41E-13
8.0E-2	9.22E-13	9.25E-13	8.97E-13	3.17E-13	3.00E-13
1.0E-1	7.64E-13	7.66E-13	7.50E-13	3.97E-13	3.88E-13
1.5E-1	7.79E-13	7.79E-13	7.75E-13	6.58E-13	6.59E-13
2.0E-1	9.73E-13	9.72E-13	9.73E-13	9.45E-13	9.51E-13
3.0E-1	1.47E-12	1.47E-12	1.47E-12	1.53E-12	1.54E-12
4.0E-1	1.98E-12	1.98E-12	1.99E-12	2.09E-12	2.11E-12
5.0E-1	2.48E-12	2.48E-12	2.49E-12	2.63E-12	2.65E-12
6.0E-1	2.95E-12	2.95E-12	2.97E-12	3.14E-12	3.17E-12
8.0E-1	3.84E-12	3.83E-12	3.85E-12	4.09E-12	4.13E-12
1.0E+0	4.64E-12	4.63E-12	4.66E-12	4.95E-12	5.00E-12
1.5E+0	6.38E-12	6.37E-12	6.41E-12	6.81E-12	6.88E-12
2.0E+0	7.85E-12	7.84E-12	7.88E-12	8.33E-12	8.40E-12
3.0E+0	1.05E-11	1.05E-11	1.05E-11	1.09E-11	1.10E-11
4.0E+0	1.30E-11	1.30E-11	1.30E-11	1.32E-11	1.33E-11
5.0E+0	1.54E-11	1.54E-11	1.55E-11	1.54E-11	1.54E-11
6.0E+0	1.79E-11	1.79E-11	1.79E-11	1.74E-11	1.74E-11
8.0E+0	2.29E-11	2.29E-11	2.29E-11	2.13E-11	2.12E-11
1.0E+1	2.81E-11	2.81E-11	2.80E-11	2.52E-11	2.49E-11
1.5E+1	4.19E-11	4.19E-11	4.17E-11	3.51E-11	3.43E-11
2.0E+1	5.68E-11	5.68E-11	5.64E-11	4.54E-11	4.40E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions from Table 11 of this report.

Table 18. Kerma factors for photons in various soft-tissue components of Reference Man[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^{2})				
	Skin	Muscle	Brain	Lungs	Intestine
1.0E-3	5.66E-10	6.11E-10	6.03E-10	6.14E-10	6.09E-10
1.5E-3	2.84E-10	3.09E-10	3.05E-10	3.11E-10	3.08E-10
2.0E-3	1.68E-10	1.83E-10	1.81E-10	1.85E-10	1.83E-10
3.0E-3	7.99E-11	8.71E-11	8.74E-11	8.83E-11	8.60E-11
4.0E-3	4.58E-11	5.10E-11	5.13E-11	5.12E-11	4.95E-11
5.0E-3	2.94E-11	3.27E-11	3.30E-11	3.29E-11	3.17E-11
6.0E-3	2.02E-11	2.26E-11	2.28E-11	2.27E-11	2.18E-11
8.0E-3	1.12E-11	1.25E-11	1.27E-11	1.27E-11	1.21E-11
1.0E-2	6.94E-12	7.82E-12	7.92E-12	7.92E-12	7.50E-12
1.5E-2	2.91E-12	3.29E-12	3.34E-12	3.34E-12	3.14E-12
2.0E-2	1.56E-12	1.76E-12	1.80E-12	1.79E-12	1.68E-12
3.0E-2	6.69E-13	7.55E-13	7.70E-13	7.69E-13	7.19E-13
4.0E-2	4.04E-13	4.51E-13	4.59E-13	4.58E-13	4.31E-13
5.0E-2	3.14E-13	3.42E-13	3.48E-13	3.47E-13	3.30E-13
6.0E-2	2.90E-13	3.09E-13	3.13E-13	3.12E-13	3.01E-13
8.0E-2	3.22E-13	3.33E-13	3.36E-13	3.35E-13	3.29E-13
1.0E-1	4.00E-13	4.07E-13	4.09E-13	4.08E-13	4.05E-13
1.5E-1	6.56E-13	6.60E-13	6.63E-13	6.61E-13	6.61E-13
2.0E-1	9.40E-13	9.44E-13	9.47E-13	9.44E-13	9.45E-13
3.0E-1	1.52E-12	1.52E-12	1.53E-12	1.52E-12	1.53E-12
4.0E-1	2.08E-12	2.09E-12	2.09E-12	2.09E-12	2.09E-12
5.0E-1	2.62E-12	2.63E-12	2.63E-12	2.62E-12	2.63E-12
6.0E-1	3.12E-12	3.13E-12	3.14E-12	3.13E-12	3.14E-12
8.0E-1	4.07E-12	4.08E-12	4.09E-12	4.08E-12	4.09E-12
1.0E+0	4.92E-12	4.94E-12	4.95E-12	4.94E-12	4.95E-12
1.5E+0	6.77E-12	6.79E-12	6.81E-12	6.79E-12	6.81E-12

Table 18. (cont'd.)

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)				
	Skin	Muscle	Brain	Lungs	Intestine
2.0E+0	8.29E-12	8.31E-12	8.34E-12	8.31E-12	8.33E-12
3.0E+0	1.09E-11	1.09E-11	1.10E-11	1.09E-11	1.10E-11
4.0E+0	1.32E-11	1.33E-11	1.33E-11	1.33E-11	1.33E-11
5.0E+0	1.54E-11	1.55E-11	1.55E-11	1.55E-11	1.55E-11
6.0E+0	1.74E-11	1.76E-11	1.76E-11	1.76E-11	1.76E-11
8.0E+0	2.14E-11	2.16E-11	2.17E-11	2.16E-11	2.16E-11
1.0E+1	2.54E-11	2.57E-11	2.58E-11	2.57E-11	2.57E-11
1.5E+1	3.57E-11	3.62E-11	3.62E-11	3.62E-11	3.61E-11
2.0E+1	4.63E-11	4.71E-11	4.71E-11	4.72E-11	4.70E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions from Table 12 of this report.

Table 19. Comparison of kerma factors for photons in compact bone[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)					
	ICRP-revised	ICRP-1975	Kim-1974	Tipton-1969	ICRU-1964	Woodard-1962
1.0E-3	5.95E-10	5.91E-10	5.86E-10	5.83E-10	5.44E-10	5.94E-10
1.5E-3	3.08E-10	3.03E-10	3.07E-10	3.03E-10	2.75E-10	3.05E-10
2.0E-3	1.86E-10	1.82E-10	1.86E-10	1.82E-10	1.65E-10	1.83E-10
3.0E-3	1.38E-10	1.38E-10	1.51E-10	1.35E-10	1.11E-10	1.36E-10
4.0E-3	8.35E-11	8.28E-11	9.22E-11	8.07E-11	6.57E-11	8.15E-11
5.0E-3	1.48E-10	1.35E-10	1.66E-10	1.33E-10	9.83E-11	1.37E-10
6.0E-3	1.10E-10	1.00E-10	1.24E-10	9.81E-11	7.24E-11	1.02E-10
8.0E-3	6.71E-11	6.13E-11	7.60E-11	5.99E-11	4.40E-11	6.22E-11
1.0E-2	4.53E-11	4.13E-11	5.14E-11	4.04E-11	2.95E-11	4.19E-11
1.5E-2	2.13E-11	1.94E-11	2.42E-11	1.89E-11	1.38E-11	1.97E-11
2.0E-2	1.23E-11	1.11E-11	1.39E-11	1.09E-11	7.87E-12	1.13E-11
3.0E-2	5.47E-12	4.95E-12	6.22E-12	4.84E-12	3.51E-12	5.04E-12
4.0E-2	3.08E-12	2.79E-12	3.49E-12	2.72E-12	1.98E-12	2.83E-12
5.0E-2	1.99E-12	1.80E-12	2.25E-12	1.77E-12	1.30E-12	1.83E-12
6.0E-2	1.42E-12	1.30E-12	1.60E-12	1.27E-12	9.60E-13	1.32E-12
8.0E-2	9.25E-13	8.58E-13	1.03E-12	8.45E-13	6.80E-13	8.69E-13
1.0E-1	7.66E-13	7.24E-13	8.33E-13	7.17E-13	6.17E-13	7.30E-13
1.5E-1	7.79E-13	7.63E-13	8.15E-13	7.61E-13	7.30E-13	7.63E-13
2.0E-1	9.72E-13	9.64E-13	1.00E-12	9.65E-13	9.61E-13	9.62E-13
3.0E-1	1.47E-12	1.46E-12	1.50E-12	1.47E-12	1.49E-12	1.46E-12
4.0E-1	1.98E-12	1.98E-12	2.02E-12	1.98E-12	2.02E-12	1.97E-12
5.0E-1	2.48E-12	2.48E-12	2.52E-12	2.49E-12	2.54E-12	2.47E-12
6.0E-1	2.95E-12	2.95E-12	3.00E-12	2.96E-12	3.03E-12	2.94E-12
8.0E-1	3.83E-12	3.84E-12	3.90E-12	3.85E-12	3.93E-12	3.82E-12
1.0E+0	4.63E-12	4.64E-12	4.72E-12	4.65E-12	4.76E-12	4.62E-12
1.5E+0	6.37E-12	6.38E-12	6.48E-12	6.40E-12	6.55E-12	6.36E-12
2.0E+0	7.84E-12	7.85E-12	7.98E-12	7.87E-12	8.03E-12	7.82E-12
3.0E+0	1.05E-11	1.05E-11	1.07E-11	1.05E-11	1.07E-11	1.04E-11
4.0E+0	1.30E-11	1.29E-11	1.33E-11	1.30E-11	1.31E-11	1.29E-11
5.0E+0	1.54E-11	1.54E-11	1.58E-11	1.54E-11	1.54E-11	1.53E-11
6.0E+0	1.79E-11	1.78E-11	1.83E-11	1.79E-11	1.77E-11	1.77E-11
8.0E+0	2.29E-11	2.27E-11	2.35E-11	2.27E-11	2.22E-11	2.27E-11
1.0E+1	2.81E-11	2.78E-11	2.90E-11	2.77E-11	2.69E-11	2.78E-11
1.5E+1	4.19E-11	4.12E-11	4.33E-11	4.11E-11	3.91E-11	4.13E-11
2.0E+1	5.68E-11	5.57E-11	5.89E-11	5.54E-11	5.21E-11	5.58E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions as calculated by using the RMCOMP/BAS computer program in the case of the ICRP-revised and ICRP-1975 formulations and mass fractions from Table 13 of this report in the case of the other formulations for compact bone.

