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Center for Human Radiobiology

July 1970 through June 1971

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THE APPEARANCE TIMES OF RADIUM-INDUCED MALIGNANCIES

R. E. Rowland, A. T. Keane, and P. M. Failla

The appearance time of tumors after initial acquisition of radium has been examined as a function of the initial quantity of radium acquired. It is evident that the median appearance time of the sarcomas increase with decreasing initial dose, whereas no such change in appearance time with initial dose is evident for the carcinomas. The median appearance time for carcinomas is significantly greater than that for sarcomas.

It is the purpose of this report to examine the times after the first exposure to radium that the radiation-induced malignancies have appeared. Of particular interest is the question, "Is there a change in the latent period with the magnitude of the radiation insult?"

We have chosen for this study to divide the population of cases which have developed malignancies considered to be radiation induced into groups based on the quantity of radium initially acquired. The calculation of this parameter is described in another report within this volume.[1]

The average skeletal dose and the body burden are time-dependent variables, whereas the initial activity acquired is not. It is an advantage, of course, when examining a time distribution of events, to utilize a time-independent measure of the radiation insult. In a sense, dividing our cases up in this manner gives a distribution somewhat analogous to the structure of laboratory animal experiments, where a number of dose levels are set up according to the amount of injected radioactivity, and the results may be compared between dose levels.

Table 1 shows the breakdown of the radium cases with malignancies into five groups, tabulates the number of malignancies in each group, gives the time of first tumor diagnosis, and gives the median tumor appearance times. The actual appearance times for each of the 71 malignancies is shown in Figure 1.

Two features are immediately apparent from this analysis of tumor appearance times. First, the median appearance time for sarcoma induction increases with decreasing initial dose. Second, the carcinomas,

TABLE 1. Tumor Appearance Time as a Function of Initial Radium Concentration

Initial radium concentration range in nCi/g	Sarcomas			Carcinomas		
	No.	Yrs to 1st diagnosis	Median tumor induction period (yrs)	No.	Yrs to 1st diagnosis	Median tumor induction period (yrs)
> 250	10	7	19	5	33	39
125 - 250	12	7	24	1	19	19
62.5 - 125	10	9	27	9	26	34
31.25 - 62.5	13	12	30	3	30	38
< 31.25	6	27	34.5	2	34	35
Total	51		30	20		35

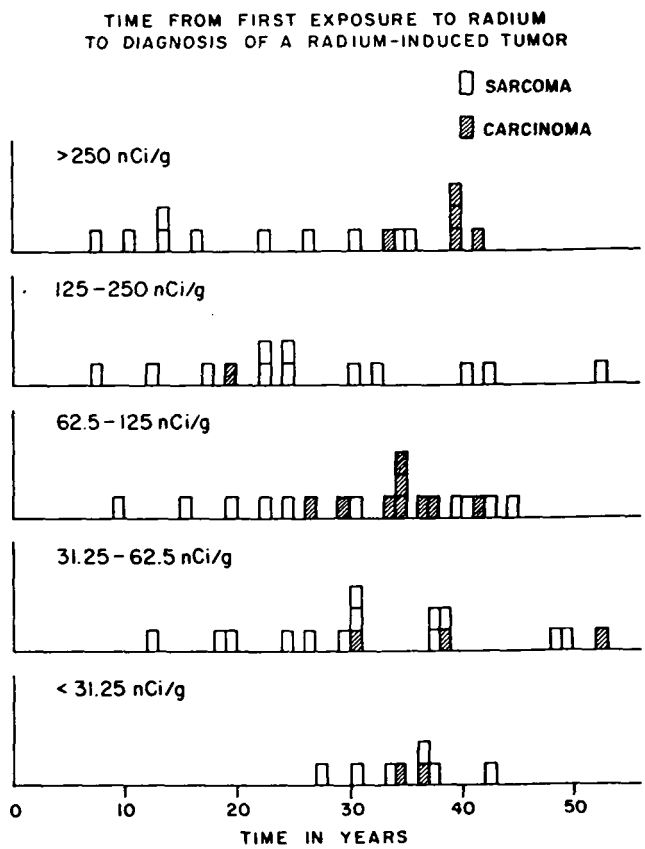

FIG. 1.--The time in years between initial acquisition of radium and the diagnosis of a radiation-induced malignancy is shown for each of the 71 tumors in the current radium population, plotted as a function of the initial quantity of radium acquired.

which definitely appear at later times than the sarcomas, indicate no such change in appearance time with dose.

The earliest tumor appearance times are 7 years for sarcomas and 19 years for carcinomas. The median appearance time for all sarcomas, regardless of dose level, is 30 years, and for the carcinomas, 35 years. Both types of malignancy have been diagnosed as late as 52 years after first exposure to radium.

Reference

1. Stehney, A. F. A Time-Invariant Dose Parameter for Radium Cases. This report.

= 1 EXPOSURE DATA FOR RADIUM PATIENTS AS OF 1969

=	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT,BONE NANOCURIE/G	CUMULATIVE RADS
01	M	1883	1928	1913	1967	329.787	11200.00
02	F	1896	1922	1917	1966	260.638	3680.00
03	F	1894	1927	1917	1966	888.297	44400.00
04	F	1900	1931	1917	1963	325.797	11500.00
05	F	1901	1939	1917	1963	117.919	6640.00
06	F	1903	1930	1918	1969	232.712	11800.00
07	F	1903	1935	1919	1963	92.952	5160.00
09	F	1899	1928	1921	1968	98.271	2490.00
20	M	1888	1925	1912	1969	40.558	1200.00
27	F	1902	1942	1918	1969	156.914	6980.00
28	F	1902	1933	1917	1969	347.074	11800.00
01	F	1878	1949	1922	1945	933.510	43200.00
02	F	1906	1939	1922	1960	636.968	22300.00
03	M	1888	1956	1925	1967	428.191	20800.00
04	F	1869	1953	1918	1941	426.861	23300.00
05	M	1877	1939	1927	1939	321.808	16800.00
06	F	1899	1938	1919	1968	184.840	8530.00
07	F	1886	1949	1926	1967	147.606	6140.00
08	F	1900	1958	1917	1960	363.031	22300.00
09	F	1898	1945	1918	1960	307.180	14700.00
10	M	1882	1956	1926	1967	172.872	8570.00
11	F	1872	1937	1919	1967	158.244	5380.00
12	F	1867	1956	1922	1942	207.446	11100.00
14	F	1901	1949	1916	1968	124.734	6790.00
15	M	1888	1967	1917	1935	4.335	281.00
16	F	1891	1966	1921	1968	174.202	12000.00
17	F	1883		1926	1967	104.787	7040.00
18	M	1889	1958	1911	1950	26.329	1110.00
19	F	1903	1936	1922	1965	36.436	2070.00
20	F	1905	1956	1923	1950	66.090	3480.00
21	F	1887		1916	1965	84.574	6030.00
22	F	1900	1951	1917	1968	29.388	1540.00
24	F	1901	1956	1919	1943	61.170	3680.00
25	F	1886	1952	1924	1951	56.515	2770.00
26	F	1905	1958	1925	1950	46.675	2830.00
27	M	1889	1957	1912	1960	17.819	973.00
28	M	1883	1965	1914	1953	9.800	702.00
29	M	1876	1958	1902	1950	12.752	948.00
30	M	1882	1952	1936	1950	0.448	14.90
31	F	1906	1934	1925	1963	122.739	6330.00
32	F	1908	1940	1924	1968	292.552	18200.00
33	F	1908	1931	1923	1963	414.893	19700.00
34	F	1913		1929	1965	0.728	48.30
35	F	1901		1920	1958	1.046	77.90
37	F	1908		1928	1959		< 1.0
38	F	1910		1927	1950	0.408	26.00
39	F	1913		1934	1959	0.222	13.00
40	F	1907	1929	1923	1963	599.733	22600.00
41	F	1909		1927	1959	0.376	25.60
43	F	1912		1927	1958	0.829	56.50

