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Thorium in Occupationally Exposed Men[1]

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This work was done in conformity with policy of what was then the U. S. Department of Health, Education and Welfare on protection of human subjects. The scope of the work and protocol of procedures was approved by and monitored by the Argonne National Laboratory Review Committee for Research Projects Involving Human Subjects.

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Higher than environmental levels of ^{232}Th have been found in autopsy samples of lungs and other organs from four former employees of a thorium refinery. Working periods of the subjects ranged from 3 to 24 years, and times from end of work to death ranged from 6 to 31 years. Examination of the distribution of thorium among the organs revealed poor agreement with the distribution calculated from the dosimetric models in Publication 30 of the International Commission on Radioprotection (ICRP). Concentrations in the lungs relative to pulmonary lymph nodes, bone or liver were much higher than calculated from the model for class Y thorium and the exposure histories of the workers. Much better agreement was found with more recently proposed models in Publications 68 and 69 of the ICRP. Radiation doses estimated from the amounts of thorium in the autopsy samples were compatible with health studies that found no significant difference in mortality from that of the general population of men in the United States of America.

INTRODUCTION

This paper reports work done as an outgrowth of a study of the health status and body radioactivity of former employees of a thorium refinery (*1*). The plant produced thorium and rare-earth chemicals from ores and monazite sands from 1932 to 1973 and manufactured thorium mantles from 1936 to 1947. In studies of inhalation exposures at the refinery, Mausner (*2*) reported high concentrations of airborne ^{232}Th at the plant and high concentrations of ^{232}Th in autopsy samples from two former employees, and Stehney (*3*) pointed out that retention of thorium in the lungs appeared to be much higher than expected from the dosimetric models in Publication 30 of the International Commission on Radioprotection (*4*) for class Y aerosols.

The ICRP recently reviewed data on long term human retention of numerous radionuclides and proposed much longer retention of the actinides in new dosimetric models for the respiratory system (*5*) and internal organs (*6*). Additional measurements of the ^{232}Th concentrations in autopsy samples from former employees of the thorium refinery have been made (A. F. Stehney and H. F. Lucas, unpublished results), and these findings provided an opportunity to test whether the new models yielded a better fit to measured values than the model from ICRP Publication 30. In this paper, results of the test are reported, and the measured concentrations and dosimetric models are used to estimate the radiatiation doses from ^{232}Th inhaled by the thorium workers.

MATERIALS AND METHODS

Calculation from metabolic models of the amount of activity expected in autopsy samples requires knowledge of the duration of exposure of the subject and the interval from exposure to death. These time factors are shown in Table 1 as the work dates and year of death

for the four thorium workers for whom measurements of ^{232}Th in the lungs and at least one other organ were obtained.

Table 2 gives the geometric means of ^{232}Th concentrations in autopsy samples from each case, the standard errors of the geometric means (GSE), and the number of samples analyzed for each case and type of tissue. If only one sample was analyzed, the measured concentration and the standard error of the measurement are shown. As an adjustment for environmental exposure, the geometric means of autopsy samples from all men in two non-occupationally exposed populations studied by Wrenn et al. (7) were subtracted from the concentrations measured in the workers, and the adjusted concentrations are those actually shown in the table. Since samples from the former thorium workers had ^{232}Th concentrations 10 to 1000 times greater than the "normal" levels shown in the table, the adjustments for environmental exposure were trivial. For convenience, the adjusted concentrations shown in Table 2 are referred to in this paper as "measured" values.

The amounts of activity expected in autopsy tissues were calculated from the dosimetric models with equations of the type described in ICRP Publication 30 (*4*) or with the matrix method of Birchall and James (*8*). For subjects with multiple exposures, the activities calculated for each exposure were summed to obtain the total amount expected. Since the basic experimental data consisted of determinations of activity concentration, i.e., the amount of radioactivity in a tissue sample divided by the fresh sample weight, the expected values of these quantities for unit intake rates were estimated by dividing the calculated organ activities by organ masses based on those for Reference Man (9). For the skeleton, the wet fat-free mass (8000 g) was used, because this condition most closely resembles the type of bone sample

ordinarily used for laboratory measurements (7).

RESULTS

Comparison of autopsy data with ICRP dosimetric models

In Table 3, ratios of the measured concentrations of ^{232}Th in pulmonary lymph nodes, bone, liver, and kidneys to the measured concentration in the lungs are compared with the corresponding ratios calculated from the dosimetric models of the ICRP.. The two top values displayed for each subject under each organ heading are the measured ratio of organ concentration to lung concentration divided by the ratio calculated from the exposure history of that case, and the GSE of the measured ratio is shown on the next line. If the measured and calculated ratios were in good agreement, then these ratios of ratios would have values close to unity to within the limits implied by the GSEs.

