ANL-7760
Part II

ANL-7760
Part II

Argonne National Laboratory

RADIOLOGICAL PHYSICS DIVISION
ANNUAL REPORT

Center for Human Radiobiology

July 1969—June 1970

RETURN TO REFERENCE FILE
TECHNICAL PUBLICATIONS
DEPARTMENT

REPOSITORY ARGONNE LAB - CHR
ER DIVISION
COLLECTION ANNUAL REPORTS
BOX No.
FOLDER

PARTIAL DOCUMENT

0019280

FOREWORD

The Center for Human Radiobiology has been formed in the Radiological Physics Division of the Argonne National Laboratory. This center has been assigned the responsibility for the continuation of the investigations of the biological effects of radium in man, with the general understanding that in the future the responsibility may be broadened to include the study of human subjects contaminated with internal emitters other than radium.

One of the primary purposes underlying the foundation of the center is the need to obtain information from human subjects exposed to various internally deposited radionuclides and to apply this information to radiation protection guides. In this regard, the United Nations Scientific Committee on the Effects of Atomic Radiation reported in 1964, "...that investigations aimed at recording significant quantitative relationships between doses and observed incidence of any specific malignancy in man should be strongly encouraged and supported." Very probably, radiation protection guides for humans can best be obtained from the study of the biological effects of radiation on man. Although studies on laboratory animals can provide the basic framework, the experience obtained from man is extremely valuable and must be considered most carefully. However, these studies are difficult and time consuming, for human exposures are usually accidental, unexpected, difficult to evaluate and the consequences of these exposures may not be visible for many years. The numbers of people exposed are relatively small, and in order to obtain meaningful results, the largest available segment of the exposed populations should be rigorously studied until death.

These considerations have given rise to the concept that a single organization be formed with the primary responsibility of fulfilling our moral obligation to derive the greatest amount of information from those known cases of internal contamination from radionuclides. Such an organization should have a long lifetime with the necessary staff and equipment to provide the multiplicity of investigations required to extract the greatest

0019281

possible information from the available cases. This then is the basic concept on which the center was founded.

It is of interest to record here the history leading to the formation of the Center for Human Radiobiology. It was during the symposium on the Delayed Effects of Bone Seeking Radionuclides, held at Sun Valley, Idaho, September 1967, that Professor Robley D. Evans proposed the creation of a National Center for Human Radiobiology. This proposal was later discussed early in 1968 at a meeting of the AEC Advisory Committee for Biology and Medicine. Subsequently, a subcommittee of the ACBM was appointed and charged with the responsibility to advise the AEC on Professor Evans' proposal. The report of this subcommittee recommending the formation of the center at the Argonne National Laboratory was reviewed and subsequently approved by the ACBM on May 11, 1968.

The first assignment given the center was the responsibility for the continuation and extension of the radium studies which had been carried out previously at MIT under the direction of Professor Evans. This has resulted in the transfer of some personnel, medical records, and equipment from MIT to ANL which was completed by August 1970. As of 1 September of this year a satellite laboratory, funded by a subcontract from the Argonne National Laboratory, remains at MIT.

0019282

TABLE OF CONTENTS

Center for Human Radiobiology

A. F. Stehney, Section Head

Some Dose-Response Relationships for Tumor Incidence in Radium Patients 1
R. E. ROWLAND, PATRICIA M. FAILLA, A. T. KEANE, and A. F. STEHNEY

A Way to Put Error Bars on Points of Zero Incidence on Dose-Response Curves 18
J. H. MARSHALL

Skeletal Concentrations and Metabolic Parameters of ^{226}Ra in Radium-Burdened People 22
R. B. HOLTZMAN

^{210}Pb and ^{210}Po Metabolism in Radium-Dial Painters 35
R. B. HOLTZMAN

Measurements of Americium-241 in Two Subjects 36
JOHN RUNDO, A. T. KEANE, and H. A. MAY

Construction of New Shielded Rooms 45
JOHN RUNDO

Thorium and Uranium in Blood, Urine, and Cigarettes 47
H. F. LUCAS, JR. and FRANCIS MARKUN

Boat Sampling Methods for Analysis of Lead and Tellurium in Biological Materials 53
F. H. ILCEWICZ and R. B. HOLTZMAN

Quantitative Characterization of Bone. A Computer Analysis of Microradiographs 63
ELIZABETH LLOYD and DONALD HODGES

A Comprehensive Model of Alkaline Earth Metabolism in Bone: Preliminary Report 95
J. H. MARSHALL

^{45}Ca, ^{133}Ba, and ^{226}Ra in 6- to 10-Year-Old Beagle Dogs: a 100-Day Study 110
S. K. WOOD, J. E. FARNHAM, and J. H. MARSHALL

0019283

Estimates of the Radiation-Induced Leukemic Risk in Man 133
L. D. MARINELLI

Regularization Unfolding of Low γ-Ray Activity Measurements. II. Evaluation of Time-of-Flight Scanning in One Dimension 154
I. K. ABU-SHUMAYS, P. E. HESS, and L. D. MARINELLI

A Special Regularization-Unfolding Technique for the Numerical Solution of Two-Dimensional Fredholm Equations of the First Kind 176
I. K. ABU-SHUMAYS and L. D. MARINELLI

A Comparison of Recovery from α- and γ-Ray Induced Mitotic Delay in Fertilized Sea Urchin Eggs 202
PATRICIA M. FAILLA

Application of Cellulose Nitrate Films for Alpha Autoradiography of Bone. II. Resolution and Sensitivity of Cell Nitrate Films 208
D. J. SIMMONS and K. T. FITZGERALD

Chondroclastic Resorption in the Long Bones of Newts Treated with Parathyroid Extract 217
D. J. SIMMONS, D. J. MC WHINNIE, and H. T. CUMMINS

Development and Healing of Rickets in Rats. III. Studies with ^{3}H-Uridine 225
D. J. SIMMONS and A. S. KUNIN

Mineral Metabolism in the Skeletons of Teleosts--a Review 240
D. J. SIMMONS

Electron Microscope Measurements of Alkaline Earth Transport 242
ELIZABETH LLOYD

Publications 253

0019284

SKELETAL CONCENTRATIONS AND METABOLIC PARAMETERS OF ^{210}Pb AND ^{226}Ra IN RADIUM-BURDENED PEOPLE*

R. B. Holtzman

The concentrations of ^{226}Ra and its decay product, ^{210}Pb, were determined in 44 bone samples taken from 13 persons who had acquired the radium either as dial painters or under medical treatment. The whole-body burdens, carried 4 to 36 years, ranged from 0.4 to 10 μCi ^{226}Ra. The ^{210}Pb was derived almost entirely from the radium in bone, an assumption supported by measurements on radium-injected dogs with short-term exposures of 7 to 500 days. Despite great differences from sample to sample, such as differing body burdens, exposure times and methods of acquisition, differing bone types (femur, rib, vertebra, etc.), and large differences in ^{226}Ra concentration (10^2 to 10^4 pCi/g ash), the ratios of ^{210}Pb specific activities to those of ^{226}Ra were fairly uniform, with an average of 0.34 ± 0.03 (S.E.). This uniformity and the large variations in radium concentrations within an individual (factors of 10 or more) indicate either that the ^{226}Ra and ^{210}Pb were metabolized similarly, or that little ^{210}Pb was translocated from the site of formation. That some translocation may occur is shown by the high ratios of 1.6 to 30 in some samples. The low values of ^{226}Ra in these specimens relative to those in other samples from the same subject may indicate that little radium was taken up initially.

