IMPLICATIONS OF ENVIRONMENTAL STRONTIUM 90 ACCUMULATION IN TEETH AND BONE OF CHILDREN

HAROLD L. ROSENTHAL
WASHINGTON UNIVERSITY SCHOOL OF DENTISTRY

1. Introduction

In order to define and document possible hazards of environmental radioactive pollutants that occur from fallout or nuclear reaction emissions, my laboratory has been studying the accumulation of strontium 90 in teeth and bone of children as related to dietary consumption of the nuclide. Following the suggestion of Kalckar [1], we selected to study strontium 90 for the following reasons:

(1) Strontium 90, deposited during formation of stable calcified tissues, such as teeth, represents a marker atom that indicates the maximum amount of nuclide deposited during formation of the teeth.

(2) Strontium is biochemically similar to calcium and is permanently deposited in calcified tissues.

(3) Strontium 90 is a potentially hazardous nuclide because of its long physical half-life ($T/2 = 28$ yrs.) and its very slow biological turnover time, ranging between no turnover for teeth to less than eight per cent per year in vertebral bone [2].

We have concentrated our studies on deciduous and permanent teeth because deposition of alkaline earth radionuclides is only minimally affected by such factors as mineral turnover, exchange, accretion, and remodeling during the time the tooth crown is formed. Thus, the concentration of radionuclide in the tooth crown represents the equilibrium established between the crown and the diet at the time the crown is mineralized. Once the crown is complete, the nuclide concentration becomes a permanent record and is representative of the total mineralization process when mineralizing tissues are in their most active metabolic state.

Our previous data [3], [4], [5], [6] demonstrated that the accumulation of strontium 90 in the deciduous and permanent teeth of children was adequately described by a linear equation of the form $C_T = KC_D$ where C_T and C_D represent tooth crown and diet strontium 90 concentrations respectively, and K is a constant. The constant K differs for each specific kind of tooth formed *in utero* and after birth (Table I), chronological age for tooth development, attendant discrimination factors, and other factors as far as they are known.

TABLE I

FRACTION OF TOOTH CROWN DEPOSITED DURING TOOTH DEVELOPMENT

Tooth	Prenatal (X)	Postnatal (Y)
Fetal buds	1.00	0.00
Incisor (deciduous)	0.32	0.68
2nd molar (deciduous)	0.05	0.95
1st bicuspid (permanent)	0.00	1.00

A theoretical expression for the Sr 90/g calcium of teeth (C_t) was derived by expansion of the basic equation of Reiss [7]

$$C_t = X \text{ prenatal Sr 90/g Ca} + Y \text{ postnatal Sr 90/g Ca.} \tag{1}$$

The factors X and Y represent the fraction of tooth crown calcium deposited during pre- and postnatal periods respectively. These factors vary with the kind of tooth as shown in Table I.

In order to account for dietary intake and discrimination factors, equation 1 becomes:

$$C_t = (X)(A)C_d^m D_m + (Y)(A)C_d^I D_I, \tag{2}$$

where C_d^m is the mother's dietary intake of Sr 90/g calcium from commercial milk, D_m is the discrimination factor against strontium 90 between dietary intake and calcified tissue. The variable A relates the concentration of Sr 90/g calcium in milk to that of the total diet, and varies with the dietary habits of the individual. For pregnant mothers, A is estimated to be equal to 1.6. For bottle-fed infants during the first year of life the value is 1.0 and for pre-adolescent children between one and 14 years of age, the value is about 1.2.

In order to solve equation 2, values for D_m and D_I must be experimentally determined. A discrimination factor of 0.18 for D_m appears reasonable (see end of Section 3). A value of 0.8 for D_I for bottle-fed infants has been selected as an intermediate value on the basis that children under 60 days of age do not discriminate against strontium 90 [5], [8], and strontium 90 discrimination in children under one year of age is probably less than 0.5 [8], [9], and 0.35 for D_I of pre-adolescents [5] appears to be a satisfactory estimate.

