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World-wide Distribution of Strontium-90 and its Uptake in Man[1]

By J. Laurence Kulp, Professor of Geochemistry

Introduction

With the first identification of Sr^{90} in foodstuffs and human bone in 1953 it became evident that a thorough understanding of the movement and uptake of Sr^{90} in man was essential while the concentrations were still small. The research program at Columbia University has been directed primarily at the actual distribution of Sr^{90} in the world population. In addition studies have been made of the geochemical and biochemical mechanisms that are involved in the movement of the Sr^{90} from the atmosphere to the human skeleton. Previous results of this program including the analytical and radiometric techniques have been described elsewhere (1–4).

The ultimate objective of this research is to be able to predict with considerable accuracy the average Sr^{90} content and the nature of the distribution around this average for any segment of the world population at any time in the future given a certain pattern of nuclear testing. This then will provide the basic data for the medical scientists who must assess the potential hazard.

The important parameters for such predictions are:

1. The quantity of fission introduced into the atmosphere with specification of time, altitude and location.
2. Rate and mechanism of transfer from stratosphere to troposphere.
3. Mean annual rainfall distribution.
4. The local diet, particularly with regard to the calcium-rich components.
5. Place of origin of foodstuffs in diet.
6. Discrimination factor between strontium and calcium from food to bone.

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[1] Lamont Geological Observatory cont. No 299.

7. Age of the individual.

8. Distribution of common strontium and Sr^{90} in present groups of the population.

With these factors in hand it then becomes possible to predict for any given program of nuclear testing how much Sr^{90}, for example, a 12-year-old boy in Bangkok, New York, Cape Town, or the Amazon jungle would have on the average in 1978 and the distribution curve for 12-year-olds at each locality.

Libby and *Stewart* (5) have summarized the current knowledge on the atmospheric problems. It is clear that the least well-defined factors at present are the quantity of Sr^{90} in the stratosphere, the mean residence time in the stratosphere, and the total world fallout. If the reasonable assumption is made that the bulk of the fallout in the North Temperate Zone is from atomic debris which a) did not enter the stratosphere or b) has a short residence time in the stratosphere (because of the northerly latitude in which it was injected), then these factors can be ignored. In this case the total fission produced can be compared directly with the current food levels.

The existing data on fallout show a rough correlation with integrated rainfall for a restricted latitude zone. Once on the ground, the Sr^{90} remains in the top few inches of the soil and the concentration available for plants and eventually man is primarily determined by the exchangeable calcium content of the soil. The soil-plant relationship is extremely complex due to the sharp vertical gradient of Sr^{90} in the ground; hence this step in the transfer of Sr^{90} is not readily subject to quantitative treatment. On the other hand, the discrimination factors from grass to milk and from food to human bone are now fairly well known, so that food analyses permit accurate estimates of bone levels.

It is the purpose of this paper to report the present bone levels, to compare these with fallout and diet and to indicate on the basis of these data what certain future levels may be.

Sr^{90} in Human Bone

Autopsy samples of human bone are now being received from about 30 stations in a world-wide network (fig. 1). Already several thousand have been or are being analyzed. Samples have been rather evenly distributed with regard to age. An attempt has also been made to obtain a maximum spread in geographic and dietary setting but the restriction in the location of medical centers has limited the samples largely to urban populations.