The effective half-life of the ^{210}Pb, based on the ^{210}Pb-to-^{226}Ra ratio of 0.34, appears to be about half that of the radium in an exponential retention model. The dose from the $^{210}Pb(^{210}Po)$ series appears to be about 10% of that of the ^{226}Ra series over the period of 10 to 40 years after acquisition.

Introduction

Studies of the skeletal distributions of ^{226}Ra and of its long-lived daughter, the 21.4-year ^{210}Pb, in people with large body burdens of ^{226}Ra can provide valuable information on the metabolism of both ^{210}Pb and stable Pb in man. The quantitative relations between the ^{210}Pb and the ^{226}Ra concentrations and determination of the whole-body content of the ^{226}Ra through whole-body counting of these people make possible the determination of the whole-body content of the ^{210}Pb. This latter quantity, which is

*Data in this paper were presented at the Second International Congress of the International Radiation Protection Association, Brighton, England, May 3-8, 1970 and abstracted in Health Phys. 19, 152 (1970).

0019285

not otherwise measurable in vivo, is necessary for the assessment of the metabolic parameters of ^{210}Pb and for the accurate evaluation of the radiation exposure of these people. In addition, these studies allow the confirmation of some of the metabolic parameters of ^{226}Ra and of its rare gas daughter, ^{222}Rn, such as retention and emanation rates.

Preliminary results on some of the data in this paper were reported earlier.[1] The ratio of the specific activity of ^{210}Pb to that of ^{226}Ra was about 0.3 at 30 years after acquisition. The residence time of ^{210}Pb appeared to be quite long; the exponent of the power function retention

$$R = AT^{-b}, \tag{1}$$

where R is the fractional retention, A is the retention at 1 day, and T is the burden time, was about 0.1. This value indicates a much slower release of Pb than of ^{226}Ra.[2,3]

Subsequently, Petrow reported ^{226}Ra and ^{210}Pb measurements on 89 bone sites from two radium dial painters with 48- and 49-year burden times.[4] The ratios of specific activities of ^{210}Pb to ^{226}Ra ranged from about 0.17 to 0.48, and corrected for storage time between death and measurement, the mean ratio weighted by sample size was 0.27 ± 0.01 (S.E.). The biological half-lives of both ^{226}Ra and ^{210}Pb were estimated to be identical at 15 to 20 years. The ratios of specific activities of ^{210}Pb to those of ^{226}Ra were fairly constant. In the long bones the ratios showed a small negative correlation with the ^{226}Ra concentrations.

Experimental

Presented in this paper are measurements of the specific activities of ^{226}Ra and ^{210}Pb in surgical and autopsy bone specimens taken from a group of 13 subjects characterized in Table 1 by the identification numbers and data from Miller et al.[5] They included 4 men and 9 women of whom 5 had been dial painters, 7 were patients injected with ^{226}Ra, and one had taken radium water for medicinal purposes. They had carried their burdens from 4 to 36 years, and their residual burdens ranged from 0.45 to 10.5 μCi,

TABLE 1. Data on Subjects

Subject Number[a]	Terminal Body Burden, μCi ^{226}Ra	Time Ra Carried, yr	Sex	Source of Radium[b]
03-140	0.5	4.08	M	I.V.
03-455	1.2	12	F	D.P.
03-118	3.09	24	F	I.V.
03-109	0.63	26	F	I.V.
03-117	1.54	26	M	I.V.
03-210	1.35	29	M	I.V.
03-402	1.2	31	F	D.P.
03-671	3.82	32	F	D.P.
03-215	4.00	33	M	I.V.
03-648	7.61	33	F	D.P.
03-551	1.33	35	F	D.P.
03-208	10.5	36	F	Ra H_2O
03-216	0.45	36	F	I.V.

(a) Case number of Miller et al.[5]

(b) Source of Radium: I.V. = Intravenous injection
D.P. = Dial painter
Ra H_2O = Drank radium water.

as measured by C. E. Miller.[5] Except for the specimen from Subject 03-455, which was preserved in formalin, the samples from each patient were preserved in ethanol and stored in a single glass bottle.

The ^{210}Pb was determined by wet-ashing the 0.2- to 2-g samples in nitric and perchloric acids and plating the ^{210}Po daughter onto a silver disk, and the α radiation was then α-counted.[6] The ^{226}Ra in the dissolved specimens was determined by the radon emanation method of Lucas.[7]

The errors originating in counting statistics were about 5% of the counting rate at the 90% confidence level and since they are much less than the variation between samples, will not be reported.

Corrections for the growth of ^{210}Pb from the ^{226}Ra during the period the specimens were stored, which ranged from 1.7 to 28 years, were calculated from

$$R_0 = \frac{R_m - f[(1 - \exp(-\lambda t)]}{\exp(-\lambda t)} , \qquad (2)$$

where R_0 is the $^{210}Pb/^{226}Ra$ ratio at the time of death or surgery, R_m is this ratio measured at time t (the storage time), f is the fraction of ^{222}Rn retained in the specimen during storage, and λ is the radioactive decay constant of ^{210}Pb; f was estimated as that value which when used to calculate the R_0's gave a minimum correlation between R_0 and the storage time (the correlation coefficient, $r \rightarrow 0$).

Only data from the subjects with burden times between 24 and 36 years were used in the calculations, so that R_0 would be approximately independent of burden time. In addition, only those data with ratios below 0.9 were included, since those specimens with greater ratios appeared to be in a different class, one which exhibited very low concentrations of both nuclides relative to those in other specimens from the same person.

Results and Discussion

The results of measurements on the particular specimens are shown in Table 2. In the last column are given the $^{210}Pb/^{226}Ra$ terminal ratios corrected for the growth and decay of ^{210}Pb during storage.