With these estimates, equation 2 may be solved for each appropriate age group to become:

$$C_T = KC_D, \tag{3}$$

where C_T and C_D are the Sr 90/g calcium for tooth crown and commerical bottle milk respectively and K is a constant.

We prefer to relate our data to cow's milk because the strontium 90 content of commercial milk is readily available for past and current years and cow's milk represents the primary source of dietary calcium in the American diet.

2. Strontium 90 content of milk and diet

In St. Louis, the strontium 90 level in milk increased from negligible levels prior to 1950 to an average maximum level of 20 pCi/g Ca for the first six months of 1964 and declined rapidly thereafter until 1967. For the past four years since 1967, the strontium 90 level in milk appears to be quite steady, and averages about 9 pCi/g Ca (Figure 1). A maximum monthly average of 38 pCi/g Ca occurred during June 1963.

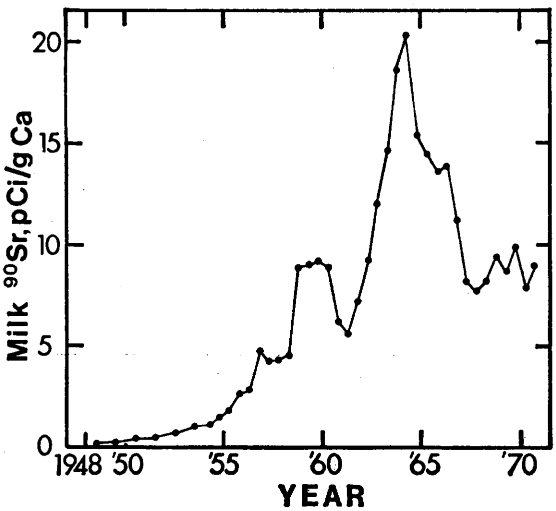

FIGURE 1

Average yearly milk levels of strontium 90 in St. Louis.

The strontium 90 level in milk appears to be the best parameter of dietary intake because measurements are easily obtained, milk calcium represents the greatest source of dietary calcium in the American diet, and because milk is a relatively stable foodstuff with respect to chemical composition. Nonetheless, the total dietary strontium 90 intake is the important datum and numerous measurements to relate the contribution of milk strontium 90 to diet strontium 90 have been made [10]. Although the dietary contribution varies with individuals, with geographic area, with seasonal variation and rainfall, and with cultural or habitual dietary habits, the Federal Radiation Commission has accepted a factor of 1.2 to 1.6 times the milk strontium 90 level as the best average value for the adult American diet [11]. For bottle-fed American children during the first postnatal year, the factor is essentially 1.0 and the factor gradually increases as the dietary habits change and approach that of the adult society.

It must be recognized, however, that the conversion factor is probably valid only for the United States and European countries in which milk and dairy products contribute the major portion of calcium and strontium to the total diet.

In countries where grains and cereals represent the major source of alkaline-earth elements, this factor is probably not valid and measurements of strontium 90 and calcium in the total diet are required.

3. Accumulation of strontium 90 in fetal bone and teeth

The relative strontium 90 content of fetal tooth buds and mandibular bone obtained from the same fetus averaged 0.99 ± 0.18 (S.D.) for 62 fetal samples. In 56 comparisons between fetal femur and mandibular bone, an average of 0.94 ± 0.22 (S.D.) was obtained. It is apparent therefore that strontium 90 is distributed equally throughout the various hard tissues of the fetus during *in utero* development.