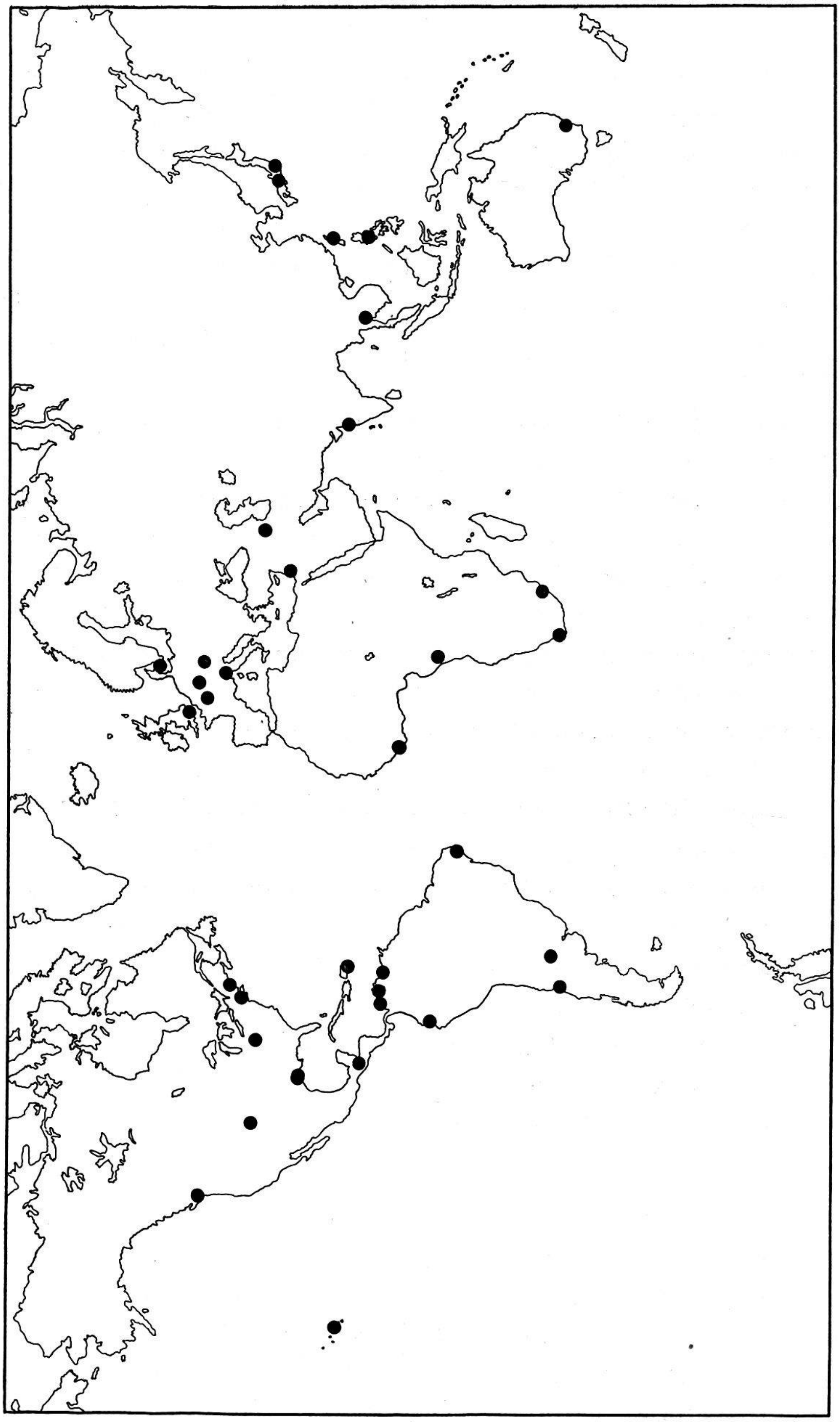

Fig. 1. World-wide bone collection stations.

Skeletal Averages from Single Bones

Since most of the samples are a single bone (normally rib, vertebrae or femur), it is necessary to establish the correction factors which relate a particular bone type to the whole skeleton. Experiments have been conducted (table 1) using 1. single dose Sr^{85} spike in terminal patients, 2. actual Sr^{90} distribution among adult bones, and 3. common strontium distribution. Within the experimental error common strontium is uniformly distributed in the skeleton. This should be the situation for Sr^{90} 1. if a uniform diet is ingested for a lifetime, and 2. in young children who are building bone nearly in equilibrium with the diet. The Sr^{90} dose to adults who are merely exchanging, not building, bone at a slow rate approaches the Sr^{85} experiment.

Table 1

Distribution of Sr^{90} in Adult Skeleton

Method	Investigator	Vertebrae skeleton	Rib skeleton	Long bone skeleton
Sr^{85} spike, autopsy	*Schulert* et al. (1958)	4.8±0.4	2.0±0.2	0.68±0.06
Sr^{90}, N.Y. 1956 cadavers	*Schulert* and *Kulp* (1958)	3.3±0.3	2.0±0.3	0.86±0.13
Common strontium	*Thurber* et al. (1958)	0.9±0.1	0.9±0.1	1.0 ±0.1

These results are used to correct analyses of individual bones to whole skeletons in the case of adults. No correction is made for children whose bones most closely approximate uniform distribution. Preliminary Sr^{90} results on a few children's skeletons confirm this procedure.

Present Levels

The bone data for 1956–57 are summarized in table 2. Note that the adult levels from 20 years and up are essentially constant, independent of age. The Northern Hemisphere averages about twice that of the Southern Hemisphere. The entire world average at the end of 1956 was about 0.2 $\mu\mu c$ Sr^{90}/g Ca.

Age Effect

The data for the U.S. and Western Europe are shown in fig. 2. The solid curve is calculated using the following five assumptions:

a) The Sr^{90} content in the diet of the U.S. and western Europe is known from the milk and food analyses made by the *Harwell* group, the Health and Safety Laboratory of the U.S. Atomic Energy Commission, and the Geochemical Laboratory at Columbia University (2).

