Children's Exposure Assessment: A Review of Factors Influencing Children's Exposure, and the Data Available to Characterize and Assess That Exposure

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We review the factors influencing children's exposure to environmental contaminants and the data available to characterize and assess that exposure. Children's activity pattern data requirements are demonstrated in the context of the algorithms used to estimate exposure by inhalation, dermal contact, and ingestion. Currently, data on children's exposures and activities are insufficient to adequately assess multimedia exposures to environmental contaminants. As a result, regulators use a series of default assumptions and exposure factors when conducting exposure assessments. Data to reduce uncertainty in the assumptions and exposure estimates are needed to ensure chemicals are regulated appropriately to protect children's health. To improve the database, advancement in the following general areas of research is required: identification of appropriate age/developmental benchmarks for categorizing children in exposure assessment; development and improvement of methods for monitoring children's exposures and activities; collection of activity pattern data for children (especially young children) required to assess exposure by all routes; collection of data on concentrations of environmental contaminants, biomarkers, and transfer coefficients that can be used as inputs to aggregate exposure models. *Key words*: activity patterns, aggregate exposure, children, environmental exposure, exposure assessment, susceptible populations. *Environ Health Perspect* 108:475–486 (2000). [Online 11 April 2000]
http://ehpnet1.niehs.nih.gov/docs/2000/108p475-486cohen_hubal/abstract.html

Children's exposures to environmental contaminants are expected to be different and, in many cases, much higher than adults (*1–7*). Differences in exposure are due in part to differences in physiologic function and surface-to-volume ratio. However, differences in the behavior of children, particularly the way in which children interact with their environment, may also have a profound effect on the magnitude of exposures to contaminants.

The U.S. Environmental Protection Agency (EPA) has pledged to increase its efforts to provide a safe and healthy environment for children by ensuring that all EPA regulations, standards, policies, and risk assessments take into account special childhood vulnerabilities to environmental contaminants. The Food Quality Protection Act of 1996 (FQPA) (*8*) requires that exposure assessments be used in the pesticide tolerance-setting process. Exposure assessments for the FQPA must consider the potential susceptibility of infants and children to pesticide exposures from all sources including those from food, water, dust, soil, and air. To meet these regulatory requirements, existing information on children's exposure to environmental contaminants needs to be used to develop and improve exposure assessment methods and models for children. In addition, research on exposure that will answer questions about age-related differences and will lead to better exposure assessments for children needs to be designed and conducted.

We review the factors influencing the exposure of children and the data available to characterize and assess exposure, with a focus on children's activity patterns. Activity pattern data requirements are demonstrated in the context of algorithms used to estimate exposure by inhalation, dermal contact, and ingestion. Finally, we identify data gaps and areas for future research to improve exposure assessment for children.

General Principles for Studying Children's Exposure

Exposure is defined as the contact (at visible external boundaries) of an individual with a pollutant for specific durations of time. Exposure assessments are developed to characterize real-life situations, whereby *a*) potentially exposed populations are identified; *b*) potential pathways of exposure are identified; and *c*) the magnitude, frequency, duration and time-pattern of contact with a chemical (potential doses) are quantified. Exposure assessments are conducted using either a direct or an indirect approach. A direct assessment measures a person's contact with a chemical concentration in a media over an identified period of time using personal monitoring techniques. Because of high study costs, direct exposure assessments are not often conducted and few methods exist for making them. For a few environmental contaminants, biomarkers can serve as a useful measure of direct exposure aggregated over time for all sources and pathways. However, few studies using biomarkers have collected all of the information required to accurately estimate exposure. An indirect assessment uses available information on concentrations of chemicals in the various media, along with information about when, where, and how individuals might contact the chemical. The indirect approach uses models and a series of exposure factors (e.g., pollutant transfer and pollutant uptake) to estimate exposure. The specific information and factors needed to conduct an indirect assessment for a given contaminant depend on the significant routes and pathways for exposure to that contaminant.

Because of difficulties associated with performing direct exposure assessments, indirect exposure assessments are typically used to perform formal risk assessments needed to make regulatory decisions. Indirect exposure assessments require data on the following exposure factors:

- Contaminant concentrations in the exposure media in the environment where the individual spends time
- Contact rates of the individual with the exposure media
- Contaminant transfer efficiency from the contaminated medium to the portal of entry
- Contaminant uptake rates
- Activity patterns.