The terminal ratios (R_0) for each sample were calculated from Equation (2), based on f = 0.75. The mean ratio was 0.34 ± 0.03 (S.E.). The value of f is not critical in that a 30% variation in this number produces about a 15% variation in the mean ratio. In order to produce a statistically significant change ($P < 0.05$) it is necessary to vary f from 0.55 to 0.95.

The means of these ratios as a function of burden time for each subject are shown in Figure 1. The standard errors are also given and for reference the points represented by a single measurement are given standard errors which are twice the average of the calculated ones for the other points, 0.16, and represented by the dashed error bars. Also shown are the

TABLE 2. Specific Activities and Ratios in Individual Samples.

Subject[a]	Specimen Description	Sample Size, g ash	Storage Time, yr.	Specific Activities, pCi/g ash ^{226}Ra	Specific Activities, pCi/g ash ^{210}Pb	$^{210}Pb/^{226}Ra$ Measured at $\tau = 0$	$^{210}Pb/^{226}Ra$ (f=0.75) ± S.E.[b]
03-140	Femur shaft	0.367	24.55	234	114	0.488	0.169
	Femur shaft	0.296	24.55	77	47	0.611	0.442
	Femur shaft	0.219	24.55	167	67	0.401	-0.024
	Femur shaft	0.217	24.55	204	82	0.401	-0.024
							0.141 ± 0.11
03-455	Radius shaft	0.028	27.05	715	534	0.746	0.740
03-118	Femur shaft	0.056	7.10	675	220	0.326	.216
03-109	Femur shaft	0.390	2.18	811	214	0.264	0.228
03-117	Vertebra	0.0650	5.89	47	40	0.85	0.872
	Vertebra	0.179	8.07	187	53	0.291	0.228
	Femur shaft	0.065	5.89	661	238	0.360	0.278
							0.43 ± 0.22
03-210	Tibia shaft	0.626	1.74	105	39	0.375	0.353
	Tibia shaft	0.640	1.74	96	40	0.421	0.409
							0.38 ± 0.05
03-402	Femur shaft, cort.	0.052	9.12	855	343	0.401	0.281
	Femur joint, cort.	0.031	9.03	453	201	0.443	0.339
	Femur shaft, trab.	0.011	9.02	926	405	0.437	0.375
	Femur joint, cort.	0.0015	9.08	2353	1278	0.543	0.440
	Femur tumor	0.0013	9.04	0.51	2.25	4.4	9
							0.358 ± 0.033
03-671	Tibia shaft	0.064	8.98	891	362	0.406	0.290
03-215	Radius shaft	0.0175	4.93	411	144	0.350	0.281
	Radius, trab.	0.0057	4.93	262	108	0.412	0.353
	Humerus joint	0.0593	4.97	4480	1442	0.323	0.249
							0.294 ± 0.031
03-648	Vertebra A	0.0609	6.37	521	421	0.808	0.821
	Vertebra Al	0.116	8.66	362	236	0.652	0.620
	Rib	0.0609	6.38	3650	1475	0.404	0.324
	Femur shaft	0.0529	6.38	972	415	0.426	0.352
	Joint	0.0289	6.39	3330	969	0.291	0.185
	Femur joint, cort.	0.0018	6.39	107	169	1.58	2.0
	Femur joint, trab.	0.129	6.66	932	2360	2.53	3.0
							0.460 ± 0.114
03-551	Mastoid chips	0.0581	3.43	367	109	0.297	0.244
03-208	Humerus joint, trab.	0.290	8.74	1622	535	0.330	0.193
	Humerus joint, trab.	0.203	8.74	714	236	0.331	0.194
	Rib	0.0028	9.66	6000	3830	0.639	0.598
	Rib	0.0121	9.03	1110	686	0.618	0.573
	Rib	0.0469	12.23	4550	2050	0.451	0.305
	Sternum	0.0609	10.03	5620	2080	0.370	0.224
	Vertebra	0.0614	9.67	8130	3010	0.371	0.232
	Calvarium	0.0640	9.82	3.95	33.3	8.43	12
	Calvarium	0.0143	12.27	2.21	33.2	30	48
	Humerus joint	0.0593	9.68	10830	3950	0.365	0.223
	Femur shaft cort.	0.0640	10.04	0.91	12.1	13.3	20
	Femur shaft trab.	0.0204	9.97	12.6	161	12.8	19
							0.318 ± 0.060
03-216	Femur shaft (mid)	0.204	2.08	14.9	48	0.321	0.291
	Femur shaft (mid)	0.254	2.08	122	40	0.328	0.299
	Femur shaft (mid)	0.197	2.08	88	30	0.344	0.316
							0.302 ± 0.007

(a) Case number of Miller et al.[5]
(b) Ratios greater than 1.0 were not included in the averages. See text.

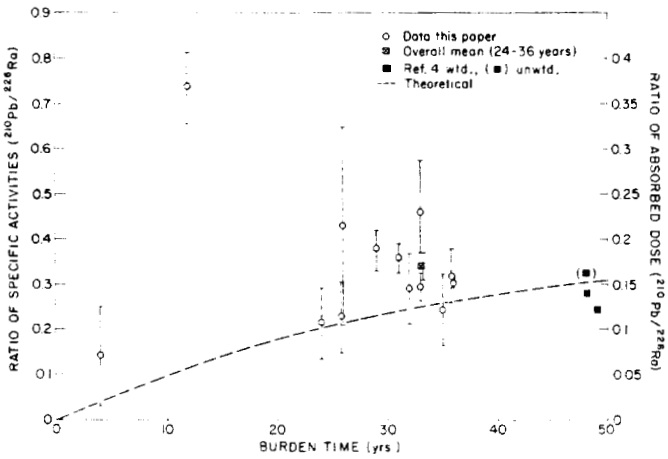

FIG. 1.--The mean terminal ratios of the activities of ^{210}Pb to ^{226}Ra and dose ratios for each subject as a function of burden time. The fractional retention of the ^{222}Rn during storage was estimated to be 0.75. Also shown are the theoretical curve and data from Reference 4, both weighted and unweighted (Subject 5278 in parentheses) by sample size (see text).

mean values for Petrow's 2 subjects at 48 and 49 years (the standard errors on these points are about the size of the symbols), corrected for storage time and weighted by sample size. In addition, the unweighted mean of his Subject 5278 is also shown in parentheses for comparison with the data of this paper. The unweighted and weighted means of the other subject were essentially identical.