Table 2

World-wide Distribution of Strontium-90 in Man – July 1, 1956 to June 30, 1957

(All values are given in micromicrocuries of strontium-90 per gram of calcium normalized to the whole skeleton. The figures in parentheses give the number of samples in the category)

Location	Age at death (years)								
	0–4	5–9	10–19	20–29	30–39	40–49	50–59	60–80	20–80 (average)
North America	0.67 (30)	0.69 (17)	0.38 (15)	0.07 (14)	0.06 (9)	0.08 (16)	0.05 (5)	0.07 (18)	0.070 (62)
South America	0.16 (3)	0.20 (1)	0.19 (5)	0.03 (5)	0.02 (2)	0.03 (2)	0.06 (3)	0.01 (1)	0.034 (13)
Europe	0.65 (2)	0.34 (4)	0.34 (9)	0.06 (20)	0.07 (4)	0.04 (6)	0.06 (1)	0.08 (2)	0.059 (33)
Africa			0.06 (2)	0.03 (2)	0.03 (3)	0.04 (4)			0.035 (9)
Asia	0.93 (1)	0.12 (2)	0.32 (2)	0.06 (8)	0.04 (6)	0.12 (8)	0.06 (5)	0.05 (5)	0.070 (32)
Australia	0.75 (3)	0.60 (2)			0.03 (3)	0.03 (4)	0.03 (3)		0.030 (10)
Entire world	0.64 (39)	0.57 (26)	0.30 (33)	0.059(49)	0.047(27)	0.070(40)	0.052(17)	0.065(26)	0.060 (159)