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This paper has been reviewed in accordance with the U.S. EPA peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Received 11 August 1999; accepted 7 January 2000.

It is difficult to develop and verify exposure factors such as contaminant uptake rates and transfer rates for young children. Children cannot intentionally be exposed to contaminants; thus, controlled laboratory studies with children cannot be conducted. Using adult surrogates for these studies introduces bias, because adults do not behave like young children and therefore cannot mimic their contact activities. It is also difficult to collect personal air, blood, urine, and duplicate-diet samples from a child. In addition, it is difficult to accurately record a child's activity patterns. Direct observation (which may include videotaping) is considered the most accurate way to record a child's activities, especially as they relate to dermal absorption and ingestion. However, this methodology is labor intensive and costly. Finally, children engage in a wider range of contact activities than adults, so a much wider distribution of activities must be considered. Developing realistic estimates of children's exposures to environmental contaminants requires the understanding and quantification of children's activity patterns.

It is important to understand that physiologic characteristics and behavioral patterns will result not only in different exposures for children and adults, but also for children of different developmental stages. Thus, exposure assessments are required for children in each age group, with age group defined by a developmental stage. The classification of children by age group should be based on estimates of when developmental changes commonly occur. For example, walking typically develops between 12 and 14 months of age. However, there are children who are early walkers (8–11 months) and late walkers (after 15 months). This variability in development produces challenges for exposure assessment. If an age-dependent model of exposure is based on a prototypical child at that age, it may have little bearing on the exposure patterns of specific individuals who are delayed or advanced in development.

Children's Characteristics That Influence Exposure

Both physiologic and behavioral characteristics influence children's exposures to environmental contaminants. Physiology and behavior is a function of age, sex, race/ethnicity, and socioeconomic status (SES). All of these characteristics pose challenges for categorizing children and collecting data on their exposures.

Physiologic characteristics. These characteristics influence exposure by affecting a child's rate of contact with exposure media or by altering the exposure–uptake relationship that governs internal dose resulting from an exposure. Children have a much larger surface area relative to body weight than do adults. The surface-area-to-body-weight ratio for newborn infants is more than 2 times greater than that for adults. This ratio decreases by approximately one-third within the first year of life and remains constant until approximately 17 years of age, when it decreases to the adult value (*9*). In addition to providing more area for dermal absorption, the larger relative surface area of children means that body heat will be lost more rapidly to the environment, requiring a higher rate of metabolism to maintain body temperature. In addition, children need extra metabolic energy to fuel growth and development. The higher basal metabolic rate and energy requirements in children mean that both oxygen and food requirements are greater per kilogram body weight for a child than for an adult. The higher breathing rate and food consumption rate required to meet these physiologic needs for children will result in higher relative exposures to environmental contaminants in air and food.

The absorbed dose—the amount of chemical that crosses a receptor's external boundaries—of an environmental contaminant probably is the relevant measure of exposure for the assessment of health risk. Age-dependent barrier properties of the skin, respiratory tract lining, and gastrointestinal tract lining influence absorbed dose. The permeability of the skin, highest at birth, decreases in the first year such that the skin of a 1-year-old child is similar to that of an adult (*5*). In addition, a layer of subcutaneous fat develops at approximately 2–3 months of age in infants and continues to exist through the early toddler period (*10*). This layer of fat may act as a sink for lipophilic chemicals absorbed through the skin. Changes in the permeability of lung epithelial cells during childhood have not been reported. However, the gas-exchange sacs, or alveoli, continue to develop until adolescence, increasing the surface area for absorption so that the same exposure might lead to a higher absorbed dose as a child ages. Finally, in the neonate, the stomach produces gastric acid at approximately 50% of the adult level (*11*). As a result, stomach pH exceeds 2 until several months after birth, when it drops by > 15% to adult levels. Gastric pH affects absorption by altering the ionization state of chemicals. Absorption and permeability in the gut are also regulated by the body to provide nutritional needs that vary with age. For example, to satisfy growth needs, children can absorb more calcium than adults from their gastrointestinal contents. The absorption of similar positive ions such as lead can also be enhanced inadvertently by the same mechanism used to actively absorb calcium.

Behavioral development. Children's behavior and the way that children interact with their environment may have a profound effect on the magnitude of their exposures to contaminants.