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
01-044	F	1904		1924	1959	1.311	96.30
01-045	F	1889		1922	1959		< 1.0
01-046	F	1903	1943	1920	1963	167.553	11300.00
01-047	F	1896		1920	1962	31.515	2330.00
01-048	F	1900		1920	1957	53.058	3920.00
01-049	F	1903	1937	1920	1960	363.031	24200.00
01-050	F	1911		1925	1959	0.885	64.80
01-051	F	1904		1923	1957	57.579	4240.00
01-052	F	1910	1930	1924	1965	200.797	6900.00
01-054	F	1909	1937	1924	1965	352.393	20300.00
01-055	F	1907		1925	1959	1.688	123.00
01-056	F	1904		1920	1965	48.537	3580.00
01-057	F	1908	1931	1924	1963	640.957	26400.00
01-059	F	1904	1967	1920	1964	71.276	5240.00
01-063	F	1912		1927	1967	5.093	329.00
01-066	F	1904		1925	1958		< 1.0
01-069	F	1905		1922	1959	0.775	57.20
01-070	F	1910		1927	1958	0.885	59.90
01-071	F	1908	1967	1927	1958		< 1.0
01-072	F	1900		1921	1954	27.526	2020.00
01-073	F	1900	1969	1921	1966	41.223	3050.00
01-074	F	1909		1927	1959	0.738	50.10
01-075	F	1902		1922	1959	2.007	148.00
01-078	F	1909		1925	1958	1.075	74.90
01-079	F	1901	1943	1920	1960	307.180	21300.00
01-080	F	1902		1921	1968	36.037	2650.00
01-081	F	1907		1923	1959	2.619	193.00
01-082	F	1902	1935	1919	1963	223.404	13700.00
01-084	F	1904		1923	1966	13.962	1020.00
01-085	F	1913		1927	1958	0.537	36.40
01-086	F	1907	1966	1925	1959		< 1.0
01-087	F	1905		1921	1964	255.319	18700.00
01-090	F	1910		1927	1958	0.781	52.70
01-091	F	1909		1927	1959		< 1.0
01-092	F	1906		1922	1959	0.828	61.30
01-093	F	1904		1926	1959	0.485	34.00
01-094	F	1891	1966	1921	1964	4.906	361.00
01-095	F	1907		1922	1959	3.803	282.00
01-096	F	1909		1927	1960	2.101	137.00
01-097	F	1905		1921	1963	44.015	3250.00
01-099	F	1905	1945	1924	1963	44.547	3010.00
01-100	F	1904	1967	1924	1957	13.297	977.00
01-101	F	1905		1924	1959		< 1.0
01-105	F	1898	1945	1921	1963	178.191	12500.00
01-106	F	1902		1924	1959	2.978	218.00
01-110	F	1909		1925	1958	0.938	65.20
01-111	F	1910		1927	1958	0.183	12.50
01-112	F	1908	1955	1924	1960	22.074	1550.00
01-113	F	1912		1928	1959	0.264	17.80
01-115	F	1908	1944	1924	1963	71.808	4530.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
01-116	F	1899	1965	1920	1955	80.585	5860.00
01-118	F	1909		1923	1959		< 1.0
01-119	F	1899		1920	1958	2.632	196.00
01-120	F	1910		1925	1959	1.074	74.70
01-122	F	1912		1927	1965	1.026	69.80
01-123	F	1889		1923	1959	0.373	27.60
01-124	F	1909		1927	1967	5.066	338.00
01-125	F	1911		1927	1959	0.190	13.00
01-126	F	1903	1969	1922	1960	66.223	4870.00
01-127	F	1908		1927	1959		< 1.0
01-128	F	1910		1927	1959	0.190	13.00
01-130	F	1909		1926	1964	1.079	72.90
01-132	F	1908	1944	1923	1966	351.063	23600.00
01-133	F	1910		1926	1958	1.462	102.00
01-136	F	1907		1923	1967	20.345	1490.00
01-137	F	1901		1923	1958		< 1.0
01-138	F	1883	1963	1918	1959	0.547	35.30
01-139	M	1881	1964	1928	1962	77.792	4920.00
01-140	F	1900		1919	1959	0.214	14.70
01-141	M	1886		1928	1962	0.913	60.40
01-142	F	1899		1922	1959	1.622	116.00
01-143	F	1904		1921	1959	0.105	7.04
01-144	F	1897		1922	1968	41.755	2760.00
01-145	F	1900	1957	1918	1966	418.882	25700.00
01-146	F	1881	1967	1927	1966	9.640	644.00
01-147	F	1902		1917	1965	3.085	218.00
01-148	F	1907		1936	1958	1.449	70.70
01-149	F	1888	1959	1919	1969	287.233	20200.00
01-150	F	1881		1930	1967	0.154	8.87
01-151	F	1905		1927	1959	2.154	131.00
01-152	F	1904		1920	1959		< 1.0
01-153	M	1890	1964	1920	1963	11.103	694.00
01-154	M	1896		1923	1959		< 1.0
01-156	F	1900	1959	1918	1959	2.154	127.00
01-157	F	1894		1925	1968	3.789	257.00
01-158	F	1901		1922	1959	0.051	3.40
01-159	F	1915		1933	1959	0.080	4.27
01-160	F	1873	1965	1925	1959	14.627	993.00
01-161	F	1896		1918	1959	0.054	3.82
01-162	M	1898	1966	1920	1959	3.444	214.00
01-163	F	1903		1920	1959	0.925	67.20
01-164	F	1900		1918	1959	0.490	34.20
01-165	F	1904		1922	1959	1.409	94.20
01-166	F	1897		1916	1959		< 1.0
01-168	F	1895		1919	1966	0.055	3.62
01-169	F	1918		1936	1959		< 1.0
01-170	M	1893	1966	1940	1959	0.105	4.75
01-171	M	1895		1914	1958	60.904	4470.00
01-172	F	1898	1968	1916	1961	136.968	9630.00
01-173	M	1881	1959	1917	1959	2.247	110.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT,BONE NANOCURIE/G	CUMULATIVE RADS
01-175	F	1900	1966	1927	1965	158.244	10400.00
01-176	F	1893		1917	1959	1.835	129.00
01-177	M	1915		1936	1959	1.515	77.20
01-178	M	1939		1958	1958		< 1.0
01-179	F	1890	1966	1924	1959	100.132	6120.00
01-180	F	1900		1918	1959	0.109	7.62
01-181	M	1913	1963	1940	1959	5.571	225.00
01-182	M	1902	1959	1936	1959	0.289	14.80
01-183	F	1900	1969	1915	1965	14.760	1060.00
01-184	M	1886		1922	1968	1.994	132.00
01-185	M	1881	1962	1912	1959	1.688	116.00
01-186	M	1925		1943	1959	0.631	25.60
01-187	M	1917		1943	1959	0.984	43.60
01-188	F	1886		1933	1959	0.172	9.63
01-189	M	1921		1958	1958		< 1.0
01-190	F	1928		1958	1958		< 1.0
01-191	M	1897	1966	1913	1959	0.164	11.70
01-192	F	1902	1962	1925	1959	1.781	102.00
01-193	F	1886	1960	1917	1959	2.500	153.00
01-194	M	1898		1916	1959		< 1.0
01-195	F	1893	1958	1912	1959	0.054	3.32
01-196	M	1907		1929	1969	5.106	342.00
01-197	F	1883	1965	1916	1958	0.888	60.50
01-198	F	1888		1913	1959	12.539	943.00
01-200	F	1910		1925	1959		< 1.0
01-201	F	1911		1925	1959	2.872	200.00
01-203	F	1908		1923	1959		< 1.0
01-204	F	1901		1917	1959	0.276	19.60
01-205	M	1921		1951	1967	0.377	13.30
01-206	M	1896		1918	1959	0.312	21.80
01-207	F	1909	1967	1927	1959	0.378	25.50
01-208	M	1901		1939	1967	24.335	891.00
01-209	F	1908		1926	1959	0.723	50.60
01-210	M	1878		1918	1959	0.279	14.10
01-214	M	1890	1965	1915	1959	2.765	159.00
01-215	F	1898		1925	1959		< 1.0
01-216	F	1903	1963	1924	1959		< 1.0
01-217	M	1894		1914	1959	0.200	14.40
01-218	M	1924		1950	1963	0.083	3.02
01-219	F	1910		1927	1959	0.094	6.46
01-220	F	1907		1924	1959	0.590	43.20
01-221	M	1892		1916	1967	0.414	27.90
01-223	F	1912		1927	1963		< 1.0
01-225	F	1906		1931	1959		< 1.0
01-226	F	1915		1927	1959		< 1.0
01-227	F	1908		1950	1959	0.049	1.85
01-228	F	1906		1926	1959	0.363	25.40
01-229	F	1903		1923	1959	3.018	223.00
01-230	F	1913		1927	1959		< 1.0
01-231	F	1910		1930	1959		< 1.0

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
01-232	F	1908		1926	1959		< 1.0
01-233	F	1912		1927	1959	0.171	11.50
01-234	F	1913		1927	1959		< 1.0
01-235	F	1908		1925	1959	0.296	21.70
01-236	F	1910		1927	1965	0.105	7.22
01-237	F	1907		1927	1959		< 1.0
01-238	F	1896	1967	1920	1959	0.543	40.40
01-239	F	1901	1958	1917	1957	52.792	3280.00
01-240	F	1910		1927	1958	0.091	6.25
01-243	M	1874	1959	1905	1958	0.636	43.40
01-244	F	1901		1927	1962		< 1.0
01-245	F	1920		1957	1959	0.261	7.19
01-246	F	1885		1915	1967	0.184	13.40
01-247	M	1901		1923	1968		< 1.0
01-248	F	1903		1917	1959	2.220	153.00
01-249	M	1928		1928	1967	0.300	21.50
01-250	M	1894		1916	1959		< 1.0
01-251	M	1890	1966	1912	1959	2.061	147.00
01-252	F	1898		1917	1968	1.875	130.00
01-253	F	1898	1964	1916	1959	2.220	147.00
01-254	F	1910		1927	1965		< 1.0
01-255	F	1920		1942	1959	0.068	3.12
01-256	M	1920		1949	1959	0.232	8.32
01-257	M	1885	1962	1941	1959		< 1.0
01-258	M	1903		1923	1959	0.328	18.10
01-259	F	1910		1927	1959	0.404	23.30
01-260	F	1891	1961	1918	1959	0.817	50.80
01-261	F	1909	1969	1927	1959		< 1.0
01-262	F	1895		1918	1959	0.603	42.20
01-263	F	1897		1917	1960	0.759	54.10
01-264	M	1906	1967	1944	1964	1.808	58.80
01-265	F	1902		1919	1959	1.848	138.00
01-266	F	1904	1961	1923	1959	0.377	27.40
01-267	F	1904		1926	1966	2.406	148.00
01-268	F	1901	1968	1917	1967	31.117	2300.00
01-269	M	1911		1932	1959	0.343	19.30
01-270	F	1922		1943	1959		< 1.0
01-271	F	1898		1917	1969		< 1.0
01-272	M	1888		1956	1959	0.543	15.00
01-273	F	1907		1924	1959	0.699	51.50
01-274	F	1906		1922	1961	2.154	160.00
01-275	M	1930		1959	1959		< 1.0
01-276	M	1930	1963	1945	1959	1.236	41.10
01-277	F	1909		1925	1962		< 1.0
01-278	F	1904		1925	1959	1.742	111.00
01-279	M	1901		1928	1966		< 1.0
01-280	F	1905		1926	1959		< 1.0
01-282	M	1893		1916	1967	2.074	146.00
01-283	F	1895		1918	1959	0.163	11.40
01-284	M	1892		1943	1959	0.073	2.66

