Estimating Soil Ingestion: The Use of Tracer Elements in Estimating the Amount of Soil Ingested by Young Children

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ABSTRACT. In this pilot study, we modified methods used in estimating the amount of soil ingested by ruminants to measure soil ingested by children. Using aluminum, silicon, and titanium as tracers, we estimated soil ingestion for 59 children aged 1-3 yr from East Helena, Montana. Estimated daily soil ingestion based on aluminum and silicon concentrations were 181 and 184 mg/day, respectively, whereas the estimate based on the titanium concentration was about 10 times higher, 1,834 mg/day. Although we do not consider these estimates accurate measures of soil ingestion, the method we used is a reasonable approach that, to our knowledge, has not been used before in humans. However, our estimates will be revised as refinement of this method and better understanding of the metabolism of aluminum, silicon, and titanium lead to more accurate data for analysis.

AN ASSESSMENT of the human health risk associated with toxic materials in the environment is only as good as the estimate of exposure. Relatively good estimates are available for the amount of air breathed and water ingested. However, estimates of the amount of soil and dust ingested during normal activities are based on little objective evidence, and they vary widely. These estimates are used in risk assessments at hazardous waste sites throughout the United States to determine cleanup levels and health actions. For example, the decision to relocate residents exposed to dioxin at Times Beach, Missouri, was based on a risk assessment, with exposure to dioxin through soil ingestion contributing over half the estimated risk to inhabitants of the area.

Previous estimates of children's soil ingestion have generally been guesses or a combination of guesswork and measurements. Lepow et al. measured a mean of 10 mg of dirt on the hands of 22 children. They guessed that a child puts its hands into its mouth approximately 10 times a day for a daily soil intake of 100 mg/day. The National Research Council estimated that young children ingest an average of 40 mg/day of street dust. Day et al. measured 5-50 mg of dirt transferred from a child's hand to a sticky sweet and estimated that a daily intake of 2-20
sweets would lead to a dirt intake of 10-1,000 mg. Kimbrough et al. estimated that the average amount of soil ingested per day is 1 g for children aged 9 to 18 mo, 10 g for those 18 to 42 mo, 1 g for those 42 mo to 5 yr, and 100 mg for persons 5 yr old through adulthood.

Veterinary scientists have developed methods for measuring soil ingested by grazing animals. Using non-absorbed elements as tracers, they have measured fecal excretion of elements that have high concentrations in soil. Silicon and titanium are the elements most often used for this purpose, and estimates of soil ingestion in ruminants, such as cows, have ranged from .42 to 4.219 g/day. We adapted this method for estimating the amount of soil ingested by children.

Materials and methods

As part of a health study of residents living near a lead smelter in East Helena, Montana, during the summer of 1984, after obtaining informed parental consent, we collected all diapers used in three days from children aged 1 through 3 yr who were not toilet trained. After soiled diapers were collected, as much stool as possible (and urine which was mixed with the stool) was recovered from the diaper and liner. Plastic bottles containing the 3-day stool collections were stored in a walk-in refrigerator at 4°C for several months before being freeze dried. Some of the samples required additional drying in an oven. The stool samples were then homogenized to a fine powder in a food blender with stainless steel blades and analyzed for aluminum, silicon, and titanium by inductively coupled plasma atomic emission spectrometry (ICP). Precision of stool element estimates and recovery of elements were studied with pooled stool samples spiked at two levels with aluminum, silicon, and titanium. Replicate measurements on all samples were similar, and recovery of the elements ranged from 68 to 97%.

In addition to stool samples, yard soil samples were collected from most of the participating children's houses. Four soil samples from the front yard and one from the back were obtained from the top 1 inch of ground with a stainless steel corer. Samples were composited in the field. Soil aluminum, silicon, and titanium concentrations were analyzed by x-ray fluorescence.