A child's motor capacities determine how that child interacts with his or her environment. The manner in which infants and toddlers move is significantly different from the manner in which adults move and can significantly impact their exposure to contaminants in the air and on residential surfaces. Motor capacity increases as a child develops. As a result, children spend less time playing on the floor and touching other potentially contaminated surfaces as they gain mobility and extend the boundaries of their interactions.

Measurements or descriptions of the changes in motor capacity that occur as a child develops are described in the developmental psychology and pediatrics literature (*12*). Much of this literature, however, focuses on changes in motor capacity that can be used to identify developmental disabilities and whether children have arrived at various developmental milestones (*13*). None of it directly addresses how a child's behavior might contribute to exposure to environmental chemicals. Using developmental milestones as an indication of children's interactions with the environment is problematic because there is significant variability between when a child first achieves a milestone and when the child performs the activities on a regular basis. In addition, activities such as crawling are not included because not all children crawl, and there is tremendous variation in how and when children first move around. Despite these drawbacks, developmental milestones can serve as useful guidelines for classifying children in exposure studies.

Manual dexterity includes the ability to pick up, hold, and manipulate objects held in the hand. A child's hands are the means for placing food in the mouth and are the immediate source of nondietary exposure through hand-to-mouth and object-to-mouth behavior. Because the hand is used to act on the environment and probably has more contact with water, soil, and dust than any other part of the body, hands have been used as the equivalent of dermal surfaces in several studies (*14–16*).

There is extensive research documenting the changes in manual coordination of very young children as they mature (*17–21*). Children show wide variability in manipulative performance. A young child has not developed a stable manner of handling objects, and the performance is variable in both style and effectiveness (*20*). Quantifying

significant intra- and interchild differences for exposure assessment in moving about and handling objects remains a challenge.

Characterizing and quantifying children's mouthing behaviors is also important for assessing the potential for contacting and transferring contaminants from objects and surfaces in the environment. Sucking and mouthing hands and objects are natural behaviors in childhood development. Infants are born with a sucking reflex, providing them with both nutrition and a sense of comfort or security. If infants do not receive unrestricted breast feeding, they will suck on a pacifier, thumb (or other finger), or other object like a blanket or stuffed animal. As infants develop, they begin to explore their world through mouthing (*22*). During this stage of development, children put almost everything that they contact into their mouths for a few seconds. Young children may also begin to use the mouth as a third hand, placing some objects in the mouth to manage them.

Teething is another important stimulus for mouthing activities. Biting and chewing on fingers and objects to relieve the discomfort of teething may be extensive. Teething usually begins between 4 and 7 months of age, but may start several months earlier or later. As with all childhood behaviors, mouthing activities vary significantly from child to child and, therefore, the impact on exposure will also be highly variable.

Physical activities. Exposure to contaminants is a function of the specific physical activities in which a child is engaged (e.g., playing games or watching television), the location of these activities (e.g., outdoors, at school, or in the living room), and the child's activity level while so engaged. Different activities lead to exposures by different pathways. Locations where a child spends time determine the exposure media that may be contacted, and affect the activity level that determines contact rate with those media. Differences in duration and frequency of periods spent in particular locations result in different exposures and risks to children that vary with age and development stage. Additional variability among children of similar developmental stages is associated with seasonal and geographic differences in activity patterns and the use of indoor and outdoor space.

Diet and eating habits. Children's diets differ significantly from those of adults. The diet of newborns is limited exclusively to breast milk or formula, both of which may expose infants to significant concentrations of environmental contaminants (*23,24*). Infants and young children eat more fruit and milk products in proportion to their body size and have a less varied diet than adults. In addition, there may be tremendous variability in diet among young children of similar ages and for a single child at different periods in time. Some infants and toddlers go through phases where only a few preferred foods are eaten for weeks and months at a time. Such a limited diet may potentially increase the dietary exposure of young children to environmental contaminants such as pesticide residues in fruit (*3,6*).

In addition to the exposures associated with the foods that children eat, the manner in which children handle food as they eat may also impact their exposure to environmental contaminants. Small children are less likely than adults to consume food in a structured environment. Small children may sit on the floor or lawn to eat and often pick up and eat foods that have fallen to the ground. Infants and young children also eat most of their food with their hands. Increased exposure occurs when children handle and eat foods that have come in contact with the floor or other contaminated residential surfaces (*25,26*).