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
01-361	F	1907		1924	1962		< 1.0
01-362	F	1906		1923	1962		< 1.0
01-363	F	1888		1918	1962	3.750	279.00
01-364	F	1911		1927	1964	0.461	29.50
01-365	F	1901		1924	1962	3.430	251.00
01-367	F	1899		1920	1962	2.180	161.00
01-368	M	1925		1947	1956	20.744	830.00
01-369	F	1908		1923	1962		< 1.0
01-370	F	1904		1927	1962		< 1.0
01-371	F	1912		1928	1962		< 1.0
01-372	F	1911		1927	1962	0.720	49.30
01-373	F	1911		1927	1962	0.163	10.90
01-374	F	1910		1927	1962	1.235	84.60
01-376	F	1907		1927	1963	0.203	13.90
01-377	F	1915		1929	1962		< 1.0
01-378	F	1907		1925	1968	0.376	26.30
01-379	F	1909		1926	1964	3.550	246.00
01-380	F	1910		1927	1963		< 1.0
01-381	M	1887		1927	1964	0.420	29.00
01-382	F	1900		1920	1963	5.265	373.00
01-383	F	1907		1923	1963	2.433	179.00
01-384	F	1905		1923	1963		< 1.0
01-385	F	1906		1924	1963	1.781	131.00
01-386	F	1904		1927	1963	0.929	63.50
01-388	F	1873	1944	1928	1965	167.553	8440.00
01-389	F	1910	1930	1923	1963	211.436	9510.00
01-390	F	1887	1931	1925	1965	339.095	7710.00
01-391	F	1914		1950	1964		< 1.0
01-392	M	1913		1950	1964		< 1.0
01-393	M	1937		1950	1964	0.034	1.04
01-394	F	1944		1950	1964	0.071	2.18
01-395	F	1945		1950	1964	0.095	2.90
01-396	M	1947		1950	1964	0.050	1.56
01-397	F	1950		1950	1964		< 1.0
01-398	M	1951		1951	1964	0.051	1.56
01-399	F	1953		1953	1964		< 1.0
01-400	M	1903		1961	1964		< 1.0
01-401	F	1910		1961	1964		< 1.0
01-402	F	1898		1920	1963		< 1.0
01-403	F	1912		1925	1964	17.287	1280.00
01-404	M	1875	1945	1912	1965	49.202	1660.00
01-405	F	1885	1957	1912	1965	3.577	204.00
01-406	M	1902		1916	1963	0.735	51.10
01-407	M	1912		1930	1963	1.240	67.80
01-408	F	1918		1934	1966	0.897	45.30
01-409	F	1914		1930	1963	1.901	112.00
01-410	F	1920		1940	1966	2.140	100.00
01-411	M	1915		1935	1963	0.433	22.40
01-412	M	1915		1929	1963	0.071	4.79
01-413	F	1901		1924	1964	3.550	260.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
C1-414	F	1897		1931	1963	0.216	11.30
01-415	M	1898		1921	1964		< 1.0
C1-416	F	1908		1924	1963	3.178	234.00
C1-417	F	1907		1923	1963		< 1.0
01-418	M	1900		1919	1963	0.240	16.40
C1-419	M	1895	1965	1916	1963	0.368	24.20
C1-420	F	1903	1967	1920	1963	0.111	7.33
01-421	F	1898		1915	1963	0.460	32.20
C1-423	M	1897		1919	1963	1.023	68.40
01-424	F	1882		1924	1964	15.159	977.00
01-425	M	1933		1961	1964		< 1.0
C1-426	F	1930		1961	1964	0.054	1.11
01-427	F	1960		1961	1964	0.054	1.11
C1-428	F	1957		1961	1964		< 1.0
01-429	F	1897		1922	1965	0.438	28.30
01-430	M	1880	1969	1930	1966	4.135	285.00
C1-431	F	1901		1922	1967	51.728	3400.00
01-432	M	1895		1915	1964	0.690	47.00
C1-434	M	1880	1932	1927	1965	183.510	4120.00
01-435	F	1907		1925	1964	1.595	112.00
01-436	F	1895		1927	1964	0.740	49.40
01-437	F	1910		1931	1965	0.048	2.78
01-438	M	1867	1940	1925	1965	94.414	4740.00
01-439	F	1880	1953	1922	1968	19.281	971.00
C1-440	F	1908		1924	1965		< 1.0
C1-446	F	1907		1925	1964		< 1.0
01-447	F	1909		1925	1965	0.357	25.00
01-448	F	1907		1925	1964	3.071	215.00
01-449	F	1899		1922	1965	3.257	241.00
01-450	M	1877	1936	1912	1966		< 1.0
C1-456	M	1878	1948	1928	1965	8.297	529.00
01-457	F	1904		1920	1964	0.450	30.40
01-458	F	1892		1957	1964	1.312	36.60
C1-459	M	1887		1921	1964	0.398	26.60
01-460	M	1880	1967	1912	1964		< 1.0
C1-461	M	1914		1930	1964	0.319	18.60
01-466	F	1902	1946	1920	1965		< 1.0
01-468	F	1910		1927	1965		< 1.0
C1-469	M	1894		1918	1965	0.167	11.60
01-470	F	1912		1927	1965		< 1.0
01-472	F	1896		1919	1965	0.400	27.10
01-474	F	1904		1921	1965		< 1.0
01-475	F	1902		1929	1965	0.648	44.00
C1-476	F	1909		1927	1965		< 1.0
01-477	F	1897		1925	1965	108.643	7370.00
01-478	F	1914		1935	1965		< 1.0
C1-479	F	1912		1927	1965	0.319	21.80
01-480	F	1915		1927	1965	3.949	243.00
01-481	F	1909		1927	1965		< 1.0
01-482	F	1912		1927	1965		< 1.0

BLF 1 (CONTINUED)

ASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
-483	M	1907		1923	1965	3.071	226.00
-484	F	1908		1926	1965		< 1.0
-485	M	1870	1951	1911	1965		< 1.0
-486	F	1907		1923	1965	5.757	425.00
-487	F	1911		1927	1965		< 1.0
-489	F	1910		1926	1965	22.872	1360.00
-490	F	1908		1924	1965		< 1.0
-491	F	1922	1966	1943	1963	0.202	6.69
-492	F	1900		1921	1965	0.055	3.58
-493	M	1893		1927	1965	0.164	7.06
-494	M	1906	1966	1926	1966		< 1.0
-495	F	1909		1924	1965		< 1.0
-496	F	1918		1934	1966	0.142	7.63
-497	F	1902		1921	1966	6.755	501.00
-498	F	1897		1920	1965		< 1.0
-501	M	1867	1937	1926	1966	82.712	3250.00
-503	M	1936		1936	1966		< 1.0
-504	F	1913		1927	1967		< 1.0
-505	F	1902		1927	1966	0.966	66.10
-506	F	1897		1923	1966	0.393	25.70
-507	F	1909		1927	1967	5.970	407.00
-508	F	1906		1944	1966	1.176	51.20
-509	F	1943		1942	1967		< 1.0
-510	F	1897		1927	1966	4.042	276.00
-511	F	1908		1927	1966		< 1.0
-514	F	1904		1926	1966	0.378	24.60
-515	F	1886		1940	1966	0.172	8.39
-516	F	1907		1927	1967	0.761	52.00
-518	M	1912		1949	1966	0.372	14.20
-519	M	1919		1937	1967	0.413	20.20
-520	F	1882	1969	1930	1967	50.265	3200.00
-521	M	1910		1942	1967	0.680	29.30
-522	M	1905		1942	1966	2.513	98.90
-523	M	1917		1942	1968	0.868	37.30
-525	M	1923		1943	1968	0.503	22.20
-526	M	1921		1945	1968	0.747	31.80
-529	M	1920		1943	1968		< 1.0
-530	M	1920		1943	1968	1.542	67.90
-531	M	1918		1941	1968	0.232	10.00
-536	M	1916		1943	1968	0.484	20.30
-537	M	1917		1944	1968	1.675	69.80
-540	M	1890		1940	1968		< 1.0
-543	M	1920		1943	1968	0.710	31.20
-544	F	1879	1953	1928	1968	6.143	336.00
-546	F	1897		1914	1967		< 1.0
-548	M	1917		1930	1967	0.594	37.30
-552	M	1907		1936	1967	0.666	34.40
-553	F	1910		1948	1967		< 1.0
-554	F	1928		1952	1967	7.805	184.00
-555	F	1894		1921	1968	1.081	80.40

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
C1-556	F	1910		1927	1967		< 1.0
01-557	F	1910		1925	1967	1.742	122.00
C1-558	M	1913		1927	1968	40.159	2990.00
01-565	F	1892	1957	1925	1968	191.489	9860.00
C1-567	M	1884	1949	1925	1968	68.484	4120.00
01-568	M	1908	1928	1927	1968	17.021	112.00
01-570	F	1908		1926	1968	0.537	32.30
01-571	F	1911		1928	1968	0.098	6.63
01-573	F	1892	1945	1916	1968	83.909	4950.00
01-574	M	1885	1937	1924	1968	57.047	1610.00
C1-575	M	1910		1945	1967	0.039	1.26
01-576	F	1930		1946	1968	5.212	169.00
01-578	F	1904	1930	1926	1968	32.047	452.00
01-579	F	1928	1928	1928	1968		< 1.0
01-580	F	1894		1918	1968	0.301	21.00
01-581	M	1918		1946	1968	0.280	11.50
01-582	F	1893		1917	1968	0.183	13.00
01-583	M	1890	1969	1918	1968		< 1.0
01-584	F	1908		1926	1968	0.537	32.30
01-585	F	1906	1969	1925	1968		< 1.0
01-586	F	1879		1924	1968	7.393	476.00
01-588	F	1908		1929	1968	0.263	15.50
C1-589	M	1907		1927	1964	0.073	4.47
01-590	M	1929		1929	1968		< 1.0
01-591	F	1891		1918	1968		< 1.0
01-592	F	1902		1917	1968		< 1.0
01-594	M	1927		1962	1966		< 1.0
01-595	F	1897		1917	1969	14.760	1020.00
C1-597	F	1923		1940	1969		< 1.0
01-598	M	1869	1953	1941	1952	7.127	223.00
01-599	F	1909		1927	1968	0.763	52.10
C1-601	F	1902		1919	1969		< 1.0
C1-603	F	1894		1915	1968	0.413	28.00
C1-604	F	1896		1914	1968	0.251	18.40
01-609	F	1906		1927	1968	0.384	23.60
01-610	M	1904		1919	1968	0.420	28.30
01-615	F	1909		1927	1969		< 1.0
C1-621	F	1908		1924	1969	5.398	397.00
C1-625	F	1911		1927	1968	0.308	17.70
01-626	F	1932		1932	1968	0.501	30.90
01-628	F	1908		1925	1969	2.087	132.00
C1-629	F	1892		1926	1969	0.654	39.30
01-640	F	1908		1924	1969	1.954	125.00
C1-659	F	1912		1928	1969	0.601	36.30
C3-101	F	1908		1931	1963	75.930	4370.00
03-102	M	1905		1931	1964	23.537	1350.00
C3-103	F	1868	1952	1931	1951	15.824	620.00
C3-104	F	1880	1941	1931	1931	79.401	1977.54
03-105	M	1903	1957	1931	1951	69.813	3140.00
C3-106	F	1870	1953	1931	1932	26.196	1062.99

ABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT,BONE NANOCURIE/G	CUMULATIVE RADS
3-107	F	1884	1957	1931	1932	20.598	929.51
3-108	F	1876	1941	1931	1932	13.696	338.00
3-109	F	1904	1957	1931	1953	24.867	1120.00
3-110	F	1899	1967	1931	1964	28.324	1570.00
3-111	F	1909		1931	1963	43.484	2500.00
3-112	F	1899	1968	1931	1960	271.276	15300.00
3-113	F	1914	1946	1931	1932	8.763	277.00
3-114	F	1901	1968	1931	1964	48.005	2720.00
3-115	F	1906		1931	1964	33.776	1940.00
3-116	F	1908		1931	1964	78.191	4500.00
3-117	M	1898	1957	1931	1953	43.218	1940.00
3-118	F	1898	1955	1931	1953	121.542	5160.00
3-119	F	1880	1960	1931	1959	46.675	2250.00
3-120	F	1879	1937	1931	1932	39.228	711.00
3-121	F	1909		1931	1964	21.143	1220.00
3-122	M	1908	1942	1931	1931	12.380	326.86
3-123	M	1914	1937	1931	1931	52.792	962.00
3-124	M	1910	1942	1931	1931	8.005	211.12
3-125	F	1913		1931	1963	35.106	2020.00
3-126	F	1910	1965	1931	1965	64.494	3450.00
3-127	F	1908		1931	1962	26.728	1530.00
3-135	M	1906		1931	1964	37.101	2140.00
3-139	M	1908		1933	1963	14.494	802.00
3-141	M	1906	1963	1933	1962	31.382	1560.00
3-201	F	1909	1963	1922	1962	160.904	9740.00
3-202	M	1885		1925	1960	94.148	5980.00
3-203	F	1903		1933	1959	3.630	203.00
3-204	F	1898		1922	1960	1.107	73.40
3-205	F	1900		1928	1968	15.824	955.00
3-206	M	1914		1936	1964	95.877	5050.00
3-207	F	1879		1922	1960	37.500	2340.00
3-209	M	1895	1960	1925	1951	26.994	1320.00
3-210	M	1906	1958	1926	1958	48.537	2550.00
3-211	M	1890		1923	1960	0.371	24.10
3-212	F	1902	1951	1927	1951	55.053	2400.00
3-213	F	1892	1955	1925	1952	289.893	14400.00
3-214	F	1895	1966	1925	1964	76.462	4670.00
3-215	M	1896		1925	1961	132.978	8440.00
3-216	F	1907	1961	1922	1961	28.324	1660.00
3-217	M	1912		1921	1963	18.218	1230.00
3-218	M	1895		1925	1959	0.639	40.60
3-219	F	1899		1919	1951	2.792	188.00
3-220	M	1920		1928	1964	5.252	318.00
3-221	M	1909	1963	1924	1957	21.675	1270.00
3-222	M	1872	1960	1922	1951	73.271	3021.43
3-223	F	1886	1968	1929	1951	160.904	9340.00
3-224	M	1870	1960	1922	1951	164.893	8930.00
3-225	M	1922		1929	1964	1.082	64.60
3-226	M	1874	1953	1934	1951	261.968	9590.00
3-227	F	1878	1952	1930	1952	34.175	1390.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
03-228	M	1899		1927	1951	166.223	10200.00
03-230	F	1899		1927	1965	28.989	1780.00
03-231	F	1883		1939	1952	1.293	89.60
03-232	F	1898	1957	1917	1956	251.329	15000.00
03-233	F	1879	1948	1922	1947	170.212	7660.00
03-234	F	1890	1965	1915	1965	55.984	3860.00
03-235	F	1900	1968	1928	1965	67.021	4000.00
03-236	F	1880	1961	1926	1951	21.143	1160.00
03-237	F	1890		1923	1961	0.154	9.90
03-238	M	1883	1957	1926	1951	421.542	21300.00
03-239	F	1884	1953	1925	1951	489.361	23200.00
03-401	F	1900	1963	1923	1960	117.420	6900.00
03-402	F	1905		1923	1965	96.675	6220.00
03-403	F	1915	1964	1935	1957	0.281	12.30
03-404	F	1897		1923	1966	45.478	2910.00
03-405	F	1904		1924	1962	32.446	2060.00
03-406	F	1914		1935	1957	0.944	73.00
03-407	F	1905	1961	1923	1958	69.148	3880.00
03-408	F	1908	1959	1924	1957	7.739	417.00
03-409	F	1924		1942	1957	1.369	62.80
03-410	F	1899		1923	1957	2.938	189.00
03-411	F	1899		1931	1957		< 1.0
03-412	F	1894		1922	1965	11.728	763.00
03-413	F	1917		1938	1957	0.139	6.85
03-414	F	1921		1946	1957	0.156	5.52
03-415	F	1911		1930	1957	0.547	27.90
03-416	F	1907		1924	1966	66.090	4220.00
03-417	F	1909	1966	1924	1964	33.111	2020.00
03-418	F	1896		1926	1957	0.296	16.80
03-419	F	1906		1924	1962	35.239	2240.00
03-420	F	1906	1960	1922	1957	0.881	49.10
03-421	F	1908		1924	1957	0.577	36.60
03-422	F	1907		1925	1957	1.382	87.40
03-423	F	1907		1923	1962	30.984	1980.00
03-424	F	1905		1923	1957	17.686	1130.00
03-425	F	1916		1935	1957	0.521	26.60
03-426	F	1906		1924	1957	10.611	673.00
03-427	F	1906		1925	1962	1.449	91.10
03-428	F	1908		1925	1962	30.718	1940.00
03-429	F	1908		1923	1966	102.127	6530.00
03-430	F	1922		1940	1957	0.208	9.18
03-431	F	1901		1922	1963	69.813	4570.00
03-432	F	1902		1924	1957	2.167	138.00
03-433	F	1904		1924	1964	56.250	3570.00
03-434	F	1920		1941	1960	0.533	24.50
03-435	F	1912		1935	1957	0.271	14.30
03-436	F	1910		1926	1957	1.053	59.70
03-437	F	1906		1926	1957	2.593	160.00
03-438	F	1908		1925	1957		< 1.0
03-439	F	1906		1925	1957		< 1.0

LF 1 (CONTINUED)

