^{226}Ra AND THE NATURAL AIRBORNE NUCLIDES ^{210}Pb AND ^{210}Po IN ARCTIC BIOTA*

RICHARD B. HOLTZMAN

Radiological Physics Division, Argonne National Laboratory

Abstract—In order to better determine the characteristics and effects on humans of arctic biota with high concentrations of ^{210}Pb and ^{210}Po, these nuclides, along with their long-lived predecessor, ^{226}Ra, were measured in lichens, in bone and muscle of caribou and other arctic animals, and in Eskimo placenta. ^{226}Ra with concentrations 1/3 to 1/50 those of the other nuclides, cannot be the direct source of the other nuclides. In caribou bone the ^{210}Po was in radioactive equilibrium with the ^{210}Pb and averaged about 11.7 pCi/g ash, twice the ^{210}Pb in reindeer bone. The ^{210}Pb content of muscle of both species was 10 pCi/kg (wet). By contrast, the ^{210}Po content was much greater, about 200 pCi/kg. A definite seasonal decrease was noted in the ^{210}Pb in muscle during the second half of the year. Similar variations were indicated for ^{210}Po in muscle and for ^{210}Pb in bone. The high levels in caribou are attributed to the high fallout levels of these nuclides in lichens, their winter forage, which contain (in dry weight) 6 pCi ^{210}Pb/g and 12 pCi ^{210}Po/g. The other animals exhibited appreciably lower concentrations in bone and muscle. Wolf, which consumes large quantities of caribou, exhibited activities in bone of 1 pCi/g ash, about that observed in some Eskimo bone by Hill. The ^{210}Po content of wolf muscle was about the same as that of caribou, 200 pCi/kg, but the ^{210}Pb was only about 1 pCi/kg. Similar, but less dramatic, differences were observed in Eskimo placenta.

Estimates of uptake show that Eskimos could acquire sufficient of the long-lived ^{210}Pb to double the total skeletal radiation dose (rad) over that of Midwesterners. However, despite the high concentrations of the ^{210}Po in meat, direct intake accounts for only a relatively small increase in total dose.

BECAUSE of their ubiquity and contribution to the total radiation dose to man and animals, the naturally occurring nuclides ^{226}Ra, ^{210}Pb, and ^{210}Po have been studied extensively in man and his environment. The latter nuclides appear to enter the environment to a large extent through natural fallout, analogous to that of nuclear bomb fallout which yields nuclides such as ^{137}Cs [1-3] and ^{90}Sr.[4] In the natural case, as shown in the decay scheme of Fig. 1, ^{226}Ra in the soil decays to the inert gas, ^{222}Rn, some of which emanates into the atmosphere and decays therein through a series of short-lived species to the 21.4-year ^{210}Pb. This nuclide then decays further to the 5.0-day ^{210}Bi and to the 138-day ^{210}Po.

In Arctic biota, although relatively small concentrations of ^{226}Ra have been found,[5, 6] the concentrations of the ^{210}Pb and ^{210}Po have been found to be higher than those in analogous biota of the temperate zone.[5-9] These fallout nuclides tend to accumulate on the sedges and lichens, which because of their slow growth acquire high specific activities. This vegetation forms a substantial portion of the diet of caribou and reindeer which, in turn, constitute a substantial fraction of the diets of predators and of man in these regions. The long-lived precursor of the series, ^{226}Ra, is also of interest in the animal, both for its contribution to the dose and as a possible direct source of the ^{210}Pb series.

In order to establish the origin of the ^{210}Pb series and to determine the effects on the food chain, the possible accumulations in man,