Instead of unity, a wide range of values is seen for every case when the organ to lung ratio was calculated from the models in ICRP Publication 30, and some values differ from unity by factors of more than a hundred. Similar results were obtained for particle sizes with AMAD values of 0.1 μm to 20 μm. The calculated values included estimates of the amount of thorium in tissue that comprise the lungs and lymph nodes (as distinguished from activity deposited in air passages); disagreement with calculated ratios was even greater when these amounts of thorium were not included in the calculation of the expected amounts of thorium activity in the lung. Since values much less than one were obtained , it is evident that the thorium concentrations calculated for the lungs of the thorium workers were too low and/or that the concentrations calculated for the other organs were too high. It may also be noticed that the lowest ratios were found for subjects with the longest times between the end of exposure and death, an indication

that the respiratory model in Publication 30 underestimates retention of thorium in the lungs.

The second line for each subject and each tissue shows the results of analyses made with organ to lung ratios calculated from the model for the respiratory system described in ICRP Publication 68 (*5*) and the new biokinetic model of ICRP Publication 69 (*6*). Since the biokinetic model involves feedback of material to the blood, equations of the type described in Publication 30 were not applicable for calculation of transfer between compartments. Instead, the matrix method of Birchall and James (*8*) was used for the complete system of respiratory and metabolic compartments that comprise the new ICRP compartmental model for thorium. The results indicate quite good agreement between measured and calculated ratios for almost all of the organs.

Inhalation rates and dose equivalents

Although only the organ to organ ratios of thorium concentrations were used when testing the models, the quantity actually calculated for each organ was the concentration per unit inhalation rate of thorium activity (Bq d^{-1}), so estimates of the thorium intake rate of a subject averaged over every day of his exposure period could be obtained by dividing the measured concentration in each organ by the concentration calculated for that organ. Each organ provided an estimate of the inhalation rate, and how well the estimates agreed for a given subject depended on how well the calculation model provided a good fit to the measured body distribution of thorium.

The ratios of the measured concentration of ^{232}Th in autopsy samples to the concentrations calculated from the new ICRP models are shown in Table 4. These estimates of daily intake for the thorium workers agree to within a factor of 10 with a mean (± SE) of 0.33 ±

0.27 Bq d^{-1} (120 ± 90 Bq y^{-1}) for the 13 values that do not include those from L1521 who seems to be in a class by himself (*vide infra*).

SUMMARY AND DISCUSSION

From Table 3, it is evident that the new ICRP models give much better agreement with the observed long-term retention and distribution of inhaled thorium in men than the dosimetric models described in ICRP Publication 30. The improved agreement probably is due to the longer retention half-times that were introduced into the models. The new model for the respiratory system (*5*) includes half-times of 700 and 7000 days for retention of thorium in the lungs instead of the longest half-time of 500 days in the earlier model, and the new biokinetic model for thorium (*6*) includes half-times of 1 y and 9 y instead of 700 days. Acceptance of the new models may lead to less restrictive limits on thorium exposure being set by regulatory agencies (*10*).

Differences between measured concentrations of thorium in autopsy samples and concentrations calculated with the new models may reflect variability in the aerosols inhaled by the thorium workers. Aerosols at the thorium refinery included monazite sands and compounds such as thorium nitrate and thorium oxides in various stages of drying and grinding, so job differences among the workers might well have involved exposure to the various kinds of aerosols in different proportions. Physical evidence of the inhalation of unusually insoluble thorium aerosols by subject L1521 was obtained when more than 10% of the ^{232}Th in lung samples from this subject was found in large residues remaining after attempted dissolution of the samples, whereas lung and lymph samples from the other thorium workers left much smaller residues that contained little or no thorium. In addition, large amounts of rare earths were found

in the lungs of L1521[3], so the matrix material in which thorium was inhaled may have been qualitatively different from that of the other cases and/or the sheer mass of material may have impaired lung clearance. Subject L1521 worked in the rare-earth production facility of the plant for many years (Table 1), and he specifically mentioned working on production of "glass polishes", which are refractory rare-earth compounds, in describing his work.

Except for L1521, the average annual intake of ^{232}Th calculated for all tissue samples from the thorium workers was 120 Bq. Dividing by the occupational breathing rate of 2400 m^3 y^{-1} yields an estimate of 0.05 Bq m^{-3} as the mean concentration of ^{232}Th inhaled in air at the refinery. This concentration is at the low end of the values of 0.05 to 5 Bq m^{-3} that have been reported for the plant (*2, 11*), but it seems like a reasonable representation of intake by individuals averaged over long periods of time.

The committed effective dose would be about 0.005 Sv for each year of intake of 120 Bq ^{232}Th and 120 Bq of ^{228}Th (*5*). Since only 20% of all employees of the thorium refinery worked a year or more (*12*), the committed doses from inhalation of thorium probably would not be much more than about 0.005 Sv as an average for the entire workforce. On the basis of a total cancer mortality risk of about 0.01 Sv^{-1} (*13*), it appears that internal doses from exposure to thorium at the refinery would not have had a significant effect on cancer mortality of the workers. This is consistent with mortality studies of the employees of the thorium refinery that have been done principally by means of standardized mortality ratios (SMR), i.e., the ratio of the number of deaths in the study group to the number expected on the basis of U.S. death rates. An early study of deaths among 3039 male workers (*12*) found SMRs greater than unity for all causes combined (SMR = 1.05), cancers of the digestive organs (1.34), and lung cancer (1.44),