The dashed line is a theoretical one representative of the change in ratio with time calculated from the γ-ray retention curve of Norris et al.,[2]

$$R_\gamma = 0.021t^{-0.28}, \tag{3}$$

their radium retention equation

$$R_{Ra} = 0.54t^{-0.52}, \tag{4}$$

and an exponential loss of ^{210}Pb with an effective half-life of 15 years.[8,9] The ratio of the specific activities of ^{210}Pb to that of ^{226}Ra, R_0, which is essentially the build-up of ^{210}Pb derived by Evans et al.,[10] is

$$R_0 = \frac{\lambda A_\gamma e^{-\lambda e T}}{0.54\, T^{-0.52}} \int_1^T e^{\lambda e t} t^{-b}\, dt\,, \tag{5}$$

where T is the burden time,

λ is the physical half-life of ^{210}Pb,

λ_e is the effective half-life of ^{210}Pb,

A_γ is the constant of the radium gamma power function, the 0.021 in Equation (3), and

b is the exponent of the radium γ-retention function, the 0.28 in Equation (3).

The values are obtained by numerical integration.

R_0 is fairly insensitive to the assumed effective half-life of the ^{210}Pb, but it is very sensitive to the value of b. Thus, this curve is lower than the data of this paper and higher than Petrow's values. Slight changes in the empirical constants of the equations could change the location of the curve to fit either these data or Petrow's better.

One cause of apparent differences between samples could be that the ratios in cortical are different from those in highly trabeculated bone. Thus, the mean ratio in the cortical bone specimens is 0.311 ± 0.016 (S.E.), compared to 0.382 ± 0.057 (S.E.) of the more trabeculated specimens. However, because of the large range of values in the latter set (0.19-0.85) Student's t test showed no significant difference ($P > 0.10$). It should also be noted that the higher values of the ratios (> 0.45) were in the group of highly trabeculated bone.

The weighted averages taken from Petrow's data[4] were lower for cortical, 0.273 ± 0.042, than for highly trabeculated bone, 0.328 ± 0.069, and the difference is probably significant ($P < 0.05$). However, taking his first subject alone, the unweighted ratios 0.267 ± 0.036 for cortical and 0.343 ± 0.021 for trabecular bone, were significantly different (32 samples, $P < 0.001$), but for the second subject the respective ratios were much closer, 0.314 ± 0.054 and 0.353 ± 0.67. The difference was barely significant (57 samples, $P \approx 0.05$).

In addition to biological variation, the wide variations in the ratios reported here could be caused by the small sample sizes, 0.001 to 0.64 g ash, which could exaggerate the nonuniform distribution of ^{226}Ra as seen in autoradiographs. Larger, more representative samples might have

reduced some of the large variations.[11] Nevertheless, fairly uniform ratios were obtained for most of the specimens, and, although the sampling from Subject 03-216, in particular, previously presented by Lucas et al.[11] shows nonuniform ^{226}Ra and ^{210}Pb concentrations, the ratios were essentially identical.

One possible source of error in the estimates of ^{210}Pb metabolic parameters, especially if the loss rate of this nuclide is slow, is the possibility of uptake of ^{210}Pb along with the ^{226}Ra at the time of injection or ingestion since the injection solution may have been quite old at this time. However, such uptake appears to be small as shown by data based on the injections of 2 dogs with ^{226}Ra by Rowland and Marshall of this laboratory as shown in Table 3.[12,13] The ^{226}Ra solutions for these experiments were obtained about 1 month and 1-1/4 years prior to injection for the first and second dogs, respectively. On the first dog, 28 days after the last of 8 weekly injections, the ratio corrected for 50% radon retention* during storage was about 0.4% in the amputated left humerus; 353 days later on the other humerus it was only about 6%. For the second dog, with a single injection and sacrifice 7 days later, the ratio was less than 0.1%. Thus, it appears that little ^{210}Pb was likely to have been injected in the I.V. cases.

TABLE 3. ^{226}Ra-Injected Dogs.

Dog	Conditions	Time after Last Injection, Days	Storage Time, Days	Specific Activities, pCi/g ash ^{226}Ra	Specific Activities, pCi/g ash ^{210}Pb	$^{210}Pb/^{226}Ra$ Measured	$^{210}Pb/^{226}Ra$ Corrected (f = 0.50)
1	8 I.V. injections in 7 weeks	28	1332	797,000	47,400	0.059	0.004
		353	979	30,500	3,180	0.096	0.059
2	One I.V. injection	7	229	8,390	60	0.0072	-0.004

*A value of 50% retention was used in order to reduce the number of negative ratios.

0019292

Consistencies and variability of the data can be seen in Table 2 in Subject 03-208. Although the ^{226}Ra in the humerus joint and vertebra ranged from 714 to 10,800 pCi/g ash, the $^{210}Pb/^{226}Ra$ ratios were essentially identical. In the rib sample these ratios varied from 0.30 to 0.60, but 2 of the 3 values are similar and about 0.6. The ^{226}Ra concentrations are all within a factor of 6 of the mean skeletal concentration of about 4000 pCi/g ash. On the other hand, in calvarium and femur in this subject the concentrations are much lower and ratios much higher.

A bone of particular interest is the mastoid since this is a site of soft tissue tumors in the dial painters. A possible cause could be the deposition of ^{210}Pb from ^{222}Rn on the mastoid surfaces. However, in this one sample from Subject 03-551 (Table 2) the ^{226}Ra concentration is slightly lower than the 500 pCi/g expected for a uniform distribution, and there is no excess accumulation of ^{210}Pb, the ratio actually being a little lower than average.

The large variation in specific activities and the fairly uniform ratios of these activities in most specimens indicate that unless the ^{226}Ra and ^{210}Pb are metabolized nearly identically, only a small fraction of these nuclides is redistributed in the skeleton. However, some of the specimens have anomalously high ratios of 1.6 to 30 (measured) and these are associated with concentrations of ^{226}Ra and ^{210}Pb low relative to those in other specimens from the same subject. This effect could be caused by a high rate of removal of nuclide, especially ^{226}Ra, from these sites. However, the high ratio in newer tissue (tumor, Subject 03-402) indicates that this could also be caused either by a low initial deposition of Ra or resorption of both nuclides, and subsequent preferential deposition of the ^{210}Pb. These high ratios and low concentrations are also consistent with the inverse correlation of ratio with ^{226}Ra concentration in long bone shown by Petrow.[4]

In the case of calvarium (skull bone) there may have been little original deposition of ^{226}Ra with subsequent slow accumulation. This bone

is unusual, not only in its origin, but it apparently behaves differently as shown by some measurements on bone from people only environmentally exposed as shown in Table 4.[6] In two subjects, 1 and 2, the ^{226}Ra is much higher in the skull than in the other bones, while in Subjects 1 and 3 the ^{210}Pb values are much greater.

