RBE OF α-PARTICLES vs. β-PARTICLES IN BONE SARCOMA INDUCTION*

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^{226}Ra and ^{90}Sr were injected intravenously into 17-month-old beagles at the University of Utah (13) and 70-day-old CF1 female mice at the Argonne National Laboratory (2,3,4). Bone sarcomas, mostly osteosarcomas, were the main radiation-induced cancers (Tables 1 and 2).

^{226}Ra is an α-emitter and ^{90}Sr is a β-emitter. Both are bone volume seekers, so that the mean endosteal dose is roughly equal to the skeletal dose averaged over both bone and marrow (1,8). The average skeletal dose in rads was computed for ^{226}Ra including its retained α-emitting daughters (7,9), and for ^{90}Sr including its β-emitting daughter, ^{90}Y (7,10). The average skeletal dose was calculated at the assumed start of tumor enlargement, which was taken as 1 year before death in the beagles (10), 140 days before death with bone sarcoma in the mice injected with ^{90}Sr (10), and 100 days before radiographic appearance of the tumors in the mice injected with ^{226}Ra (9). Since the shapes of the retention curves for ^{226}Ra and ^{90}Sr are similar in beagles (and in mice), assumptions on the time span of the "wasted" radiation have little influence on the calculated RBE (11).

The relative biological effectiveness (RBE) of α-particles vs. β-particles in producing bone sarcomas was taken as the ratio of ^{90}Sr dose/^{226}Ra dose at a given level of incidence. The RBE progressively increased as the incidence decreased, reaching RBE = 26 at 8.7% incidence in beagles, and RBE = 25 at 7.7% incidence in mice (Table 3). The increase in RBE was largely due to the decreased effectiveness per rad of ^{90}Sr β-radiation at low doses and low dose-rates (10). Because of statistical fluctuations, the RBE's are not shown below an incidence of 7.5%, but the trends are compatible with even higher RBE's. In this experiment all of the mice have died. None of the beagles injected with ^{90}Sr are still alive. However, if future bone sarcomas appear among the 9 surviving beagles which received low levels of ^{226}Ra, the α-particle RBE at low doses will be increased above the values indicated in this paper. Of special relevance is the RBE at the low doses and low risks that are considered permissible for man. The ICRP recently increased their quality factor for α-particles up to 20 (5). But is that enough? Additional information should come in a few years from beagles injected with ^{226}Ra and ^{90}Sr at Davis, California.

The increase of RBE with decreasing dose seems a general property of densely-ionizing radiation. It also applies to the fast-neutron-induction of leukemia in people, chromosome aberrations in human lymphocytes, skin damage (human, rat, mouse, pig), breast tumors in rats, cataracts in mice, inactivation of intestinal crypt cells in mice, mutations in Tradescantia, and growth reduction in Vicia Faba (6,12).

*Research supported by the U.S. Department of Energy.

TABLE 1. Bone sarcomas in *beagles* injected with ^{226}Ra or ^{90}Sr

Nuclide	Inj. μCi/kg	Yr. inj. to death	Injected dogs	Sar. dogs	Incidence (%)	Av. skel. rads 1 yr before death
^{226}Ra	10.4	2.86	10	9	90.0	13400
	3.21	4.13	13	12	92.3	5700
	1.07	6.12	12	11	91.7	2500
	0.339	10.05	13	5	38.5	1100
	0.166	9.40	14	1	7.1	447
	0.062	---	23(3)*	2	8.7	∿ 210
	0.022	---	25(4)*	1	4.0	∿ 74
	0.0074	---	10(2)*	0	0	∿ 25
	0	---	44(14)*	0	0	0
^{90}Sr	97.9	3.40	14	8	57.1	10100
	63.6	5.82	12	8	66.7	9360
	32.7	9.98	12	2	16.7	7940
	10.8	12.27	12	0	0	2870
	3.46	10.79	12	0	0	798
	1.72	11.31	13	0	0	445
	0.57	12.93	12	0	0	143
	0	11.49	13	0	0	0

*Living dogs, as of 1 January 1980, shown in parentheses.

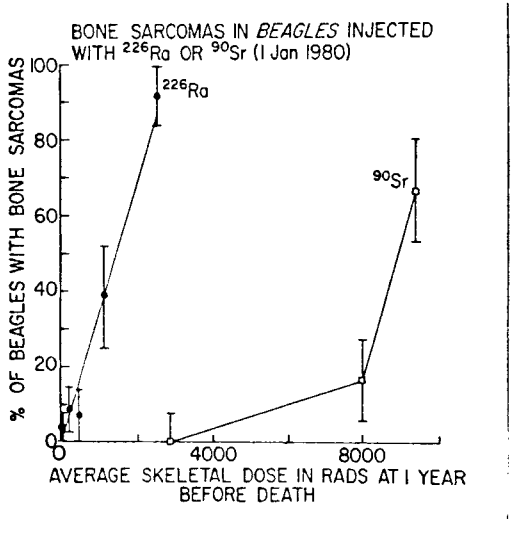

FIGURE 1. Bone sarcoma incidence in beagles. The response seems approximately linear up to 2500 rads from ^{226}Ra, but is strongly concave upwards for ^{90}Sr. Standard deviations in incidence are shown here and on Fig. 2.

