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ACCUMULATION OF ENVIRONMENTAL ^{90}Sr IN TEETH OF CHILDREN

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ABSTRACT

Accumulation of environmental ^{90}Sr in deciduous and permanent tooth crowns of American children has been studied during neonatal development, infancy and early adolescence. Teeth were selected for study because they represent a stable calcified tissue in which rates of turnover, exchange, remodeling, and accretion are minimal or absent. They reflect, therefore, the nuclide equilibrium with the body constituents at the time of tooth crown calcification. In the fetus, during the last trimester of development, the nuclide is equally distributed in tooth buds, mandibular bone, and femur and represents the contribution of the mother's diet and body burden to the developing fetus.

The ^{90}Sr content of deciduous teeth of infants who were bottle fed from birth represents the small fraction incorporated in utero plus the amount obtained from the diet during the first 6 to 9 months after birth.

The crown of sound permanent bicuspids begins to calcify at 1.5 years of age with the mid-point of development occurring at age 5. The ^{90}Sr content of these teeth represents the incorporation of dietary milk nuclide during late infancy and is not influenced by the maternal in utero contribution.

The assumptions inherent in the development of the equations with respect to discrimination factors, time of development of the tooth crown, and estimations of dietary ^{90}Sr intakes are discussed.

For the past 10 years, my laboratory has been studying the accumulation of fallout ^{90}Sr in mineralized tissues of the human ranging from in utero development through early adolescence. Some of the data have been published as individual reports for the fetal tooth buds and bone,[1] deciduous teeth,[2,3] and permanent teeth.[4] We have concentrated our studies on deciduous and permanent teeth because the 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 was 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[1-5] demonstrated that the accumulation of ^{90}Sr in the deciduous and permanent teeth of primates was adequately described by a linear equation of the form $C_T = KC_D$, where C_T and C_D represent the tooth-crown and diet ^{90}Sr concentrations, respectively, and K is a constant. The constant K differs for each specific kind of tooth crown and includes such variables as the fraction of the tooth formed in utero and after birth and the attendant discrimination factors. This paper extends the study to include American children born between 1951 and 1963, a period associated with increasing fallout that reached maximum levels during late 1963 and early 1964. Additionally, the data obtained for fetal tooth buds and bone encompass the period between 1961 and 1968, a period of both increasing and decreasing fallout levels.

MATERIALS AND METHODS

Methods of collection and sampling and detailed descriptions of the analytical procedures have been thoroughly documented in previous reports.[1-5] However, data in the literature are somewhat confusing because of variations in the methods of reporting. In some instances dietary intakes have been reported on the basis of ^{90}Sr per liter of milk, ^{90}Sr per gram of milk calcium, or as estimates of the total diet ^{90}Sr per gram of calcium. We prefer to relate our data to cow's milk because the ^{90}Sr content of market milk is readily available for past and current years and cow's milk represents the primary source of dietary calcium in the American diet. For countries where grain represents the main source of dietary calcium, the various parameters will require different values although the equation remains valid.

A theoretical expression for the ^{90}Sr per gram calcium of teeth (C_t) was derived by expansion of the basic equation of Reiss:[6]

$$C_t = X \text{ prenatal } {}^{90}\text{Sr/g Ca} + Y \text{ postnatal } {}^{90}\text{Sr/g Ca} \qquad (1)$$

The factors X and Y represent the fraction of tooth-crown calcium deposited during prenatal and postnatal periods, respectively. These factors vary with the kind of tooth, as shown in Table 1.

To account for dietary intake and discrimination factors, Eq. 1 becomes

$$C_t = (X)(A)C_d^m D_m + (Y)(A)C_d^I D_I \qquad (2)$$

where C_d^m = mother's dietary intake of ^{90}Sr per gram of calcium from commercial milk

D_m = discrimination factor against ^{90}Sr between the mother's dietary intake and her fetus

C_d^I = infant's milk intake of ^{90}Sr per gram of calcium

D_I = infant's discrimination factor against ^{90}Sr between dietary intake and calcified tissue

Table 1

FRACTION OF TOOTH CROWN DEPOSITED DURING TOOTH DEVELOPMENT

Tooth	Prenatal	Postnatal
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

The variable A relates the concentration of ^{90}Sr per gram of calcium in milk to that of the total diet and varies with the dietary habits of the individual. For pregnant women, A is estimated[7] to be equal to 1.6; for bottle-fed infants during the first year of life, the value is 1.0; and for preadolescent children between 1 and 14 years of age, the value is about 1.2.