TABLE 4. Distribution of ^{226}Ra and ^{210}Pb in Bone of Unexposed People[a]

Subject	Age	Sex	Bone	^{226}Ra, pCi/g ash	^{210}Pb, pCi/g ash
1	68	M	Tibia	0.012	0.269
				0.019	0.247
			Mandible	0.012	0.093
			Skull	0.070	0.201
				0.070	0.419
			Joint	0.016	0.152
2	43	F	Tibia	0.025	0.090
			Mandible	0.028	0.049
			Skull	0.051	0.092
				0.100	0.146
			Joint	0.025	0.083
3	52	F	Tibia	0.026	0.078
				0.030	0.132
			Mandible	0.030	0.077
			Skull	0.032	0.366
				0.037	1.33
			Joint	0.027	0.071

[a] Taken from Reference 6, Table 4.

Finally, these results allow some estimates of the metabolic and dosimetric parameters. As noted in Figure 1 the more reliable data points (storage time less than 10 years) range in time from 24 to 36 years. Petrow's data extend the time to 49 years. Although there is some increase in ratio between 24 and 36 years, overall there appears to be little change. The theoretical curve based on a power function retention of ^{226}Ra and an

0019294

exponential loss of ^{210}Pb fits moderately well, i.e., it is only a slowly increasing function after 20 years. These values are not consistent with an exponential loss of both ^{226}Ra and ^{210}Pb with equal biological half-lives of these two nuclides.[4] For this condition the ratio is about 0.27 at 49 years, as found by Petrow, but at shorter times it is lower (at 30 years it is only 0.20). However, the biological half-lives derived from excretion data[8] indicate biological half-lives of 57 and 35 years for ^{210}Pb and ^{226}Ra, respectively. Thus, with an in vivo radon retention of 0.31,[5] the $^{210}Pb/^{226}Ra$ ratios are 0.19, 0.22, and 0.29 at burden times of 24, 30, and 50 years, respectively. The model using the power function radium gamma-ray retention model as shown in Figure 1 gives a better fit to the data over the 24- to 49-year region.

The absorbed skeletal dose due to the ^{210}Pb and its decay product, ^{210}Po, was estimated by Petrow to be about 5 to 6% that of the other members of the radium series.[4] However, the additional data of this paper indicate the dose to be somewhat higher, especially after about 10 years of burden time; this dose ratio could be 10% or more, as seen in Figure 1 (right-hand scale, in which it is assumed that the dose from the ^{210}Pb is 50% that from the ^{226}Ra and its daughters with 30% ^{222}Rn retention).[1] Although the dose depends on the retention model assumed in calculating the $^{210}Pb/^{226}Ra$ ratio, this factor does not appear to vary drastically from model to model.

If it is assumed that the dose-producing nuclide, ^{210}Po, with its 5.3-MeV alpha particle, is in radioactive equilibrium with the ^{210}Pb and that the Rn retention is 30%, then the dose rate from the ^{210}Pb per unit of activity is half that of the ^{226}Ra and its daughters. Thus, the dose rate from the ^{210}Pb-^{210}Po pair as shown in Figure 1 is about 12 to 15% that of the parent ^{226}Ra after about 24 years and 8 to 10% averaged over a long period of time after 10 years. For a single injection case the ^{210}Pb may be relatively small, only a few percent of the cumulative dose because of the initial high ^{226}Ra dose. However, for long-term intake, such as for

dial painters exposed for a year or more, the fractional dose of the ^{210}Pb may approach 10% or more that of the ^{226}Ra when averaged over 30 years or more.

Summary

In summary, these results show that many factors are highly variable. The ^{226}Ra concentrations may vary by more than a factor of 10 in a given individual, terminal body burdens may vary by factors of 20, and many different varieties of bone are involved. Nevertheless, the ratio of the specific activity of ^{210}Pb to that of ^{226}Ra is relatively constant at 0.34 ± 0.03. This factor is particularly useful in that it allows assessment of the whole-body content of ^{210}Pb from the ^{226}Ra whole-body measurements in high radium people which, because ^{210}Pb and its daughters emit no high energy γ rays, is not otherwise possible.

The constancy of the ratio indicates that there is little translocation of ^{210}Pb from its site of origin. However, some translocation does occur, as shown by some higher values of this ratio. Other results of very low ^{226}Ra concentrations and ratios greater than 10 indicate also that either initially little ^{226}Ra was taken up, or that the original bone was resorbed and rebuilt with preferential redeposition of the ^{210}Pb.

The $^{210}Pb/^{226}Ra$ ratio appears to be somewhat higher in more trabeculated bone than in cortex.

None of the models proposed appears to fit the data well. The single exponential models, with or without equal biological half-lives of ^{210}Pb and ^{226}Ra, fit the long-term results but are too low for the shorter-term ones. The model using the radium gamma-ray retention power function fits the 24- to 36-year data.

The absorbed dose from the ^{210}Pb averaged over long times is about 6% that of the ^{226}Ra and its daughters, but depending on the mode of acquisition, it may be 10% or more.

I thank Dr. R. J. Hasterlik for human bone specimens,

0019296

Dr. R. E. Rowland for both human and dog bone specimens, and Dr. C. E. Miller for use of his data on the ^{226}Ra whole-body content of these subjects.

References

1. Holtzman, R. B. RaD (^{210}Pb) in the Human Skeleton: Estimates of the Exponent of the Retention Function, the Skeletal Content, and Dose Rate in High-Radium People. Radiology 80, 122-123 (1963).
2. Norris, W. P., T. W. Speckman, and P. F. Gustafson. Studies of the Metabolism of Radium in Man. Am. J. Roentgenol. 73, 785-802 (1955).
3. Miller, C. E. and A. J. Finkel. Radium Retention in Man after Multiple Injections: The Power Function Re-evaluated. Am. J. Roentgenol. 103, 871-880 (1968).
4. Petrow, H. G. The Metabolic and Dosimetric Significance of ^{210}Pb and ^{226}Ra Ratios in the Bone of Radium Dial Painters. Proc. First Int. Congr. of Radiation Protection, Rome, September 5-10, 1966. (Pergamon Press, Oxford, 1968), Part I, pp. 727-741.
5. Miller, C. E., R. H. Hasterlik, and A. J. Finkel. The Argonne Radium Studies, Summary of Fundamental Data. Argonne National Laboratory and Argonne Cancer Research Hospital Report ANL-7531 (1969).
6. Holtzman, R. B. Measurement of the Natural Contents of RaD (^{210}Pb) and RaF(^{210}Po) in Human Bone--Estimates of Whole-Body Burdens. Health Phys. 9, 385-400 (1963).
7. Lucas, H. F., Jr. Correlation of the Natural Radioactivity of the Human Body to that of its Environment: Uptake and Retention of ^{226}Ra from Food and Water. Argonne National Laboratory Radiological Physics Division Semiannual Report, July-December 1960, ANL-6297, pp. 55-66.
8. Holtzman, R. B. and H. F. Lucas, Jr. Excretion of ^{210}Pb and ^{226}Ra by Radium Dial Painters, Health Phys. 13, 940 (1967).
9. Holtzman, R. B. ^{210}Pb and ^{210}Po Metabolism in Radium Dial Painters. Paper presented at a meeting, "The Biology and Ecology of Polonium and Radiolead," The Institute of Cancer Research, Belmont, Sutton, Surrey, England, April 30 and May 1, 1970.
10. Evans, R.D. et al. Radium and Mesothorium Poisoning and Dosimetry and Instrumentation Techniques in Applied Radioactivity. MIT Annual Progress Report, 1964. MIT-952-1, pp. 54-58.
11. Lucas, H. F., Jr., R. E. Rowland, C. E. Miller, R. B. Holtzman, R. J. Hasterlik, and A. J. Finkel. An Unusual Case of Radium Toxicity. Am. J. of Roentgenol. 90, 1042-1051 (1963).
12. Rowland, R. E. Microscopic Metabolism of ^{226}Ra in Canine Bone and Its Bearing on the Radiation Dosimetry of Internally Deposited Alkaline Earths. Radiat. Res. 15, 126-137 (1961).
13. Rowland, R. E. Personal communication.