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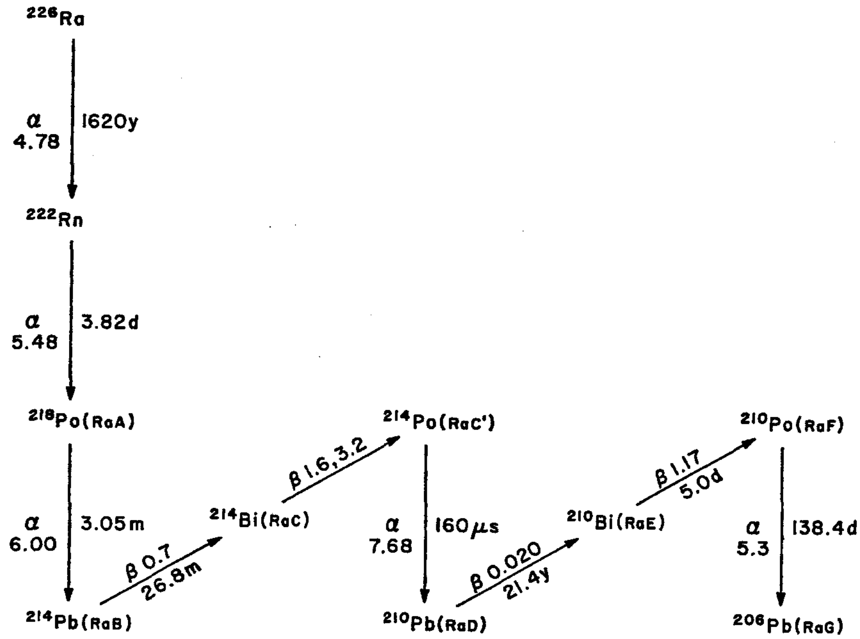

FIG. 1. Radioactive decay scheme of ^{226}Ra series.

radiation effects, and methods of reducing the accumulation of these nuclides, various studies have been made.

The winter food base, lichens, has been shown to contain relatively large amounts of both the ^{210}Pb and ^{210}Po compared to fresh grasses.[6,7] Animals consuming these plants, reindeer and caribou, have been shown to accumulate relatively large amounts of these nuclides. Reindeer muscle, kidney, liver, and spleen exhibit a high concentration of the daughter nuclide, ^{210}Po[8], which, like that of ^{137}Cs in man and caribou, is seasonally variable.[10, 11] The ^{210}Pb concentrations in reindeer and Alaskan caribou[6] account for a large fraction of the excess amounts observed in the tissues of humans whose diets consist of meat from these animals. Some bones from a group of Canadian Eskimos, measured by Hill, contained ^{210}Pb concentrations substantially higher than in others of the same group.[7, 8] Placental tissues from Alaskan Eskimos appeared to contain more ^{210}Pb and ^{210}Po than tissues of non-Arctic residents,[6] and in some groups of Canadian Eskimos the concentrations of the daughter were substantially greater than in other Canadians.[12]

Presented here are the results of further analyses of these three nuclides in Alaskan animals of various types, comparison of the ^{210}Po–^{210}Pb ratios, and a discussion of the seasonal variations of the ^{210}Pb activities in caribou and reindeer bone and muscle.

Except for these previously described samples (Tables 1–3), 62–2, 3 and 61–1, 2, from Finland and College, Alaska,[6] and all the lichens except samples 65–13, 14, 15, these samples were collected near Anatukvuk Pass in northern Alaska by W. C. Hanson of Battelle-Northwest Laboratories. The caribou muscle was taken from the hind quarter and the bone from the shaft of the rear femur of the animal. Most of these specimens had been dry-ashed at about 450°C (for ^{137}Cs analysis).

The ^{210}Po and ^{210}Pb concentrations were determined as previously described.[13] To ensure complete dissolution, the samples, even though previously dry-ashed, were wet-ashed in nitric and perchloric acids. The solution was then converted to 0.5 N hydrochloric acid and the ^{210}Po plated onto a silver disk which was counted for alpha particles. The ^{210}Pb was determined by replating the solution after allowing the ^{210}Po to grow in for at least 3 months. The actual activities of the ^{210}Po and ^{210}Pb and the statistical errors were determined and calculated for the time of collection from the parent-daughter relationships of the Bateman equations. The calculated errors are based on counting statistics only. The ^{226}Ra was determined by the ^{222}Rn emanation method of Lucas.[14]

Along with the dates of collection, the specific activities of the various nuclides in the muscle and bone specimens of caribou are presented in Table 1. Similar data and average values for each group of other animals, reindeer, moose, willow ptarmigan, seal, fish and wolf, are given in Table 2, and for lichens in Table 3. ^{210}Po activities are presented only for samples dried at no higher than 110°C and measured within a few months of collection.