Values for D_m and D_I must be experimentally determined before Eq. 2 can be solved. A discrimination factor of 0.18 for D_m appears reasonable.[1] A value of 0.8 for D_I for bottle-fed infants has been selected as an intermediate value since children under 60 days of age[8,9] do not discriminate against ^{90}Sr and discrimination in children under 1 year of age[9,10] is probably less than 0.5. A value of 0.35 for D_I for preadolescents[4] appears to be a satisfactory estimate.

With these estimates, Eq. 2 can be solved for each appropriate age group to become

$$C_t = KC_d \qquad (3)$$

where C_t and C_d are the ^{90}Sr per gram of calcium for tooth crown and commercial bottle milk, respectively, and K is a constant.

RESULTS

Accumulation of ^{90}Sr in Fetal Bone and Teeth

The relative ^{90}Sr content of 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 ^{90}Sr is distributed equally throughout the various hard tissues of the fetus during in utero development. During the years 1961 through 1968, a period encompassing both increasing and decreasing ^{90}Sr fallout, ^{90}Sr concentra-

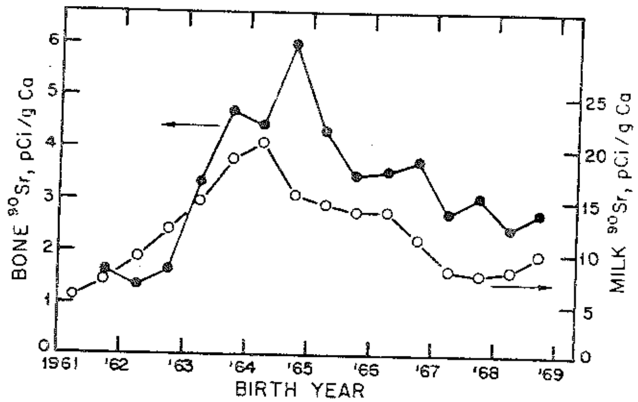

Fig. 1—Strontium-90 content of fetal mandibular bone (●) and of commercial cow's milk (○) vs. the first and the last half of the year of birth. Each point represents average values for 2 to 12 fetuses.

tions in fetal mandibular bone samples followed that present in market milk (Fig. 1). However, it may be noted that the peak ^{90}Sr content of milk occurs about 6 months earlier than that occurring in the fetuses. This lag appears to be due to at least two factors that are difficult to evaluate by direct analysis. First, 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 represent, in part, contributions from the mother's mineral stores deposited before fetal bone mineralization occurs. Second, part of the mother's dietary intake of calcium and strontium includes dairy products (cheese, powdered skim milk, etc.) and other foods that have an appreciable shelf life and are consumed at some time after processing. When the dietary intake of ^{90}Sr is constant or changing very slowly, the lag will be absent. This situation appears to be occurring for the period after 1965.

The data for fetal and mandibular bone are plotted for 6-month intervals against the milk concentration existing 6 months before abortion (Fig. 2), and the line has been fitted through the origin by the method of least squares. The experimental points adequately fit the line for both ...