^{210}Pb AND ^{210}Po METABOLISM IN RADIUM-DIAL PAINTERS*

R. B. Holtzman

The excretion rates and blood levels of ^{210}Pb and ^{210}Po were measured in 14 dial painters 35 to 40 years after their exposure to ^{226}Ra. The residual body burdens of the ^{226}Ra, ranging from 0.028 to 2.4 μCi, and of the associated daughters were sufficient to produce levels of ^{210}Pb and ^{210}Po in the blood and excreta much greater than those in unexposed persons.

The ratios of the urinary-to-fecal excretion rates were 1.7 and 0.12 for ^{210}Pb and ^{210}Po, respectively. Thus, urinary excretion was 63% for lead, but only 10% for polonium. The coefficients of excretion (fraction of body burden excreted per day) were 32×10^{-6} and 270×10^{-6} per day (1.2 and 9.8% per year) for the ^{210}Pb and ^{210}Po, respectively. These data, when fitted to a single exponential excretion model, led to biological half-lives of about 57 years for lead and 7 years for polonium. The blood clearance rates were 0.088 liters/day for ^{210}Pb and 1.2 liters/day for ^{210}Po. This rate for lead is low compared to the 10 liters/day for strontium and 100 liters/day for radium. However, if the concentration of lead in serum only is used, then the clearance rate is 1.6 liters/day which is similar to that of the polonium, but still less than that of strontium and radium.

These results make possible more accurate estimates of body burdens of humans exposed to high levels of lead and ^{210}Pb. Their application to evaluating the hazards of lead is presented.

*This is the abstract of a paper presented at the meeting on the Biology and Ecology of Polonium and Radiolead at The Institute of Cancer Research, Belmont, Surrey, U.K., April 30 and May 1, 1970.

0019298

MEASUREMENTS OF AMERICIUM-241 IN TWO SUBJECTS

John Rundo, A. T. Keane, and H. A. May

The "best" estimates of the americium-241 contents of the scientist and his 10-year-old son are 60 nCi and 40 nCi, respectively. The calibration methods are described in some detail.

For a period of 3 months in 1964 a scientist, H, worked in the detached garage of his home with a source of americium-241 of supposed strength about 10 mCi. The americium was reported by the supplier to be safe and not to release activity on smearing. The scientist's 4- year old son, R, followed the proceedings attentively.

In February, 1970, alpha-particle contamination at the scientist's new place of employment was identified as americium-241, and its origin was eventually traced to contaminated furniture and fittings in his new home. Body radioactivity measurements at a nearby research institute demonstrated the presence of americium-241 in all members of the household, but at levels of concern only in the scientist and his son (now aged 10). At the request of the local Department of Health we agreed to make confirmatory measurements of the levels in these two subjects.

Methods

Measurements were made in an iron room in the basement of Building 203, using the 6-inch diameter by 8-inch thick "log" crystal[1,2] and a new 11.5-inch diameter by 0.5-inch thick crystal with a thin window. Because of fluctuations in the radon concentration in the air in the room there was some instability of the counter backgrounds, and it was necessary to correct for this in some of the measurements.

The log crystal was used in tilting chair geometry to establish the general level of contamination in both subjects, and also in the multiposition method of Miller[1,2] with the subjects both supine and prone. The large-area thin crystal was similarly used in the multiposition technique,

0019299

but with the subjects supine only.

Calibration

The available sources of americium-241 had been prepared from a solution which had been standardised by absolute alpha counting. The detector (log crystal or thin crystal) was placed over the first position of the Presdwood phantom (Figure 1 of Reference 1), and the response was determined with a calibrated source placed in turn in each of the seven sections. This procedure was repeated with the crystal over each of the other six positions, to produce a 7 x 7 response matrix for the seven measurements made of the scientist's radioactivity. For his 10-year-old son, a much smaller phantom was prepared, and a 5 x 5 response matrix was obtained for the five measurements made of the boy's radioactivity.

Measurements were also made on two control subjects of similar builds to determine the response at 60 keV of the two detectors in the different geometries to the subjects' potassium-40 and caesium-137 contents. In Table 1 are set out the physical characteristics of the contaminated and control subjects, together with the counting-rates obtained in the energy

TABLE 1. Physical Characteristics of Contaminated and Control Subjects

	Height, cm	Weight, kg	Age, years	Counts/min,[a] 80-160 keV
Subject H	170	89	57	114.2
Control J.D.	169	88	50	112.4
Subject R	144	35	10	42.2
Control D.R.	144	39.5	10	44.0

[a] Measured with log crystal in chair geometry

band 80 to 160 keV (i.e., above the region of the photopeak at 60 keV from americium-241 but still in the energy region which is sensitive to the effects of body size). It can be seen that the control subjects are well matched