Kerma factors for photons in the various compact-bone, red-marrow, and muscle-tissue formulations listed in Tables 13 to 15 are compared in Tables 19 to 21, respectively. The ICRU-1964 and ICRP-1975 formulations for compact bone (i.e., wet cortical bone) yield kerma factors, as pointed out by White and Fitzgerald,[22] that differ by as much as 30% at low photon energies. Their suggestion to abandon the ICRU-1964 bone formulation,[30,35] which predates the work of Kim,[31] Tipton and coworkers[32,52–54] and Woodard,[33] for ex-

Table 20. Comparison of kerma factors for photons in red bone marrow[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)		
	ICRP-revised	ICRP-1975	Aspden-1972
1.0E-3	4.95E-10	4.94E-10	4.75E-10
1.5E-3	2.44E-10	2.43E-10	2.37E-10
2.0E-3	1.44E-10	1.43E-10	1.37E-10
3.0E-3	6.79E-11	6.55E-11	6.40E-11
4.0E-3	3.93E-11	3.69E-11	3.70E-11
5.0E-3	2.52E-11	2.34E-11	2.36E-11
6.0E-3	1.73E-11	1.60E-11	1.62E-11
8.0E-3	9.68E-12	8.77E-12	8.95E-12
1.0E-2	6.04E-12	5.41E-12	5.56E-12
1.5E-2	2.54E-12	2.24E-12	2.33E-12
2.0E-2	1.37E-12	1.20E-12	1.25E-12
3.0E-2	5.95E-13	5.17E-13	5.43E-13
4.0E-2	3.68E-13	3.24E-13	3.39E-13
5.0E-2	2.93E-13	2.65E-13	2.75E-13
6.0E-2	2.77E-13	2.58E-13	2.64E-13
8.0E-2	3.17E-13	3.07E-13	3.09E-13
1.0E-1	3.97E-13	3.91E-13	3.92E-13
1.5E-1	6.58E-13	6.56E-13	6.54E-13
2.0E-1	9.45E-13	9.44E-13	9.41E-13
3.0E-1	1.53E-12	1.53E-12	1.52E-12
4.0E-1	2.09E-12	2.09E-12	2.08E-12
5.0E-1	2.63E-12	2.63E-12	2.62E-12
6.0E-1	3.14E-12	3.14E-12	3.13E-12
8.0E-1	4.09E-12	4.09E-12	4.08E-12
1.0E+0	4.95E-12	4.96E-12	4.94E-12
1.5E+0	6.81E-12	6.82E-12	6.79E-12
2.0E+0	8.33E-12	8.33E-12	8.30E-12
3.0E+0	1.09E-11	1.09E-11	1.09E-11
4.0E+0	1.32E-11	1.32E-11	1.32E-11
5.0E+0	1.54E-11	1.54E-11	1.53E-11
6.0E+0	1.74E-11	1.74E-11	1.73E-11
8.0E+0	2.13E-11	2.13E-11	2.12E-11
1.0E+1	2.52E-11	2.52E-11	2.51E-11
1.5E+1	3.51E-11	3.50E-11	3.48E-11
2.0E+1	4.54E-11	4.52E-11	4.49E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions as calculated by using the RHCOMP/BAS computer program in the case of the ICRP-revised or ICRP-1975 formulations and from Table 14 in the case of Aspden's formulation for red marrow.

Table 21. Comparison of kerma factors for photons in muscle tissue[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)			
	ICRP-1975	Kim-1974	Tipton-1969	ICRU-1964
1.0E-3	6.11E-10	6.14E-10	6.13E-10	6.04E-10
1.5E-3	3.09E-10	3.11E-10	3.10E-10	3.05E-10
2.0E-3	1.83E-10	1.84E-10	1.84E-10	1.81E-10
3.0E-3	8.71E-11	8.81E-11	8.73E-11	8.71E-11
4.0E-3	5.10E-11	5.16E-11	5.11E-11	5.10E-11
5.0E-3	3.27E-11	3.31E-11	3.28E-11	3.28E-11
6.0E-3	2.26E-11	2.29E-11	2.26E-11	2.27E-11
8.0E-3	1.25E-11	1.27E-11	1.26E-11	1.26E-11
1.0E-2	7.82E-12	7.92E-12	7.83E-12	7.85E-12
1.5E-2	3.29E-12	3.33E-12	3.29E-12	3.30E-12
2.0E-2	1.76E-12	1.79E-12	1.77E-12	1.78E-12
3.0E-2	7.55E-13	7.65E-13	7.55E-13	7.61E-13
4.0E-2	4.51E-13	4.56E-13	4.50E-13	4.54E-13
5.0E-2	3.42E-13	3.45E-13	3.42E-13	3.44E-13
6.0E-2	3.09E-13	3.11E-13	3.09E-13	3.11E-13
8.0E-2	3.33E-13	3.34E-13	3.32E-13	3.33E-13
1.0E-1	4.07E-13	4.07E-13	4.06E-13	4.07E-13
1.5E-1	6.60E-13	6.61E-13	6.59E-13	6.60E-13
2.0E-1	9.44E-13	9.44E-13	9.42E-13	9.44E-13
3.0E-1	1.52E-12	1.52E-12	1.52E-12	1.52E-12

Table 21. (cont'd.)

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)			
	ICRP-1975	Kim-1974	Tipton-1969	ICRU-1964
4.0E-1	2.09E-12	2.09E-12	2.08E-12	2.09E-12
5.0E-1	2.63E-12	2.63E-12	2.62E-12	2.62E-12
6.0E-1	3.13E-12	3.13E-12	3.13E-12	3.13E-12
8.0E-1	4.08E-12	4.08E-12	4.07E-12	4.08E-12
1.0E+0	4.94E-12	4.94E-12	4.93E-12	4.94E-12
1.5E+0	6.79E-12	6.80E-12	6.78E-12	6.79E-12
2.0E+0	8.31E-12	8.32E-12	8.30E-12	8.31E-12
3.0E+0	1.09E-11	1.09E-11	1.09E-11	1.09E-11
4.0E+0	1.33E-11	1.33E-11	1.33E-11	1.33E-11
5.0E+0	1.55E-11	1.55E-11	1.54E-11	1.54E-11
6.0E+0	1.76E-11	1.76E-11	1.75E-11	1.76E-11
8.0E+0	2.16E-11	2.17E-11	2.16E-11	2.16E-11
1.0E+1	2.57E-11	2.57E-11	2.57E-11	2.57E-11
1.5E+1	3.62E-11	3.62E-11	3.62E-11	3.61E-11
2.0E+1	4.71E-11	4.72E-11	4.71E-11	4.71E-11

[a]Based on photon cross-section data from Hubbell (Refs. 48-50) and on mass fractions as calculated by using the RMCOMP/BAS computer program in the case of the ICRP-1975 formulation and from Table 15 in the case of the other formulations for muscle tissue.

