13 September 1957, Volume 126, Number 3272 SCIENCE

Strontium-Calcium Movement from Soil to Man

C. L. Comar, R. Scott Russell, R. H. Wasserman

Attention has been focused on the possibility of hazards from contamination of the biosphere with strontium-90 produced and disseminated by atomic explosions. Other fission products have been considered less potentially hazardous because of lower fission yield, shorter half-life, or smaller incorporation into biological systems. Some heed, however, has been paid to possible hazards from radioisotopes of iodine (*1*) and cesium (*2*) and to the irradiation of the gastrointestinal tract from radioactive material that is ingested but not absorbed. The concern regarding strontium-90 arises because it moves similarly to calcium in food chains; it is well absorbed by plants, animals, and man; it is deposited and retained in bones; it is transmitted to milk and to the developing fetus; and it is known to cause bone tumors and is suspected of causing leukemia.

The incorporation of strontium-90 in the biosphere generally occurs as follows (*3*). Large weapons (megaton) deposit a large fraction of their strontium-90 in the stratosphere; this material slowly passes back into the troposphere with an average residence time in the stratosphere of about 10 years. Small weapons (kiloton) deposit their strontium-90 in the troposphere. The radioactivity in the troposphere, regardless of origin, is relatively quickly deposited on the surface of the earth, primarily by precipitation. Thus "kiloton" debris is deposited in restricted latitudes of origin, whereas "megaton" debris is widely distributed over the world. The strontium-90 falls out upon the surface of the soil and foliage. At any given time the strontium-90 available to the grazing animal can be classified as follows: (i) strontium-90 on the surface of foliage, (ii) strontium-90 incorporated in plant tissue by foliar absorption and mixed to a variable degree with plant calcium, and (iii) strontium-90 in plant tissue that had been mixed with the labile calcium of the soil and absorbed by the roots. The extent to which the strontium-90 is diluted with calcium will be least in source i and greatest in source iii. The relative contributions of these three sources will change with time; sources i and ii will become less significant when the contribution of new fallout is small compared with the previous contamination of the soil.

Two major areas of information are required to evaluate the potential hazard from the deposition of strontium-90 on the earth's surface: (i) What are and will be the levels of strontium-90 in the human population? (ii) At what levels of strontium-90 will damage occur? The second question does not fall within the scope of the present paper. In the evaluation of levels of strontium-90 in the biosphere, there is considerable advantage in dealing with strontium-90 to calcium ratios rather than with the absolute amounts of strontium-90 entering or leaving an organism. This is because exposure of the population occurs by way of strontium-90 contamination of dietary calcium, and strontium metabolism generally parallels and is interrelated with calcium metabolism; for example, the strontium-to-calcium ratios in the bones and tissues of animals are directly related to the ratio in the dietary intake. The level of contamination can easily be calculated from the strontium-90-to-calcium ratio when the calcium concentration in the tissue is known. The question to be considered therefore resolves itself as follows: What will be the strontium-90-to-calcium ratio in the human population as related to the strontium-90-to-calcium ratio of the dietary intake and as related to the strontium-90-to-calcium ratio of the vegetation, and how will this vary with the quantity of strontium-90 that is deposited on the ground surface? Under steady-state conditions, the relation between the strontium-90-to-calcium ratio of the body and the deposition in soil will be governed by the differential behavior of the two elements in a series of physical and physiological processes.

This article (*4*) reviews the findings related to the differential behavior of the two elements and is intended to serve as a basis for predicting the levels to be expected when the soil content and dietary intake can be estimated.

General Methods

Several modes of expression have been used to denote the comparative movement of strontium and calcium in biological systems (*5, 6*). We propose to use the term *strontium-calcium observed ratio* (OR) to denote the over-all discrimination that is observed in the movement of the two elements from one phase to another.

$$OR_{\text{sample-precursor}} = \frac{\text{Sr/Ca of sample}}{\text{Sr/Ca of precursor}} \quad (1)$$

As is brought out in subsequent paragraphs, care must be taken in estimation of OR values; it is especially important that the strontium-to-calcium ratios as measured truly represent the ratio as actually available to the organism, and as actually derived from the measured precursor.

To denote the discrimination that is

Dr. Comar and Dr. Wasserman are with the medical division, Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tenn., under contract with the U.S. Atomic Energy Commission; Dr. Russell is with the department of agriculture, University of Oxford, Oxford, England, and the Agricultural Research Council Radiobiological Laboratory, Compton, Berkshire. Dr. Comar and Dr. Russell will present an evening lecture on the subject of this article during the UNESCO International Conference on the Scientific Use of Radioisotopes, which is to be held in Paris, France, 9–20 Sept.

produced by a given physiological process, we propose to use the term *strontium-calcium discrimination factor* (DF). By definition:

$$OR = (DF_1)(DF_2)(DF_3) \ . \ . \ . \ (DF_n) \quad (2)$$

The DF values are given specific names to denote the physiological process involved—for example, $DF_{urinary}$ designates the contribution to the over-all discrimination in the body that results from differential handling of the two elements by the kidney.

There are three types of procedures used to obtain information on the comparative metabolism of strontium and calcium.

1) *Analysis of natural strontium-calcium ratios in the precursor material and in the tissues deriving these minerals from the precursor* (*6*). A disadvantage is the difficult technique required for analysis of naturally occurring strontium. Another difficulty, particularly in soil-plant studies, is that the chemically determined values for strontium and calcium in the soil may not represent accurately the relative amounts available to the plant. In studies of man and animals by this method, it is necessary that the subjects have been exposed to a constant strontium-to-calcium ratio all their lives in order that reasonable interpretations may be made.

2) *Analysis and radioassay of tissue deriving its strontium and calcium from precursors with a constant ratio of added radiostrontium (strontium*) to naturally occurring calcium* (*7*). This method requires feeding of the "spiked" nutrients (strontium-90 enriched) for a time long enough so that there is no interference from calcium stores laid down before the feeding began. Survey studies on the ratios of strontium-90 to calcium from fallout belong in this category. Difficulties of interpretation arise because (i) there may be preexisting stores of uncontaminated calcium in the organism; (ii) all the calcium of the intake may not become uniformly labeled with the strontium-90, since some of the strontium-90 that enters food chains will have been deposited aerially on the leaves, while part will have been absorbed from the soil; (iii) the discrimination may change with time—for example, from development *in utero* where there is a placental barrier, through the heavy milk-drinking stage where there is a lactation barrier, to the normal adult diet; (iv) the strontium-90-to-calcium ratio may also change with time as fallout occurs. In some instances, however, such as the analysis of foliage and of milk produced by animals grazing thereon, useful information is already available for certain discrimination processes.