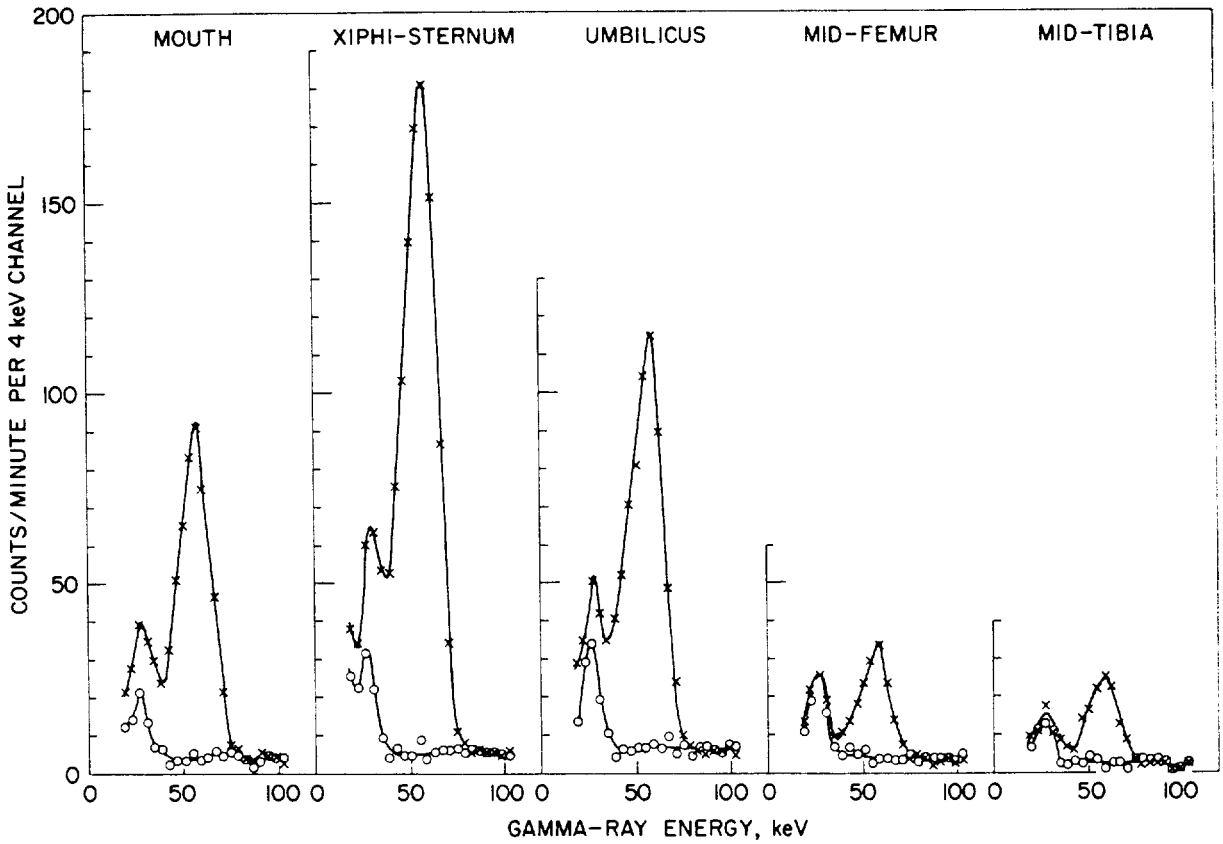

FIG. 1.--Gamma-ray spectra (20 to 100 keV) taken with the 11.5" x 0.5" crystal at five points above the supine subjects. The crystal was 30 cm above the bed and it was placed in turn over the indicated parts of the body. X, contaminated subject R; O, control subject D.R.

with the contaminated subjects in almost all respects. In Figure 1 are shown the gamma-ray spectra (20 to 100 keV) taken with the large thin crystal at five positions over the supine boys (contaminated and control subjects). The presence of americium-241 in the former is unequivocal.

The control subjects were also used to obtain calibration factors by determining the geometric mean of the counts observed with a calibrated source of americium-241 on the posterior and anterior surfaces of the subjects, at 7 or 5 points directly beneath the center of the respective detectors.

The counting-rates obtained in this way corresponded to the diagonals of the response matrices, and there were substantial differences between those obtained from the phantom and those from the control subjects. In Table 2 the sets of values are compared, for the 11.5-inch x 0.5-inch crystal. Differences are not unexpected, for in theory the geometric mean of counting rates on the posterior and anterior aspects of a phantom is not equal to the counting rate from a source at the center. Theoretical considerations show that for exponential absorption the former should exceed the latter by about 4% to 33% for a phantom thickness in the range 10 to 20 cm. However, the absorption of americium-241 gamma rays in Presdwood, determined with the large-area thin crystal, was not exponential because of the effects of forward scatter. Use of the experimental attenuation curve showed that the geometric mean of the two counting rates from a source on the surfaces should always be <u>less</u> than the counting rate from the source at the center, by an amount not greater than 11%. Thus the differences shown in Table 2 are not entirely due to the assumption that the geometric mean counting rate equals the counting rate with the source at the center. It seems likely, but has not been proved, that the principal cause of the differences is the

TABLE 2. Comparison of Response (counts/min/nCi) of Large-Area Thin Crystal to Americium-241 in Phantom with Geometric Means of Response to Sources on Posterior and Anterior Surfaces of the Control Subjects

	Counter Position Number						
	1	2	3	4	5	6	7
Large phantom	35.4	49.8	36.5	44.7	45.1	48.6	45.9
Control subject J.D.	27.7	31.4	27.5	25.0	34.2	30.3	26.2
Ratio	1.28	1.59	1.33	1.79	1.32	1.61	1.76
Small phantom	49.6	46.6	46.9	49.9	49.1		
Control subject D.R.	37.6	31.7	30.5	41.1	36.6		
Ratio	1.32	1.47	1.54	1.21	1.34		

inadequacy of the phantom (dimensions, shape, and composition). Thus, there is some uncertainty as to the more reliable sets of calibration data. Similar considerations apply to the data obtained with the log crystal.

A very approximate value for the body content of each subject was calculated from the measurements in chair geometry, using the potassium-40 as an internal standard. It was even possible to derive a result without a calibration for potassium; the necessary quantities are set out in Table 3.

TABLE 3. Data for the Calculation of Americium-241 Body Content from Potassium-40 Photopeak as Internal Standard

Subject	Wt, kg	Assumed K Concentration, g/kg body weight	Assumed Average Absorption Thickness, cm	^{40}K Counting Rate, counts/min
H	89	1.6	6	92.3
R	35	2.0	3	54.9

Specific γ-ray activity of potassium, 93 pCi/g; absorption coefficient in tissue at 1.46 MeV, 0.055 cm^{-1}; absorption coefficient in tissue at 0.06 MeV, 0.2 cm^{-1}; transmission of crystal can (0.05-cm steel) at 0.06 MeV, 0.644; photo-efficiency of log crystal at 1.46 MeV, 0.54; photo-efficiency of log crystal at 0.06 MeV (corrected for escape peak), 0.75; abundance of 0.06-MeV γ-ray in americium-241 decay scheme, 0.36.