TABLE 2. Bone sarcomas in *female CF1 mice* injected with ^{226}Ra or ^{90}Sr.

	Inj. µCi/kg	Mice at 150 days Post Inj.	Sar. Mice	Inc. (%)	Bone Sarcoma Mice: Days, inj. to appear. (Ra) or death (Sr)	Bone Sarcoma Mice: Av. skeletal rads 100 d before appear. or 140 d before death
^{226}Ra	120	45	14	31.1	328	28900
	80	44	31	70.5	359	21300
	40	45	33	73.3	394	11800
	20	44	38	86.4	428	6420
	10	43	34	79.1	484	3640
	5	45	28	62.2	544	2040
	2.5	104	45	43.3	639	1190
	1.25	104	22	21.2	657	614
	1.00	239	56	23.4	643	480
	0.75	504	94	18.7	686	383
	0.50	683	80	11.7	655	244
	0.25	247	19	7.7	580	109
	0.10	252	5	2.0	853	62
	0.05	254	11	4.3	710	26
	0	521	6	1.2	730	0
^{90}Sr	2200	26	19	73.1	216	12000
	880	45	41	91.1	260	6630
	440	42	34	81.0	440	6300
	200	59	8	13.6	510	3310
	88	74	2	2.7	760	2090
	44	83	3	3.6	640	900
	8.9	104	0	0	---	172*
	4.5	119	2	1.7	600	87
	1.3	148	2	1.4	630	26
	0	149	2	1.3	550	0

*Dose for 8.9 µCi/kg level calculated at (600-140) = 460 days.

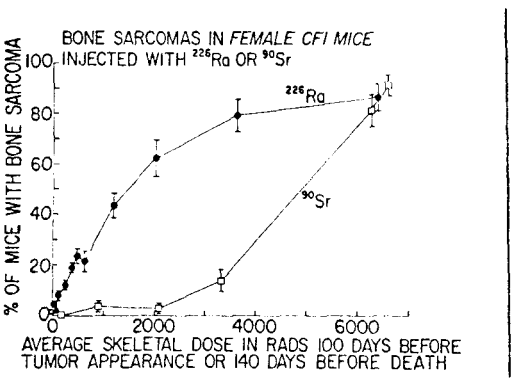

FIGURE 2. Bone sarcoma incidence in mice. ^{226}Ra is much more effective than ^{90}Sr at low doses, but at very high doses the effectivenesses converge.

TABLE 3. Bone sarcoma RBE of ^{226}Ra vs. ^{90}Sr.

Species	Incidence (%)	^{90}Sr β-particles (rads)	^{226}Ra α-particles (rads)	RBE (α vs. β)
Beagles	66.7	9360	1900*	5
	38.5	8600*	1100	8
	16.7	7940	480*	17
	8.7	5500*	210	26
Mice	86.4	6500*	6420	1
	81.0	6300	4400*	1.4
	79.1	6200*	3640	2
	62.2	5500*	2040	3
	43.3	4600*	1190	4
	21.2	3700*	614	6
	23.4	3800*	480	8
	18.7	3500*	383	9
	13.6	3310	280*	12
	11.7	3100*	244	13
	7.7	2700	109*	25

*Interpolated from curves on Figures 1 and 2.

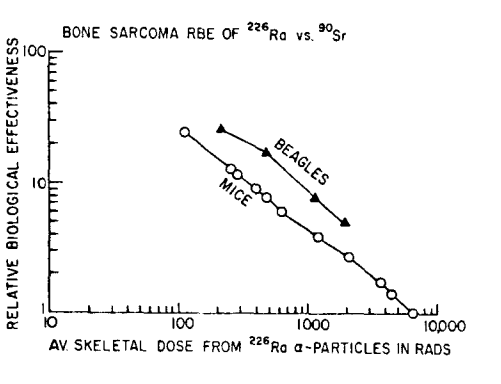

FIGURE 3. Relative biological effectiveness of α-particles from ^{226}Ra and retained daughters, relative to β-particles from ^{90}Sr and its daughter, ^{90}Y. The RBE increases as dose decreases, both in beagles and in mice. The effect is mainly due to decreased effectiveness per rad in bone sarcoma induction by β-particles at low doses and low dose-rates.

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