Table 22. Comparison of kerma factors for photons in bone and soft-tissue compositions developed for use in red-bone-marrow dosimetry[a]

Photon energy (MeV)	Kerma factor (Gy photon^{-1} cm^2)					
	ICRP-revised			ICRU-1964		
	Trabecular bone	Red marrow	Ratio	Compact bone	Muscle tissue	Ratio
1.0E-3	5.98E-10	4.95E-10	1.21	5.44E-10	6.04E-10	0.90
1.5E-3	3.10E-10	2.44E-10	1.27	2.75E-10	3.05E-10	0.90
2.0E-3	1.87E-10	1.44E-10	1.30	1.65E-10	1.81E-10	0.91
3.0E-3	1.36E-10	6.79E-11	2.00	1.11E-10	8.71E-11	1.27
4.0E-3	8.20E-11	3.93E-11	2.09	6.57E-11	5.10E-11	1.29
5.0E-3	1.42E-10	2.52E-11	5.63	9.83E-11	3.28E-11	3.00
6.0E-3	1.05E-10	1.73E-11	6.07	7.24E-11	2.27E-11	3.19
8.0E-3	6.43E-11	9.68E-12	6.66	4.40E-11	1.26E-11	3.49
1.0E-2	4.56E-11	6.04E-12	7.55	2.95E-11	7.85E-12	3.76
1.5E-2	2.04E-11	2.54E-12	8.03	1.38E-11	3.30E-12	4.18
2.0E-2	1.17E-11	1.37E-12	8.54	7.87E-12	1.78E-12	4.42
3.0E-2	5.24E-12	5.95E-13	8.81	3.51E-12	7.61E-13	4.61
4.0E-2	2.95E-12	3.68E-13	8.02	1.98E-12	4.54E-13	4.36
5.0E-2	1.91E-12	2.93E-13	6.51	1.30E-12	3.44E-13	3.78
6.0E-2	1.37E-12	2.77E-13	4.95	9.60E-13	3.11E-13	3.09
8.0E-2	8.97E-13	3.17E-13	2.83	6.80E-13	3.33E-13	2.04
1.0E-1	7.50E-13	3.97E-13	1.89	6.17E-13	4.07E-13	1.52
1.5E-1	7.75E-13	6.58E-13	1.18	7.30E-13	6.60E-13	1.11
2.0E-1	9.73E-13	9.45E-13	1.03	9.61E-13	9.44E-13	1.02
3.0E-1	1.47E-12	1.53E-12	0.96	1.49E-12	1.52E-12	0.98
4.0E-1	1.99E-12	2.09E-12	0.95	2.02E-12	2.09E-12	0.97
5.0E-1	2.49E-12	2.63E-12	0.95	2.54E-12	2.62E-12	0.97
6.0E-1	2.97E-12	3.14E-12	0.95	3.03E-12	3.13E-12	0.97
8.0E-1	3.85E-12	4.09E-12	0.94	3.93E-12	4.08E-12	0.96
1.0E+0	4.66E-12	4.95E-12	0.94	4.76E-12	4.94E-12	0.96
1.5E+0	6.41E-12	6.81E-12	0.94	6.55E-12	6.79E-12	0.97
2.0E+0	7.88E-12	8.33E-12	0.95	8.03E-12	8.31E-12	0.97
3.0E+0	1.05E-11	1.09E-11	0.96	1.07E-11	1.09E-11	0.98
4.0E+0	1.30E-11	1.32E-11	0.99	1.31E-11	1.33E-11	0.99
5.0E+0	1.55E-11	1.54E-11	1.01	1.54E-11	1.54E-11	1.00
6.0E+0	1.79E-11	1.74E-11	1.03	1.77E-11	1.75E-11	1.01
8.0E+0	2.29E-11	2.13E-11	1.08	2.22E-11	2.16E-11	1.03
1.0E+1	2.80E-11	2.52E-11	1.11	2.69E-11	2.57E-11	1.05
1.5E+1	4.17E-11	3.51E-11	1.19	3.91E-11	3.61E-11	1.08
2.0E+1	5.64E-11	4.54E-11	1.24	5.21E-11	4.71E-11	1.11

[a]See discussion in text and data in Tables 17, 19, and 21 of this report.

ample, appears to be noncontroversial. The abandonment of the ICRU-1964 muscle-tissue formulation as an approximation for the red and yellow marrow also appears to be noncontroversial. It was previously suggested by Kerr[55] that caution should be excercised in the use of the ICRP-1975 formulation for red marrow since the trace-element content was not defined (Table 14). However, the trace-element content of red marrow and the trace-element and mineral content of trabecular bone are both reasonably well defined for Reference Man as a result of this work.

According to the ICRP-1975 Reference Man Report,[5] there is a difference between the water content of cortical and trabecular bone. Thus, the ICRP-revised formulation for trabecular bone, rather than corical bone, is used in the kerma-factor comparisons shown in Table 22. Note, at the lower energies, that the ratio of kerma factors for photons in the ICRP-revised formulations for trabecular bone and red marrow are significantly greater than the ratio of kerma factor for photons in the ICRU-1964 formulations for compact bone (i.e., wet cortical bone) and muscle tissue (i.e., typical soft tissue) that has been used as an approximation for red marrow. The differences at low photon energies would be even larger if the factors for kerma (i.e., kinetic energy released to charged particles) in the ICRP-revised formulation for cortical bone had been used in place of those in the ICRP-revised formulation for trabecular bone (Table 17).

Kerma Factors for Neutrons

Kerma factors for neutrons in 19 different isotopes and elements, including the 12 elements of interest here, have been tabulated by Caswell et al.[29] Their tabulations give the kerma factors for a monoenergetic "thermal-neutron" energy of 0.0253 eV and for 119 contiguous energy "groups" or "bins" extending from 0.026 eV to 30 MeV. Each bin is characterized by a central or mean energy and an energy interval of a given width (Table 23). The kerma factors are calculated from cross sections averaged over the full energy width of each bin. Averaging over binned energy widths eliminates the somewhat irregular behavior of the kerma factors due to resonance absorption of neutrons by elements other than hydrogen. Only their tabulated data for bins with neutron energies less than 20 MeV are used since this is the highest energy of interest in the case of a fission neutron source such as a nuclear weapon.[27]

Table 23. Kerma factors for neutrons in various total-body components of Reference Man[a]

Neutron energy (Mev)	Energy interval (MeV)	Kerma factor (Gy neutron^{-1} cm^2) Total body	Skeleton	Total soft tissue
2.53E-8		1.97E-13	2.45E-13	1.89E-13
3.60E-8	2.00E-8	1.67E-13	2.10E-13	1.60E-13
6.30E-8	3.40E-8	1.26E-13	1.58E-13	1.21E-13
1.10E-7	6.00E-8	9.56E-14	1.20E-13	9.15E-14
2.00E-7	1.20E-7	7.11E-14	8.95E-14	6.80E-14
3.60E-7	2.00E-7	5.30E-14	6.67E-14	5.06E-14
6.30E-7	3.40E-7	4.02E-14	5.10E-14	3.84E-14
1.10E-6	6.00E-7	3.04E-14	3.88E-14	2.90E-14
2.00E-6	1.20E-6	2.28E-14	2.93E-14	2.18E-14
3.60E-6	2.00E-6	1.73E-14	2.23E-14	1.64E-14
6.30E-6	3.40E-6	1.34E-14	1.74E-14	1.28E-14
1.10E-5	6.00E-6	1.08E-14	1.39E-14	1.03E-14

Table 23 (cont'd.)