World average = 0.20

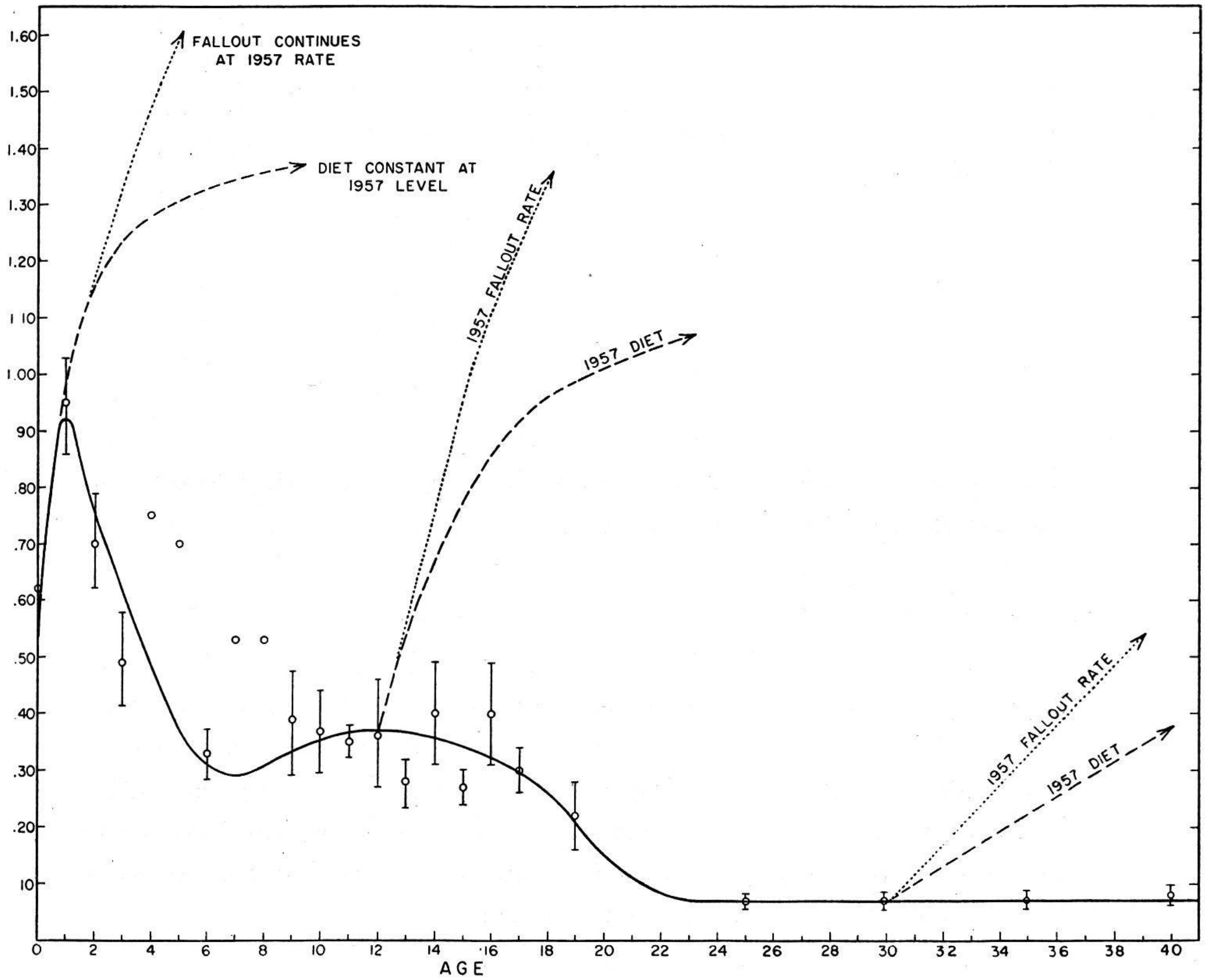

Fig. 2. Theoretical and observed Sr^{90} level in northern hemisphere bone at end of 1956.

b) The discrimination factor between food and bone is 4 (table 3 and reference 6).

c) The yearly deposition of calcium in children from birth to 20 years is that given by *Mitchell* et al. (7).

d) The fetal protective factor is 2 (8).

e) The rate of exchange of calcium in adults is about 2 per cent per year.

The experimental points follow the theoretical curve with the exception of four ages (4, 5, 7 and 8) each set of which contained one very high value (1.5 to 2.4 $\mu\mu c$ Sr^{90}/g Ca). It is expected that an improved fit will be obtained or more samples become available.

The highest concentration occurs in 1-year-olds in the present state of strong disequilibrium. The minimum around age 6 is a reflection of the bone growth curve. It is evident that for purposes of examining

Table 3

Sr/Ca Discrimination – Food to Bone

Species	Investigator	Method	$\frac{\text{Sr/Ca food}}{\text{Sr/Ca bone}}$
Rat	*Comar* et al. (1956)	Sr^{85}/Ca^{45}	3.7
	Macdonald (1956)	Sr/Ca	3.7
Sheep	*Bryant* et al. (1956)	Sr/Ca	4.2
		Sr^{90}/Ca	4.3
Man	*Schulert* et al. (1957)	Sr^{85}/Ca^{45}	4.0
		Sr^{90}/Ca	4.0

distribution in a population nearly at equilibrium with its diet, the 14- to 18-year group would be best.

Growth Curves for Next Five Years

Prediction curves are also drawn for people who in March of 1958 are 1, 12, and 30 years old, respectively. The curves show their average skeletal level in the next 5 years on two assumptions: a) that atomic tests stop today and that the stratospheric fallout just equals the radioactive decay of the Sr^{90} in the atmosphere-geosphere-biosphere reservoir; b) that the fallout rate on northeast U.S. and England of 10 mc/mi^2/year observed during 1957 continues at this rate.