3) *Radioassay of tissues from organisms receiving nutrient intakes of strontium* and calcium* in known and constant ratio* (*5*). This method (also called double labeling) is most convenient from an experimental standpoint, because the feeding time usually need not be more than a few days, since there is no interference from the preexisting calcium reservoir in the organism.

Strontium-Calcium Relationships in Plants

When plants are grown in soil, their content of strontium and calcium reflects the behavior of the two ions both before and after they cross the interface between the soil and the plant. It is therefore convenient to consider first the simpler systems of plants growing in inorganic solutions. By comparing the effects observed under these conditions with those occurring in plant-soil systems, information can be obtained on the behavior of the two ions in the complex physicochemical system of the soil.

The major part of the dietary strontium and calcium that man or animals receive from plants is contained in leaves; other aerial tissues make a much smaller contribution. It is known that strontium that has reached leaves is redistributed to other tissues to only a negligible extent (*8*); thus its movement through the plant is unidirectional from the root upward. Many studies in water culture have suggested that strontium and calcium are absorbed in a similar manner, and some results have encouraged the view that plants do not discriminate between the two ions. More detailed investigations, however, indicate that the interaction between strontium and calcium is more complex and that the OR may decrease progressively from the absorbing roots to the more remote aerial tissues (*9, 10*). Values for the aboveground parts of the majority of plants of major agricultural importance have been reported or can be calculated from published data. The range of values for the $OR_{\text{total plant shoot-outer medium}}$ appears to be in the order 0.7 to 1.3 (*9, 11, 12*). The majority of values are slightly below 1. Little information is available regarding storage organs—that is, potatoes, carrots, and so forth. Whereas only a small discrimination between the two ions appears to occur in the total shoot, the $OR_{\text{stem tissues-outer medium}}$ may reach values in excess of 5 (*12*).

These results are compatible with the view that the two ions interact in a sequence of exchange reactions during their passage from the outer medium to the shoots, strontium being retained to a somewhat greater extent at each step. Since plants possess no excretory mechanism, and since the major fraction of both ions entering the plants eventually reaches the leaves, no great discrimination is possible in these tissues. In the stem nodes, however, where a fraction of the upwardly moving divalent cations is temporarily retained, the separation of the two ions is subject to no such limitation. The high OR values that can occur in stems are attributed to this cause.

It is to be expected that the extent of discrimination between the two ions in such a system will vary with time and with the degree to which possible sites of retention are saturated. The possible extent of such changes has been shown by allowing barley plants to absorb strontium-89 and calcium-45 for 24 hours and examining them either immediately or after an interval of 56 days, no further tracers being applied. During this interval, upward movement from roots increased the strontium-89 content of the shoots by 40 percent, and the $OR_{\text{total shoot-outer medium}}$ rose from 0.85 to 0.95, while the $OR_{\text{stem nodes-outer medium}}$ rose from 0.99 to 2.4. It therefore appears possible that the range in the observed value for the $OR_{\text{total shoot-outer medium}}$ may largely reflect contrasting experimental conditions and, furthermore, that when plants differ in their growth habits, no consistent relationship can be expected between their OR values. Reports of varying ratios of native calcium to strontium in miscellaneous fragments of wild plants (*13*) at different stages of their development therefore provide no basis for interspecific comparisons. The available evidence thus points to the conclusion that little discrimination between the dietary calcium and strontium of man or animals occurs in its passage through plants. Fuller information with regard to storage organs is, however, desirable.

Plant/Soil Relationships

The similarity of the behavior of strontium and calcium in plants has, not surprisingly, encouraged the hope that the absorption of strontium-90 from soil can be reduced by addition of lime. Unfortunately this optimistic generalization is not supported by experimental evidence. The majority of the data now available have been derived from small-scale experiments, but a sufficiently wide range of soils has been used for a broad pattern to be apparent for a reasonable range of agricultural soils in temperate climates. Fuller and Flocker (*14*) found that lime equivalent to 2 tons per acre reduced the strontium content of plants grown in an acid forest soil by nearly one-fifth, and the strontium-89-to-calcium ratio was lowered by more than 45 percent. However, much smaller and highly variable

Table 1. Effect of lime applied at a rate equivalent to 2 tons per acre on the strontium*-to-calcium ratio in cereals (after Fuller and Flocker, *14*).

Soil	Exchangeable Ca (milliequivalents/100 g)	Lime	Sr (%)	Ca/Sr ratio
Pima clay loam	30.0	−	0.00408	48
Pima clay loam	30.0	+	0.00353	59
Chino clay	20.4	−	0.00350	64
Chino clay	20.4	+	0.00364	69
Sandy loam from Flagstaff	17.9	−	0.00656	32
Sandy loam from Flagstaff	17.9	+	0.00600	39
Gila sandy clay loam	17.7	−	0.00713	35
Gila sandy clay loam	17.7	+	0.00684	39
Mohave sandy clay loam	15.4	−	0.00931	26
Mohave sandy clay loam	15.4	+	0.00902	26
Laveen sandy loam	8.6	−	0.00942	19
Laveen sandy loam	8.6	+	0.00919	21
Tucson sandy loam	8.4	−	0.01224	19
Tucson sandy loam	8.4	+	0.01094	20
Tubac sandy loam	8.0	−	0.01001	16
Tubac sandy loam	8.0	+	0.00953	17
Tucson sandy loam	7.5	−	0.01304	17
Tucson sandy loam	7.5	+	0.01299	19
Pima sand loam	5.0	−	0.01704	14
Pima sand loam	5.0	+	0.01953	13
Least significant difference 0.05 for $CaCO_3$ treatment only			0.00031	4

effects occurred in a wide range of agricultural soils (Table 1). Fuller and Flocker concluded that "little practical significance attaches to the effect of lime."