Neutron energy (MeV)	Energy interval (MeV)	Kerma factor (Gy neutron^{-1} cm^2)		
		Total body	Skeleton	Total soft tissue
2.00E-5	1.20E-5	9.32E-15	1.16E-14	8.95E-15
3.60E-5	2.00E-5	9.14E-15	1.05E-14	8.91E-15
6.30E-5	3.40E-5	1.06E-14	1.09E-14	1.05E-14
1.10E-4	6.00E-5	1.43E-14	1.32E-14	1.45E-14
2.00E-4	1.20E-4	2.27E-14	1.89E-14	2.33E-14
3.60E-4	2.00E-4	3.86E-14	3.03E-14	3.99E-14
6.30E-4	3.40E-4	6.52E-14	4.94E-14	6.78E-14
1.10E-3	6.00E-4	1.12E-13	8.35E-14	1.17E-13
2.00E-3	1.20E-3	2.01E-13	1.48E-13	2.10E-13
3.60E-3	2.00E-3	3.58E-13	2.64E-13	3.74E-13
6.30E-3	3.40E-3	6.15E-13	4.51E-13	6.43E-13
1.10E-2	6.00E-3	1.04E-12	7.60E-13	1.09E-12
2.00E-2	1.20E-2	1.81E-12	1.32E-12	1.89E-12
3.60E-2	2.00E-2	2.99E-12	2.19E-12	3.12E-12
6.30E-2	3.40E-2	4.64E-12	3.40E-12	4.85E-12
8.20E-2	4.00E-3	5.61E-12	4.11E-12	5.86E-12
8.60E-2	4.00E-3	5.80E-12	4.26E-12	6.06E-12
9.00E-2	4.00E-3	5.99E-12	4.39E-12	6.25E-12
9.40E-2	4.00E-3	6.17E-12	4.52E-12	6.44E-12
9.80E-2	4.00E-3	6.34E-12	4.65E-12	6.62E-12
1.05E-1	1.00E-2	6.64E-12	4.87E-12	6.93E-12
1.15E-1	1.00E-2	7.05E-12	5.17E-12	7.36E-12
1.25E-1	1.00E-2	7.44E-12	5.46E-12	7.77E-12
1.35E-1	1.00E-2	7.81E-12	5.74E-12	8.15E-12
1.45E-1	1.00E-2	8.17E-12	6.00E-12	8.53E-12
1.55E-1	1.00E-2	8.51E-12	6.25E-12	8.88E-12
1.65E-1	1.00E-2	8.82E-12	6.48E-12	9.21E-12
1.75E-1	1.00E-2	9.14E-12	6.73E-12	9.55E-12
1.85E-1	1.00E-2	9.43E-12	6.93E-12	9.85E-12
1.95E-1	1.00E-2	9.72E-12	7.14E-12	1.02E-11
2.10E-1	2.00E-2	1.01E-11	7.46E-12	1.06E-11
2.30E-1	2.00E-2	1.07E-11	7.86E-12	1.12E-11
2.50E-1	2.00E-2	1.12E-11	8.22E-12	1.16E-11
2.70E-1	2.00E-2	1.17E-11	8.63E-12	1.22E-11
2.90E-1	2.00E-2	1.22E-11	8.97E-12	1.27E-11
3.10E-1	2.00E-2	1.27E-11	9.31E-12	1.32E-11
3.30E-1	2.00E-2	1.30E-11	9.62E-12	1.36E-11
3.50E-1	2.00E-2	1.36E-11	9.99E-12	1.41E-11
3.70E-1	2.00E-2	1.40E-11	1.03E-11	1.46E-11
3.90E-1	2.00E-2	1.46E-11	1.08E-11	1.53E-11
4.20E-1	4.00E-2	1.58E-11	1.17E-11	1.65E-11
4.60E-1	4.00E-2	1.61E-11	1.19E-11	1.68E-11
5.00E-1	4.00E-2	1.59E-11	1.17E-11	1.66E-11
5.40E-1	4.00E-2	1.64E-11	1.21E-11	1.71E-11
5.80E-1	4.00E-2	1.70E-11	1.25E-11	1.77E-11
6.20E-1	4.00E-2	1.76E-11	1.30E-11	1.83E-11
6.60E-1	4.00E-2	1.82E-11	1.34E-11	1.90E-11
7.00E-1	4.00E-2	1.87E-11	1.38E-11	1.95E-11
7.40E-1	4.00E-2	1.92E-11	1.42E-11	2.00E-11
7.80E-1	4.00E-2	1.98E-11	1.46E-11	2.06E-11
8.20E-1	4.00E-2	2.02E-11	1.49E-11	2.11E-11
8.60E-1	4.00E-2	2.08E-11	1.53E-11	2.17E-11
9.00E-1	4.00E-2	2.14E-11	1.58E-11	2.23E-11
9.40E-1	4.00E-2	2.23E-11	1.65E-11	2.33E-11
9.80E-1	4.00E-2	2.39E-11	1.77E-11	2.49E-11
1.05E+0	1.00E-1	2.43E-11	1.80E-11	2.54E-11
1.15E+0	1.00E-1	2.42E-11	1.79E-11	2.53E-11
1.25E+0	1.00E-1	2.53E-11	1.87E-11	2.63E-11
1.35E+0	1.00E-1	2.61E-11	1.93E-11	2.72E-11
1.45E+0	1.00E-1	2.66E-11	1.97E-11	2.78E-11
1.55E+0	1.00E-1	2.73E-11	2.02E-11	2.85E-11
1.65E+0	1.00E-1	2.84E-11	2.10E-11	2.96E-11
1.75E+0	1.00E-1	2.88E-11	2.13E-11	3.00E-11
1.85E+0	1.00E-1	2.99E-11	2.22E-11	3.12E-11
1.95E+0	1.00E-1	3.02E-11	2.23E-11	3.15E-11
2.10E+0	2.00E-1	3.12E-11	2.32E-11	3.25E-11
2.30E+0	2.00E-1	3.17E-11	2.35E-11	3.30E-11
2.50E+0	2.00E-1	3.30E-11	2.46E-11	3.43E-11
2.70E+0	2.00E-1	3.45E-11	2.58E-11	3.59E-11
2.90E+0	2.00E-1	3.60E-11	2.73E-11	3.75E-11
3.10E+0	2.00E-1	3.71E-11	2.80E-11	3.86E-11
3.30E+0	2.00E-1	4.04E-11	3.08E-11	4.20E-11
3.50E+0	2.00E-1	4.14E-11	3.17E-11	4.30E-11
3.70E+0	2.00E-1	4.23E-11	3.24E-11	4.39E-11
3.90E+0	2.00E-1	4.17E-11	3.20E-11	4.33E-11
4.20E+0	4.00E-1	4.27E-11	3.27E-11	4.44E-11
4.60E+0	4.00E-1	4.27E-11	3.26E-11	4.44E-11
5.00E+0	4.00E-1	4.48E-11	3.42E-11	4.66E-11
5.40E+0	4.00E-1	4.40E-11	3.36E-11	4.58E-11
5.80E+0	4.00E-1	4.59E-11	3.51E-11	4.77E-11
6.20E+0	4.00E-1	4.73E-11	3.63E-11	4.91E-11

Table 23 (cont'd.)

Neutron energy (MeV)	Energy interval (MeV)	Kerma factor (Gy neutron^{-1} cm^2)		
		Total body	Skeleton	Total soft tissue
6.60E+0	4.00E-1	4.80E-11	3.67E-11	4.99E-11
7.00E+0	4.00E-1	4.99E-11	3.81E-11	5.18E-11
7.40E+0	4.00E-1	5.27E-11	4.06E-11	5.47E-11
7.80E+0	4.00E-1	5.28E-11	4.10E-11	5.47E-11
8.20E+0	4.00E-1	5.20E-11	4.02E-11	5.40E-11
8.60E+0	4.00E-1	5.32E-11	4.11E-11	5.52E-11
9.00E+0	4.00E-1	5.46E-11	4.25E-11	5.66E-11
9.40E+0	4.00E-1	5.54E-11	4.34E-11	5.74E-11
9.80E+0	4.00E-1	5.62E-11	4.39E-11	5.83E-11
1.05E+1	1.00E+0	5.74E-11	4.49E-11	5.95E-11
1.15E+1	1.00E+0	6.13E-11	4.81E-11	6.35E-11
1.25E+1	1.00E+0	6.16E-11	4.89E-11	6.38E-11
1.35E+1	1.00E+0	6.39E-11	5.08E-11	6.61E-11
1.45E+1	1.00E+0	6.65E-11	5.31E-11	6.87E-11
1.55E+1	1.00E+0	6.85E-11	5.51E-11	7.08E-11
1.65E+1	1.00E+0	6.97E-11	5.62E-11	7.20E-11
1.75E+1	1.00E+0	7.06E-11	5.68E-11	7.28E-11
1.85E+1	1.00E+0	7.16E-11	5.78E-11	7.39E-11
1.95E+1	1.00E+0	7.28E-11	5.88E-11	7.52E-11

[a]Based on mass fractions from Table 10 of this report and on kerma factors for neutrons from Caswell, Coyne, and Randolph (Ref. 29). Also see their calculations for ICRP-1975 Reference Man.

Mass fractions for the total-body, skeletal, and soft-tissue components given in Tables 10 to 12 were used to obtain the kerma factos for neutrons listed in Tables 23 to 25. The sum of the products of the kerma factor in an element for a specified neutron energy from Caswell et al,[29] and the mass fraction of the element in a specified tissue (or organ) gives a kerma factor for that neutron energy and that tissue with units of rad per neutron per square centimeter, or units of gray per neutron per square centimeter if the sum is multiplied by 1.00×10^{-2}. In the case of fast neutrons (i.e., neutrons with energies greater than 1 keV), most of the kerma is due to recoil-hydrogen ions (recoil protons), and in the case of lower energy neutrons, especially thermal neutrons, most of the kerma is due to 620 keV protons produced by the $^{14}N(n,p)\ ^{14}C$ reaction. Thus, the kerma factors for fast neutrons and for thermal neutrons in a specified organ-tissue component of the body depend to a large extent on the hydrogen content and on the nitrogen content, respectively, of that organ-tissue component. Since nitrogen is a 1/V absorber of thermal neutrons with velocity, V, the kerma factors for a monoenergetic "thermal-neutron" energy of 0.0253 eV can be used to obtain an estimate of the kerma factor for a Maxwell-Boltzman distribution of thermal neutrons at various temperatures.[56,57] For example, the kerma factors for a monoenergetic "thermal-neutron" energy of 0.0253 eV would be divided by 1.128 to obtain an estimate of the kerma factors for a Maxwell-Boltzman distribution of thermal neutrons at a normal temperature of 20 °C (or 293° K).

Comparisons between kerma for neutrons in the ICRP-revised formulations for trabecular bone and red marrow and the kerma factors for neutrons in the ICRU-1964 formulations for compact bone (i.e., wet cortical bone) and muscle tissue (i.e., typical soft tissue) are given in Table 26. Note that there are significant differences in the ratios of the kerma factors (bone-to-soft tissue), due to the bone formulations (i.e., ICRP-revised trabecular bone versus. ICRU-1964 compact bone), rather than the soft-tissue formulations (i.e., ICRP-revised red marrow versus. ICRU-1964 muscle tissue). The abandonment of the ICRU-1964 bone

Table 24. Kerma factors for neutrons in various skeletal components of Reference Man[a]