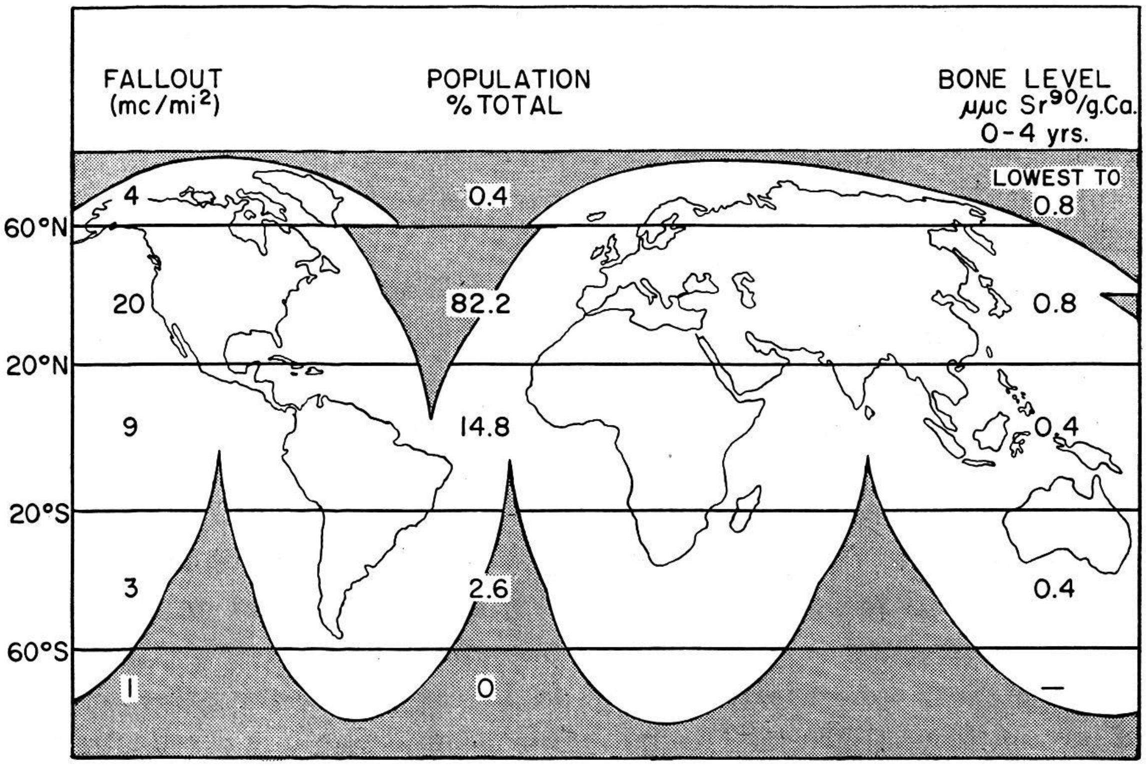

Fig. 3. Latitude effect March 1958 (Equal Area Projection).

Latitude and Time

Comparison of estimated fallout of Sr^{90} in mc/mi^2, population and bone level for various latitude sectors are shown in fig. 3. It appears that the bone levels in the Southern Temperate Zone may be held up somewhat from food from the Northern Hemisphere.

The increase in the Sr^{90} content with time is most clearly displayed by analyses of average diet and a large number of total body ash samples from New York City (fig. 4).

In passing it might be noted that radium analyses (table 4) on these unusual total body samples and composites of bones from the worldwide collection network give the most complete picture of natural radium levels in the human population so far and that the effective radiation to the bones of young children from Sr^{90} now exceeds the radium dose by about a factor of 3. On the other hand the Sr^{90} dose is still a small fraction of the total dose from natural background. This work will be reported in detail elsewhere (9).

Distribution in the World Population

The distribution of radium and common strontium in the whole body ash of New York City cadavers is approximately normal[1] with a standard

Table 4

Radium in Human Bone

		Ra content of ash (10–14 g Ra/g)		
Investigator	Locality	Average	Number samples	Range
Krebs (1942)	Germany	500.0	18	<30–1800
Hursh and *Gates* (1950)	9 states	5.0	27	1.9 – 9.0
Palmer and *Queen* (1956)	18 states 11 countries	1.6	50	0.6 – 5.0
Muth et al. (1957)	Frankfurt	13.0	14	5.0 –31.0
Kulp and *Eckelmann* (1957)	8 countries	1.4	21	0.13– 4.0
Walton, Kologrivov, Kulp (1958)	N.Y. City cadavers	0.9	150	0.24– 5.3
	20 countries (composite)	1.2	200	0.35– 3.6

Best Estimate:

World average radium burden 0.03 $\mu\mu c/g$ Ca
Northern Hemisphere Sr^{90} (0–5 years) March 1958 0.80 $\mu\mu c/g$ Ca

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[1] Recent data on many additional samples indicate a distribution that is closer to lognormal than normal. These will be published subsequently in *Walton* et al. (9) and *Thurber* et al. (6)