The ^{210}Pb levels in animal bone are of significance in determining the radiation levels in the animal and, in terms of human intake, as representative of average intake levels. Also because of the relatively high specific activities, the ^{210}Pb content is easier to determine in bone than in muscle. As shown in Fig. 2 the ^{210}Pb specific activities in caribou bone are nearly twice those in reindeer, which in general are more than twice those in other animals. This confirms earlier suggestions[5, 6] that, although reindeer are closely related to caribou, their dietary habits are different, even though in this case as contrasted to the previous one, the reindeer live in the same region as the caribou, i.e. the reindeer appear to run in herds and consume forage with growth more rapid than that of lichens (the specific activities of ^{210}Pb are lower), while the caribou feed more widely and probably consume more lichens. The ^{210}Pb in the bones of other animals is quite a bit lower; moose is similar to U.S. cattle;[15] and the amount of ^{210}Pb in seal and fish is still lower and similar to that in human bone from residents of the midwestern United States.[13] The high levels observed in wolf bone indicate that a large fraction of the diet of wolves is caribou meat and they attain levels similar to those of the human Eskimo bones of Hill.[8] The willow ptarmigan shows a relatively high average, mainly because one of three specimens was high, possibly because of consumption of older plants (lichens?) and a high respiratory rate.

Because muscle is probably the major tissue consumed by the man, the ^{210}Pb activity in this tissue is the most significant one in the animal. In this case, as shown in Fig. 2, the concentrations in caribou and reindeer are about the same (averaging all the samples at hand) and much higher than those of the other animals and humans. In most animals the ratio of this nuclide in bone to that in muscle is 2000 or greater, while in caribou and reindeer it is one half this ratio, even if the higher level of "winter" for caribou is taken.

The seasonal variations of the ^{210}Pb in caribou can be seen in Figs. 3 and 4 in which the concentrations in muscle and bone are plotted seasonally, regardless of year of collection. Figure 5 shows the quarterly averages with standard errors. Seasonal variations in bone are apparent and confirmed by Student's *t*-test in that the specific activity of 8.3 pCi/g ash in the fourth quarter of the year is probably significantly different than the 11.6 pCi/g ash in the other quarters ($P < 0.05$). The concentrations in these quarters are not significantly different from each other.

In muscle the seasonal variations of the ^{210}Pb are more striking (Fig. 5), and here the concentration of 9.7 pCi/kg (wet) during the first half of the year is significantly different than the 4.1 pCi/kg in the last half ($P < 0.005$). The two quarters within each half are not significantly different from each other.

These seasonal variations probably are caused by caribou feeding on vegetation high in ^{210}Pb (lichens), principally when no other vegetation is available, i.e. during the winter. Thus, as seen in muscle, a minimum would be expected during the summer or third quarter and then a rise in the last one. In bone, however, the slower rate of turnover causes a time delay which produces a minimum in the fourth quarter and also reduces the magnitude of the variations. The correlation between the ^{210}Pb in