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^2)				
	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow
2.53E-8	3.12E-13	3.27E-13	2.99E-13	2.49E-13	5.61E-14
3.60E-8	2.68E-13	2.80E-13	2.57E-13	2.11E-13	4.75E-14
6.30E-8	2.02E-13	2.12E-13	1.94E-13	1.60E-13	3.59E-14
1.10E-7	1.53E-13	1.60E-13	1.46E-13	1.21E-13	2.72E-14
2.00E-7	1.15E-13	1.20E-13	1.10E-13	8.96E-14	2.02E-14
3.60E-7	8.55E-14	8.95E-14	8.20E-14	6.68E-14	1.51E-14
6.30E-7	6.56E-14	6.86E-14	6.29E-14	5.06E-14	1.14E-14
1.10E-6	5.01E-14	5.24E-14	4.80E-14	3.83E-14	8.71E-15
2.00E-6	3.80E-14	3.97E-14	3.64E-14	2.86E-14	6.62E-15
3.60E-6	2.90E-14	3.03E-14	2.78E-14	2.15E-14	5.17E-15
6.30E-6	2.26E-14	2.36E-14	2.17E-14	1.66E-14	4.33E-15
1.10E-5	1.80E-14	1.87E-14	1.73E-14	1.33E-14	4.01E-15
2.00E-5	1.45E-14	1.51E-14	1.41E-14	1.11E-14	4.38E-15
3.60E-5	1.23E-14	1.27E-14	1.20E-14	1.06E-14	5.75E-15
6.30E-5	1.13E-14	1.16E-14	1.12E-14	1.18E-14	8.56E-15
1.10E-4	1.16E-14	1.17E-14	1.18E-14	1.56E-14	1.38E-14
2.00E-4	1.39E-14	1.38E-14	1.46E-14	2.43E-14	2.42E-14
3.60E-4	1.94E-14	1.91E-14	2.08E-14	4.10E-14	4.30E-14
6.30E-4	2.90E-14	2.84E-14	3.18E-14	6.90E-14	7.44E-14
1.10E-3	4.66E-14	4.53E-14	5.16E-14	1.19E-13	1.29E-13
2.00E-3	8.04E-14	7.80E-14	8.96E-14	2.13E-13	2.33E-13
3.60E-3	1.41E-13	1.37E-13	1.57E-13	3.79E-13	4.16E-13
6.30E-3	2.39E-13	2.31E-13	2.67E-13	6.51E-13	7.15E-13
1.10E-2	4.01E-13	3.89E-13	4.49E-13	1.10E-12	1.21E-12
2.00E-2	6.97E-13	6.75E-13	7.81E-13	1.91E-12	2.10E-12
3.60E-2	1.15E-12	1.12E-12	1.29E-12	3.17E-12	3.48E-12
6.30E-2	1.79E-12	1.74E-12	2.01E-12	4.92E-12	5.41E-12
8.20E-2	2.17E-12	2.11E-12	2.43E-12	5.94E-12	6.54E-12
8.60E-2	2.25E-12	2.18E-12	2.52E-12	6.15E-12	6.76E-12
9.00E-2	2.32E-12	2.25E-12	2.60E-12	6.34E-12	6.97E-12
9.40E-2	2.39E-12	2.31E-12	2.67E-12	6.53E-12	7.18E-12
9.80E-2	2.46E-12	2.38E-12	2.75E-12	6.71E-12	7.38E-12
1.05E-1	2.57E-12	2.49E-12	2.88E-12	7.03E-12	7.73E-12
1.15E-1	2.73E-12	2.65E-12	3.06E-12	7.47E-12	8.21E-12
1.25E-1	2.89E-12	2.80E-12	3.23E-12	7.88E-12	8.67E-12
1.35E-1	3.06E-12	2.96E-12	3.41E-12	8.27E-12	9.10E-12
1.45E-1	3.18E-12	3.09E-12	3.56E-12	8.65E-12	9.51E-12
1.55E-1	3.32E-12	3.22E-12	3.71E-12	9.01E-12	9.91E-12
1.65E-1	3.44E-12	3.34E-12	3.85E-12	9.35E-12	1.03E-11
1.75E-1	3.59E-12	3.48E-12	4.01E-12	9.68E-12	1.07E-11
1.85E-1	3.69E-12	3.57E-12	4.12E-12	9.99E-12	1.10E-11
1.95E-1	3.80E-12	3.68E-12	4.24E-12	1.03E-11	1.13E-11
2.10E-1	3.98E-12	3.86E-12	4.44E-12	1.07E-11	1.18E-11
2.30E-1	4.19E-12	4.07E-12	4.68E-12	1.13E-11	1.24E-11
2.50E-1	4.43E-12	4.29E-12	4.93E-12	1.18E-11	1.30E-11
2.70E-1	4.63E-12	4.49E-12	5.16E-12	1.24E-11	1.36E-11
2.90E-1	4.82E-12	4.67E-12	5.37E-12	1.29E-11	1.41E-11
3.10E-1	5.00E-12	4.85E-12	5.58E-12	1.34E-11	1.47E-11
3.30E-1	5.21E-12	5.05E-12	5.79E-12	1.38E-11	1.51E-11
3.50E-1	5.42E-12	5.26E-12	6.03E-12	1.43E-11	1.56E-11
3.70E-1	5.64E-12	5.47E-12	6.27E-12	1.47E-11	1.61E-11
3.90E-1	5.93E-12	5.76E-12	6.58E-12	1.53E-11	1.66E-11
4.20E-1	6.64E-12	6.45E-12	7.33E-12	1.64E-11	1.75E-11
4.60E-1	6.63E-12	6.44E-12	7.34E-12	1.68E-11	1.81E-11
5.00E-1	6.28E-12	6.09E-12	6.99E-12	1.68E-11	1.85E-11
5.40E-1	6.45E-12	6.26E-12	7.19E-12	1.73E-11	1.93E-11
5.80E-1	6.71E-12	6.51E-12	7.47E-12	1.81E-11	1.99E-11
6.20E-1	6.99E-12	6.79E-12	7.78E-12	1.87E-11	2.06E-11
6.60E-1	7.24E-12	7.03E-12	8.05E-12	1.93E-11	2.12E-11
7.00E-1	7.43E-12	7.22E-12	8.27E-12	1.99E-11	2.19E-11
7.40E-1	7.62E-12	7.39E-12	8.48E-12	2.04E-11	2.24E-11
7.80E-1	7.86E-12	7.63E-12	8.74E-12	2.10E-11	2.31E-11
8.20E-1	8.05E-12	7.82E-12	8.96E-12	2.15E-11	2.36E-11
8.60E-1	8.31E-12	8.07E-12	9.24E-12	2.20E-11	2.41E-11
9.00E-1	8.64E-12	8.39E-12	9.59E-12	2.26E-11	2.47E-11
9.40E-1	9.15E-12	8.89E-12	1.01E-11	2.34E-11	2.54E-11
9.80E-1	1.01E-11	9.84E-12	1.12E-11	2.47E-11	2.64E-11
1.05E+0	1.02E-11	9.90E-12	1.13E-11	2.53E-11	2.71E-11
1.15E+0	9.85E-12	9.57E-12	1.09E-11	2.55E-11	2.79E-11
1.25E+0	1.03E-11	9.97E-12	1.14E-11	2.66E-11	2.90E-11
1.35E+0	1.07E-11	1.04E-11	1.18E-11	2.75E-11	3.00E-11
1.45E+0	1.07E-11	1.04E-11	1.19E-11	2.82E-11	3.09E-11
1.55E+0	1.10E-11	1.07E-11	1.23E-11	2.89E-11	3.17E-11
1.65E+0	1.15E-11	1.12E-11	1.28E-11	2.99E-11	3.27E-11
1.75E+0	1.17E-11	1.13E-11	1.29E-11	3.05E-11	3.35E-11
1.85E+0	1.22E-11	1.19E-11	1.35E-11	3.16E-11	3.45E-11
1.95E+0	1.22E-11	1.18E-11	1.35E-11	3.20E-11	3.51E-11
2.10E+0	1.26E-11	1.23E-11	1.40E-11	3.32E-11	3.67E-11

Table 24 (cont'd.)

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^2)				
	Total bone	Cortical bone	Trabecular bone	Red marrow	Yellow marrow
2.30E+0	1.27E-11	1.24E-11	1.41E-11	3.39E-11	3.75E-11
2.50E+0	1.34E-11	1.30E-11	1.48E-11	3.52E-11	3.91E-11
2.70E+0	1.43E-11	1.39E-11	1.58E-11	3.69E-11	4.09E-11
2.90E+0	1.52E-11	1.48E-11	1.67E-11	3.89E-11	4.35E-11
3.10E+0	1.59E-11	1.55E-11	1.75E-11	3.95E-11	4.34E-11
3.30E+0	1.81E-11	1.77E-11	1.97E-11	4.29E-11	4.71E-11
3.50E+0	1.87E-11	1.83E-11	2.04E-11	4.43E-11	4.88E-11
3.70E+0	1.93E-11	1.89E-11	2.10E-11	4.50E-11	4.94E-11
3.90E+0	1.89E-11	1.85E-11	2.06E-11	4.46E-11	4.92E-11
4.20E+0	1.96E-11	1.92E-11	2.14E-11	4.53E-11	4.93E-11
4.60E+0	1.94E-11	1.90E-11	2.12E-11	4.51E-11	4.92E-11
5.00E+0	2.07E-11	2.02E-11	2.25E-11	4.69E-11	5.06E-11
5.40E+0	1.99E-11	1.94E-11	2.18E-11	4.63E-11	5.10E-11
5.80E+0	2.11E-11	2.06E-11	2.30E-11	4.82E-11	5.24E-11
6.20E+0	2.19E-11	2.14E-11	2.38E-11	5.00E-11	5.47E-11
6.60E+0	2.24E-11	2.18E-11	2.44E-11	4.99E-11	5.37E-11
7.00E+0	2.36E-11	2.31E-11	2.57E-11	5.14E-11	5.47E-11
7.40E+0	2.55E-11	2.50E-11	2.76E-11	5.43E-11	5.81E-11
7.80E+0	2.54E-11	2.49E-11	2.74E-11	5.60E-11	6.14E-11
8.20E+0	2.50E-11	2.44E-11	2.70E-11	5.43E-11	5.92E-11
8.60E+0	2.59E-11	2.53E-11	2.80E-11	5.51E-11	5.90E-11
9.00E+0	2.68E-11	2.62E-11	2.89E-11	5.73E-11	6.22E-11
9.40E+0	2.73E-11	2.67E-11	2.94E-11	5.88E-11	6.46E-11
9.80E+0	2.80E-11	2.74E-11	3.01E-11	5.88E-11	6.36E-11
1.05E+1	2.89E-11	2.83E-11	3.11E-11	5.98E-11	6.42E-11
1.15E+1	3.18E-11	3.12E-11	3.41E-11	6.33E-11	6.72E-11
1.25E+1	3.23E-11	3.17E-11	3.45E-11	6.46E-11	6.97E-11
1.35E+1	3.39E-11	3.34E-11	3.62E-11	6.69E-11	7.18E-11
1.45E+1	3.57E-11	3.51E-11	3.79E-11	6.98E-11	7.51E-11
1.55E+1	3.71E-11	3.65E-11	3.93E-11	7.26E-11	7.89E-11
1.65E+1	3.76E-11	3.71E-11	3.98E-11	7.43E-11	8.12E-11
1.75E+1	3.81E-11	3.76E-11	4.03E-11	7.52E-11	8.20E-11
1.85E+1	3.88E-11	3.82E-11	4.10E-11	7.64E-11	8.33E-11
1.95E+1	3.97E-11	3.91E-11	4.19E-11	7.75E-11	8.44E-11

[a]Based on mass fractions in Table 11 of this report and on kerma factors for neutrons from Caswell, Coyne, and Randolph (Ref. 29).