Romney *et al.* (*10*) found that calcium carbonate at a rate equivalent to 2 to 5 tons per acre reduced the absorption of strontium-90 from a soil very poor in calcium by approximately 60 percent. Higher dressing caused no further reduction, and the dressing that reduced the absorption of strontium-90 was similar to that necessary to insure good crop production. Calcium sulfate caused a greater reduction in the absorption of strontium-90. Neither treatment, however, caused a significant effect when the soils contained calcium in the range optimal for growth of crops. Reitemeier (*15*) has reported a significant reduction of the strontium-89-to-calcium ratio in soybeans, but not in bluegrass, when 4 tons of lime per acre was rotary-tilled into the upper 6 inches of a contaminated silt loam having an initial *p*H of 5.2. Surface applications of lime at the same rate had no significant effect on the ratio in either crop. In a field-scale experiment on a calcareous soil in the United Kingdom, lime at the rate of 2 tons per acre has been without effect on the absorption of strontium-89 or on the strontium*-to-calcium ratio (*16*). It appears in general that, when soils contain sufficient lime to promote good growth of crops, further additions will provide little protection against strontium-90. Fuller investigations of acid soil types are, however, desirable; no data for tropical and subtropical conditions are yet available.

Despite the lack of any great effect of liming on the strontium-90 content of plants grown in many soils, a close negative correlation exists between the quantity of strontium absorbed by plants and the quantity of calcium that can be displaced from soils by the ammonium ion (*14*). A comparable relationship holds between the absorption of strontium by the plant and the quantity of isotopically exchangeable calcium in soils (*17*). The explanation of this seemingly paradoxical situation must be sought in the physicochemical reactions by which calcium and strontium can be retained in the soil or in the rate of reaction of liming materials with soils. Although these mechanisms are as yet very incompletely understood, there is abundant evidence of their complexity. For example, when soils are suspended in solutions of labeled calcium, a rapid isotopic exchange of calcium occurs in 1 day or less, but thereafter a slow exchange reaction may continue so that isotopic equilibrium is not reached in some soils even after 2 weeks or more.

Interesting information has also been obtained from experiments in which carrier-free strontium-89 or strontium-90 was added to soils from which labile cations were subsequently extracted. When the time between contamination with strontium-89 and extraction was increased from 2 to 71 days, the ratio of strontium-89 to calcium decreased from 9.5 to 6.9 and from 3.6 to 2.6 for a light acid soil and a heavy clay, respectively (*17*). It has also been observed, especially in calcareous soils, that the ratio decreases if the extraction procedure is made more rigorous so that larger quantities of calcium are removed. For example, in a highly calcareous soil derived from coral contaminated with radioactive fallout, the strontium-90-to-calcium ratio fell by a factor of 4 when the period of extraction with normal ammonium acetate was extended from 1 to 14 days (*18*). The extent of this effect may vary greatly among soils.

Before the advent of tracer methods, it was impossible to observe relationships of the types discussed in the foregoing paragraphs, and much work must be carried out before the situation is clear. Nonetheless, present information justifies some conclusions.

1) Although the widely varying reaction of soils makes generalization difficult, present findings suggest that the addition of lime is unlikely to reduce the absorption of fallout strontium-90 to an extent which is of practical importance except in soils for which this treatment is desirable to obtain good crops.

2) The complexity of the equilibria in which calcium and strontium take part in soil is such that no simple relationship can be expected between the total calcium in the soil and that which "dilutes" fallout strontium-90 on its entry into plants. For this reason, the effective ratio of strontium-90 to calcium in the soil cannot readily be determined. The comparison of strontium-to-calcium ratios in plants with those in soil is therefore not necessarily a valid measure of the manner in which plants discriminate between the two ions. This may explain why some experiments on plants grown in soil have suggested a marked discrimination against strontium as compared with calcium (*19*).

3) The decrease in the ratios of strontium-90 to calcium observed when soils are extracted at intervals after the addition of strontium-90 suggests that the accessibility of strontium to plants may progressively decrease. Conclusive evidence on this important question can, however, be obtained only in prolonged experiments.

Movement of Strontium-90 in Soils

Both laboratory experiments and surveys of current fallout indicate that strontium-90 penetrates to only a small depth below the soil surface. The greater part of the deposition remains in the upper 2 inches of soil for considerable periods (*12, 20*). This immobility precludes the possibility that deposits of mineral calcium that may be used for dietary purposes will become contaminated. Many factors, however, will affect the depth of penetration of strontium-90 in the upper soil layers; for example, the nature of the soil, the extent of leaching by rain, the action of worms, and the cracking of the soil in dry weather.

The results of different soil-leaching treatments (*21*) suggest that the movement of strontium-90 in the soil could be greatly accelerated only by drastic treatments, which could be highly expensive and often very injurious to soil structure and fertility.

Fraction of Total Strontium-90 Absorbed by Plants

Part of the fallout descending from the stratosphere will lodge in plants, and part will enter the soil whence it may enter plants through their roots. If the long-term effects of fallout are to be adequately assessed, it is of fundamental importance to estimate the relative extent to which these two sources are responsible for the observed contamination of herbage. If aerial deposition is the major source, the level of contamination would depend on current fallout. If, however, absorption from the soil is the major source, the quantity of strontium-90 in herbage will be related to the total fallout which has reached the soil. An accurate estimate of the fraction of strontium-90 in soil that will be absorbed by crops each year is, however, necessary for an adequate assessment of the long-term situation. This cannot readily be achieved by surveys of current contamination, and the possibility of obtaining this information by tracer experiments has therefore been considered.

Strontium-89 or strontium-90 in carrier-free form can be applied as a fine spray to the soil surface, and the subsequent entry of either into crops can be measured with precision. This approach assumes that the tracer applied as a fine spray will behave similarly to strontium-90 in fallout. This appears to be a reasonable assumption, provided that the strontium-90 in fallout is relatively soluble or will be liberated in an ionic form subsequent to its incorporation in the soil. There is evidence that world-wide fallout possesses these characteristics (*22*). Thus the behavior of strontium-90, whether applied as a tracer or in fallout, can be expected to be similar; it will enter the cation exchange complex of the soil whence it may slowly enter plants. The absorption of plants may initially be overestimated by the tracer method if a significant period elapses before a fraction of the fallout strontium-90 passes into a free ionic form from the particles in which it is deposited, but the slow rate at which strontium-90 is withdrawn from the soil by plants should make such effects small.