Table 1. ^{210}Pb, ^{210}Po *and* ^{226}Ra *in Caribou Bone and Muscle*

Sample No.	Date of collection	BONE			MUSCLE		
		^{210}Pb pCi/g ash	^{210}Po pCi/g ash	^{226}Ra pCi/g ash	^{210}Pb pCi/kg (wet)	^{210}Po pCi/kg (wet)	^{226}Ra pCi/kg (wet)
62–1	8–28–62	16.0 ± 0.2	—	0.532 ± 0.025	4.3 ± 0.6	—	1.97 ± 0.12
62–2	12–6–62	11.0 ± 0.2	15.5 ± 0.7	—	6.1 ± 0.6	222 ± 4	—
62–3	12–6–62	11.1 ± 0.2	14.6 ± 0.7	—	8.3 ± 0.6	163 ± 4	—
63–1	6–6–63	9.86 ± 0.15	—	—	4.8 ± 0.5	—	—
63–2	7–22–63	10.9 ± 0.18	—	—	1.3 ± 0.4	—	—
63–3	7–28–63	8.46 ± 0.14	—	—	3.9 ± 0.9	—	—
63–4	10–19–63	—	—	—	4.6 ± 1.3	—	—
63–5	11–25–63	5.54 ± 0.12	—	—	7.4 ± 1.1	—	—
63–6	11–25–63	5.65 ± 0.12	—	—	3.6 ± 1.3	—	0.3 ± 0.3
64–1	1–10–64	14.8 ± 0.2	—	—	12.7 ± 1.9	—	6.3 ± 1.0
64–2	1–14–64	12.4 ± 0.2	—	—	9.4 ± 1.4	—	—
64–3	2–22–64	8.95 ± 0.20	—	—	13.3 ± 1.6	—	—
64–4	2–22–64	13.4 ± 0.2	—	—	5.7 ± 0.9	—	—
64–5	3–2–64	13.2 ± 0.2	—	0.421 ± 0.020	15.8 ± 1.7	—	3.5 ± 0.6
64–6	3–16–64	12.4 ± 0.2	—	—	9.8 ± 1.4	—	—
64–7	3–16–64	7.95 ± 0.15	—	—	12.8 ± 1.7	—	—
64–8	3–17–64	7.00 ± 0.13	—	—	10.4 ± 1.6	—	—
64–9	3–17–64	10.2 ± 0.2	—	—	12.0 ± 1.7	—	—
64–10	3–26–64	14.0 ± 0.2	—	—	16.1 ± 1.6	—	—
64–11	5–9–64	9.27 ± 0.14	—	—	15.6 ± 1.7	—	—
64–12	5–24–64	11.0 ± 0.15	—	0.429 ± 0.022	10.2 ± 1.2	—	3.4 ± 0.4
64–13	5–24–64	9.88 ± 0.14	—	—	9.3 ± 1.4	—	—
64–14	6–2–64	9.81 ± 0.14	—	0.380 ± 0.020	7.8 ± 1.4	—	0.9 ± 0.3
64–15	6–4–64	12.0 ± 0.16	—	—	9.6 ± 1.6	—	—
65–1	3–21–65	20.3 ± 0.2	—	0.591 ± 0.033	4.0 ± 1.3	360 ± 7	0.3 ± 0.2
65–2	3–21–65	12.33 ± 0.16	11.8 ± 0.3	—	5.5 ± 0.7	—	—
65–3	4–24–65	17.35 ± 0.15	15.33 ± 0.26	—	11.0 ± 0.7	—	—
65–4	4–24–65	5.23 ± 0.08	4.86 ± 0.15	0.442 ± 0.015	3.1 ± 0.9	—	0.0 ± 0.2
65–5	5–28–65	9.44 ± 0.09	7.98 ± 0.12	0.466 ± 0.016	6.2 ± 0.5	—	0.09 ± 0.07
65–6	5–31–65	15.40 ± 0.14	11.18 ± 0.18	—	9.9 ± 0.7	—	—
65–7	8–18–65	18.79 ± 0.39	17.07 ± 0.59	0.698 ± 0.040	6.0 ± 1.6	72 ± 3	0.57 ± 0.019
65–8	8–18–65	17.13 ± 0.39	11.89 ± 0.34	0.554 ± 0.032	3.3 ± 1.3	87 ± 4	0.17 ± 0.15
65–9	8–24–65	11.72 ± 0.38	12.62 ± 0.12	0.488 ± 0.031	1.1 ± 1.0	97 ± 3	0.13 ± 0.13

Table 2. ^{210}Pb, ^{210}Po and ^{226}Ra in Reindeer, Moose, Ptarmigan, Wolf, Seal and Fish