During the years 1961 through 1970, a period encompassing both increasing and decreasing strontium 90 fallout, strontium 90 concentrations in fetal mandibular bone followed that present in market milk. Fetal bone reached average maximal strontium 90 concentrations of 6.1 pCi/g Ca during the latter half of 1964. However, the peak strontium 90 content of milk occurs about six months earlier than that occurring in the fetus (Figure 2). This lag period appears to be

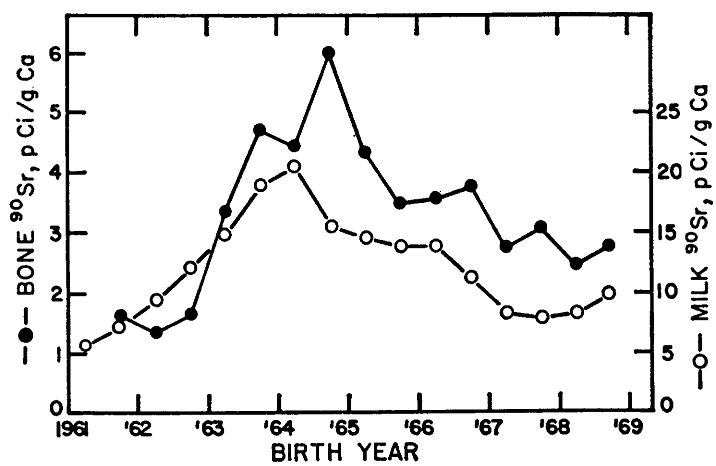

FIGURE 2

Strontium 90 content of fetal mandibular bone (●) and of commerical cow's milk (o) vs. the first and last half of the year of birth. Each point represents average values for 2 to 18 fetuses.

due to at least two factors that are difficult to evaluate by direct analysis. In the first instance, it needs to be recognized that fetal calcium (and strontium) is drawn from the mother's body mineral pool in addition to the mother's dietary intake. Consequently the fetal calcium and strontium represents, in part, a contribution from the mother's mineral stores previously deposited before fetal bone mineralization occurs. In the second instance, part of the mother's dietary intake of calcium and strontium includes dairy products (cheese, powdered skim milk, and so forth) and other foods that have an appreciable shelf life and are consumed at some time after processing. Under steady state conditions, when the dietary intake of strontium 90 is constant or changing very slowly, correction for the lag period will be of no consequence. This situation appears to be occurring for the period after 1965.

The data for fetal mandibular bone, when plotted for six month intervals against the milk concentration existing six months previous to abortion, adequately fits a linear equation for both increasing and decreasing strontium 90 concentrations of milk, with a slope K of 0.28 (Figure 3). If the total diet strontium 90 during pregnancy is considered to be 1.6 times the milk concentration, then the slope K becomes 0.18. This value is D_m in equation 2.

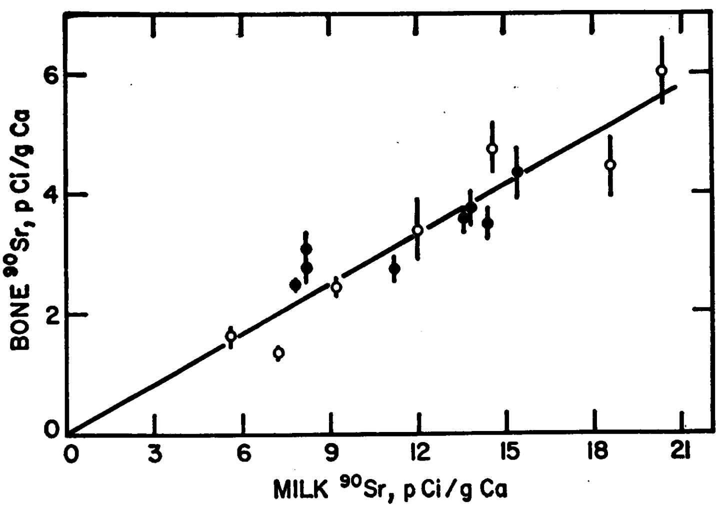

FIGURE 3

Strontium 90 content of fetal mandibular bone during increasing (ϕ) and decreasing fallout (♦) *versus* strontium 90 in cow's milk 6 months prior to birth. The vertical bars represent ±S.E. for samples shown in Figure 2.