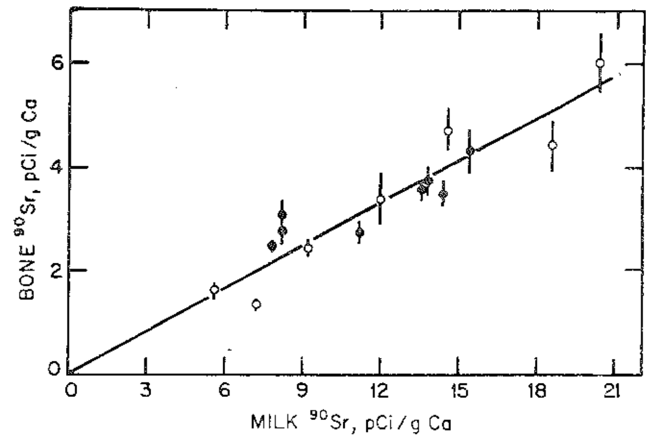

Fig. 2—Strontium-90 content of fetal mandibular bone during increasing (○) and decreasing (●) fallout vs. ^{90}Sr content of commercial cow's milk 6 months prior to birth. The vertical bars represent ±S.E. for the samples shown in Fig. 1.

pear reasonable. Because of the variability of the data, an uncertainty of 20% for either factor appears to be acceptable.

Accumulation of ^{90}Sr in Deciduous Teeth of Infants

The concentration of ^{90}Sr in the tooth crown of sound incisors and carious second molars of children born between 1951 through 1963 who were bottle fed is shown in Fig. 3. During 1963 the ^{90}Sr content in deciduous tooth crowns increased from negligible amounts prior to 1950 to values of 9 pCi/g of Ca and 14.6 pCi/g of Ca for incisors and 2nd molars, respectively. The tooth-crown data vs. milk ^{90}Sr levels plotted in Fig. 4 are adequately described by a linear equation. Similar results have been obtained for 1st molar and cuspid crowns, but the data are not as yet complete. The values of K for incisors (0.63) and second molars (0.77) are consistent with the results previously reported for limited data[2,8] and indicate the validity of the estimates for the parameters of A, X, Y, D_m, and D_I.

Accumulation of ^{90}Sr in Permanent Teeth of Preadolescents

Calcification and crown formation of first bicuspids begins at about 1½ to 2 years of age and is completed at about 6 years of age. Thus, the crown is half formed at about 4 years of age. However, the sigmoid developmental curve suggests that considerable calcification is still in process at 5 years of age. In these teeth, the concentration of ^{90}Sr rep-

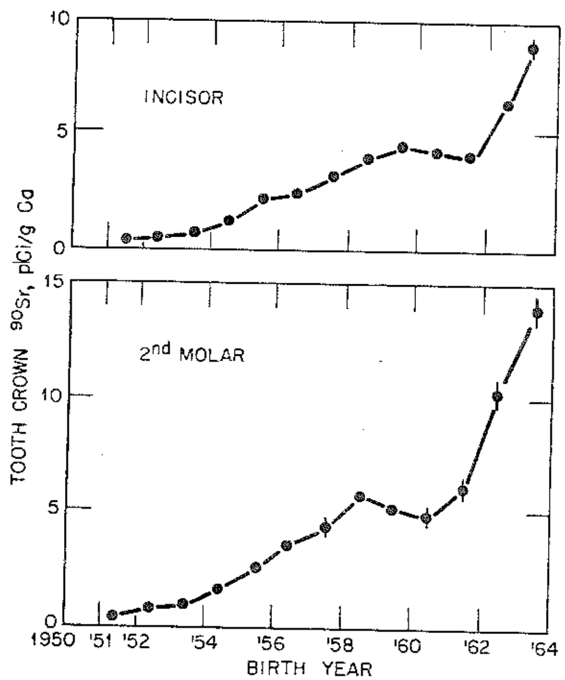

Fig. 3—Strontium-90 content of deciduous incisor and 2nd molar tooth crowns vs. year of birth. Each point represents average values for 5 to 21 pooled samples. The S.E. are given as vertical bars except where the diameter of the points is equal to or larger than ±S.E.

concentration of ^{90}Sr in the crowns of sound first bicuspids extracted for orthodontic purposes is plotted for yearly intervals vs. the birth year + 5 years, a time at which the tooth is about half calcified, in Fig. 5. The radionuclide concentration has increased in a regular fashion from about 0.5 pCi/g of Ca to 4.7 pCi/g of Ca during the years 1951 through 1963. This time interval is associated with the time of increasing fallout. The tooth-crown data, plotted in Fig. 5 vs. the milk ^{90}Sr concentration at the time the crown is half calcified, is again adequately described by a linear equation. From these data, D_I is estimated to be 0.35 when A is 1.2, estimates that are consistent with previous expectations. Proof of the validity of the equation during periods of decreasing dietary ^{90}Sr must await the availability of teeth that will be extracted from children in the next few years.