Table 25. Kerma factors for neutrons in various soft-tissue components of Reference Man[a]

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^2)				
	Skin	Muscle	Brain	Lungs	Intestine
2.53E-8	3.66E-13	2.21E-13	1.06E-13	2.35E-13	1.71E-13
3.60E-8	3.10E-13	1.88E-13	8.95E-14	1.99E-13	1.45E-13
6.30E-8	2.34E-13	1.42E-13	6.76E-14	1.50E-13	1.10E-13
1.10E-7	1.77E-13	1.07E-13	5.11E-14	1.14E-13	8.29E-14
2.00E-7	1.32E-13	7.95E-14	3.80E-14	8.43E-14	6.15E-14
3.60E-7	9.80E-14	5.93E-14	2.83E-14	6.28E-14	4.58E-14
6.30E-7	7.43E-14	4.49E-14	2.15E-14	4.76E-14	3.47E-14
1.10E-6	5.61E-14	3.40E-14	1.63E-14	3.60E-14	2.63E-14
2.00E-6	4.19E-14	2.54E-14	1.22E-14	2.69E-14	1.97E-14
3.60E-6	3.14E-14	1.91E-14	9.32E-15	2.02E-14	1.49E-14
6.30E-6	2.40E-14	1.48E-14	7.42E-15	1.56E-14	1.16E-14
1.10E-5	1.88E-14	1.19E-14	6.28E-15	1.25E-14	9.44E-15
2.00E-5	1.52E-14	1.01E-14	5.94E-15	1.05E-14	8.28E-15
3.60E-5	1.35E-14	9.67E-15	6.68E-15	1.00E-14	8.40E-15
6.30E-5	1.37E-14	1.10E-14	8.86E-15	1.12E-14	1.01E-14
1.10E-4	1.66E-14	1.47E-14	1.33E-14	1.49E-14	1.42E-14
2.00E-4	2.42E-14	2.31E-14	2.25E-14	2.32E-14	2.30E-14
3.60E-4	3.97E-14	3.90E-14	3.96E-14	3.94E-14	3.96E-14
6.30E-4	6.55E-14	6.59E-14	6.77E-14	6.61E-14	6.73E-14
1.10E-3	1.12E-13	1.13E-13	1.17E-13	1.13E-13	1.16E-13
2.00E-3	1.99E-13	2.03E-13	2.11E-13	2.03E-13	2.09E-13
3.60E-3	3.55E-13	3.63E-13	3.77E-13	3.63E-13	3.73E-13
6.30E-3	6.09E-13	6.23E-13	6.47E-13	6.23E-13	6.40E-13
1.10E-2	1.03E-12	1.05E-12	1.09E-12	1.05E-12	1.08E-12
2.00E-2	1.79E-12	1.83E-12	1.90E-12	1.83E-12	1.88E-13
3.60E-2	2.96E-12	3.03E-12	3.14E-12	3.03E-12	3.11E-12
6.30E-2	4.60E-12	4.70E-12	4.88E-12	4.70E-12	4.83E-12
8.20E-2	5.56E-12	5.68E-12	5.90E-12	5.68E-12	5.83E-12
8.60E-2	5.75E-12	5.87E-12	6.10E-12	5.87E-12	6.03E-12

Table 25 (cont'd.)

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^2)				
	Skin	Muscle	Brain	Lungs	Intestine
9.00E-2	5.93E-12	6.06E-12	6.29E-12	6.05E-12	6.22E-12
9.40E-2	6.11E-12	6.24E-12	6.48E-12	6.24E-12	6.41E-12
9.80E-2	6.28E-12	6.42E-12	6.66E-12	6.41E-12	6.59E-12
1.05E-1	6.57E-12	6.72E-12	6.97E-12	6.71E-12	6.90E-12
1.15E-1	6.98E-12	7.13E-12	7.40E-12	7.13E-12	7.32E-12
1.25E-1	7.36E-12	7.53E-12	7.81E-12	7.52E-12	7.73E-12
1.35E-1	7.73E-12	7.90E-12	8.20E-12	7.89E-12	8.11E-12
1.45E-1	8.09E-12	8.26E-12	8.58E-12	8.26E-12	8.48E-12
1.55E-1	8.42E-12	8.61E-12	8.93E-12	8.60E-12	8.83E-12
1.65E-1	8.74E-12	8.93E-12	9.26E-12	8.92E-12	9.16E-12
1.75E-1	9.05E-12	9.25E-12	9.60E-12	9.24E-12	9.50E-12
1.85E-1	9.34E-12	9.54E-12	9.90E-12	9.54E-12	9.79E-12
1.95E-1	9.63E-12	9.84E-12	1.02E-11	9.83E-12	1.01E-11
2.10E-1	1.01E-11	1.03E-11	1.07E-11	1.03E-11	1.05E-11
2.30E-1	1.06E-11	1.08E-11	1.12E-11	1.08E-11	1.11E-11
2.50E-1	1.10E-11	1.13E-11	1.17E-11	1.13E-11	1.16E-11
2.70E-1	1.16E-11	1.19E-11	1.23E-11	1.19E-11	1.22E-11
2.90E-1	1.21E-11	1.23E-11	1.28E-11	1.23E-11	1.27E-11
3.10E-1	1.25E-11	1.28E-11	1.33E-11	1.28E-11	1.32E-11
3.30E-1	1.29E-11	1.32E-11	1.37E-11	1.32E-11	1.36E-11
3.50E-1	1.34E-11	1.37E-11	1.42E-11	1.37E-11	1.41E-11
3.70E-1	1.39E-11	1.42E-11	1.47E-11	1.42E-11	1.46E-11
3.90E-1	1.45E-11	1.49E-11	1.54E-11	1.49E-11	1.53E-11
4.20E-1	1.57E-11	1.63E-11	1.68E-11	1.63E-11	1.66E-11
4.60E-1	1.59E-11	1.64E-11	1.70E-11	1.64E-11	1.68E-11
5.00E-1	1.57E-11	1.60E-11	1.66E-11	1.60E-11	1.64E-11
5.40E-1	1.63E-11	1.66E-11	1.72E-11	1.65E-11	1.70E-11
5.80E-1	1.68E-11	1.71E-11	1.78E-11	1.71E-11	1.76E-11
6.20E-1	1.74E-11	1.77E-11	1.84E-11	1.77E-11	1.82E-11
6.60E-1	1.80E-11	1.83E-11	1.90E-11	1.83E-11	1.88E-11
7.00E-1	1.86E-11	1.89E-11	1.96E-11	1.89E-11	1.94E-11
7.40E-1	1.90E-11	1.94E-11	2.01E-11	1.94E-11	1.99E-11
7.80E-1	1.96E-11	2.00E-11	2.07E-11	1.99E-11	2.05E-11
8.20E-1	2.01E-11	2.05E-11	2.12E-11	2.04E-11	2.10E-11
8.60E-1	2.06E-11	2.10E-11	2.18E-11	2.10E-11	2.16E-11
9.00E-1	2.12E-11	2.17E-11	2.25E-11	2.17E-11	2.22E-11
9.40E-1	2.21E-11	2.27E-11	2.35E-11	2.27E-11	2.33E-11
9.80E-1	2.37E-11	2.46E-11	2.54E-11	2.46E-11	2.52E-11
1.05E+0	2.41E-11	2.49E-11	2.57E-11	2.49E-11	2.55E-11
1.15E+0	2.40E-11	2.46E-11	2.55E-11	2.46E-11	2.52E-11
1.25E+0	2.50E-11	2.56E-11	2.66E-11	2.56E-11	2.63E-11
1.35E+0	2.59E-11	2.65E-11	2.74E-11	2.65E-11	2.72E-11
1.45E+0	2.64E-11	2.69E-11	2.79E-11	2.69E-11	2.76E-11
1.55E+0	2.71E-11	2.76E-11	2.86E-11	2.76E-11	2.84E-11
1.65E+0	2.81E-11	2.87E-11	2.98E-11	2.87E-11	2.95E-11
1.75E+0	2.86E-11	2.91E-11	3.01E-11	2.91E-11	2.98E-11
1.85E+0	2.97E-11	3.03E-11	3.14E-11	3.03E-11	3.11E-11
1.95E+0	2.99E-11	3.05E-11	3.16E-11	3.04E-11	3.12E-11
2.10E+0	3.09E-11	3.14E-11	3.25E-11	3.13E-11	3.22E-11
2.30E+0	3.14E-11	3.18E-11	3.30E-11	3.18E-11	3.26E-11
2.50E+0	3.27E-11	3.31E-11	3.43E-11	3.30E-11	3.39E-11
2.70E+0	3.42E-11	3.46E-11	3.58E-11	3.45E-11	3.54E-11
2.90E+0	3.58E-11	3.59E-11	3.72E-11	3.58E-11	3.68E-11
3.10E+0	3.68E-11	3.73E-11	3.86E-11	3.72E-11	3.82E-11
3.30E+0	4.01E-11	4.06E-11	4.19E-11	4.06E-11	4.15E-11
3.50E+0	4.12E-11	4.14E-11	4.27E-11	4.13E-11	4.24E-11
3.70E+0	4.20E-11	4.24E-11	4.38E-11	4.24E-11	4.34E-11
3.90E+0	4.15E-11	4.17E-11	4.31E-11	4.17E-11	4.27E-11
4.20E+0	4.25E-11	4.30E-11	4.44E-11	4.30E-11	4.40E-11
4.60E+0	4.24E-11	4.31E-11	4.45E-11	4.31E-11	4.41E-11
5.00E+0	4.45E-11	4.56E-11	4.70E-11	4.56E-11	4.66E-11
5.40E+0	4.36E-11	4.44E-11	4.59E-11	4.43E-11	4.54E-11
5.80E+0	4.55E-11	4.65E-11	4.80E-11	4.64E-11	4.76E-11
6.20E+0	4.68E-11	4.76E-11	4.92E-11	4.75E-11	4.87E-11
6.60E+0	4.76E-11	4.89E-11	5.05E-11	4.89E-11	5.01E-11
7.00E+0	4.94E-11	5.11E-11	5.26E-11	5.11E-11	5.22E-11
7.40E+0	5.23E-11	5.38E-11	5.54E-11	5.38E-11	5.50E-11
7.80E+0	5.23E-11	5.29E-11	5.46E-11	5.28E-11	5.41E-11
8.20E+0	5.15E-11	5.26E-11	5.43E-11	5.25E-11	5.38E-11
8.60E+0	5.27E-11	5.43E-11	5.59E-11	5.42E-11	5.55E-11
9.00E+0	5.41E-11	5.51E-11	5.69E-11	5.51E-11	5.64E-11
9.40E+0	5.49E-11	5.55E-11	5.73E-11	5.54E-11	5.68E-11
9.80E+0	5.58E-11	5.69E-11	5.86E-11	5.68E-11	5.81E-11
1.05E+1	5.70E-11	5.83E-11	6.00E-11	5.83E-11	5.95E-11
1.15E+1	6.09E-11	6.25E-11	6.42E-11	6.24E-11	6.37E-11
1.25E+1	6.13E-11	6.22E-11	6.39E-11	6.21E-11	6.34E-11
1.35E+1	6.36E-11	6.46E-11	6.63E-11	6.45E-11	6.58E-11
1.45E+1	6.62E-11	6.70E-11	6.88E-11	6.70E-11	6.83E-11
1.55E+1	6.83E-11	6.86E-11	7.04E-11	6.85E-11	6.99E-11
1.65E+1	6.95E-11	6.95E-11	7.13E-11	6.94E-11	7.08E-11
1.75E+1	7.04E-11	7.04E-11	7.22E-11	7.02E-11	7.17E-11