4. Accumulation of strontium 90 in deciduous teeth of infants

The concentration of strontium 90 in the tooth crown of sound incisors and carious second molars of children born between 1951 through 1963 (Figure 4), and who were bottle-fed from birth, is also adequately described by a linear equation (Figure 5). The strontium 90 content in deciduous tooth crowns increased from negligible amounts prior to 1950 to maximum average values of 10.6 pCi/g Ca for incisors and 14.6 pCi/g Ca for 2nd molars during late 1963 and early 1964 when milk strontium 90 was maximal. The values of K for in-

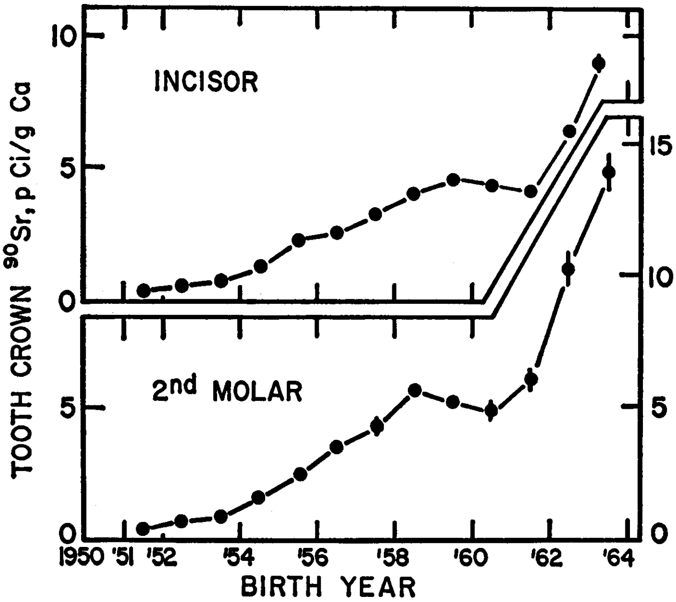

FIGURE 4

Strontium 90 content of deciduous incisor and 2nd molar crowns *versus* year of birth. Each point represents average values for 5 to 21 pooled samples. The S.E. are given as vertical bars except where the diameter of the points is equal to or larger than ±1 S.E.

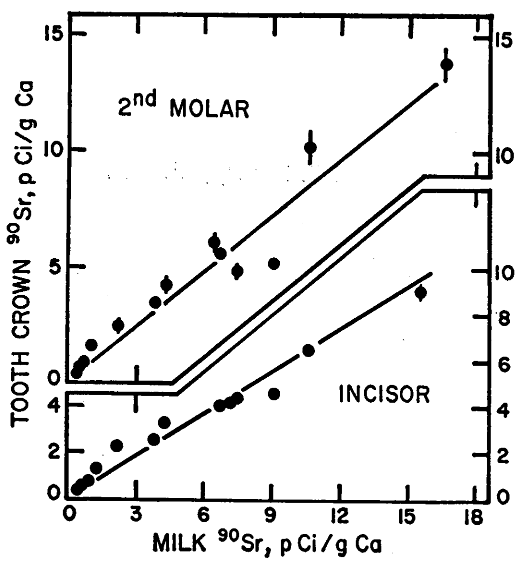

FIGURE 5

Strontium 90 content of deciduous incisor and 2nd molar crowns *versus* strontium 90 content of cow's milk. See Figure 4 for details.

cisors (0.63) and 2nd molars (0.77) are consistent with results previously reported for limited data. For this age group, the strontium 90 content of milk and total diet is approximately equal.