DISCUSSION

It is apparent from the data presented here that ^{90}Sr accumulation in the tooth ...

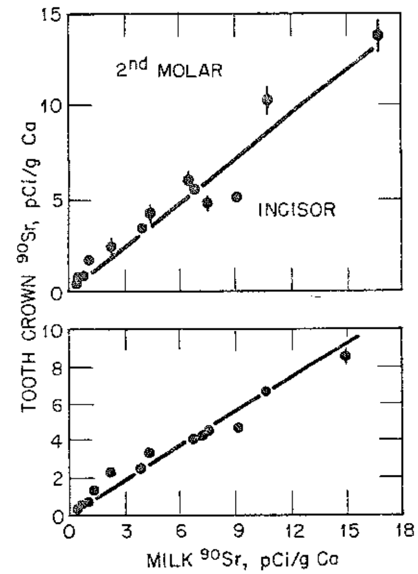

Fig. 4—Strontium-90 content of deciduous incisor and 2nd molar tooth crowns vs. ^{90}Sr content of commercial cow's milk. See Fig. 3 for details.

to the concentration of the nuclide in the diet. The equations that we have developed are based on various assumptions that appear to be valid but may, in fact, require some modification.

For the fetus, a discrimination factor (D_m) of 0.18 and a factor of 1.6 times the mother's dietary milk ingestion appears to be reasonable. However, the D_m has been reported to be 0.08 (Ref. 11), 0.10 (Ref. 12), and 0.13 (Ref. 7). This variation is most probably due to our incomplete knowledge of the dietary factor, A, that appears to vary between 1.0 and 2.0. Unfortunately, the dietary habits and ^{90}Sr intake of pregnant American women are not sufficiently documented to clarify this issue. The discrimination factor (D_I) of infants during the first year of life is also an estimate although a value of 0.8 appears to be reasonable. However, recent measurements of the discrimination factor for bone appear to be lower, ranging from 1 at birth[10,13] to about 0.25 at 1½ years of age, with an average of 0.35 during the first year of life. Our studies with deciduous and permanent tooth crowns suggest that D_I decreases rapidly from a value of 1 at birth to about 0.5 at 1 year of age and gradually reaches an adult value of 0.25 at about 10 to 12 years of age.[4]

These differences are apparently due to the fact that bone is continuously being remodeled with turnover rates approximating 3.5% per year for the adult total skeleton and 8% per year for vertebrae.[14]

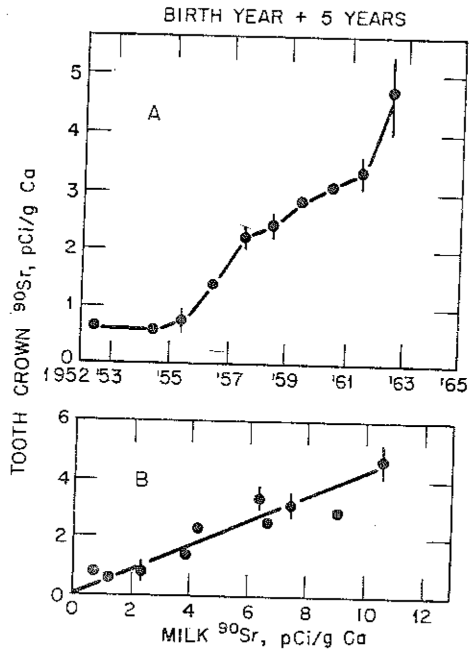

Fig. 5—(A) Strontium-90 content of permanent bicuspid tooth crowns vs. birth year + 5 years. (B) Strontium-90 content of permanent bicuspid tooth crowns vs. ^{90}Sr content of commercial cow's milk 5 years after birth. Each point represents average values of 1 to 20 pooled samples extracted during 1967. The S.E. are given as vertical bars except where the diameter of the points is equal to or larger than ±S.E.

tially separate mechanism in that turnover, remodeling, exchange, and accretion are either absent or occur to a minimal degree. Thus, these factors may be disregarded for our purposes. Our studies demonstrate that the concentration of ^{90}Sr deposited in the tooth crown reflects the equilibrium with the diet at the time the crown was formed.