Table 2. Strontium-89 content of crops expressed as a percentage of the quantity of carrier-free strontium-89 applied as spray to the soil surface (*16*).

	Yield per acre (tons)	Sr-89 content as percentage of dose applied
	Ryegrass	
First cut	0.95	0.39 ± 0.03
Second cut	0.35	0.072 ± 0.005
Total		0.46
	Barley	
Grain	1.3	0.016 ± 0.0018
Straw		0.106 ± 0.0073
Total		0.122
	Sugar beet	
Roots	8.2	0.17 ± 0.01
Tops		0.61 ± 0.2
Total		0.78

Table 3. Summary of comparative strontium-to-calcium ratios in bodies and diets of various species. The OR values were determined from bone or blood values or by calculation of amounts retained from excreta values; range or mean ± standard error of mean are given where available.

Species	Diet	Method	Remarks	$OR_{body-diet}$	Reference
Man	Milk	Double tracer with each meal	4 patients, 9 to 73 years old	0.54 (0.50–0.62)	(*32*)
Man	Normal mixed	Stable Sr/Ca ratios	1 normal	0.24	(*40*)
Man	Nonmilk	Double tracer with each meal	4 patients	0.44 (0.37–0.51)	(*32*)
Man	Nonmilk	Double tracer, single dose	2 patients	0.35 (0.25, 0.45)	(*41*)
Rat	Milk	Double tracer in dietary		0.57 ± 0.02	(*5*)
Rat	Nonmilk	Double tracer in dietary		0.27 ± 0.01	(*5*)
Rat	Nonmilk	Lifetime feeding of Sr*/Ca		0.28	(*7*)
Rat	Nonmilk	Stable Sr/Ca ratios		0.27	(*6*)
Goat	Nonmilk	Double tracer, daily dose	2 animals	0.23	(*42*)
Mouse	Nonmilk	Stable Sr/Ca ratios		0.35	(*6*)
Guinea pig	Nonmilk	Stable Sr/Ca ratios		0.22	(*6*)
Jack rabbit	Natural (on desert)	Stable Sr/Ca ratios		0.20	(*6*)
Cottontail rabbit	Natural (on desert)	Stable Sr/Ca ratios		0.22	(*6*)
Kangaroo rat	Natural (on desert)	Stable Sr/Ca ratios		0.16	(*6*)

It is important that experiments of this type should be carried out under field conditions. Few results are yet available, but the first of a series of experiments of this type may, however, be considered (*16*). The purpose of the experiment was to determine the extent to which contamination was absorbed in one season by three crops—rye grass, sugar beet, and barley. A calcareous downland soil at Compton, Berkshire, England, was employed. Strontium-89 was applied as a fine spray, and, after contamination of the land, three types of cultivation were employed to prepare the seed bed. Land carrying stubble at the time of contamination was compared with fallow. The mean percentage of the applied strontium-89 recovered from the three crops in all treatments is shown in Table 2. The highest values were, as was expected, in leaf tissue. The totals for the three species varied from 0.12 to 0.78 percent. Reitemeier (*15*) has reported values ranging from 0.5 to 1.5 percent. The cultivation treatments and the condition of the land at the time of cultivation influenced absorption, but only to a relatively small extent. Since these effects differed between crops and, furthermore, are expected to change with soil type, a detailed discussion is inappropriate. The present inference, however, is that the method of cultivation appears unlikely to alter the absorption of fission products by a factor exceeding 2. The extension of this type of investigation to long-term studies with strontium-90 on permanent pastures is highly desirable.

On theoretical grounds it had been considered that 1 percent might be a medium value for the fraction of the fission-product strontium-90 (in soil) that plants absorb in a single season. The present results suggest that, in some instances, this speculation is of the correct order of magnitude. Wide variations must, however, be expected. When soils are very shallow, as they are in some hill pastures, and the soil surface is virtually a root mat, conditions are clearly in sharp contrast to those in normal agricultural land. The rate of absorption of recently added strontium-90 under such circumstances may well be much enhanced; whether, however, the total absorption over a prolonged period will be greater is a different question. No precise data for such situations are available, but it seems possible that this may in part explain sporadic exceptionally high values for the strontium-90 to calcium ratio (*23*). The detailed study of plant-to-soil relationships under such conditions is clearly desirable.

Discrimination in Man and Animals

Experimental evidence on the discrimination that occurs against strontium in favor of calcium between the diet and body is summarized in Table 3. Several conclusions may be drawn from these data. (i) From the rat experiments, which were probably the best controlled, it is clear that identical results were obtained either by short-term double-tracer techniques, lifetime feeding of a "strontium*-spiked" diet, or the analyses of stable strontium-to-calcium ratios in diet and bone. (ii) In all species on the nonmilk diet, the ratio of strontium to calcium of the body ranged from 0.16 to 0.51 of that of the diet; the average values for man were in the range from 0.24 to 0.44. The value of 0.23 for the goat may be used as representative of muscle tissue in domestic animals for calculation of the contribution of meat to the strontium-90-to-calcium ratio in the population. (iii) In man and rats having milk in the diet, the OR values were 0.54 and 0.57, respectively.

It is recognized that relatively few studies have been done on man, and these often on chronically ill patients having malignant neoplasms. Nevertheless, examination of the individual results indicates that the OR values were remarkably the same in patients having different diseases (for example, leukemia versus ovarian tumor). This, plus the general agreement with the values from other animals, permits some degree of credence in the results. Kulp *et al.* (*24*) have reported an over-all discrimination factor of 8 (0.13 in our terminology) against strontium in going from food to bones in man, based on interpretations from single intravenous dosages; this appears to be a greater discrimination than that expected from the direct observations reported in Table 3.

Minor Discrimination

To gain understanding of how the discrimination is caused, it is necessary to consider the individual processes that are operative. From a practical standpoint, this information is essential to permit a logical approach toward modification of these processes to cause decreased strontium accumulation. It is convenient to treat first the less important physiological processes, since this permits quantitative discussion of the more important ones later on.