SE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
440	F	1908		1925	1957		< 1.0
441	F	1905		1925	1957	2.672	169.00
442	F	1904		1924	1957	0.635	40.90
443	F	1914		1935	1958		< 1.0
444	F	1907		1925	1962	0.825	52.00
445	F	1905		1922	1966	75.930	4890.00
446	F	1903		1922	1966	4.880	315.00
447	F	1906		1924	1958	0.099	6.40
448	F	1903		1924	1958	1.240	79.70
449	F	1905		1922	1964	61.436	3960.00
450	F	1910		1924	1958	0.993	63.80
451	F	1922		1940	1958	0.147	6.32
452	F	1908		1925	1966	1.199	75.50
453	F	1912		1925	1958		< 1.0
454	F	1914		1934	1958	1.715	84.10
455	F	1906		1922	1958	44.015	2890.00
456	F	1921	1965	1943	1958	0.896	32.00
457	F	1915		1933	1958	0.150	7.57
458	F	1925		1946	1953	0.316	10.80
459	F	1906		1924	1965	48.005	3070.00
460	F	1905		1923	1958	0.605	39.40
461	F	1896		1922	1958	0.307	20.30
462	F	1906		1922	1962	17.287	1120.00
463	F	1918	1966	1942	1959	0.531	17.60
464	F	1907		1923	1958		< 1.0
465	F	1908		1925	1958	0.097	6.20
466	F	1904		1924	1958	0.198	12.80
467	F	1911		1926	1958	0.672	39.50
468	F	1908		1926	1958	1.369	84.20
469	F	1903		1925	1958	0.488	30.80
70	F	1926		1942	1958	0.708	30.90
471	F	1908		1926	1958	0.618	38.10
72	F	1922		1941	1958	0.352	15.70
73	F	1904	1965	1923	1962	61.436	3710.00
74	F	1909		1925	1958	0.928	58.70
75	F	1903	1962	1921	1958		< 1.0
76	F	1895		1927	1958		< 1.0
77	F	1899		1925	1959	0.546	34.60
78	F	1907		1924	1958	0.248	16.00
79	F	1908		1924	1958	3.856	250.00
80	F	1909		1924	1958		< 1.0
81	F	1922		1941	1958	0.577	24.30
82	F	1927		1944	1958		< 1.0
83	F	1901		1922	1959		< 1.0
84	F	1888	1966	1919	1962	89.494	5810.00
85	F	1909		1929	1958		< 1.0
86	F	1909		1925	1966	14.494	917.00
87	F	1907	1964	1924	1958	17.952	1050.00
88	F	1907		1922	1958	8.683	573.00
89	F	1911	1964	1926	1958	5.718	326.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
03-490	M	1904		1925	1958	0.986	61.00
03-491	F	1908		1924	1959	2.832	182.00
03-492	F	1928		1946	1959	0.128	4.91
03-493	F	1893		1920	1959	0.364	24.20
03-494	F	1902		1925	1959	0.198	12.40
03-495	F	1910		1923	1959		< 1.0
03-496	F	1907		1923	1959	0.154	10.00
03-497	F	1903		1923	1959	0.819	53.50
03-498	F	1905		1923	1959	0.126	7.07
03-499	F	1906		1924	1964	19.946	1360.00
03-500	F	1901	1959	1922	1959		< 1.0
03-501	F	1912		1928	1959	0.331	20.10
03-502	F	1887	1964	1918	1959	9.148	585.00
03-503	F	1894	1960	1922	1959	6.396	362.00
03-504	F	1905		1922	1959	1.139	75.20
03-505	F	1907		1923	1965	9.321	605.00
03-506	F	1917		1935	1959	0.622	30.30
03-507	F	1907	1962	1923	1959	0.614	36.00
03-508	F	1905		1923	1959	0.511	33.40
03-509	F	1910		1936	1959	2.140	85.00
03-510	F	1907		1923	1962	38.563	2500.00
03-511	F	1910		1946	1959	0.155	5.26
03-512	F	1906		1925	1959	0.545	34.50
03-513	F	1908		1925	1966	5.345	337.00
03-514	F	1909		1925	1959	1.283	80.90
03-515	F	1908		1925	1959	0.542	34.20
03-516	F	1911		1925	1959	0.888	56.00
03-517	F	1922		1943	1959	0.122	5.19
03-518	F	1921		1940	1959	0.347	15.10
03-519	F	1903		1924	1959	4.946	318.00
03-520	F	1907		1925	1966	5.771	364.00
03-521	F	1907	1961	1925	1959	0.494	27.40
03-522	F	1898		1921	1964	7.819	522.00
03-523	F	1900		1923	1959	1.174	76.40
03-524	F	1903		1925	1959	3.311	208.00
03-525	F	1911		1931	1959	0.409	17.40
03-526	F	1896		1925	1959		< 1.0
03-527	F	1909		1926	1959	0.240	14.70
03-528	F	1904		1922	1959	82.313	5300.00
03-529	F	1903		1921	1966	7.207	477.00
03-530	F	1907	1965	1923	1963	25.398	1540.00
03-531	F	1906		1925	1959	2.021	128.00
03-532	F	1910		1926	1959	4.614	280.00
03-533	F	1908		1925	1959	0.789	49.80
03-534	F	1910		1925	1959	0.147	9.33
03-535	F	1907		1922	1964	12.579	831.00
03-536	F	1910		1925	1959	1.742	110.00
03-537	F	1900		1916	1959		< 1.0
03-538	F	1909		1927	1959	2.938	180.00
03-539	F	1900		1923	1959	0.765	49.90

TABLE 1 (CONTINUED)

NE S	CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULAT RA
0	03-540	F	1905		1923	1966	111.835	7150.
0	03-541	F	1913		1936	1959		< 1.
0	03-542	F	1904		1922	1959	1.555	103.
0	03-543	F	1918		1946	1959		< 1.
0	03-544	F	1906		1922	1959	0.259	17.
	03-545	F	1898		1920	1959		< 1.
0	03-546	F	1903		1925	1959	4.694	296.
0	03-547	F	1907	1962	1923	1959	0.958	55.
7	03-548	F	1906		1922	1959	9.853	652.
0	03-549	F	1910		1925	1959	3.018	190.
	03-550	F	1900		1917	1959	0.712	49.
0	03-551	F	1903		1922	1967	65.558	4220.
0	03-552	F	1904		1924	1959	8.058	512.
0	03-553	F	1904		1924	1959	1.311	84.
0	03-554	F	1899		1924	1961	102.526	6510.
0	03-555	F	1913		1928	1959	0.513	30.
0	03-556	F	1911		1928	1959	0.327	19.
0	03-557	F	1910		1925	1959		< 1.
0	03-558	F	1904		1923	1959	15.957	1140.
0	03-559	F	1907		1922	1959	0.881	58.
0	03-561	F	1909		1924	1959	3.377	218.
6	03-562	F	1909		1930	1959	0.384	21.
0	03-563	F	1909		1924	1959	0.756	48.
0	03-564	F	1906		1923	1959	0.511	33.
0	03-565	F	1913		1930	1959	0.793	41.
0	03-566	F	1910		1930	1959		< 1.
0	03-567	F	1900		1922	1959	2.300	151.
9	03-568	F	1905		1922	1959	6.063	390.
0	03-569	F	1901		1922	1959	7.273	468.
0	03-570	F	1908		1925	1959		< 1.
0	03-571	F	1909		1925	1966	60.505	3810.
0	03-572	F	1906		1925	1959	4.242	268.
0	03-573	F	1900		1925	1959	1.382	87.
0	03-574	F	1904		1920	1959		< 1.
0	03-575	F	1913		1931	1959		< 1.
0	03-576	F	1909		1925	1959	0.345	21.
	03-577	F	1903		1921	1959	4.215	279.
0	03-578	F	1909		1925	1959	0.841	53.
0	03-579	F	1905		1922	1959	1.555	103.
0	03-580	F	1904		1923	1959	0.102	6.
0	03-581	F	1904		1922	1959	0.675	44.
0	03-583	M	1893	1962	1920	1959	2.367	188.
0	03-584	F	1905	1959	1923	1959	307.180	17100.
0	03-585	F	1894		1918	1966	4.281	290.
3	03-586	F	1908	1968	1926	1967	48.803	2970.
0	03-587	F	1906		1925	1959	0.643	40.
0	03-588	F	1901		1922	1962	16.622	1070.
	03-589	F	1906		1924	1959	3.882	249.
0	03-590	F	1900		1922	1965	5.824	385.
0	03-591	F	1907		1926	1959	0.700	31.

TABLE 1 (CONTINUED)