ACKNOWLEDGMENTS

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REFERENCES

1. H. L. Rosenthal, S. A. Austin, J. E. Gilster, and J. T. Bird, Accumulation of Strontium-90 into Human Fetal Teeth and Bone, *Proc. Soc. Exp. Biol. Med., 125*: 493-495 (1967).

2. H. L. Rosenthal, J. T. Bird, J. E. Gilster, P. V. C. Pinto, and S. O'Neill, Strontium-90 Content of Deciduous Teeth of Children, *J. Dental Res., 45*: 343-349 (1966).
3. H. L. Rosenthal, Discussion of Effectiveness and Failures of Monitoring Systems, *Pediatrics, 41*: 202-206 (1968).
4. H. L. Rosenthal, J. T. Bird, and J. E. Gilster, Strontium-90 Content of First Bicuspids, *Nature, 210*: 210-212 (1966).
5. H. L. Rosenthal, Chronological Age Determination as Estimated from Strontium-90 Content of Teeth and Bone, *Bibliotheca Primatologica, 7*: 48-58 (1968).
6. L. Z. Reiss, Strontium-90 Absorption by Deciduous Teeth, *Science, 134*: 1669-1673 (1961).
7. Federal Radiation Council, Staff Report No. 6, October 1964.
8. H. L. Rosenthal, S. Austin, S. O'Neill, K. Takeuchi, J. T. Bird, and J. E. Gilster, Incorporation of Fall-out Strontium-90 in Deciduous Incisors and Foetal Bone, *Nature, 203*: 615-616 (1964).
9. S. Lough, A. Rivera, and C. L. Comar, Retention of Strontium, Calcium, and Phosphorus in Human Infants, *Proc. Soc. Exp. Biol. Med., 112*: 631-636 (1963).
10. F. J. Bryant and J. F. Loutit, Human Bone Metabolism Deduced from Strontium Assays, British Report AERE-R3718, 1961.
11. J. L. Kulp, A. R. Schulert, and E. J. Hodges, Strontium-90 in Man. IV, *Science, 132*: 448-454 (1960).
12. C. L. Comar, I. R. Whitney, and F. W. Lengemann, Comparative Utilization of Dietary Sr^{90} and Calcium by Developing Rat Fetus and Growing Rat, *Proc. Soc. Exp. Biol. Med., 88*: 232-236 (1955).
13. D. Beninson, E. Ramos, and R. Touzet, Strontium in Children, USAEC Report HASL-165, Health and Safety Laboratory, 1966.
14. J. Rivera, Factors Affecting the Uptake and Retention of Bone Seeking Radionuclides, *Pediatrics, 41*: 231-236 (1968).

OPEN DISCUSSION

STERNGLASS: Have you compared these values with the geographical or temporal distribution of ^{90}Sr in milk? I have been looking at infant and fetal mortality; are there other effects that you have considered examining in these populations?

ROSENTHAL: Taking your second question first, no, we have not. We started on this for the very simple purpose of getting involved in a controversy many years ago about ^{90}Sr in fallout. All we wanted to do was characterize and record how much ^{90}Sr was being deposited, and we followed Kalckor's suggestion that teeth were a stable tissue in which ^{90}Sr could be used as a permanent marker. With respect to the effect of ^{90}Sr on the fetus, our stock answer to scientists and laymen alike is that we might see some in two or three generations or in 70 or 90 years.

In answer to your first question, we have been concentrating on teeth from the St. Louis area, but we have made comparisons using teeth from Toronto, Detroit, Chicago, San Francisco, and New Orleans. The concentration in the teeth in any particular area was comparable to the milk ^{90}Sr in that area.