Estimates of daily soil ingestion for each child \( i \) \( (M_i) \) based on aluminum, silicon, and on titanium were calculated according to the following formula:

\[
T_{i,e} = \frac{f_{i,e} \times F_i}{S_{i,e}}
\]

where \( T_{i,e} \) = estimated soil ingestion for child \( i \) based on element \( e \) in g/day, \( f_{i,e} \) = concentration of element \( e \) in fecal sample for child \( i \) in mg/g, \( F_i \) = daily fecal dry weight for child \( i \) in g/day, and \( S_{i,e} \) = concentration of element \( e \) in yard soil in mg/g.

Because the fecal weights measured in this study (1.8-17.2 g/day) were so much lower than expected, \( F_i \) was replaced with 15 g/day, an estimate of the daily fecal dry weight for all children in this age group. This estimate was derived from a reanalysis of data presented in a 1979 paper. Seventeen infants aged 13-24 mo produced a mean of 1.7 stools per day. Average stool weight was 35 g, of which 73.8% was water. The calculated mean dry weight of the stools was approximately 15 g/day.

In addition to aluminum, silicon, and titanium that children ingest as part of their normal diets, certain materials provide concentrated sources of these elements. For example, baked goods can contain large amounts of aluminum, beer is a saturated solution of silicon, and paint contains large quantities of titanium. If a child has consumed a concentrated source of one element, the estimated amount of soil ingested based on that element will be higher than the estimates based on the other two elements. An alternative method of estimating soil ingestion is to use the minimum of the three soil ingestion estimates for each child. Using the same notation as before, according to this method:

\[
T_i = \text{Minimum } (M_{i,e})
\]

where \( M_i \) = estimated soil ingestion for child \( i \) in mg/day, and \( M_{i,e} \) = estimated soil ingestion for child \( i \) based on element \( e \) in mg/day.

Results

Stool samples from 65 children were analyzed by ICP. Sixty-five percent were male, and the mean age of both males and females was 1.6 yr. Mean and median amounts of daily fecal mass were 7.5 g/day and 7.1 g/day, respectively.

Composite soil samples from front and back yards were obtained from 59 of the 65 children for whom we had ICP stool data. The mean, median, and geometric mean fecal and yard soil concentrations of aluminum, silicon, and titanium are shown in Table 1. The distributions are highly skewed; only fecal silicon and soil silicon and titanium appeared to be normally distributed with logarithmic transformation.

Estimates of soil ingestion based on aluminum, silicon, and titanium concentrations were calculated on the 59 children for whom we had both composite yard soil and ICP data (Table 2). The arithmetic mean of soil ingestion estimates based on aluminum (121 mg/day) was similar to the one based on silicon (184 mg/day), but the estimate based on titanium (1,834 mg/day) was 10-fold higher. As would be expected, the arithmetic mean estimate based on the minimum of the three estimates for each child (108 mg/day) was lower than that based on any individual element (Table 3, Fig. 1).

Discussion

We estimated that mean daily soil ingestion in the East Helena children was between 108 mg/day (based on the minimum estimate of all elements for each child) and 1,834 mg/day (based on titanium). The estimates of soil ingestion for the children based on aluminum and silicon were an order of magnitude less than the estimate based on titanium.

An ideal tracer element for a study such as ours is one with soil concentrations much greater than those in other ingested substances. It should be poorly absorbed from the gastrointestinal tract, and laboratory techniques for its
measurement should be well developed. To determine which of our estimates best represents the amount of soil a child ingests, we would have to know which element is the best tracer for soil ingestion—and that information is not available.