ULAT RA	CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
150.	03-592	F	1905		1922	1966	6.981	462.00
< 1.	03-593	F	1905		1922	1959	0.882	58.50
103.	03-594	F	1905		1922	1959	2.114	139.00
< 1.	03-595	F	1902		1928	1959		< 1.0
17.	03-596	F	1904		1922	1959	0.468	30.90
< 1.	03-597	F	1903		1925	1959	7.606	479.00
296.	03-598	M	1891		1933	1959		< 1.0
55.	03-599	F	1906		1922	1959	0.466	30.80
652.	03-600	F	1902		1926	1960		< 1.0
190.	03-601	F	1893		1925	1960	0.300	19.00
49.	03-602	F	1899		1925	1960	0.150	9.48
220.	03-603	F	1888		1924	1960		< 1.0
512.	03-604	F	1899		1916	1960	0.541	36.80
84.	03-605	F	1900		1923	1960	0.154	9.90
510.	03-606	F	1905		1924	1952	0.449	28.90
30.	03-607	F	1906		1922	1960	10.186	672.00
19.	03-608	F	1901		1919	1960	1.029	70.10
< 1	03-609	F	1898		1923	1960		< 1.0
1140.	03-610	F	1917		1935	1960	0.332	17.50
58.	03-611	F	1902		1916	1960	0.166	11.60
218.	03-612	F	1892		1918	1960	26.994	1830.00
21.	03-613	F	1905		1925	1960	0.401	25.30
48.	03-614	F	1909		1924	1960	6.968	445.00
33.	03-615	F	1905		1923	1960	1.178	75.90
41.	03-617	F	1902	1951	1921	1951	555.851	26000.00
< 1	03-618	F	1893		1920	1960	0.538	36.50
151.	03-619	F	1903	1962	1922	1962	84.973	5040.00
390.	03-620	F	1923		1942	1960	0.570	25.10
468.	03-621	F	1916		1942	1960	0.436	19.20
< 1	03-622	F	1906		1924	1960		< 1.0
3810.	03-623	F	1906		1924	1963	0.748	48.20
268.	03-624	F	1905	1959	1923	1959	51.329	2860.00
87.	03-625	F	1906		1924	1960		< 1.0
< 1	03-626	F	1906		1924	1960	14.893	957.00
< 1	03-627	F	1905	1966	1924	1960	3.643	220.00
21.	03-628	F	1905		1921	1962		< 1.0
279.	03-629	F	1904		1922	1960	4.587	304.00
53.	03-630	F	1906		1924	1960		< 1.0
103.	03-634	F	1906		1924	1960	0.718	46.20
6.	03-635	F	1906		1924	1960	3.696	238.00
44.	03-636	F	1906		1924	1960	0.718	46.20
188.	03-637	F	1906		1924	1960	2.965	191.00
7100.	03-638	F	1906		1924	1960	0.718	46.20
290.	03-639	F	1907		1925	1960	5.066	319.00
2970.	03-640	F	1902		1924	1960	0.253	16.20
40.	03-641	F	1904		1922	1960	1.529	101.00
1070.	03-642	F	1906		1922	1959	2.606	172.00
249.	03-643	F	1906		1924	1960	2.167	138.00
385.	03-645	F	1906		1924	1959	2.792	178.00
31.	03-647	F	1908		1925	1960	2.925	186.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT,BONE NANOCURIE/G	CUMULATIVE RADS
03-648	F	1903	1956	1922	1955	449.468	25300.00
03-649	F	1906	1954	1924	1954	56.382	2730.00
03-671	F	1906	1953	1922	1952	211.436	11500.00
03-672	F	1906		1924	1960	0.718	46.20
03-673	F	1906		1924	1960	2.965	191.00
03-674	F	1908		1925	1960	0.452	28.50
03-676	F	1906		1924	1963	90.824	5850.00
03-677	M	1906	1965	1924	1961	12.367	750.00
03-678	M	1906		1924	1961	8.617	555.00
03-679	F	1910		1929	1961	2.739	163.00
03-681	F	1906		1922	1962	0.757	50.20
03-682	F	1907		1925	1962		< 1.0
03-683	F	1906		1923	1961		< 1.0
03-684	F	1907		1927	1961	2.978	183.00
03-685	F	1902		1921	1966	7.606	506.00
03-686	F	1904		1922	1964	1.515	97.60
03-687	F	1900		1925	1961	2.593	164.00
03-688	F	1918		1936	1961	0.481	24.10
03-689	F	1903		1923	1961	6.715	429.00
03-690	F	1909	1967	1924	1958	15.691	995.00
03-692	M	1887		1920	1961	0.235	16.00
03-693	F	1920		1942	1952	0.176	7.10
03-695	F	1921		1942	1962		< 1.0
03-696	F	1932		1950	1963		< 1.0
03-697	F	1899		1924	1967	10.132	650.00
03-726	F	1902		1922	1968	32.712	2110.00
03-727	F	1906		1922	1966	13.563	881.00
03-729	F	1927		1941	1952	1.462	65.60
03-730	M	1894		1923	1961	0.263	17.20
03-778	F	1898		1922	1968	3.164	207.00
03-784	F	1906		1924	1954	34.973	2250.00
03-801	F	1900		1924	1965		< 1.0
03-828	M	1915		1950	1959		< 1.0
03-836	F	1908		1924	1967		< 1.0
05-001	F	1900		1919	1967	5.359	379.00
05-007	F	1896		1920	1967	3.523	254.00
05-014	F	1900		1916	1968	15.425	1120.00
05-017	F	1894		1919	1968	1.808	133.00
05-025	F	1893		1917	1967	6.422	454.00
05-039	F	1899		1917	1968	1.324	97.10
05-040	F	1899		1918	1967	0.658	45.70
05-044	M	1895		1915	1968	0.511	35.10
05-089	F	1900		1916	1967	0.731	52.00
05-094	F	1927		1945	1968	0.200	8.50
05-100	F	1907		1919	1968	0.631	45.70
05-118	F	1901		1917	1967	1.204	87.90
05-119	F	1905		1924	1966	2.805	194.00
05-121	F	1906		1921	1967	2.194	157.00
05-127	M	1893		1918	1967	0.760	46.30
05-138	F	1917		1941	1968	0.216	10.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
05-146	M	1897		1920	1968	0.082	5.41
05-199	F	1901		1917	1967		< 1.0
05-201	F	1919		1941	1967	0.496	22.30
05-215	F	1887	1968	1917	1969	175.531	12700.00
05-251	F	1896		1917	1965	0.771	54.40
05-278	F	1893	1965	1917	1965	2.606	174.00
05-279	F	1896		1917	1969		< 1.0
05-284	F	1899		1919	1967	15.292	1070.00
05-291	F	1902		1920	1968	0.674	49.00
05-307	F	1920		1944	1967	0.438	19.00
05-321	F	1899		1916	1966	2.021	147.00
05-351	F	1892		1917	1968	1.609	115.00
05-372	F	1888		1916	1968	0.860	60.90
05-377	F	1895		1916	1969		< 1.0
05-383	F	1901		1920	1968	6.569	456.00
05-401	M	1898		1917	1968	1.382	100.00
05-413	F	1900		1916	1967	2.513	179.00
05-439	F	1898		1916	1967	12.167	861.00
05-464	M	1895		1917	1968	0.219	15.50
05-528	F	1892		1917	1967		< 1.0
05-541	F	1918		1937	1966	0.397	19.70
05-631	F	1897		1917	1965	1.781	126.00
05-742	F	1898		1916	1969		< 1.0
05-751	F	1901	1933	1920	1969		< 1.0
05-818	F	1901	1969	1918	1967	1.502	104.00
05-880	F	1921		1940	1969		< 1.0
05-885	F	1917		1939	1969		< 1.0
05-892	F	1904		1917	1968	4.295	304.00
05-897	F	1899	1968	1917	1968	90.824	6360.00
05-905	F	1916		1937	1969	1.222	61.20
05-912	M	1877	1951	1918	1969		< 1.0
05-942	M	1901		1918	1968		< 1.0
05-994	F	1886		1922	1967	1.196	85.30
05-998	F	1902		1918	1968	0.789	55.20
09-001	F	1901		1917	1959	0.773	54.50
09-002	F	1902		1917	1959	1.555	110.00
09-003	M	1892	1963	1914	1959	15.691	989.00
09-004	F	1890	1961	1912	1960	31.250	2010.00
09-006	F	1898		1917	1963	0.057	4.06
09-007	F	1901	1965	1917	1960	1.835	121.00
09-008	F	1900		1917	1960	1.123	79.50
09-009	F	1893		1915	1960	0.114	8.21
09-010	F	1897		1914	1960	0.582	42.80
09-013	F	1900		1917	1960	0.224	15.90
09-015	M	1890		1914	1960		< 1.0
09-019	F	1903		1917	1960		< 1.0
09-020	F	1897		1917	1963	0.057	3.97
09-024	M	1873	1960	1915	1960		< 1.0
09-026	F	1902		1917	1960	2.127	150.00
09-028	F	1897		1917	1960	3.563	250.00

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT,BONE NANOCURIE/G	CUMULATIVE RADS
09-029	F	1901	1962	1917	1960	0.898	57.70
09-031	F	1897		1913	1960	16.223	1150.00
09-032	F	1902	1969	1918	1960	9.109	633.00
09-038	F	1903		1919	1960		< 1.0
09-041	M	1889	1952	1914	1965	4.135	229.00
09-043	F	1898		1917	1960	0.280	19.80
09-046	F	1902		1917	1960	0.555	38.80
09-051	F	1900		1917	1960	2.779	194.00
09-052	F	1899		1916	1960	1.131	80.60
09-053	M	1874	1966	1919	1960	3.178	210.00
09-057	F	1890		1917	1960		< 1.0
09-058	F	1899		1917	1960	0.223	15.80
09-059	F	1903		1917	1960	0.056	3.98
09-060	F	1899		1917	1960	1.901	133.00
09-062	F	1901		1918	1960	0.386	26.80
09-064	F	1891		1916	1960		< 1.0
09-065	F	1887		1915	1960	0.057	4.10
09-066	F	1899		1917	1960	0.336	23.80
09-070	M	1875	1967	1913	1960	0.123	8.73
09-071	F	1897		1917	1960		< 1.0
09-072	F	1893		1917	1960	0.333	23.30
09-073	M	1886	1963	1916	1962		< 1.0
09-074	F	1892		1920	1962	0.712	47.90
09-075	M	1893	1967	1913	1963	0.039	2.54
09-076	M	1882	1966	1913	1964	0.466	25.40
09-077	M	1894		1924	1962	0.069	4.16
09-078	M	1883	1966	1911	1963	0.121	8.04
09-079	M	1891		1916	1962		< 1.0
09-080	M	1886		1919	1962	0.192	12.80
09-082	M	1892		1916	1962	0.404	28.00
09-083	M	1889	1964	1915	1962	0.210	14.30
09-084	M	1888	1927	1912	1965	5.957	121.00
09-086	M	1895		1921	1963		< 1.0
09-088	M	1900		1922	1959	0.848	53.70
09-089	M	1890		1915	1959	2.579	185.00
09-090	M	1888		1913	1963		< 1.0
09-095	M	1894		1918	1963	0.273	18.10
09-096	M	1892		1919	1963	0.365	25.10
09-097	M	1896		1916	1963	0.333	21.00
09-098	M	1902		1921	1963	0.547	36.30
09-099	M	1898		1913	1963	0.042	3.09
09-100	M	1888		1918	1963	0.355	23.60
09-101	M	1884	1964	1920	1963	0.239	15.10
09-102	M	1882	1951	1915	1964	5.492	306.00
09-103	M	1895		1918	1965	0.040	2.66
09-104	M	1880		1906	1965	1.928	149.00
09-105	M	1886	1928	1912	1966	27.127	761.00
09-106	M	1901		1922	1965		< 1.0
09-107	M	1897		1913	1965	0.043	3.22

TABLE 1 (CONTINUED)

CASE	SEX	BORN	DIED	FIRST EXPOSED	LAST MEASURED	INPUT, BONE NANOCURIE/G	CUMULATIVE RADS
C9-108	M	1891		1915	1965	0.171	12.30
09-109	M	1895		1914	1965	0.174	12.60
09-110	M	1900		1914	1965	0.305	22.30
09-111	M	1874	1944	1913	1967		< 1.0
09-112	M	1898		1940	1966	2.367	104.00
C9-115	M	1894		1920	1953	0.694	47.00

TABLE 2. Summary of Exposure Histories and Body Burdens of Radioactivity for 49 Dial Painters Examined May 1970-30 June 1971.

Case No.	Sex	Year of birth	Exposure: date and duration	Estimated Ra(μCi)	Yrs after first exposure	Age at first exposure
05-014	F	1900	1916-1920 4 yr	0.11	54	16
05-001	F	1900	1919 1 yr	0.061	51	19
05-040	F	1899	1917-1918 ~ 1 yr	0.010	54	18
05-094	F	1927	1945 1 yr	0.009	26	18
05-121	F	1906	1921-1922 6 mo intermittently	0.009	49	15
01-090	F	1910	1927-1929 ~ 1-1/2 yr	0.008	44	17
01-074	F	1909	1927-1928 12 mo	0.007	44	18
01-075	F	1902	1922-1923 12 mo	0.007	49	20
01-078	F	1909	1925-1926 10 mo	0.006	46	16
01-110	F	1909	1925-1927 19 mo	0.006	46	16
05-306	F	1903	~1921-1924 2-3 yr	0.006	49	18
01-137	F	1901	1923-1936	0.005	48	22
01-715	F	1907	1927 1 mo	0.005	43	20
01-289	F	1899	1919-1921 19 mo	0.004	52	20
01-728	F	1912	1927 6 wk	0.004	43	15
01-070	F	1910	1927-1928 3 mo	0.003	43	17

TABLE 2. (contd.)