For subject H the calculation for the counting efficiency for americium-241 is as follows

$$92.3 \times \frac{1000}{89 \times 1.6 \times 93} \times \frac{e^{-6 \times 0.2}}{e^{-6 \times 0.055}} \times \frac{0.75}{0.54} \times 0.644 \times 0.36 .$$

$$= 0.94 \text{ counts/min/nCi.}$$

Similarly, for subject R the counting efficiency for americium-241 was 1.8 counts/min/nCi. These calibration factors are probably not reliable to much better than a factor of about two.

Results

The simultaneous equations were solved by a matrix inversion method with the aid of a fast digital computer.

In Table 4 are set out the americium-241 contents of the two subjects computed from the multiposition γ-ray measurements with the two detectors. Two points are immediately apparent. First, despite considerable differences in the contents of the same regions as determined by the two detectors, the total contents are in respectable agreement (10%). The difference in the apparent distributions can be attributed to differences in detector positioning.

TABLE 4. Solutions of Matrix Equations

	Americium-241 Content, nCi			
	Subject H		Subject R	
Position Number	Log Crystal	Thin Crystal	Log Crystal	Thin Crystal
1	18.4 ± 1.5	4.2 ± 0.3	12.2 ± 1.0	3.2 ± 0.2
2	8.6 ± 2.3	17.3 ± 0.3	13.5 ± 1.6	17.4 ± 0.3
3	9.1 ± 2.5	8.6 ± 0.4	-3.3 ± 1.8	7.4 ± 0.3
4	1.4 ± 2.6	2.2 ± 0.3	1.8 ± 1.7	-1.8 ± 0.2
5	4.9 ± 2.7	2.6 ± 0.3	2.0 ± 1.3	2.4 ± 0.2
6	1.2 ± 2.8	4.0 ± 0.3		
7	2.2 ± 2.1	2.7 ± 0.2		
Total	45.8	41.6	26.2	28.6

Second, in the case of subject R, for the results from both detectors there is one position where the exact solution to the equation is negative. This is a consequence of the inadequacy of the phantom. The calibration matrices were such that the computed activity at position 2 (log crystal) or 3 (thin crystal) would contribute a higher counting rate than was observed at position 3 (log crystal) or 4 (thin crystal).

0019304

Thus we can put less faith in the values for the contents of the various regions than in the totals. However, the differences between the values along the diagonals of the calibration matrices and the geometric means of the response on posterior and anterior surfaces of the control subjects suggest that the values in Table 4 are probably all too low. If we multiply the results in Table 4 by the ratios of these responses we may obtain more reliable results and these values are shown in columns 2 and 4 of Table 5.

TABLE 5. Americium-241 Contents

	Log Crystal		Thin Crystal	
Position Number	Corrected Matrix, nCi	Empirical Method, nCi	Corrected Matrix, nCi	Empirical Method, nCi
Subject H				
1	21.2	10.8	5.4	10.8
2	18.1	29.2	27.5	22.3
3	12.0	9.3	11.4	13.0
4	2.5	8.0	4.0	6.0
5	7.7	5.1	3.5	4.0
6	1.8	4.8	6.4	5.5
7	2.8	4.3	4.7	5.4
Total	66.1	71.5	62.9	67.0
Subject R				
1	29.3	22.7	4.2	9.4
2	20.4	12.6	25.7	17.4
3	-4.9	5.3	11.4	10.8
4	2.9	2.7	-2.2	1.9
5	1.7	2.7	3.2	2.0
Total	49.4	46.0	42.3	41.5

Columns 3 and 5 of Table 5 contain results obtained by an alternative method. First, a value for the americium-241 content at each position was calculated from the observed net counting rate and the appropriate geometric mean response to the calibrated source. The values so obtained were all

overestimates because they ignored the contributions to the counting rates from activity in adjacent positions. Empirical (and approximate) corrections for this were derived from the phantom response matrix, by dividing the estimate at position i by the ratio

$$\frac{\sum_{j=1}^{j=n} C_{i,j}}{C_{i,i}} ,$$

where $\sum_{j=1}^{j=n} C_{i,j}$ is the sum of the responses of the counter in position i to the source in all n positions, $C_{i,i}$ is the response of the counter in position i to the source in position i, and n is 7 or 5. This correction factor would be exact only if there were equal activity in all n positions. However, since the response of the counter in position i to a source in position i ± 2 was not more than 5% of the response in position i, the error introduced by this empirical correction was not great. The total contents by this method were in quite good agreement with those from the matrix method after correction.

The best estimates we can make of the contents of H and R are 60 nCi and 40 nCi, respectively; the precision of the calibration does not warrant more than one significant figure. It is difficult to assess confidence limits on the estimated contents. Reliance solely on the phantom calibration matrix would give values about 25% lower; the uncertainty introduced by the assumption that the geometric mean rate is the same as that from a source in the center of the subject would raise the values by less than 10%. On the other hand, although the actual distribution within the body is not known, it is clear that the "effective" position of the americium-241 is not close to the center of any part of the body except perhaps the thighs and parts of the arm.

What does emerge from this analysis is that apparently about

three-quarters of the total content is in the upper half of the body in both subjects. If the distribution of the americium-241 is uniform throughout the skeleton (a major assumption of doubtful validity), this suggests that as much as half the total content could be in soft tissue, presumably liver and/or lung.

A single measurement was made with the thin crystal positioned over the liver of subject H. (An outline of the liver was cut out of a sheet of lead 3 mm thick which was used to shield the thorax and upper abdomen.) The americium-241 peak at 60 keV was clearly seen in the resulting spectrum; thus there was some evidence for activity in the liver.

The values for the total body contents from the measurements in chair geometry were 132 nCi and 193 nCi for subjects H and R, respectively. These are twice the values obtained from the detailed analysis described above, but in view of the imprecision of the calibration factors, there is no real inconsistency. An additional discrepancy arises because of the effect of distribution in the body; activity in liver or lung would be counted in the chair geometry with a higher efficiency than would activity in the whole skeleton.

There were several unsatisfactory features of the method adopted to derive the "best" estimates, in particular the empirical correction factors. Much work remains to be done to improve the method of calibration.

References

1. Miller, C. E. Multiple-crystal-position Technique for Whole Body Measurements. Argonne National Laboratory Health Division Gamma-Ray Spectroscopy Group Semiannual Report, January through June 1964. ANL-6839, pp. 12-17.
2. Miller, C. E. A New Technique for Determining the Distribution of Radium and Thorium in Living Persons. Assessment of Radioactivity in Man. Int. Atomic Energy Agency, Vienna, 1964, Vol. 1, pp. 67-77.