The movements of alkaline earths between circulating fluids and bone result from ion exchange, accretion, resorption and deposition in growth, and remodeling of Haversian systems. Three types of experiments have given data on the comparative movement between circulating fluids and bone. In the double-tracer studies at steady state, described in Table 3, it was noted for one patient, for rats, and for goats that the $OR_{\text{bone-diet}}$ values were about the same as for $OR_{\text{blood-diet}}$. If anything, there was a tendency in the rat for the $OR_{\text{bone-diet}}$ to be slightly higher, indicating an over-all preferential movement of strontium from blood to bone. Further details are available from tissue-culture studies in which chick embryo bone was grown in substrate containing constant levels of strontium-89 and calcium-45 (*25*). For short experimental periods, the $OR_{\text{bone-substrate}}$ was 1.08, suggesting a slight preferential movement of strontium into the bone. When labeled bone was placed in unlabeled substrate, it was calculated that the strontium-89 was released from the bone at a ratio of 1.2 times that of calcium-45. This finding was confirmed in studies with rats in which previously deposited strontium-85 and calcium-45 were removed from nephrectomized rats by peritoneal lavage; the $OR_{\text{lavage solution-bone}}$ was 1.3 (*26*). It was necessary to use nephrectomized animals to avoid the discriminatory effects of the kidney, which masked the bone-circulating fluid effects. From kinetic studies of radioisotopes of strontium and calcium, Bauer *et al.* (*27*) also concluded that there was no marked difference between the two elements with regard to skeletal accretion and exchange, as did MacDonald *et al.* (*28*) from studies with nephrectomized rats. It appears, then, that strontium tends to be preferentially deposited and removed from bone, but these processes make little contribution to the over-all discrimination.

The excretion of circulating strontium and calcium into the lumen of the gastrointestinal tract could be a cause of discrimination. Greenberg and Troescher (*29*) reported essentially the same excretion rate for the two isotopes in the bile of rats. Singer *et al.* (*30*), however, showed that in the dog the biliary excretion of strontium* was about twice that of calcium.* In the same experiments it was also shown that, in the total endogenous excretion, only about 20 percent more strontium* than calcium* appeared in the gastrointestinal tract; the biliary strontium* and calcium* comprised only 6 to 9 percent of the total endogenous excretion. It is thus considered that this process does not contribute significantly to over-all discrimination.

Major Discrimination

It appears that only absorptive and urinary discrimination are of importance in the nonpregnant, nonlactating animal. The following equations have been used to calculate the relative contribution of each process; they are based on the assumption that urinary excretions are proportional to the amounts absorbed (*5*).

$$DF_{\text{absorptive}} = \frac{100 - \%\ \text{ingested Sr in feces}}{100 - \%\ \text{ingested Ca in feces}} \tag{3}$$

$$DF_{\text{urinary}} = \frac{OR_{\text{body-diet}}}{DF_{\text{absorptive}}} \tag{4}$$

Table 4 presents a summary of the relative contributions of absorption and urinary excretion to the discrimination in man and rat. Again, there seems to be general agreement between these two species. It is noted that milk apparently reduced the absorptive discrimination but had little effect on urinary discrimination. On a milk diet, the contributions of both processes were about equal; on a nonmilk diet, the absorptive process was more important.

Of greatest practical importance is the reduction of strontium-to-calcium ratio that occurs in passage of these elements from the fodder of the cow to the milk. Table 5 summarizes values obtained experimentally by double-tracer feeding, by surveys of fallout strontium-90, and by analyses of stable strontium-to-calcium ratios in feed and milk. Again, there is good agreement among all observations, and there is little question that, under conditions of daily intake, the strontium*-to-calcium ratio of the milk will be about 0.1 to 0.14 that of the ra-

Table 4. Relative contributions of absorption and urinary excretion to strontium-calcium discrimination in man and rat.

Item	One patient on milk (*32*)	Rats on milk (*5*)	Two patients on nonmilk (*41*)	Rats on nonmilk (*5*)
$OR_{\text{bone-diet}}$		0.57		0.27
$OR_{\text{retained-diet}}$			0.35	
$OR_{\text{blood-diet}}$	0.62			
$DF_{\text{absorptive}}$	0.78	0.68	0.46	0.34
DF_{urinary}	0.87	0.84	0.75	0.88

Table 5. Comparative strontium-to-calcium ratios in the milk and feed of the cow and goat.

Species	Method	$OR_{milk\text{-}diet}$	Reference
Goat	Two animals on double-tracer daily feeding for 13 days	0.08, 0.10	(*42*)
Cow	Daily and single feeding of Sr* and Ca* at different times	0.14	(*39*)
Cow	Sr^{90} assays of Wisconsin milkshed, 1953	0.16	(*3*)
Cow	Sr^{90} assays of Wisconsin milkshed, 1955	0.15	(*22*)
Cow	Sr^{90} assays in United Kingdom, 1955	0.09	(*23*)
Cow	Stable Sr and Ca ratios in feed and milk from New York area	0.12	(*20*)

tion being consumed by the animal. The studies on goats give further details—for example, $OR_{plasma\text{-}diet} = 0.24$; $OR_{milk\text{-}diet} = 0.09$. It is noted that, in going from the blood of the goat to the milk, there was a reduction in the strontium-to-calcium ratio by a factor of 0.38. Another important point, which has been anticipated on theoretical grounds, has been strongly supported by the survey results; this is the fact that the level of strontium-90 in the milk is mainly a reflection of current strontium-90 intake and is not greatly influenced by the strontium-90 level in the cow's skeleton as a whole.

The comparative passage of strontium and calcium from dam to fetus has been studied in rats and rabbits (*7, 31*). In general, the placental transfer of strontium was about one-half of that of calcium; the major site of discrimination was the placental barrier, with differential movement occurring in passage from dam to fetus but with no differential movement from fetus to dam. Under steady-state conditions in the rat, $OR_{dam\text{-}diet}$ was 0.28, and the $OR_{fetus\text{-}diet}$ was 0.17. The over-all discrimination of 0.17 between fetus and diet resulted from absorption ($DF_{absorptive} = 0.42$), urinary excretion ($DF_{urinary} = 0.63$), and placental transfer ($DF_{placental\text{-}fetus} = 0.65$). In the rat it was estimated that 92 percent of the fetal calcium had originated from the maternal diet. Of practical importance, this means that strontium content of the fetal calcium will be governed mainly by the strontium content of the calcium ingested by the mother shortly before or during gestation.