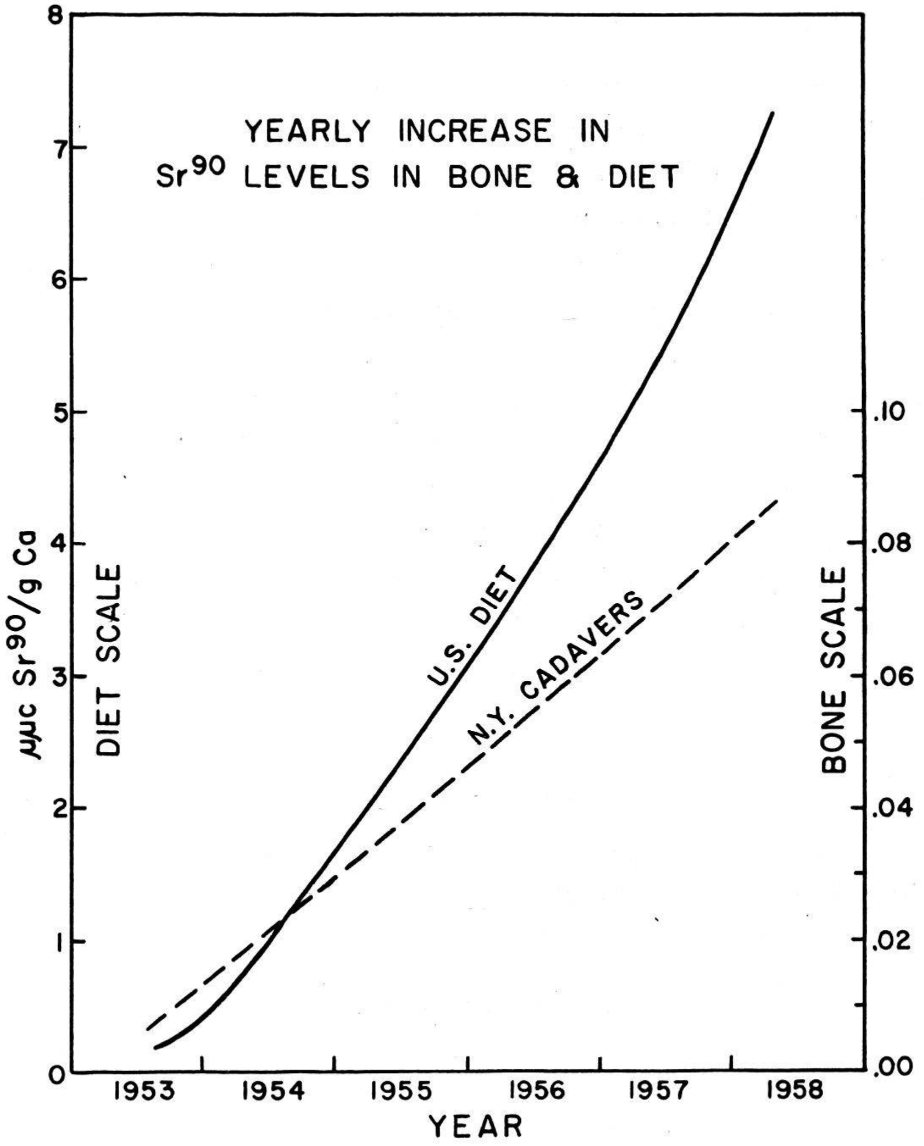

Fig. 4.

deviation of 30 to 35 per cent of the mean. Fig. 5 shows these relations as well as the present histograms for Sr^{90} distribution in Northern Hemisphere teenagers and the New York whole skeleton samples. Since the human bone even for children is far out of equilibrium with the diet, it is not surprising that the spread is somewhat larger for the Sr^{90} than the common strontium or the radium. It would be expected, however, that if the concentration of Sr^{90} in the diet becomes constant, the Sr^{90} distribution in all urban centers as well as those suburban and rural areas of western culture which experience the pooling of food should approach that of common strontium. It can therefore be concluded that the monitoring of the Sr^{90} concentration in food and bone at a limited number of centers should ultimately permit definition of the average content and the distribution of Sr^{90} in a large fraction (possibly 80 to 90 per cent) of the world's population.