Sample No.	Date of collection	BONE			MUSCLE		
		^{210}Pb pCi/g ash	^{210}Po pCi/g ash	^{226}Ra pCi/g ash	^{210}Pb pCi/kg (wet)	^{210}Po pCi/kg (wet)	^{226}Ra pCi/kg (wet)
Reindeer							
61–1	3–14–61	5.00 ± 0.11	6.33 ± 0.23	1.84 ± 0.022	15 ± 2	575 ± 36	0.3
62–4	11–1–62	8.21 ± 0.13	—	0.396 ± 0.015	3.7 ± 1.1	—	—
62–5	11–15–62	9.67 ± 0.11	—	—	6.2 ± 1.2	—	—
63–7	8–8–63	—	—	—	1.3 ± 0.6	—	—
63–8	8–8–63	6.13 ± 0.12	—	—	1.4 ± 0.7	—	—
63–9	8–8–63	4.73 ± 0.09	—	0.197 ± 0.011	1.7 ± 0.7	—	—
Average ± S.D.		6.75 ± 2.12	—	0.81 ± 0.90	4.9 ± 5.3	—	0.3 ± 0.3
Moose							
63–10	8–1–63	0.716 ± 0.042	—	—	1.5 ± 1.1	—	—
63–11	8–1–63	0.689 ± 0.042	—	0.195 ± 0.014	1.6 ± 0.7	—	0.4 ± 0.2
Average ± S.D.		0.702 ± 0.059	—	0.195	1.6 ± 1.3	—	0.4
Willow Ptarmigan							
63–12	7–27–63	6.94 ± 0.11	—	—	27.3 ± 1.9	—	—
63–13	7–27–63	1.84 ± 0.05	—	—	4.2 ± 1.3	—	11.7 ± 0.7
63–14	7–28–63	1.60 ± 0.05	—	0.031 ± 0.005	3.3 ± 0.9	—	—
Average		3.46	—	0.031	11.6	—	11.7
Wolf							
65–10	3–15–65	1.385 ± 0.034	1.315 ± 0.011	0.103 ± 0.006	1.3 ± 0.3	257 ± 5	0.12 ± 0.11
65–11	3–16–65	0.631 ± 0.022	0.634 ± 0.048	0.099 ± 0.006	2.6 ± 0.6	205 ± 5	0.23 ± 0.15
Average ± S.D.		1.018 ± 0.53	0.974 ± 0.48	0.101 ± 0.003	2.0 ± 0.9	231 ± 37	0.17 ± 0.18
Seal							
63–15	7–18–63	0.0487 ± 0.007	—	0.074 ± 0.006	2.0 ± 0.7	—	—
63–16	7–25–63	0.074 ± 0.010	—	—	2.6 ± 1.3	—	—
63–17	7–25–63	0.068 ± 0.010	—	0.064 ± 0.007	5.1 ± 1.3	—	—
Average ± S.D.		0.063 ± 0.015	—	0.054 ± 0.009	3.2 ± 1.6	—	—
Fish							
63–18	7–1–63	—	—	—	0.27 ± 0.20	—	—
63–19	8–1–63	0.289 ± 0.024	—	0.024 ± 0.006	0.76 ± 0.24	—	2.41 ± 0.13
63–20	8–24–63	0.047 ± 0.020	—	0.026 ± 0.010	1.50 ± 0.40	—	—
Average ± S.D.		0.168	—	0.025 ± 0.012	0.84 ± 0.63	—	2.41

Table 3. Lichens

	Sample No. (Old)*	Sample No. (New)	Date of collection	^{210}Pb pCi/g dry	^{210}Po pCi/g dry	^{226}Ra pCi/g dry
	Finland	61–2	3–61	4.54 ± 0.07	12.98 ± 0.12	0.035 ± 0.0010
AL	Lichens III	61–3	6–61	26.0	—	0.40 ± 0.02
AL	Lichens II	61–4	6–61	69.6	—	0.415 ± 0.017
AL	Lichens I	61–5	6–61	11.5	—	0.101 ± 0.005
AL	Rumen I	62–6	12–6–62	7.48 ± 0.06	14.28 ± 0.20	—
AL	Rumen II	62–7	12–6–62	4.96 ± 0.06	16.52 ± 0.26	—
N.H.	Lichens IV	65–12	7–10–65	7.61	7.32	—
		65–13	7–25–65	5.08 ± 0.20	7.83 ± 0.29	0.0527 ± 0.0095
		65–14	7–26–65	7.26 ± 0.23	9.77 ± 0.34	0.0318 ± 0.0082
		65–15	7–30–65	9.98 ± 0.28	17.44 ± 0.47	0.0412 ± 0.0093

* Data from first 7 specimens taken from Reference 6.

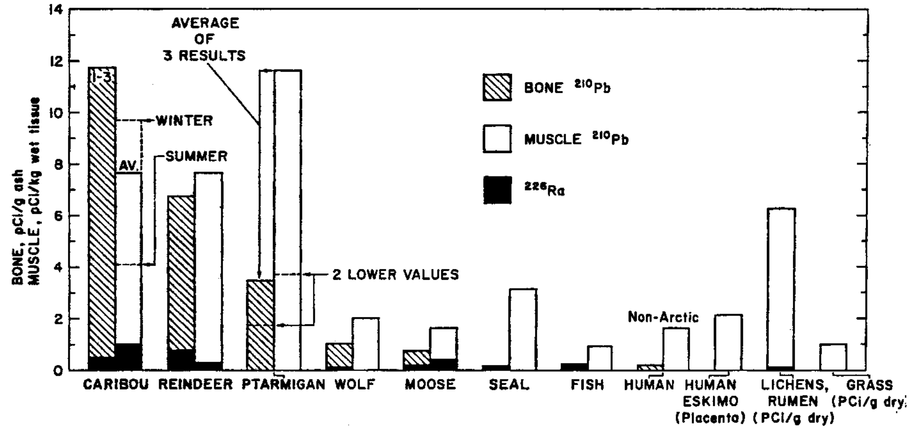

FIG. 2. ^{210}Pb and ^{226}Ra in muscle, bone and vegetation in Arctic biota and man.