Table 25 (cont'd.)

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^{2})				
	Skin	Muscle	Brain	Lungs	Intestine
1.85E+1	7.15E-11	7.14E-11	7.32E-11	7.13E-11	7.27E-11
1.95E+1	7.28E-11	7.27E-11	7.45E-11	7.25E-11	7.40E-11

[a]Based on mass fractions in Table 12 of this report and on kerma factors for neutrons from Caswell, Coyne, and Randolph (Ref. 29).

Table 26. Comparison of kerma factors for neutrons in bone and soft-tissue compositions developed for use in red-bone-marrow dosimetry[a]

Neutron energy (MeV)	Kerma factor (Gy neutron^{-1} cm^{2})					
	ICRP-revised			ICRU-1964		
	Trabecular bone	Red marrow	Ratio	Compact bone	Muscle tissue	Ratio
2.53E-8	2.99E-13	2.49E-13	1.20	2.16E-13	2.79E-13	0.77
3.60E-8	2.57E-13	2.11E-13	1.21	1.86E-13	2.37E-13	0.78
6.30E-8	1.94E-13	1.60E-13	1.22	1.40E-13	1.79E-13	0.78
1.10E-7	1.46E-13	1.21E-13	1.22	1.06E-13	1.35E-13	0.79
2.00E-7	1.10E-13	8.96E-14	1.23	7.93E-14	1.00E-13	0.79
3.60E-7	8.20E-14	6.68E-14	1.23	5.92E-14	7.48E-14	0.79
6.30E-7	6.29E-14	5.06E-14	1.24	4.53E-14	5.67E-14	0.80
1.10E-6	4.80E-14	3.83E-14	1.25	3.46E-14	4.29E-14	0.81
2.00E-6	3.64E-14	2.86E-14	1.27	2.62E-14	3.21E-14	0.82
3.60E-6	2.78E-14	2.15E-14	1.29	2.00E-14	2.41E-14	0.83
6.30E-6	2.17E-14	1.66E-14	1.31	1.57E-14	1.86E-14	0.84
1.10E-5	1.73E-14	1.33E-14	1.30	1.27E-14	1.47E-14	0.86
2.00E-5	1.41E-14	1.11E-14	1.27	1.06E-14	1.22E-14	0.87
3.60E-5	1.20E-14	1.06E-14	1.13	9.71E-15	1.13E-14	0.86
6.30E-5	1.12E-14	1.18E-14	0.95	1.00E-14	1.22E-14	0.82
1.10E-4	1.18E-14	1.56E-14	0.76	1.21E-14	1.56E-14	0.78
2.00E-4	1.46E-14	2.43E-14	0.60	1.71E-14	2.38E-14	0.72
3.60E-4	2.08E-14	4.10E-14	0.51	2.69E-14	3.93E-14	0.68
6.30E-4	3.18E-14	6.90E-14	0.46	4.40E-14	6.62E-14	0.66
1.10E-3	5.16E-14	1.19E-13	0.43	7.42E-14	1.14E-13	0.65
2.00E-3	8.96E-14	2.13E-13	0.42	1.32E-13	2.04E-13	0.65
3.60E-3	1.57E-13	3.79E-13	0.41	2.33E-13	3.63E-13	0.64
6.30E-3	2.67E-13	6.51E-13	0.41	3.99E-13	6.23E-13	0.64
1.10E-2	4.49E-13	1.10E-12	0.41	6.73E-13	1.05E-12	0.64
2.00E-2	7.81E-13	1.91E-12	0.41	1.17E-12	1.83E-12	0.64
3.60E-2	1.29E-12	3.17E-12	0.41	1.94E-12	3.02E-12	0.64
6.30E-2	2.01E-12	4.92E-12	0.41	3.01E-12	4.70E-12	0.64
1.05E-1	2.88E-12	7.03E-12	0.41	4.31E-12	6.71E-12	0.64
1.25E-1	3.23E-12	7.88E-12	0.41	4.84E-12	7.52E-12	0.64
1.45E-1	3.56E-12	8.65E-12	0.41	5.32E-12	8.25E-12	0.64
1.95E-1	4.24E-12	1.03E-11	0.41	6.33E-12	9.82E-12	0.64
2.50E-1	4.93E-12	1.18E-11	0.42	7.31E-12	1.13E-11	0.65
3.50E-1	6.03E-12	1.43E-11	0.42	8.88E-12	1.37E-11	0.65
5.00E-1	6.99E-12	1.68E-11	0.42	1.04E-11	1.60E-11	0.65
7.00E-1	8.27E-12	1.99E-11	0.42	1.23E-11	1.89E-11	0.65
1.05E+0	1.13E-11	2.53E-11	0.45	1.60E-11	2.48E-11	0.65
1.25E+0	1.14E-11	2.66E-11	0.43	1.66E-11	2.56E-11	0.65
1.45E+0	1.19E-11	2.82E-11	0.42	1.75E-11	2.69E-11	0.65
1.95E+0	1.35E-11	3.20E-11	0.42	1.99E-11	3.04E-11	0.65
2.50E+0	1.48E-11	3.52E-11	0.42	2.20E-11	3.31E-11	0.66
3.50E+0	2.04E-11	4.43E-11	0.46	2.87E-11	4.15E-11	0.69
5.00E+0	2.25E-11	4.69E-11	0.48	3.08E-11	4.55E-11	0.69
7.00E+0	2.57E-11	5.14E-11	0.50	3.42E-11	5.09E-11	0.69
1.05E+1	3.11E-11	5.98E-11	0.52	4.08E-11	5.82E-11	0.70
1.25E+1	3.45E-11	6.46E-11	0.53	4.49E-11	6.22E-11	0.72
1.45E+1	3.79E-11	6.98E-11	0.54	4.90E-11	6.70E-11	0.73
1.95E+1	4.19E-11	7.75E-11	0.54	5.47E-11	7.27E-11	0.75

[a]Based on mass fractions from Table 11 of this report in the case of the ICRP-revised formulations and from Tables 13 and 15 of this report in the case of the ICRU-1964 formulations of interest and on kerma factors for neutrons from Caswell, Coyne, and Randolph (Ref. 29). Also see their calculations for the above ICRU-1964 compact-bone and muscle-tissue formulations.

formulation in the case of neutrons, as in the case of photons, appear to be noncontroversial. In fact, Lawson[58] elected to use data on compact bone from Woodard's 1962 work,[33] rather than that from the ICRU's 1964 report,[30] in his 1967 calculations of the absorbed dose from recoil protons near a soft tissue-bone interface.