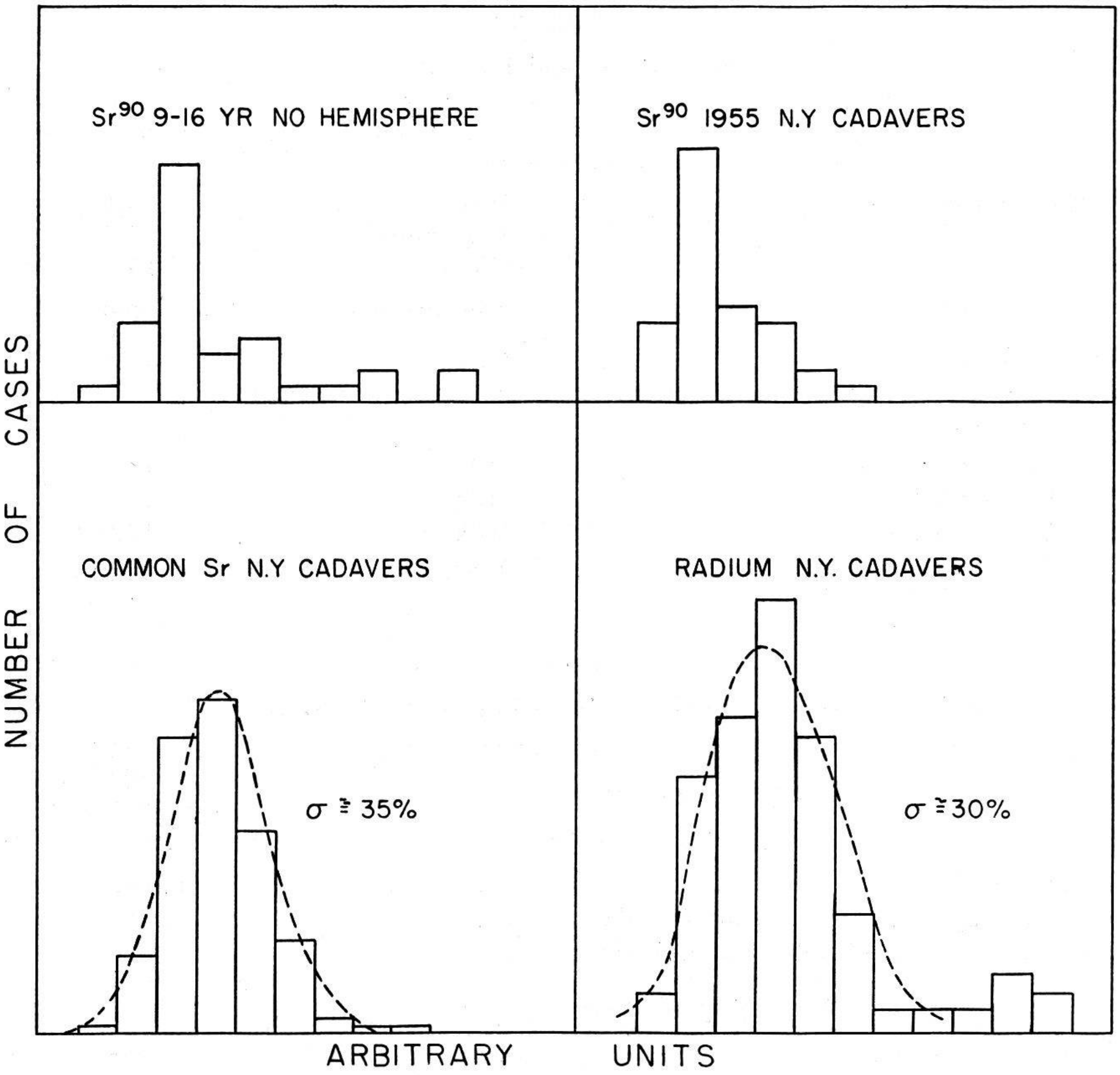

Fig. 5.

Widespread spot sampling of foods and milk in the U.S., adjacent to many of the bone stations, and in a north-south section through Central and South America shows that serious anomalies are rare. Table 5 shows the average Sr^{90} in the diet of most of the U.S. and United Kingdom in 1957. In addition, the important anomalies that have been discovered by the Harwell investigators (10), the New York Operations Office (11) and the Lamont laboratory are summarized. It is evident that a limited number of localities in the North Temperate belt have sufficiently low calcium content in the soil to raise the milk level by about a factor of 2 above the average. The Mandan samples are output from a powdered milk plant and the Kentucky samples represent liquid milk from two counties. Assuming that this milk is consumed locally it may be concluded that the people who may experience this level will be considerably under 0.1 per cent of the population.

The Ecuadorian yuca represents the major calcium food for the iso-

Table 5

Sr^{90} in Diet and Food 1957

Region	Food	$\mu\mu$c Sr^{90}/g Ca
United States	Milk	6.1
	Vegetables	8.7
	Cereals	13.5
	Average diet	6.6
United Kingdom	Milk	∼7.0
High localities		
Mandan, South Dakota	Milk	17.0
Londonderry, U.K.	Milk	10.0
Kentucky	Milk	14.0
Eastern Ecuador	Yuca	40.0

Table 6

Present and Predicted Bone Levels of Strontium-90

Situation or condition	Level ($\mu\mu$c Sr^{90}/g Ca)
Industrial MPC*	1000
Large-population or young-children MPC	100
Average background radiation equivalent	50
March 1958 Averages	
World	0.25
North American children (0 to 4 years)	0.85
North American adults	0.09
Predicted equilibrium value, North America	1.7
Predicted equilibrium value, Southern Hemisphere	0.8
Futures Averages	
No further testing	
Children (0–4) Northeast U.S. 1978	1.5
Adults Northern Hemisphere	0.6
Continuous fallout of 10 mc/mi^2/year	
Population in Northern Hemisphere (A.D. 2100)	∼20.0

* Maximum permissible concentration recommended by the International Committee on Radiation Protection.

lated jungle Indians of the Upper Amazon Basin. The high Sr^{90} concentration is due to the severe leaching of the calcium from the soil under the high temperature, high rainfall conditions. The fallout is essentially normal for the latitude and the rainfall (i.e. 5 mc/mi^2). It is concluded that the equilibrium bone level for this relatively small segment of the world population (certainly less than 0.01 per cent) is now 5 to 10 $\mu\mu$c

Sr^{90}/g Ca. Further work is being done to define the Sr^{90} level and population of the primitive people who live under such conditions of diet.

Future Levels

The present and predicted average bone levels of Sr^{90} are low compared to the average background radiation and the current maximum permissible concentrations recommended by the International Committee on Radiation Protection.