5. Accumulation of strontium 90 in permanent teeth of adolescents

Calcification and crown formation of 1st bicuspids begins at about $1\frac{1}{2}$ to 2 years of age and is completed at about 6 years of age, while the root forms between ages 6 to 14 years. The midpoint for calcification appears to occur at 4 years of age for crowns and 9 years of age for roots. In the tooth crowns, the concentration of strontium 90 represents the dietary contribution and is not influenced by maternal contributions. The root is less stable than the crown, is more like bone and reflects calcification during early adolescence. Maximum strontium 90 levels of 5 pCi/g Ca were found in the tooth crowns of children during high environmental strontium 90 levels that peaked in 1963–1964 (Figure 6). For roots calcifying during these peak years, maximum levels of 4.5 pCi/g Ca

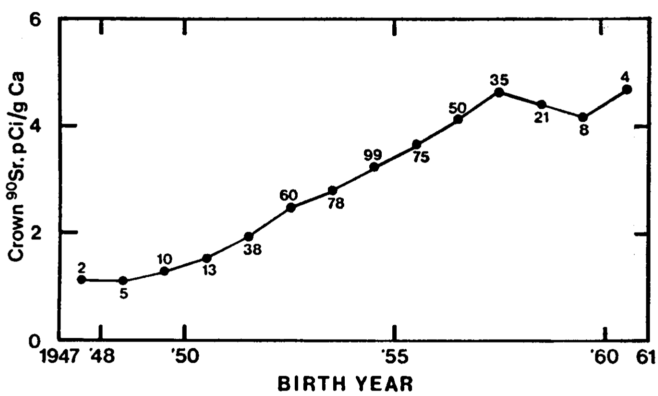

FIGURE 6

Strontium 90 content of 1st bicuspid crowns *versus* year of birth.

were found (Figure 7). Correlations between crown (Figure 8) and root (Figure 9) strontium 90 levels during the time of calcification with that found in the diet is essentially linear. The constant, K, is 0.31 for crown and 0.24 for root. Consideration of variables of turnover, exchange, remodeling and radioactive decay do not alter the equations.

6. Regional variation of strontium 90 in deciduous incisors

The strontium 90 content of teeth for children born between 1956–1958 in various geographic areas increases as the latitude decreases from Toronto to New Orleans (Table II). This relationship follows the same general pattern for atmos-

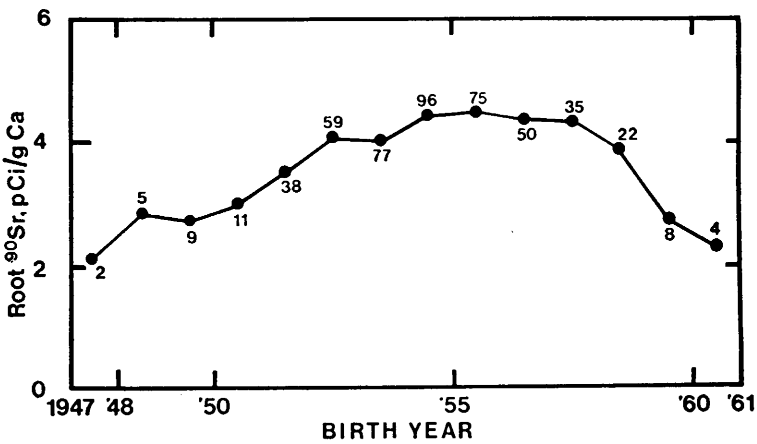

FIGURE 7

Strontium 90 content of 1st bicuspid roots *versus* year of birth.

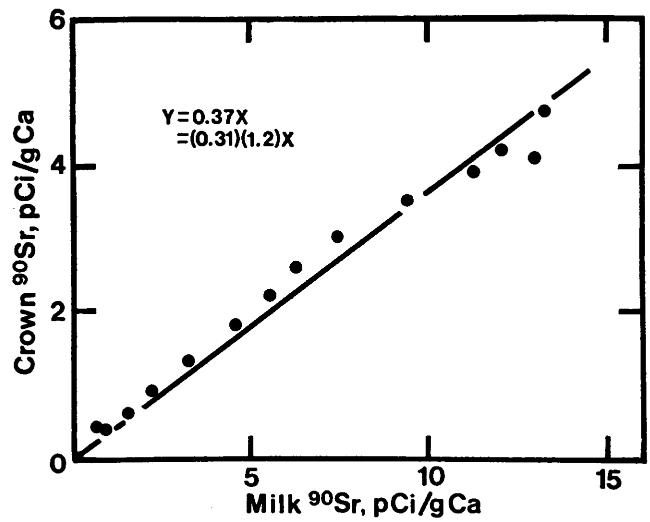

FIGURE 8

Strontium 90 content of 1st biscupid crowns *versus* strontium 90 content of cow's milk for samples shown in Figure 5.