Case No.	Sex	Year of birth	Exposure: date and duration	Estimated Ra (μCi)	Yrs after first exposure	Age at first exposure
01-180	F	1900	1918 6 mo	0.003	53	18
01-294	F	1912	1927-1928 1 yr	0.003	44	15
01-037	F	1908	1928 6 mo	0.002	43	20
01-069	F	1905	1922-1924 1-1/2 yr	0.002	48	17
01-091	F	1907	1927-1933 intermittently	0.002	44	20
01-092	F	1906	1922 6 mo	0.002	49	16
01-111	F	1910	1927 4 mo	0.002	44	17
01-127	F	1908	1927 2 mo	0.002	44	19
01-290	F	1906	1920-1924 5 summers	0.002	51	14
01-435	F	1907	1925 1 mo	0.002	46	18
05-322	M	1900	1917-1922	0.002	54	17
05-447	F	1902	1916 2 mo	0.002	54	14
10-018	F	1920	1952-1960 8 yr	0.002	19	32
01-041	F	1909	1927 6 mo	0.001	44	18
01-237	F	1908	1927 2 mo	0.001	44	19
01-254	F	1910	1927 2 wk	0.001	44	17

TABLE 2. (contd.)

Case No.	Sex	Year of birth	Exposure: date and duration	Estimated Ra (μCi)	Yrs after first exposure	Age at first exposure
01-280	F	1905	1926 1 mo	0.001	45	21
05-002	F	1903	1917-1918 2 summers	0.001	54	14
05-015	F	1891	1916-1918 16 mo	0.001	54	25
01-035	F	1901	1920 3 mo	0.000	51	19
01-125	F	1911	1927 6 wk	0.000	44	16
01-143	F	1904	1921-1922 2 summers	0.000	49	17
01-599	F	1909	1927 2 mo	0.000	43	18
05-407	F	1898	1916 2 mo	0.000	54	18
05-440	F	1896	~1922-1923 < 1 wk	0.000	49	26
01-123	F	1889	1923 3-4 mo	-0.001	47	34
05-126	F	1889	1921-1923 intermittently	-0.001	49	32
01-093	F	1904	1926 ~2 mo	0.00	45	22
01-169	F	1918	1936-1938 1 yr total	0.00	35	18
01-240	F	1910	~1925 1 mo	0.00	46	15
01-255	F	1920	1942-1943 12 mo	0.00	29	22
01-475	F	1901	1929 3 wk	0.00	42	28
01-482	F	1912	1927 1 mo	0.00	44	15

000027

TABLE 3. Summary of Exposure Histories and Body Burdens of Radioactivity for 35 Individuals, Other than Dial Painters, Examined May 1970–30 June 1971.

Case No.	Sex	Year of birth	Exposure: type, date, duration	Estimated Ra (μCi)	Yrs after first exposure	Age at first exposure
01-431	F	1901	Ra injection ~ 300 μg $RaCl_2$ 1922–1923	0.765	49	21
01-588	M	1913	Drank Radithor ~ 64–128 bottles ~ 1927–1929	0.33	43	14
01-196	M	1907	Drank Radithor ~ 1930	0.11	40	23
05-383	F	1901	Ra plant, Sec'y and lab worker 1917–1920	0.072	53	16
01-336	M	1899	Ra chemist 1945–1966	0.051	25	46
01-409	F	1914	Ra contam. home 1914–1942 Ra lab worker ~1930	0.034	57	0
01-410	F	1920	Ra contam. home Ra lab worker 1940–1943	0.033	31	20
01-157	F	1894	Drank Radithor ~ 90 bottles ~ 1925	0.032	45	31
09-088	M	1900	Ra chemist 1922–1928	0.018	49	22
01-408	F	1918	Ra contam. home 1918–1945 intermit. lab worker 1934–1942	0.015	53	0
09-106	M	1901	Ra chemist 1919–1921 3 yr	0.008	52	18

TABLE 3. (contd.)

Case No.	Sex	Year of birth	Exposure: type date, duration	Estimated Ra (μCi)	Yrs after first exposure	Age at first exposure
01-247	M	1901	Ra chemist 1923-1926 Rn chemist 3 mo 1926, 1930-1937	0.007	48	22
05-353	M	1900	Shipper, Ra plant summer 1915	0.006	56	15
09-082	M	1892	Ra chemist 1916-1917 1919-1922	0.006	55	24
01-307	M	1930	Ra chemist 1957-1961	0.005	14	27
05-401	M	1898	Supervisor of dial painters 3 yr 1917-1920	0.005	54	19
05-387	M	1902	Ra chemist 1918 1-2 mo	0.004	53	16
05-197	M	1898	Machinist Ra plant 1919, 3-4 mo	0.003	52	21
05-369	F	1901	Dial inspector 1919 6 mo	0.003	51	15
01-310	F	1928	Mother was former dial painter, Case 01-051	0.002	--	--
01-414	F	1897	Ra physicist 1931-1942	0.002	40	34
01-493	M	1893	Rn pumper 1927-1962	0.002	44	34
01-691	F	1913	Father was Radithor drinker Case 01-690	0.002	--	--
05-409	F	1900	Ra plant sec'y. 8 mo 1918-1919	0.002	53	18
10-009	M	1889	MsTh chemist 1917-1928	0.002	54	28

060029

TABLE 3. (contd.)

Case No.	Sex	Year of birth	Exposure: type, date, duration	Estimated Ra (μCi)	Yrs after first exposure	Age at first exposure
01-174	M	1897	MsTh chemist 1918, 1 yr	0.001	53	21
01-420	F	1897	Ra lab worker 1922-1926	0.001	49	25
05-450	F	1903	Ra plant worker 1918-1920	0.001	53	15
01-626	F	1932	Mother was former dial painter, Case 00-027	0.000	--	--
05-181	F	1901	Ra packer 1918, 1 mo	0.000	52	17
01-617	M	1922	Mother was former dial painter, Case 01-014	-0.001	49	0
06-501	F	1897	No exposure, control	-0.001	--	--
05-272	M	1895	Ra chemist 1918-1918	-0.002	52	23
05-161	M	1901	Ra chemist summer 1918	0.00	53	17
09-095	M	1894	Ra chemist 1918-1926	0.00	53	24

A TIME-INVARIANT DOSE PARAMETER FOR RADIUM CASES

A. F. Stehney

The suitability c [illegible] e, dose rate, and time parameters for studies of radium-burdened humans is examined. A time-invariant dose parameter is shown to be necessary for determining the time dependence of radiation effects, and the amount of initially acquired radioactivity per unit skeletal mass (nCi/g bone) is suggested as appropriate for this purpose.

The cumulative rad (CR) dose variable[1] has been used frequently for empirical comparisons of biological effect and radiation dose to the skeleton for radium-burdened humans. Exposure from both ^{226}Ra and ^{228}Ra are combined by summing the energy deposition of the radium isotopes and their decay products, and detailed procedures have been developed for taking into account biological retention and radioactive decay of the vario nuclides.[2] However, it is necessary to specify the time to which cumulative rads are to be calculated because, as for all internally deposited nuclides of appreciable half-life, the integrated dose increases with time. This dependence on time causes the CR variable to be quite inappropriate for studies of the time dependence of radiation effects.

The need for a time-invariant dose parameter is readily illustrated in the important case of the evaluation of life-shortening as a function of radiation exposure.[3,4] For simplicity, we consider the situation when the "experiment" is completed, i.e., all the subjects have died and are grouped into cohorts on the basis of CR calculated to death. For cohorts defined by narrow ranges of CR, each subject may have entered his particular cohort at death or only shortly before, spending much of the time afte intake in cohorts of lesser dose. Thus, the time of death after intake for an individual in a particular cohort would merely indicate the length of time required to accumulate the dose characterizing the cohort. It would not be a measure of his survival time in that dose range, because a true measure of the probability of an event as a function of time cannot be obtained unless the event may occur at any time in the entire interval under

consideration. This requirement may be partially satisfied when subjects are grouped into wide ranges of CR,[4] but a more logical procedure is to employ a dose parameter which does not vary with time.

As one possibility, cumulative rads calculated to some fixed time after intake of radium might be used as a time-invariant dose parameter. Examination of the CR values at various times after acquisition,[5] shows that the number of cumulative rads produced by equal amounts (μCi) of ^{226}Ra and ^{228}Ra are almost identical at t = 57 years (cf. below), so this is a logical (and convenient) choice for the fixed time. Cumulative rads calculated at t = 57 years have been dubbed "cum rads 57," or "CR57." The chief disadvantage of CR 57 is that a false inference as to the actual dose may be drawn. It does provide a relative measure of the actual amount of initially acquired radioactivity, but the only significance of CR 57 as an ionization dose is as an approximation to the number of cumulative rads which would be attained by a subject surviving a long time after injection. Thus, it seems advisable to abandon the "cumulative rads" nomenclature in referring to a time-invariant parameter.

In the absence of a model relating effect, time, dose, and dose rate, choice of a "best" dose parameter for work with internal emitters can hardly be made.[6,7] The issue is avoided in animal experiments by grouping according to nuclide and the amount of radioactivity injected per unit mass of the animal. We propose to adopt a similar approach by using injected radioactivity per unit skeletal mass as the time-invariant parameter for the human radium cases.* Since direct measurements of these quantities are not available for most of the cases in this retrospective study, the amount of radioactivity injected must be deduced from body burdens measured long after intake and nominal skeletal masses (standard man) will be

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*By "injected" radium we mean the amount of radium (μCi) which enters the blood stream by direct injection or by absorption from the gut or other body cavities (e.g., lung) external to the "body." This is the same as is meant by "initially acquired," and the two phrases will be used interchangeably in this paper.

employed. Furthermore, it will be assumed that ^{226}Ra and ^{228}Ra are equivalent in biological effect on a μCi basis for cases in which comparable amounts of both nuclides were acquired. Similar uncertainties are encountered with the CR variable.