If there is no further testing it is assumed that the stratospheric drip will just equal the radioactive decay of Sr^{90}. If the fallout in the Southern Temperate Zone is representative of the long-term stratospheric fallout the above assumption appears warranted. Under these conditions young children will reach 1.5 $\mu\mu$c Sr^{90}/g Ca and adults about 0.6 $\mu\mu$c Sr^{90}/g Ca by 1978.

If testing continues of such a character and at such locations to produce a steady fallout of 10 mc/mi^2/year as has occurred in much of the North Temperate Zone in 1957 equilibrium would be approached about 2100 A.D. with a population burden of about 20 $\mu\mu$c Sr^{90}/g Ca. Presumably the population average should reach 10 $\mu\mu$c Sr^{90}/g Ca before the year 2000 A.D.

It is concluded that the distribution of Sr^{90} in the world population and the mechanisms by which it proceeds from a nuclear test to human bone are now fairly well known. Although the present level of Sr^{90} produces only a small increment to the radiation dose from natural background sources, the problem is not trivial. Continued testing requires vigilant monitoring and a more precise definition of each important factor which affects the uptake of Sr^{90} in man. It should also be noted that such studies will provide the basic scientific data for controlling the environment in the event of a reactor accident.

Summary

The Sr^{90} concentration in the bones of young children in the Northern Hemisphere is about 1 $\mu\mu$c per gram of calcium. The level in adults is about ten times lower and is independent of age. People in the Southern Hemisphere carry a burden about half of that in the Northern Hemisphere. Results from a world-wide network of sampling stations, which have already supplied thousands of samples, are interpreted in terms of diet, latitude and time. The common strontium and radium concentrations in people in an urban area appear to be normally distributed with a standard deviation of 30 to 35 per cent of the mean. This should be the case for Sr^{90} as equilibrium with the diet is approached. The distribution curve for the entire world population is discussed. Future Sr^{90} concentrations in human bone are predicted taking various assumptions on the rate and kind of nuclear testing.

Zusammenfassung

Der Sr^{90}-Gehalt des Kleinkindknochens beträgt in der nördlichen Hemisphäre etwa 1 $\mu\mu$c pro g Calcium. Der Gehalt bei Erwachsenen ist ungefähr 10mal kleiner und vom Alter unabhängig. Die Bevölkerung der südlichen Hemisphäre weist einen halb so großen Strontiumgehalt auf als jene der nördlichen Hemisphäre. Ergebnisse eines über die ganze Erde verstreuten Netzes von Versuchsstationen, welche bereits Tausende von Proben eingebracht haben, werden unter Berücksichtigung von Diät, geographischer Breite und Zeit gedeutet.

Die gewöhnliche Strontium- und Radiumkonzentration bei Menschen eines Stadtgebietes scheint bei einer Standardabweichung von etwa 30–35% vom Mittel eine normale Verteilung aufzuweisen. Dasselbe sollte für Sr^{90} der Fall sein, da der Gleichgewichtszustand mit der Diät beinahe erreicht ist. Es wird der Versuch gemacht, für die Bevölkerung der ganzen Erde eine Verteilungskurve zu berechnen. Diese Erhebungen werden mit der natürlichen Umgebungsstrahlung verglichen. Zum Schluß werden die zu erwartenden Sr^{90}-Konzentrationen im menschlichen Knochen an Hand von Vermutungen über die künftige Zahl und Art der Kernversuche erwogen und abgeschätzt.

Résumé

La concentration du Sr^{90} dans les os de jeunes enfants de l'hémisphère nord est d'environ 1 $\mu\mu$c par g de calcium. La teneur chez les adultes est environ dix fois plus faible, elle est indépendante de l'âge. Les populations de l'hémisphère sud ont une teneur d'environ la moitié de celles de l'hémisphère nord. Les résultats livrés par tout un réseau mondial de stations de prélèvement et d'étude ont déjà donné des milliers d'épreuves, qui seront interprétées en fonction de la latitude, du temps et du type d'alimentation. La concentration du Sr et du radium des gens d'une population urbaine semble montrer une variabilité normale avec une déviation standard de la moyenne d'environ 30–35%. Ceci devrait être le cas également pour Sr^{90} puisque l'équilibre avec la diète est à peu près atteint. Les efforts actuels tendent à calculer la courbe de distribution pour la population du globe toute entière. Les moyennes obtenues seront comparées aux irradiations provenant de sources naturelles. On essaie enfin de prévoir la concentration du Sr^{90} dans le sque-

lette humain sur la base de suppositions concernant la fréquence et le genre d'expériences futures d'explosions nucléaires.

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