Factors That Affect Discrimination

It is important to know whether or how the strontium-calcium discrimination is affected by age. Comar *et al.* (*7*) showed that there was no difference in discrimination in rats between 70- and 400-gram body weight. The data from steady-state double-tracer studies on human subjects (*32*) indicated no large differences between persons ranging from 9 to 73 years; it must be noted that there were only a few persons in these experiments. Sowden and Stitch (*33*) reported as follows from analyses of stable strontium: bone strontium values in the newborn were low (as would be expected from fetal discrimination); between 6 and 74 years of age there was a tendency for the strontium values to increase. Unfortunately there are no data for very young children. Theoretically one might expect the discrimination in the very young to be decreased because of increased absorption and retention of both alkaline earths. This has been recently confirmed in studies with rats on a milk diet in which the $OR_{bone\text{-}diet}$ was 0.78, 0.62, and 0.45 at 15, 48, and 194 days of age, respectively.

Of the dietary factors that might affect discrimination, milk appears to be important. As has already been mentioned, milk tends to reduce discrimination primarily by its effect on the absorptive process. In the work that pointed the way to the milk effects, Wasserman *et al.* (*34*) showed that substances, such as lactose, lysine, and arginine, that tended to increase calcium absorption were even more effective in increasing strontium absorption. Eighteen other amino acids, including those essential for the rat, were shown to have little or no effect. Other substances such as sodium gluconate, sodium lactate, and B vitamins were shown to be without effect. Further work, as yet unpublished, indicated that ingestion of complexing agents such as phytate and citrate, when incorporated in fluid milk, had no effect; however, the sodium salt of ethylenediaminetetraacetic acid markedly decreased the discrimination by raising the strontium retention and at the same time slightly lowering the calcium retention.

The effect of dietary calcium level on discrimination is now considered. Short-term or single-dose studies usually indicate that raising the calcium level does not proportionally decrease the strontium burden. For example, in rats it was found necessary to raise the calcium content 2000-fold to reduce the strontium-90 retention by half (*35*). This probably happens, however, because the animal tends to absorb more calcium when the calcium level is raised on a short-term basis. Preliminary results of longer-term feeding studies with rats receiving diets supplemented with calcium carbonate in the normal range indicated that the retention of ingested radiostrontium was inversely proportional to the calcium level of the diet (*36*). When these calcium levels (0.5 to 2.0 percent calcium in diet) were fed for 15 days, the fourfold increase in dietary calcium decreased radiostrontium retention in the rat by a factor of 3; at 45 days, a true stoichiometric relationship was observed. Thus it appears that the usual laws of isotope dilution were operative. It was also shown that the $OR_{bone\text{-}diet}$ value was the same in rats on a normal milk diet and those on milk supplemented with calcium gluconate to contain 3 times the normal calcium content.

Discrimination between Vegetation and the Human Skeleton

It is possible to make some estimates, based on the experimental evidence already presented, about the relationships that will exist between the strontium*-to-calcium ratio of the vegetation and that in the human population when steady-state conditions have been attained. Account must be taken of the sources of dietary calcium, which will depend to a certain extent on the food technology and food habits of the region. Infants receive their calcium predominantly from cow's milk or mother's milk. In the United Kingdom, it has been estimated that the sources of calcium in the average diets of the whole population are as follows: 56 percent from dairy products; 16 percent from vegetable produce; 4 percent from meat and eggs; and 21 percent from mineral sources, primarily in fortified bread. In the United States, bread is fortified with milk solids, and it is estimated that 70 to 80 percent of the dietary calcium comes from dairy products, 14 to 20 percent from vegetable produce, and about 5 percent from meat and eggs (*37*).

When it is remembered that the strontium*-to-calcium ratio in milk is 0.1 to 0.14 of that in vegetation, it appears that plant strontium-90 should not be overlooked as an important source in the average diet. The contribution from vegetable foods, however, may be somewhat reduced because washing and removal of outer leaves causes the strontium-90-to-calcium ratio in vegetable produce consumed by man to be less than that in herbage consumed by animals; furthermore, seeds and tubers, which are not exposed to aerial contamination, may contribute some calcium to the human diet. There are insuffieicint data to permit such considerations to be taken into account. Water supplies are not considered an important source of strontium-90 because of the great dilution that takes place, the fixation of the radioisotope upon soil or rock particles, and the soil filtration of water that comes from wells or springs.

In Table 6, some estimates (based on rounded-off values) are presented of the relationship between the strontium-90-to-calcium ratio in vegetation and the strontium-90-to-calcium ratio in the skeletons for populations in the United States deriving their dietary calcium from the sources stated. The contribution of strontium-90 from fish sources appears to be small and is neglected; the effect of mineral sources of calcium is also neglected, except for the known levels used in the United Kingdom. Because of the complexity of the factors that influence the $OR_{vegetation\text{-}soil}$, no assessment of the relationships between the ratio of strontium-90 to calcium in soil and that in man has been attempted.

Estimates were made for the newborn and 6-month-old child because of the additional discrimination that occurs in fetal development and that might be caused by feeding on mother's milk. It seems, therefore, that the newborn and very young children should develop a strontium*-to-calcium ratio of 0.04 to 0.12 of that existing in the vegetation; these values range from 0.08 to 0.16 for older persons. Similar calculations based on the dietary sources in the United Kingdom give values of 0.035 to 0.11 for the newborn and young children, and 0.07 to 0.12 for older persons. The survey data on strontium-90-to-calcium ratios in children as related to that in vegetation, so far, appear to show greater discrimination against strontium than expected from the foregoing. It is impossible on the basis of present data to determine whether this is the result of underestimation of the discrimination factors, of differences in dietary habits, or of equilibrium not yet having been attained. Another point of uncertainty is that calcium and strontium from different sources may not be utilized to the same extent. The relationship between stable strontium-to-calcium ratios in human bone and in sedimentary rocks (*38*) is, however, in reasonable agreement with the values presented for adults. As more precise information becomes available on food habits and dietary calcium sources, these data can be treated according to the principles developed in Table 6. The values can also be adjusted if future work demonstrates that fallout strontium-90 becomes significantly less available with time or if procedures such as plowing produce significant dilution as related to the feeding zone of certain crops.