pheric radioactivity as determined by the surface air sampling program of the AEC-HASL installation in which contamination is lower in northern latitudes (Toronto) and higher in southern latitudes (New Orleans). Teeth from children born in California contain approximately 50 per cent less strontium 90 than teeth of St. Louis children. Two samples of deciduous teeth of children born in Japan [13] during 1956 contained 1.28 and 1.54 pCi/g Ca—values that are

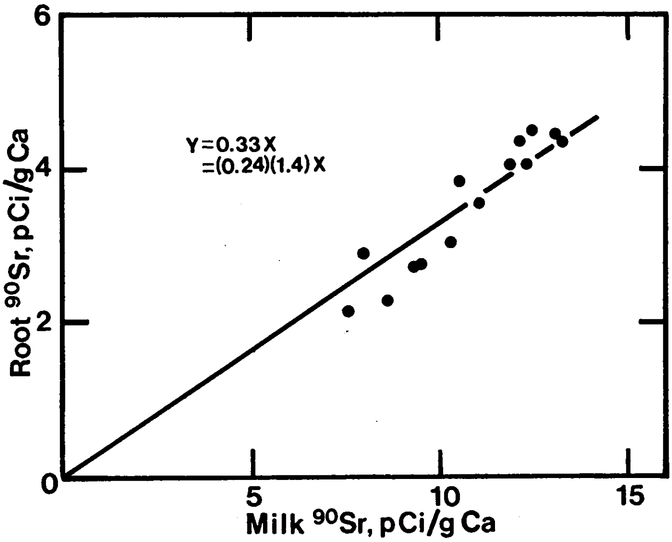

FIGURE 9

Strontium 90 content of 1st bicuspid roots *versus* strontium 90 content of cow's milk for samples shown in Figure 7.

TABLE II

STRONTIUM 90 IN DECIDUOUS INCISORS OF AMERICAN CHILDREN

Area	Birth year	No. of samples	pCi/g Ca	% of St. Louis values
Toronto	1956	6	1.82 ± 0.05	83
	1957	5	1.96 ± 0.09	70
Michigan	1957	12	2.47 ± 0.07	89
Indianapolis and Chicago	1956	5	2.46 ± 0.21	112
	1957	3	2.77 ± 0.21	99
St. Louis	1956	19	2.19 ± 0.08	100
	1957	21	2.79 ± 0.08	100
	1958	18	3.46 ± 0.12	100
East Texas and New Orleans	1957	7	3.43 ± 0.14	123
California	1956	2	1.21 ± 0.35	55
	1957	5	1.53 ± 0.13	55
	1958	3	1.74 ± 0.25	50

similar to that found in California for comparable years. Furthermore, the deciduous teeth of German children [14] and St. Louis children born during 1952–1954 contained comparable amounts of strontium 90 that averaged 0.45 pCi/g Ca. Although the data are sparse, they indicate the worldwide dissemination of strontium 90 in the teeth and calcified tissues of children.