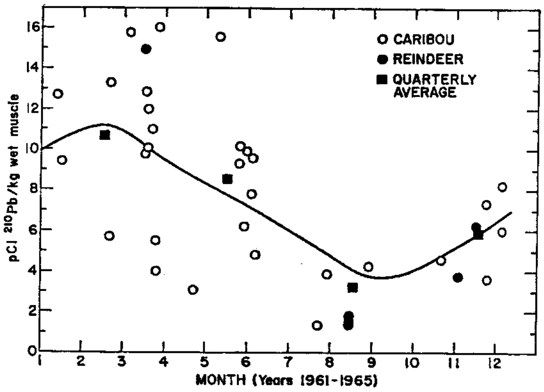

FIG. 3. ^{210}Pb in caribou and reindeer muscle.

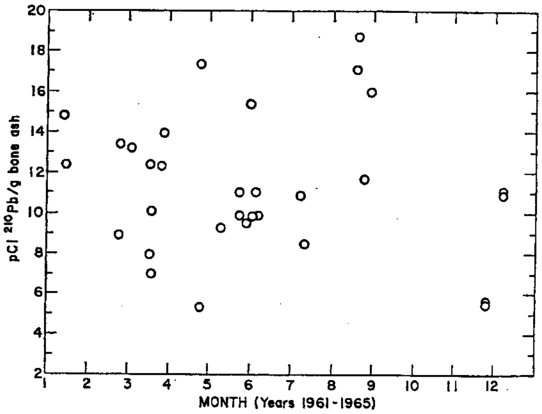

FIG. 4. ^{210}Pb in caribou bone.

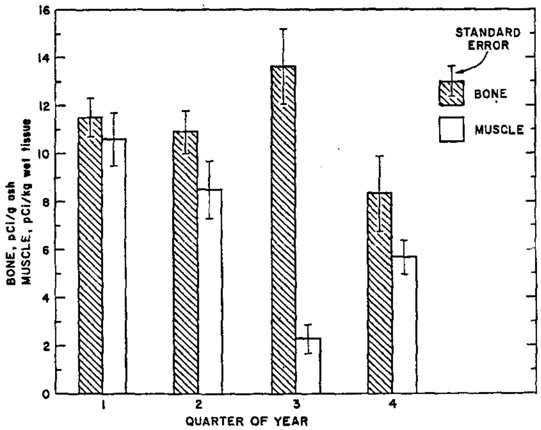

FIG. 5. Quarterly averages of ^{210}Pb in caribou muscle and bone.

muscle and that in bone from the same animal is $r = -0.36$, a value probably significantly different from zero ($P < 0.05$). This negative correlation is probably produced by a combination of the out-of-phase seasonal variations between bone and muscle and accentuated by sampling artifacts.

Although the ^{210}Po data are few, they do exhibit certain definite characteristics. In caribou bone this nuclide is in radioactive equilibrium with its parent and the seasonal variation is weak. Thus in seven specimens the ^{210}Po/^{210}Pb ratio $= 0.88 \pm 0.12$ (s.d.) and the coefficient of correlation $r = 0.91$. There is an indication of a higher ratio in the specimens collected in December. The wolf bone also exhibited radioactive equilibrium with a ratio of 0.98 (see Fig. 6).

Muscle of winter-killed caribou had more than three times the ^{210}Po concentration of summer-killed animals, but a variation less than the factor of 10 observed by Hill on Canadian reindeer.[8] The actual levels for the winter-killed animals reported here and by Hill are quite comparable while the summer-killed reindeer (15.5 pCi/kg) are significantly lower than these caribou, again probably because of the relatively lower lichen content of the reindeer summer diet.

Wolf muscle is remarkable in that the concentrations of ^{210}Pb observed here, about 200 pCi/kg, are about equal to those of caribou muscle. This effect thus suggests that other organs of the caribou supply a major fraction of the food for the wolf, i.e. liver, kidney, spleen and marrow, organs which appear to preferentially concentrate ^{210}Po by a factor of 10.[8, 9] This excess may also arise from bone consumption, rib, etc.; however, the relatively low concentrations of ^{210}Pb mitigate against this, unless this nuclide is preferentially and rapidly removed from the soft tissues.