Reducing the Extent to Which Fallout Enters Food Chains

The failure of lime to provide protection universally against the absorption of strontium-90 by crops encourages the search for other remedies. No satisfactory procedure has yet been demonstrated. It is impracticable to remove the contamination by leaching, and the modification of cultivation procedures in arable land seems likely to have only a small effect; however, these are matters that require further study.

The quantity of strontium-90 absorbed could be reduced, however, by cultivating crops that possess one or both of the following characteristics: a low concentration of strontium and calcium in their edible tissues, or a deep-rooting habit that causes them to absorb the greater part of their nutrients from below the level to which contamination has penetrated. The cultivation of crops containing a low concentration of strontium could reduce the strontium-90 intake of the population. However, since plants differ little in their OR values, the calcium content of diets would be reduced. This procedure would therefore have obvious limitations unless alternative sources of dietary calcium were provided. However, in wartime emergency, survival might be aided by the cultivation of crops low in calcium relative to their calorific value. On this basis, the potato, which contains in the order of 10 milligrams of calcium per 100 calories, is a particularly suitable crop; leafy vegetables may contain 10 to 100 times as much calcium per 100 calories.

Information is, unfortunately, lacking on the extent to which different species absorb calcium from more than 6 inches below the soil surface. The very great differences existing in root structures between different grass and legume constituents of pasture suggest, however, that plants may contrast markedly in this respect. The cultivation of species that absorb relatively little from the upper 4 to 6 inches of soil would appear to be the most practicable method for reducing the strontium-90-to-calcium ratio in herbage. Thus the investigation of the pattern of absorption by agriculturally important species is a subject of particular interest.

Table 6. Assumptions and estimated relationships between strontium*-to-calcium ratios in vegetation and the human population in the United States.

Age	Sr*/Ca of human bone / Sr*/Ca of vegetation	Assumptions
Newborn	0.04 to 0.08	70 to 80 percent of mother's calcium derived from milk; discrimination from feed to cow's milk = 0.1 to 0.14; discrimination from milk to mother's body = 0.5; 14 to 20 percent of mother's calcium of vegetable origin; discrimination from plant food to mother's body = 0.25 to 0.5; 5 percent of mother's calcium derived from meat and eggs; discrimination from vegetation to meat and eggs = 0.25; discrimination from meat and eggs to mother's body = 0.25 to 0.5; discrimination across placenta = 0.5.
Six months	0.037 to 0.12	67 percent of calcium had been laid down *in utero* with maximum discrimination, and child was nursed on mother's milk with maximum discrimination of 0.03; or, 33 percent of calcium had been laid down *in utero* with minimum discrimination, and child was fed on cow's milk with minimum discrimination of 0.14.
Over 6 months	0.08 to 0.16	Same as for newborn except that there is no placental discrimination.

Sample calculation for maximum in utero discrimination

% of mother's Ca from milk		discr. from feed to cow's milk		discr. from milk to mother's body		% of mother's Ca from plants		discr. from plant food to mother's body		% of mother's Ca from meat and eggs		discr. from feed to meat and eggs		discr. from meat and eggs to mother's body		discr. across placenta		
[(0.8	×	0.10	×	0.5)	+	(0.14	×	0.25)	+	(0.05	×	0.25	×	0.25)]	×	0.5	=	0.04

Steps to reduce the strontium-90 burden in the population by procedures with man and animals would first be concerned with assuring that an uncontaminated source of calcium contributed a maximum proportion of the dietary calcium. As has already been noted, the immobility of strontium-90 in soil would protect deposits of mineral calcium from contamination. Thus one might use mineral sources of calcium as much as possible and plant sources at a minimum. The evidence that discrimination between the two elements can be changed by dietary alterations (milk, lactose, lysine) gives some reason to believe that further research could provide an effective modification in either direction.

The possibility of using increased dietary calcium to reduce the amount of radioactive strontium entering milk has been previously reported (*39*). Short-term studies with dairy cows indicated that a fourfold elevation of dietary calcium caused only a 35-percent reduction in the strontium-90 content of the milk. Judging from the longer term rat studies previously mentioned (*36*), one might expect that stoichiometric reduction of strontium-90-to-calcium ratios should occur from supplementation of rations with uncontaminated calcium. It is emphasized, however, that further work is needed to determine whether such supplementation of dairy rations would indeed be effective and feasible. Again, judging from the longer term rat studies, it might be possible to decrease stoichiometrically the strontium-90-to-calcium ratio in man by supplementation of his diet over the years with uncontaminated calcium; but, as always, definite proof of this point must await direct observations on man. At present, mineral calcium is used to fortify flour in some countries, for example, the United Kingdom; but it would be much more difficult to justify large increases in dietary calcium for the human population than it would be to justify similar modifications of animal rations. There is, of course, the possibility of supplementation with stable strontium. Since it would most likely be necessary to use the same levels of strontium as of calcium, it is perhaps more useful to focus attention on the more physiological element, calcium.

The discussion of methods for reducing the extent to which fallout enters food chains is not meant to imply that remedial measures are now necessary. Such considerations, and in addition the matter of how much reduction would be of practical significance, are beyond the scope of this paper.

Summary

The calcium reservoirs of the biosphere are becoming labeled to varying degrees with strontium-90 from nuclear weapons. These reservoirs include the human and animal skeleton, the milk, the vegetation, the upper layers of soil, and the waters. The degree of labeling is governed by the dilution that occurs, or the differential behavior of calcium and strontium in various steps of the food chain. This differential behavior normally provides a factor of protection against strontium-90 in the soil and vegetation that may be as high as 25 for the newborn and is most likely not less than 6 for adults, depending on food habits.