Results of Lawson's calculations[58] suggest that bone has a negligibly small effect on the energy transfer between bone and red marrow at thermal-neutron and at fast-neutron energies less than several MeV due to the short range of the low energy-recoil protons. At fast-neutron energies greater than several MeV, however, there is a reduced energy transfer from bone to red marrow (and other soft tissue) due to the longer range of the higher energy-recoil protons.[58,59] An even greater sparing effect on the absorbed dose to red marrow from neutrons with energies greater than several MeV is predicted if either Woodard's formulation of the ICRP-revised formulation for compact bone (i.e., wet cortical bone) is used in place of the ICRP-revised formulation for trabecular bone. This is due to differences in the water content and, thereby, the hydrogen content of the ICRP-1975 formulations for trabecular and cortical bone (see, for example, page 79 of Reference 5 and Table 11 of this report).

The elemental composition of cortical bone has been widely used as that of typical bone. If a typical bone composition is selected for use in calculations of absorbed dose to the red marrow in trabecular bone and the endosteal cells in both trabecular and cortical bone, then the ICRP-revised formulation for total bone is recommended over the ICRP-revised formulations for either cortical bone or trabecular bone (Table 9 and 11). This recommendation provides a somewhat better approximation to kerma from either neutrons or photons in both cortical and trabecular bone (Tables 17 and 24).

Discussion

The calculation of absorbed dose to the soft tissue of the skeleton is a complex problem, since electronic equilibrium may not exist near a soft tissue- bone interface, and it is difficult to model the intricate intermixture of soft tissue and bone in the skeleton. In past calculations for neutrons[58] and photons,[60–63] for example, simple geometrical models have been used to approximate the complex geometric relationships between the trabecular laminae and cavities containing the red marrow. Recently, however, Whitwell and Spiers[64] have developed a calculational model that uses Monte Carlo sampling techniques and actual probability distributions to obtain the path-lengths of a charged particle through the trabecular laminae and cavities rather than geometrical models. The necessary probability distributions for a number of bones in the body have been compiled by Beddoe et al.[65] To calculate the energy imparted in the red marrow, for example, one considers the potential paths a charged particle may take in crossing the trabecular laminae and cavities. The energy of the charged particle upon entering a cavity will depend on its initial kinetic energy and that dissipated in reaching the cavity. The amount of energy imparted within the red marrow is dependent on the path the charged particle takes through the cavity and the energy it had on entrance. If the charged particle has sufficient energy to traverse the cavity, it will encounter another trabecular lamina. Then, if energetically possible, it will cross and enter another cavity. This method of tracking the energy imparted in red marrow has been used primarily in dosimetric calculations for beta particles from internally deposited bone-seeking radionuclides.[64,65] However, it is possible to use the path-length probability distribution, as compiled by Beddoe et al[65] and the Monte Carlo sampling techniques, as developed by Whitwell and Spiers[64] and refined by Eckerman[66–68] to improve the dosimetric calculations for photons and neutrons. The formulations for bone and soft tissue of ICRP-1975 Reference Man, as reviewed here, are currently being used in calculations of absorbed dose to soft tissue of the skeleton and in other work relating to the revisions of the organ-dose estimates for the A-bomb survivors.

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Chapter 8 Appendix 3a

RMCOMP/BAS COMPUTER PROGRAM

```
100 DIM A$(12), B$(5), F(5,4), M(5), W(12), P(12)
105 DATA "H ","C ","N ","O ","Na","Mg","P ","S ","Cl","K ","Ca","Fe"
110 DATA "Water", 0.11, 0, 0, 0.89
115 DATA "Fat", 0.12, 0.77, 0, 0.11
120 DATA "Protein", 0.07, 0.52, 0.16, 0.23
125 DATA "Carbohydrates", 0.06, 0.42, 0, 0.52
130 DATA "Bone Ash", 0, 0, 0, 0.40
135 FOR I = 1 TO 12
140 READ A$(I)
145 NEXT I
150 FOR I = 1 TO 5
155 READ B$(I)
160 FOR J = 1 TO 4
165 READ F(I,J)
170 NEXT J
```

```
175 NEXT I
180 SYSTEM "CLS"
185 PRINT "DESCRIPTION OF ORGAN OR TISSUE OF REFERENCE MAN IN ICRP REPORT 23"
190 INPUT C$
195 PRINT
200 PRINT "MASS OF ORGAN OR TISSUE IN GRAMS FROM TABLE 105 ON PAGES 280-285"
205 INPUT M
210 SYSTEM "CLS"
215 PRINT "MASS OF VARIOUS GROSS COMPONENTS OF ORGAN OR TISSUE IN GRAMS FROM"
220 PRINT "TABLE 105 ON PAGES 280-285"
225 PRINT
230 FOR I = 1 TO 5
235 PRINT B$(I); " = ";
240 INPUT M(I)
245 NEXT I
250 PRINT
255 PRINT "CONTINUE (Y/N)";
260 INPUT R$
265 IF R$ = "N" THEN 210
270 SYSTEM "CLS"
275 PRINT "MASS OF VARIOUS MINERALS AND TRACE ELEMENTS OF ORGAN OR TISSUE IN"
280 PRINT "GRAMS FROM TABLE 108 ON PAGES 290-328"
285 PRINT
290 FOR I = 5 TO 12
295 PRINT A$(I); " = ";
300 INPUT W(I)
305 NEXT I
310 PRINT
315 PRINT "CONTINUE (Y/N)";
320 INPUT R$
325 IF R$ = "N" THEN 270
330 FOR I = 1 TO 4
335 W(I) = 0
340 FOR J = 1 TO 5
345 W(I) = W(I) + M(J)*F(J,I)
350 NEXT J
355 NEXT I
360 S = 0
365 FOR I = 1 TO 12
370 S = S + W(I)
375 NEXT I
380 T = 0
385 FOR I = 1 TO 12
390 P(I) = 100*W(I)/S
395 T = T + P(I)
400 NEXT I
405 D = 100*(M - S)/M
410 ;      ###############    #.##!!!!
415 ;           ##       #.###!!!!    ##.###
420 ;         Total      #.###!!!!   ###.###
425 LPRINT C$
430 LPRINT
435 LPRINT
440 LPRINT "MASS IN GRAMS OF GROSS COMPONENTS OF ORGAN OR TISSUE"
445 LPRINT
450 LPRINT "     COMPONENT            MASS"
455 LPRINT
460 FOR I = 1 TO 5
465 IF M(I) = 0 THEN 475
470 LPRINT USING 410, B$(I), M(I)
475 NEXT I
480 LPRINT
485 LPRINT
490 LPRINT "CALCULATED MASS IN GRAMS AND PERCENT BY WEIGHT OF VARIOUS"
495 LPRINT "ELEMENTS FOR ORGAN OR TISSUE OF REFERENCE MAN"
500 LPRINT
505 LPRINT "     ELEMENT      MASS      PERCENT"
510 LPRINT
515 FOR I = 1 TO 12
520 LPRINT USING 415, A$(I), W(I), P(I)
```

```
525 NEXT I
530 LPRINT
535 LPRINT USING 420, S, T
540 LPRINT
545 LPRINT
550 LPRINT "DIFFERENCE IN PERCENT BETWEEN STANDARD MASS IN GRAMS OF"; M
555 LPRINT "FOR ORGAN OR TISSUE OF REFERENCE MAN AND ABOVE CALCULATED MASS"
560 LPRINT "IS "; D
565 SYSTEM "FORMS T"
570 END
```

Chapter 8 Appendix 3b

EXAMPLE OF OUTPUT FROM RMCOMP/BAS COMPUTER PROGRAM

#1 TOTAL BODY: ICRP-1975 REVISED

MASS IN GRAMS OF GROSS COMPONENTS OF ORGAN OR TISSUE

COMPONENT	MASS
Water	4.20E+04
Fat	1.33E+04
Protein	1.06E+04
Carbohydrates	4.00E+02
Bone Ash	2.70E+03

CALCULATED MASS IN GRAMS AND PERCENT BY WEIGHT OF VARIOUS ELEMENTS FOR ORGAN OR TISSUE OF REFERENCE MAN

ELEMENT	MASS	PERCENT
H	6.982E+03	10.052
C	1.592E+04	22.922
N	1.696E+03	2.442
O	4.257E+04	61.289
Na	1.000E+02	0.144
Mg	1.900E+01	0.027
P	5.800E+02	0.835
S	1.500E+02	0.216
Cl	9.500E+01	0.137
K	1.400E+02	0.202
Ca	1.200E+03	1.728
Fe	4.200E+00	0.006
Total	6.946E+04	100.000

DIFFERENCE IN PERCENT BETWEEN STANDARD MASS IN GRAMS OF 70000
FOR ORGAN OR TISSUE OF REFERENCE MAN AND ABOVE CALCULATED MASS
IS 0.776857