Calculation of Initially Acquired Radium from CR Values

Direct calculation of the amount of radioactivity injected may be done by measurement of ^{226}Ra and ^{228}Ra at some time, t, after injection and correction for excretion and radioactive decay to t = 0. This requires knowledge of the excretion function for radium, and the calculation is difficult for those cases in which intake of ^{228}Ra took place over an extende period of time. These difficulties have been considered in detail in calculations of the CR variable which are obtained by measurement of body radium and application of existing computer programs from which the CR values are output.[8] Thus, a convenient method of calculating original injected dose for each subject is to use the following relationships:

$$\mu\text{Ci injected } ^{226}\text{Ra} = \frac{\text{CR}(^{226}\text{Ra}) \text{ at t for the subject}}{\text{CR}(^{226}\text{Ra}) \text{ at t, per } \mu\text{Ci } ^{226}\text{Ra at t} = 0} \quad (1$$

$$\mu\text{Ci injected } ^{228}\text{Ra} = \frac{\text{CR}(^{228}\text{Ra}) \text{ at t for the subject}}{\text{CR}(^{228}\text{Ra}) \text{ at t, per } \mu\text{Ci } ^{228}\text{Ra at t} = 0}. \quad (2$$

A further simplification may be obtained by noting that CR values increase very little for ^{228}Ra at times greater than thirty years after acqui sition. It happens that for men at t = 57 years, the number of cumulative rads per μCi injected is 10.73 for ^{226}Ra and 10.75 for ^{228}Ra. These are the values obtained from the total alpha-particle energy dissipated in bon averaged over a skeletal mass taken to be 7000 g for men. Then, regardl of the original ratio of ^{228}Ra to ^{226}Ra, we have for male subjects:

$$\mu\text{Ci injected } ^{226}\text{Ra} + \mu\text{Ci injected } ^{228}\text{Ra} = \frac{\text{CR 57}}{10.74},$$

where CR 57 denotes the sum of the CR contributions of ^{226}Ra and ^{228}Ra at 57 years after injection. For female subjects (5000 g nominal skeletal mass), the corresponding result is

$$\mu Ci \text{ injected } ^{226}Ra + \mu Ci \text{ injected } ^{228}Ra = \frac{CR\,57}{15.04}.$$

The value of 15.04 in the denominator of Eq. (2) is the number of cumulative rads for women at t = 57 years per μCi of ^{226}Ra or ^{228}Ra; this differs from the value for men only by reason of the smaller skeletal mass assumed for women in calculating CR. It should be emphasized that the use of CR values in calculating injected radioactivity as above is merely a convenience. The amount of injected radioactivity calculated by Eq. (1) or (2) is independent of the skeletal mass chosen for calculation of CR, because both CR and CR per μCi are inversely proportional to skeletal mass.

Proceeding to a basis of injected radioactivity per unit mass, we divide μCi injected by the mass, or skeletal mass, of the subject. Thus, for men we have

$$(\mu Ci \text{ injected } ^{226}Ra + \mu Ci \text{ injected } ^{228}Ra) \text{ per g} = \frac{CR\,57}{10.74 \times \text{mass}},$$

and for women the denominator on the right-hand side is 15.04 x mass. In general, the actual masses or skeletal masses of the subjects at injection are unknown, so we use nominal skeletal masses of 7000 g for men and 5000 g for women, as was assumed for calculating cumulative rads. Since 10.74 x 7000 and 15.04 x 5000 are both equal to 75 200, we obtain an equation applicable to both men and women:

$$(nCi \text{ injected } ^{226}Ra + nCi \text{ injected } ^{228}Ra) \text{ per g bone} = \frac{CR\,57}{75.2}. \quad (3)$$

For intake over an extended period of time, T, cumulative rads are calculated as though radioactivity were acquired at a constant rate (total acquired radium divided by T) during T. Since CR values increase almost

linearly with time in the region of 57 years after injection, calculation of CR at t = 57 years after the mid-time of the intake period will provide values of the injection dose more akin to values for single injection than would CR values calculated at 57 years after the start or end of the period.

Other Time-Invariant Dose Parameters

Partly for comparison with the maximum permissible level for radium which is set at a body burden of 0.1 μCi ^{226}Ra, Evans[2,6] has defined a pure radium equivalent (PRE) to take into account the presence of both ^{226}Ra and ^{228}Ra. PRE(CR) is the amount of residual ^{226}Ra which would be present at time, t, if the sum of the CR contributions of ^{226}Ra and ^{228}Ra to that time had been produced by ^{226}Ra alone. It is by no means a time-invariant parameter, as may be seen from the formula for calculation[6] which is readily put into the following form:

$$\text{PRE(CR)} = \mu\text{Ci } ^{226}\text{Ra at } t + \mu\text{Ci } ^{228}\text{Ra at } t \cdot e^{+\lambda_{228} t} \cdot \text{(M/R) at } t,$$

where

$$\text{(M/R) at } t = \frac{\text{CR}(^{228}\text{Ra) at } t\text{, per } \mu\text{Ci } ^{228}\text{Ra at } t=0}{\text{CR}(^{226}\text{Ra) at } t\text{, per } \mu\text{Ci } ^{226}\text{Ra at } t=0}.$$

Since residual ^{226}Ra, residual ^{228}Ra corrected for radioactivity decay, and M/R all decrease with time, the strong time dependence of PRE is evident. Of course, one may define a PRE 57 at t = 57 years, much as CR 57 was defined; then, since M/R at 57 years is equal to unity,

$$\text{PRE 57} = \mu\text{Ci } ^{226}\text{Ra (57)} = \mu\text{Ci } ^{228}\text{Ra (57)} \cdot e^{+\lambda_{228} 57}.$$

Thus, PRE 57 would be the residual amount of ^{226}Ra and ^{228}Ra (corrected for radioactive decay) at 57 years. It is an imaginary quantity, but, like CR 57, it provides a relative measure of injected ^{226}Ra + ^{228}Ra.

Another dose parameter of special interest is the estimated maximum burden (EMB) which has been used by Miller, Finkel, and Hasterlik in work

with subjects having body burdens of ^{226}Ra.[7] For a given total amount of injected radium, the EMB depends on the length of time during which intake occurs—largest for a single injection, smaller for intake over an extended period of time. Obviously, this parameter is invariant with time after end of injection and provides a measure of the maximum dose rate. However, it is subject to the experimental difficulty that while the period during which intake of radium could have occurred may be known quite well (e.g., from work dates in the radium industry), the period during which intake did occur is much less certain. Thus the calculated EMB for an individual may be much more in error relative to the true value than is the calculated total amount of intake relative to the actual amount of intake.

Discussion

Since ionization dose increases with time of exposure to long-lived internal radioactivity, it is apparent that the time dependence observed for a biological effect in a cohort based on initial radium burden may also be interpreted as a dose dependence. Such ambiguity is unaviodable because of the interdependence of time, integrated ionization dose, and initial amount of radium (dose rate). If any of the three is chosen as a basis for a cohort, then the effect of the other two cannot be studied independently of each other. For example, if a cohort were based on time after acquisition, a dose effect within the cohort could also be interpreted as a dose-rate effect.

One may then ask whether there is anything fundamental about dividing patients into groups according to the amount of injected radium, instead of integrated dose, for studies of time effects. Apparently there is. A clue may be found by noting that the dose rate fixes the time at which an integrated dose is attained; it does not occur to us to say that the time after injection at which an individual attains a given dose controls his dose rate from internal radium. The fact is that the amount of injected radio-

activity is an intrinsic property of the individual, whereas time and accumulated dose subsequent to injection can have any positive value within the limitations of the lifetimes of the individual and of the radioactive species.

Of course, it is proper (and desirable) to compare biological effects with any one of the radiation parameters. We then recognize that the other two parameters may vary widely in each cohort, so long as the combination for each individual fits the cohort. If the comparison is with injected radioactivity, we can go a step further and examine the time (or dose) distribution of biological effects for a given amount of injected radioactivity.

References

1. Evans, R. D., A. T. Keane, R. J. Kolenkow, W. R. Neal, and M. M. Shanahan. Radiogenic tumors in the radium and mesothorium cases studied at MIT. Delayed Effects of Bone-Seeking Radionuclides, Ed. C. W. Mays, W. S. S. Jee, and R. D. Lloyd. University of Utah Press, Salt Lake City, 1969, pp. 157-194.
2. Evans, R. D. The calculation of cumulative rad and cumulative rad years. Annual Progress Report, Radioactivity Center, Massachusetts Institute of Technology, Report MIT-952-1 (May 1964), pp. 52-82.
3. Merrel, M. and L. E. Shulman. Determination of prognosis in chronic disease. J. Chron. Dis. 1, 12-32 (1955).
4. Stehney, A. F. and R. E. Rowland. Tumor incidence and life-span of human radium cases. Proc. Vth Int. Cong. of the French Society for Radioprotection, Grenoble, 1-5 February, 1971. pp. 502-515.
5. Neal, W. R. Dose variables and their calculations. Annual Progress Report, Radioactivity Center, Massachusetts Institute of Technology Report MIT-952-3 (May 1966), pp. 94-141.
6. Evans, R. D. The effect of skeletally deposited alpha-ray emitters in man. Brit. J. Radiol. 39, 881-895 (1966).
7. Miller, C. E., A. J. Finkel, and R. J. Hasterlik. The Argonne Radium Studies: Computer Radiobiological Indices. U.S. Atomic Energy Commission Report ANL-7680 and ACRH-107 (April 1969).
8. Neal, W. R. Listing and description of radium dose calculation programs. Annual Progress Report, Radioactivity Center, Massachusetts Institute of Technology, Report MIT-952-7 (May 1970) pp. 87-109.