The physiological steps that are important in the movement of the two elements in the biosphere are described to provide a basis for an approach toward increase of the discrimination against strontium in favor of calcium. Some aspects of agricultural practices are discussed from this standpoint. The matter of hazard from levels now existing and the present need to undertake remedial measures are not discussed, in major part because of lack of experimental data on which to base such considerations.

References and Notes

1. G. M. Dunning, *Nucleonics* 14, No. 2, 38 (1956); C. L. Comar *et al.*, *Science* **126**, 16 (1957).
2. C. E. Miller and L. D. Marinelli, *Science* 124, 122 (1956); E. C. Anderson *et al.*, *ibid.* 125, 1273 (1957).
3. W. F. Libby, *Proc. Natl. Acad. Sci. U.S.* 42, 365 (1956).
4. We acknowledge the encouragement and stimulation of W. F. Libby, C. L. Dunham, and other staff members of the U.S. Atomic Energy Commission, and of J. F. Loutit of the U.K. Medical Research Council Radiobiological Research Unit. Thanks are also due to R. F. Reitemeier of the U.S. Atomic Energy Commission and the U.S. Department of Agriculture for helpful suggestions. The work reported from the Oak Ridge Institute of Nuclear Studies was done under contract with the U.S. Atomc Energy Commission, and the investigations in Oxford and Compton, England, were supported by the U.K. Agricultural Research Council.
5. C. L. Comar, R. H. Wasserman, M. M. Nold, *Proc. Soc. Exptl. Biol. Med.* 92, 859 (1956).
6. G. V. Alexander, R. E. Nusbaum, N. S. MacDonald, *J. Biol. Chem.* 218, 911 (1956).
7. C. L. Comar, I. B. Whitney, F. W. Lengemann, *Proc. Soc. Exptl. Biol. Med.* 88, 232 (1955).
8. J. H. Rediske and A. A. Selders, *Plant Physiol.* 28, 594 (1953); R. S. Russell and H. M. Squire, *J. Exptl. Botany*, in press.
9. R. G. Menzel and W. R. Heald, *Soil Sci.* 80, 287 (1955); R. P. Martin and R. S. Russell, in preparation.
10. E. M. Romney *et al.*, *UCLA Rept. No. 374* (1956).
11. R. Collander, *Plant Physiol.* 16, 691 (1941).
12. L. J. Middleton, private communication (1957).
13. H. J. M. Bowen and J. A. Dymond, *Proc. Roy. Soc.* (*London*) B144, 355 (1955).
14. W. H. Fuller and W. J. Flocker, *Univ. of Arizona Tech. Bull. 130* (1955).
15. R. F. Reitemeier, *Atomic Energy Research Establishment* (*Harwell*) *Rept. SPAR 12* (1955).
16. G. M. Milburne and R. S. Russell, in preparation.
17. P. Newbould, private communication (1957).
18. R. S. Russell, R. P. Martin, H. M. Squire, *Atomic Energy Research Establishment* (*Harwell*) *Rept. SPAR 3* (1955).
19. R. G. Menzel, *Soil Sci.* 77, 419 (1954).
20. J. H. Harley *et al.*, *NYO Rept.* No. 4862 (1957).
21. R. Overstreet, private communication (1957); J. R. Miller and R. F. Reitemeier, *U.S. Dept. Agr., Soil and Water Conservation Research Div., Research Rept. No. 300* (1957).
22. E. A. Martel, *A.E.C.U. Rept.* 3262 (1956).
23. R. J. Bryant *et al.*, *Atomic Energy Research Establishment* (*Harwell*) *Rept. No. HP/P 2056* (1956).
24. J. L. Kulp, W. R. Eckelmann, A. R. Schulert, *Science* 125, 219 (1957).
25. F. W. Lengemann, *Proc. Soc. Exptl. Biol. Med.* 94, 64 (1957).
26. R. V. Talmage, J. C. Schooley, C. L. Comar, *ibid.* 95, 413 (1957).
27. G. C. H. Bauer, A. Carlsson, B. Lindquist, *Acta Physiol. Scand.* 35, 56 (1955).
28. N. S. MacDonald, P. Noyes, P. C. Lorick, *Am. J. Physiol.* 188, 131 (1957).
29. D. M. Greenberg and F. M. Troescher, *Proc. Soc. Exptl. Biol. Med.* 49, 488 (1942).
30. L. Singer *et al.*, *Arch. Biochem. and Biophys.* 66, 404 (1957).
31. R. H. Wasserman *et al.*, *Am. J. Physiol.* 189, 91 (1957).
32. C. L. Comar, *et al.*, *Proc. Soc. Exptl. Biol. Med.* 95, 386 (1957).
33. E. M. Sowden and S. R. Stitch, *Atomic Energy Research Establishment* (*Harwell*) *Rept. No. MRC/R 2030* (1956).
34. R. H. Wasserman, C. L. Comar, M. M. Nold, *J. Nutrition* 59, 371 (1956).
35. N. S. MacDonald *et al.*, *ibid.* 57, 555 (1955).
36. R. H. Wasserman, C. L. Comar, D. Papadopoulou, unpublished data.
37. The values for the United Kingdom are from "Domestic food consumption and expenditure," [*Ann. Rept. Natl. Food Survey Committee* (H.M. Stationery Office, London, 1955)] and information from the Research Association of British Flour-Millers. The values for the United States are compiled from F. C. Blanck, Ed., *Handbook of Food and Agriculture* (Reinhold, New York, 1955) and P. B. Hawk, B. L. Oser, W. H. Summerson, *Practical Physiological Chemistry* (Blakiston, Philadelphia, 1947).
38. K. K. Turekian and J. L. Kulp, *Science* 124, 405 (1956).
39. C. L. Comar and R. H. Wasserman, *Progress in Nuclear Energy, Series VI, Biological Sciences* (Pergamon, London, 1956), vol. 1, p. 153.
40. G. E. Harrison, W. H. A. Raymond, H. C. Tretheway, *Clin. Sci.* 14, 681 (1955).
41. H. Spencer, D. Laszlo, M. Brothers, *J. Clin. Invest.* 36, 680 (1957).
42. R. H. Wasserman, F. W. Lengemann, C. L. Comar, in preparation.