7. Conclusions

It is apparent from our studies that strontium 90 accumulation into calcified tissues of pre-natal and juvenile American children is linearly related to the concentration of the nuclide in the diet. The equations that we have developed appear to be valid for increasing and decreasing levels of environmental contamination. These equations become even more useful when only one variable is known. Thus, measurement of tooth strontium 90 levels may describe the dietary level of ingested strontium 90 at the time of tooth formation. Conversely, measurements of dietary strontium 90 define the maximal strontium 90 calcified tissue burden at the time of tooth formation. Although these studies have only been concerned with strontium 90 burdens, the burden of other nuclides with both short and long half-lives such as Cs 137, I 131, I 125, strontium 89 and many others need to be considered in evaluating the total radiation burden of body tissues. It would appear that the strontium 90 burden might serve as an indicator of the total body burden providing sufficient knowledge is obtained concerning the biochemical distribution and behavior of the various nuclides, their half-lives, and the quantitative distributional relationship between the various nuclides in the environment.

The rate of decrease of strontium 90 in milk from the St. Louis watershed during the past four years is somewhat less than the physical decay of the isotope. We interpret this situation to mean that additional strontium 90 is being injected into our environment in quantities sufficient to obviate natural decay. If this situation continues, children born at present levels of about 9 pCi Sr/gm Ca in milk will continue to develop, mature and bear their children at about the same level of environmental contamination. The question must then be asked, "What immediate or future biological effects, if any, are to be expected from such levels of radiation burden?" The answer to this question is unknown at present, although some effects on infant mortality have recently been suggested by Sternglass for radiation near the vicinity of nuclear reactors [15].

The accumulation of strontium 90 in bone and calcified tissues and its relationship to osteogenic tumor induction has occupied the attention of most investigators for many years [16]. With the exception of the proximity of bone strontium 90 to rapidly proliferating bone marrow, biochemical effects of low levels of strontium 90 on soft tissues such as testes, ovary, pituitary and other glands have been essentially ignored. Furthermore, the yttrium 90 daughter of strontium 90 would be expected to leach out of bone and to be in equilibrium with soft tissues. Preliminary studies in my laboratory [17] show that strontium is bound to testicular and ovarian homogenates and cell fractions more than to liver and kidney tissue groups. These binding groups appear to be largely the phosphate groups of DNA and RNA although other protein groups also bind strontium 90 and cannot be ignored. Because DNA is predominantly present in the nucleus and is the major sensitive component for genetic transmission and mutation, it is conceivable that continuous low levels of radiation for long periods of time would tend to increase DNA modification and mutation rates. It would appear, therefore, that the strontium 90 bone stores and its yttrium 90 daughter could yield such a continuous radiation to sensitive soft tissue components throughout the growth period and reproductive life of the individual.

We have previously implied that the strontium 90 body burden might result in a statistical appearance of increased mutation rates in 70 to 90 years equivalent to perhaps three or four generations. However, developments in medical knowledge during the past fifteen years with respect to genetic engineering, chromosome mapping, and biochemical function may obviate the need to wait such a long time. A number of genetic defects, such as hemoglobinopathies and inborn errors of metabolism are known to be unusually common in man and can be readily characterized in the population [18]. For example, phenylketonuria is known to occur once in each 10,000 births. The heterozygote occurs about once in 100 people and can readily be determined by phenylalanine loading tests. In some populations of the world ranging from Africa to Southeast Asia, as many as 30 per cent of the population will have some form of readily detectable hemoglobin variant. Of the many mutations amenable for study, some will be more fruitful than others. The proper choices can only be made by an interdisciplinary consortium of knowledgeable manpower.

It appears possible, therefore, to determine and characterize the existing mutation rates for many human and animal pathopathies and to study any changes in these rates during the next few years. Such studies will require a concerted effort on behalf of the scientific community such as specialists in medicine, public health, environmental engineers, statisticians and biological scientists. It is conceivable, of course, that many biological effects may result from synergistic relationships between multiple mutagens. A thorough discussion of molecular evolutionary events [19] and an annual symposium report on birth defects and mutations [20] have recently appeared. Until such studies are initiated and relevant knowledge has been obtained, it appears desirable to re-evaluate the consequences of and the need to proliferate environmental contamination by nuclear reactors and devices.