It is difficult to explain why the soil ingestion estimate based on titanium is so much larger than that for either of the other elements. Although paint contains titanium, houses in East Helena were not found to have chipping or peeling paint. One would expect the estimate from aluminum to be highest, since aluminum occurs so commonly in foods. Titanium does not occur in large quantities in drinking water or foods, including milk, and is present in children’s vitamins in only minute quantities (personal communication, Squibb Pharmaceutical Company). It is present in some toothpastes, especially gels, as the ingredient of lowest concentration (<2.5%); however, the exact amounts of titanium in toothpaste are proprietary information (personal communication, Colgate-Palmolive Company). Titanium does not leach from diapers (unpublished data, Division of Environmental Health Laboratory Sciences, Center for Environmental Health, Centers for Disease Control) and is not present in baby powder (personal communication, Johnson and Johnson Company). Furthermore, it is unlikely that stool samples were contaminated with titanium during processing. (We were unable to elute titanium from plastic sample jars, plastic gloves, etc.). We believe, therefore, that either differences in absorption or metabolism of these elements in children compared with adults or unrecognized sources of titanium (in diet or in laboratory processing of stools) are responsible for the relatively high soil ingestion estimate based on titanium.

In addition to the assumption that aluminum, silicon, and titanium are neither introduced into nor lost from samples during processing, several other assumptions are
needed in applying our algorithm. These are summarized below.

First, the algorithm assumes that children ingest predominantly soil from their own yards and that concentrations of elements in composite soil samples from front and back yards are representative of overall concentrations in the yard. Although aluminum, silicon, and titanium concentrations in residential soils may be variable, East Helena soils were homogenous with respect to those elements (Table 1). In East Helena, the calculation of soil ingestion based on the study population's mean yard soil concentrations of elements instead of each child's individual values had little effect on the estimated soil ingestion; in other places, this assumption may be more important.

The amount of house dust ingested, like that of soil ingested, is unknown. Children probably eat a combination of soil and dust; the algorithm used does not distinguish between soil and dust ingestion. If concentrations of aluminum, silicon, and titanium are different in dust than in soil (as is usually the case), soil ingestion estimated on the basis of the algorithm will be inaccurate.

Second, fecal sample weights in this study were much lower than we had expected. Although we reviewed the diaper processing procedure and could not identify any step at which stool samples were lost, it is possible that some specimens were misplaced before the weighing. It is also possible that parents did not submit all soiled diapers.

Soil ingestion calculated on the basis of the algorithm is directly proportional to fecal weight. Because of concern that the data on fecal sample weights were inaccurate, we chose to use an estimate of 15 g per day as the average fecal weight for toddlers. In reality, daily fecal weight varies among toddlers; its relation to age or size has not been well characterized.

The assumption that aluminum, silicon, and titanium are not absorbed is not entirely true. Studies have shown that aluminum, silicon, and titanium can be absorbed from the gastrointestinal tract of adults, although usually in small amounts. Furthermore, studies of lead metabolism have shown that absorption of elements may be significantly different in children and adults. In the age group we studied, urine and feces are often mixed in diapers. The specimens collected from the diapers may therefore have included both unabsorbed aluminum, silicon, and titanium from feces and absorbed elements excreted in the urine. If children are in positive aluminum, silicon, or titanium balance, the algorithm will result in an underestimate of soil ingestion.

Contrary to our assumptions, dietary intake of aluminum, silicon, and titanium is not negligible when compared with potential intake of these elements from soil. The average adult dietary intakes of aluminum, silicon, and titanium are 15, 7, and .3 mg/day, respectively. The presence of these elements in food leads to an overestimation of the amount of soil eaten by children.

The estimates of soil ingestion generated in this report range over an order of magnitude. Before accepting these estimates as true values of soil ingestion in toddlers, we need a better understanding of the mechanisms of aluminum, silicon, and titanium in children, and the validity of the assumptions we made in our calculations should be explored further. Studies of aluminum, silicon, and titanium levels in feces of volunteers; studies of these elements excreted by hospitalized children; repetition of our study in an area with homogenous soil; and similar studies that include measurements of house dust are possible next steps. Careful attention to study methods such as complete stool collection and monitoring of dietary intake will undoubtedly lead to better estimates of soil ingestion. We hope that this study will stimulate further studies on the amount of soil ingested by young children.

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References