In most, but not all cases, specific activity of the ^{226}Ra was lower than that of the ^{210}Pb and thus, the parent nuclide in the animal could not be the primary source of ^{210}Pb. Moreover, because the ages of the animals were probably less than 10 years and 70% of the ^{222}Rn would emanate anyway (by analogy to human and other bone data),[16] the ^{210}Pb could have attained only a small fraction of radioactive equilibrium.

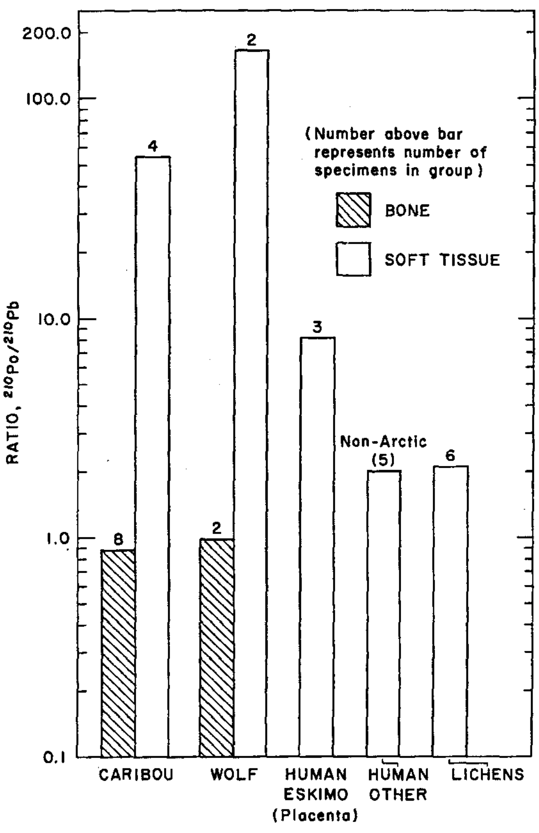

FIG. 6. ^{210}Po–^{210}Pb ratios in biota and man.

As shown in Table 1 and Fig. 2, the concentration of ^{226}Ra, 0.500 ± 0.095 (s.d.) pCi/g ash of caribou bone, was fairly consistent and about equal to that observed in bovine[17] and sheep bone,[6] a value expected on a diet of grass. Similar concentrations were observed in reindeer and moose, and levels comparable to the low ^{226}Ra levels in humans were found in ptarmigan, fish and seal. The combination of high ^{210}Pb and low ^{226}Ra levels in ptarmigan indicates a diet high in fallout products and low in ash content, such as lichens.

The wolf was somewhat higher again, indicating a relatively large ingestion of ^{226}Ra, possible either from a consumption of vegetation or herbivore bone. In the case of this nuclide, since caribou muscle and other soft tissues do not concentrate it (Table 1), these tissues would appear to be unlikely sources of excess ^{226}Ra.

The source of this nuclide in caribou and other animals appears to be vegetation other than lichens, since as seen in Table 3 most of these contain little ^{226}Ra. The high correlation of ^{226}Ra content in the lichens with fraction of ash content suggests the ash to be mainly dust contamination, so that the true digestible level of this nuclide is that in the Finnish sample which also had a low ash content.[6]

Seasonal variations in lichens are not accessible from these data. However, they confirm the previous conclusion[6] that the specific activity of the ^{210}Po may be greater than that of its parent ^{210}Pb. Because the atmospheric concentrations of ^{210}Po are lower than those of ^{210}Pb and there is no reason to expect great differential retention of the ^{210}Po over its parent from air, this result implies either greater uptake of ^{210}Po from soil or greater leaching of the parent from the plant.

The specific activities of ^{210}Pb and ^{210}Po measured in caribou muscle reported here are quite a bit higher than the concentrations in human placenta, which in wet tissue for ^{210}Pb are 1 to 5 pCi/kg and for ^{210}Pb are 9 to 30 pCi/kg.[6] These values are higher than in non-Arctic soft tissues and about equal to those found in the muscles of animals other than caribou. Hill, on the other hand, found some placentae with even higher ^{210}Po concentrations, 30 to 100 times these.[12]

These data allow some estimation of the size of the sources of the nuclides available to the groups of humans consuming caribou meat and confirm the conclusions of an earlier paper[6] that Eskimos may ingest daily 4 or more times the ^{210}Pb of non-Arctic residents. On the other hand, Beasley and Palmer's data for ^{210}Pb in caribou meat of 30 pCi/kg imply the levels of ^{210}Pb intake in some cases may be another factor of 3 or more times that estimated here.[9] Muscle tissue from the other animals, except ptarmigan, would not appear to contribute much of this nuclide to the diet.