Although most mutations in plants and animals are deleterious, many mutations are either innocuous or contribute some benefit to the individual. Thus, sickle cell anemia is advantageous to individuals in tropical areas because it contributes some immunity to malaria. Because an increase in radiation from whatever source—nuclear reactors or natural cosmic radiation for space travelers—will speed up the mutation rate and evolutionary development, some human selection for the kind of acceptable mutation (Orwell's 1984?) must be made. The answer to this question lies in philosophical considerations beyond the limits of this report. Nonetheless, it appears desirable to thoroughly understand the genetic implications of low level radiation on human and animal evolutionary mechanisms in order to make such important philosophical judgments.

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Discussion

Question: Alexander Grendon, Donner Laboratory, University of California, Berkeley

Since you commented on the possibility of genetic effects from such small amounts of Sr 90, I want to add to the record the note that the probability of such effects is extremely small. The hypothesis to which you evidently refer is that Sr 90 may replace some of the few calcium atoms that serve as binding elements in DNA, since other Sr 90 atoms are almost all in bone and remote from the gonads. One must then consider atom ratios, and 10 pCi Sr 90/gCa represents about one Sr 90 atom per 10^{13} to 10^{14} atoms of calcium. Even if there is no discrimination against strontium, the probability of an Sr 90 atom replacing a Ca atom in a cell that forms a child is extremely small.

Reply: Harold L. Rosenthal

We have studied Sr 90 deposition primarily as a long range indicator atom. However, as I mentioned earlier, strontium 90 body burdens might serve as an indicator of the total body burden if all factors concerning the biochemical distribution and physical behavior of all the various nuclides (their half lives, and so forth) and the quantitative distributional relationship between the various nuclides in the environment are considered. For example, a knowledge of the fission yield of nuclides relative to Sr 90 could be used to estimate the exposure of humans and animals to all of the radionuclides produced. I believe that upwards of 1600 nuclides have now been described so that summation and cumulative effects of all the exposures, Cs 137, I 131, Po 210, and so forth, certainly adds up to more than from just Sr 90. It would be very desirable for this conference to do such a summation recognizing all of the chemical, physical and biological factors.

Question: E. J. Sternglass, School of Medicine, University of Pittsburgh

I believe it is important to point out the great value of the data Dr. Rosenthal has so carefully gathered over the years, since it is the only truly meaningful and accurately recorded measure of the actual amounts of radioactivity in the developing human fetus and infant we now have available for future epidemiological studies.

In view of the very serious fact that the concentrations of strontium 90 did not continue to decline at the rate at which they decreased after their peak from atmospheric testing by the U.S., U.S.S.R. and U.K. in 1964 but, instead, have actually shown renewed rises since 1968, it would seem urgent not only to continue this unique monitoring technique of fallout in the developing human infant, but to expand it so as to include other geographical areas.

The fact that there exists a high correlation between the excess fetal mortality rate and the amounts of strontium 90-yttrium 90 in the fetal tooth buds strongly suggests the importance of further research in the area of the endocrinological aspects of these isotopes and other rare earth elements so as to explain the biological mechanisms whereby the premature birth of the infant and the attendant higher mortality rates are produced.

Above all, these data showing renewed rises in the bone concentrations of these isotopes in the newborn in recent years would suggest the need for a halt to all further introduction of fission products into the environment as a matter of prudence and concern for the health of our children.

Reply: Harold L. Rosenthal

We have made some measurements on regional variations in deciduous teeth of children as we showed in Table II. In general, teeth of children from Toronto contain about 25 per cent less than that for St. Louis children and New Orleans shows about 25 per cent more. This seems to follow the same north-south patterns of atmospheric levels. It is interesting to note that teeth of northern California children contain about half of the St. Louis value—presumably because the major testing program is east of California and the prevailing winds carry the fission products in an easterly direction. We don't know if the California children are contaminated from Russian or Pacific Island tests or if the Nevada test products completely circled the globe.