but none of these ratios were statistically significant at the 95% level. A second study (*14*) extended the follow-up period from 1976 to 1982 and found that the SMRs were slightly above statistical significance for deaths from all causes (95% confidence interval = 1.05 - 1.21), from all cancers (1.04 - 1.43) and from lung cancers (1.02 - 1.78), but deaths from cancers of the digestive organs decreased considerably in significance. Dose-response relationships could be tested only with secondary measures of possible radiation exposure such as job class and length of employment, and no significant effect on lung cancer from these factors was found. Probably, the most significant finding of the mortality studies was the absence of a "healthy worker effect" in which working populations have death rates substantially below those of the general U.S. population. Chen et al. (*15*) also reported no health effects that could be ascribed to thorium radioactivity in miners whom they have studied but mentioned the possibility of respiratory diseases due to the sheer mass of inhaled material.

CONCLUSIONS

The new respiratory and biokinetic models of the ICRP (*5, 6*) provided much better fits to the measured distribution of ^{232}Th in body organs from former thorium workers than provided by previous models (*4*). The improvement was probably due mostly to ascribing longer retention times for thorium in the lungs and thorium in the liver. Radiation doses from inhaled ^{232}Th and ^{228}Th were deduced to be at levels not likely to lead to observable health effects.

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Table 1. Case data for former thorium workers.

Subject	Job	Job dates at plant	Years on job	Year of death (age)	Cause of death
L0770	Millwright	1948	0.2	1981 (63)	Auto
	Electrician	1959-1966	6.6		accident
L1521	Laborer	1950-1958	7.7	1983 (63)	Cancer of
	Rare-earth prod'n	1958-1973	15.2		pancreas
L2107	Laborer	1938-1942	3.0	1979 (58)	Cancer of
	Fireman	1945-1947	1.9		esophagus
	Th production	1954-1973	18.9		
L2932	Laborer	1941	0.6	1976 (72)	Heart
	Truck driver	1943-1945	2.5		failure

Table 2. Adjusted concentrations of ^{232}Th in autopsy samples (mBq g^{-1}): geometric means and geometric standard errors (GSE) of the measured values in N samples of each type of tissue.[a]

Subject	Lung	PLN[b]	Bone	Liver	Kidney
L0770	1.74	5.40	0.70	0.17	na[c]
GSE (N)	1.10 (2)	(0.26)	1.28 (4)	(0.01)	
L1521	67.1	1210.	0.58	0.15	na
GSE (N)	1.19 (3)	(40)	1.17 (4)	1.15 (2)	
L2107	12.1	30.5	na	0.68	0.066
GSE (N)	1.29 (9)	2.01 (2)		(0.03)	(0.004)
L2932	0.23	3.64	0.15	0.013	0.007
GSE (N)	1.53 (2)	(0.20)	1.10 (2)	(0.003)	(0.002)
Normals[d]	0.0125	0.22	0.0039	0.0015	0.0018
GSE (N)	1.22 (20)	1.15 (17)	1.23 (15)	1.28 (18)	1.26 (18)

[a]If only one sample was measured, the standard error of the measurement is shown in parentheses below the measured value.
[b]PLN = pulmonary lymph nodes. [c]na = not available.
[d]Geometric means of measurements of samples from men in two general populations (*7*).

Table 3. Ratios of concentrations of ^{232}Th in organs to concentrations in the lungs: comparison of measured ratios with ratios calculated from dosimetric models from ICRP 30 (class Y, 1μm aerosols, $f_1 = 2E\text{-}4$) or from ICRP 68 and ICRP 69 (class S, 5μm aerosols, $f_1 = 5E\text{-}4$).

		Measured (organ/lungs)/Calculated(organ/lungs)			
Subject	Model	PLN	Skeleton	Liver	Kidneys
L0770	ICRP 30	2.2E-04	3.0E-03	7.4E-02	na
	ICRP 68+69	0.17	1.08	1.39	
	(GSE[a])	(1.32)	(1.30)	(1.30)	
L1521	ICRP 30	6.1E-03	3.5E-04	6.6E-03	na
	ICRP 68+69	1.03	0.023	0.033	
	(GSE)	(1.36)	(1.26)	(1.25)	
L2107	ICRP 30	4.9E-03	na	6.2E-01	5.4E-01
	ICRP 68+69	0.22		1.36	0.10
	(GSE)	(2.11)		(1.43)	(1.43)
L2932	ICRP 30	7.4E-06	4.3E-05	7.5E-03	3.3E-02
	ICRP 68+69	0.37	0.57	0.32	1.54
	(GSE)	(1.64)	(1.55)	(1.71)	(1.91)

[a]Geometric standard errors of the measured ratios.

Table 4. Ratios of measured concentrations of ^{232}Th in autopsy samples to the concentrations calculated for unit daily intake.

Subject	Lungs	PLN	Skeleton	Liver	Kidneys
L0770	0.59	0.09	0.61	0.78	na
L1521	6.4	6.5	0.15	0.21	na
L2107	0.73	0.16	na	0.1	0.09
L2932	0.49	0.18	0.28	0.16	0.076

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