The average contribution of the daughter, ^{210}Po, to the diet is probably somewhat smaller than previously estimated since seasonal variations are present and radioactive decay during storage further reduces the concentrations. Thus, we estimate, from the exponential model of nuclide metabolism below,[18] that with intakes of 50 to 90 pCi/day, the soft tissue concentrations relative to those in non-Arctic residents would be doubled,

$$T_e f \frac{mC}{I} = \frac{T_e f}{0.693}$$

where m is the mass of the body,* C is the concentration of the nuclide, I is the daily intake, T_e is the half-life of the nuclide in the body,* and f is the fraction of the nuclide entering the body.* It should be noted, however, that the ^{210}Po derived from direct ingestion would then constitute an even smaller fraction of the ^{210}Po present since most of it is derived from the much higher ^{210}Pb body content in Arctic residents.[19]

The ^{226}Ra contribution to the human diet from the caribou is fairly low being about 1 pCi/day from 900 g of meat, a value comparable to the 2 pCi/day in non-Arctic residents.[14] Again most other animals would contribute even less, except in the case of fish where this value might be doubled. Fish may also contribute substantially more since to a large extent the bone may be consumed. Unless some other sources of ^{226}Ra are present in the Eskimo diet, the body content of this nuclide would be

* Organ or tissue of interest may be substituted for "body".

expected to be about the same as that for other unexposed population groups.

The dose rates to caribou could be quite appreciable, as shown by Beasley and Palmer,[9] as high as 0.45 rad/yr to the liver. However, over the whole year the average dose might be only half of this. In bone on the other hand with little seasonal variation, the average dose is about 0.4 rad/yr, which, with the dose from other natural sources, would produce a dose about 3 times that to the "average cow" of Lucas and Di Ferrante.[15] If one assumed an RBE of 10, the skeletal dose would be about 4 rem/yr. The dose levels in reindeer would be about one half these.

The dose to human populations dependent on caribou meat may possibly be inferred from those observed in wolf in which the ^{210}Po–^{210}Pb skeletal concentrations are about 1 pCi/g ash. The specific activity of each nuclide in non-Arctic humans is about 0.145 pCi/g ash,[13] which with an RBE of 10, is equivalent to a dose rate of about 50 mrem/year from a total skeletal dose rate of 185 mrem/year. Thus, a concentration of 1 pCi/g ash is equivalent to a total dose of 500 mrem, 2.7 times the non-Arctic dose. However, if the effective dose is that delivered to the 10-μ layer of surface cells of bone,[20] the increase in dose would be about 100 mrem/yr, an increase in total dose rate of about 60%.

Although the levels of ^{210}Po are apparently greatly increased in human placenta, the actual increase in dose would be only about 10%. On the other hand if the levels are comparable to those in wolf muscle (200 pCi/kg) and some of Hill's specimens of placenta,[12] this would double the dose. These numbers, although small compared to the dose in bone, may be of relatively greater significance because the radiation effects to soft tissue may be greater than in bone.

The very high levels of these nuclides observed in wolf and in the human bone and placental specimens of Hill[8, 12] suggest that the assumed sources of these nuclides bear further investigation since it appears unlikely that these sources, caribou and reindeer muscle, can supply the large concentrations observed by Hill. Thus, the following things bear closer examination: the possibility of systematic errors of measurement; that these measurements are representative of diets and other exposure of these high-level subjects; and that the exponential model of nuclide metabolism describes these nuclides with any degree of accuracy.

The available information indicates that the measurements are probably reasonably reliable in that results from different laboratories and by different methods are reasonably consistent.[6-10] The metabolic model, which is accepted primarily for lack of a better model, could be in substantial error.[18] However, even less is known about the high level subjects. Precise studies of these people, their work, dietary and smoking habits, and health could be valuable; and although epidemiological studies might be unprofitable because of the small population receiving high dose rates, intensive studies of metabolic balance, that is, actual intake, excretion and body content of these nuclides, might be valuable in establishing the various parameters and theoretical considerations.

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