Sex. Sex has been identified as a factor influencing activity level and the types of behaviors and activities in which children participate (*27–29*). As early as preschool (3–5 years of age), sex differences exist in the types of games played, the frequency of play, and activity level. Locations in which children spend time also vary by sex. Clear differences in the frequency and type of outdoor activities have been found between boys and girls 7–15 years of age (*29,30*). Boys are more likely than girls to play outdoors, and the character of their activity is different from girls. Boys are more likely to be involved in physically vigorous activities such as soccer, hockey, and bicycling, whereas girls are more likely to sit and go for walks. Thus, in exposure assessment for school-aged children, sex differences in activity level and activity type must be addressed. There are insufficient data to indicate whether there are sex differences in the activity levels of infants and toddlers. It is useful for exposure modeling to know when the differences emerge as well as the degree to which they influence exposure.

SES and race/ethnicity. Children's exposure to environmental contaminants is likely to vary based on the SES of the child. Although there is evidence to suggest that low-income groups tend to be more exposed to many environmental pollutants than the general population, data are currently insufficient to characterize the relationship among SES, ethnicity/race, age, and exposure (*31*). Exposure factors related to children that may be affected by SES and race include proximity to source (e.g., distance from toxic release inventory sites); location (e.g., urban, suburban, or rural); housing stock (e.g., age, condition, and type); activity patterns (e.g., hygiene, housekeeping, activity level, and child care); and diet and drinking water supply.

Although there are substantial data on the influence of housing stock, location, and SES on environmental exposure and adverse health outcomes, there are few data on the relationship of these influences to children's activities and potential contact with the physical environment. One study of Swedish children from two housing projects found that proximity to parks and play areas and the floor on which children live in an apartment house influence where young children play and the amount of time urban children play outside (*30*). However, there is little to suggest that housing stock and location have any influence on children's behavior, and there are no comparable data evaluating children's activities in the United States.

Comparisons of play activities across social classes have been studied for preschool children (*32–34*). Some of the studies were conducted within the home and others at day-care centers. When the location was the same (i.e., day care centers), no differences in behaviors were observed in children of different social classes. However, within the home, class (as an indicator of poverty, social stimulation, and poor parental education) influenced what the children had to play with and the type of play in which the children engaged (*35–37*). For subjects tracked from 15 to 25 years of age at 5-year intervals, social class and education level were related to the type and level of activities in which the children participated (*38*). Children identified as low social class were less active, and children who eventually went to college were more active.

Maternal influences on children's activity patterns have been evaluated using the Home Observation for Measurement of the Environment survey (*35,36*). The mother is a major factor in determining what the child does, what the child eats, and where the child is located, particularly for infants and toddlers.

Although a disproportionate percentage of ethnic and racial minorities belongs to economically disadvantaged populations, there are few studies that specifically address the relationship between race or ethnicity and behaviors that might influence exposure to environmental contaminants. Most of the studies that address this issue consider lead exposure. One such study found that black urban children are more likely than white urban children to ingest paint lead from window sills, whereas white children ingest soil and suck fingers more than black children (*39*). These behaviors contributed to

the children's exposure to lead in multivariate analyses. However, a study of 3- to 4-year-old children in day-care programs found no differences in the behaviors of black, white, and Mexican American children within the context of the day-care setting (*40*). This does not mean that differences which are culturally or economically driven might not exist when the children are at home or away from the day-care setting.

Children's Exposure-Monitoring Data

A variety of methods have been used to collect information about children's exposure. Telephone surveys and questionnaires can be used to capture global events, particularly those that relate to air pollutant exposure. Diaries go into more detail than surveys and collect information related to temporal variations in activities and behaviors that may contribute to exposure through multiple routes. Observations, personal monitoring, and biologic monitoring are valuable tools for collecting precise and detailed information. Because monitoring methods are often labor intensive and costly to implement, these are typically used with smaller groups of subjects.

Personal monitoring. To assess dietary exposure, prototypical diets have been used to characterize children. However, these do not characterize specific subpopulations such as ethnic groups or inner-city poor. In addition, the available Food and Drug Administration data sets are out of date and do not reflect the dramatic shift to fast food diets that has occurred in the United States. Existing dietary contaminant models assume that all contaminants can be accounted for before the food enters the home or institution. Data presented by Wilson et al. (*41*) and Sheldon et al. (*42*) suggest that there are sources of food contamination within the institution and home that need to be addressed. These include the influence of residential and institutional pesticide treatment on food pesticide levels and the influence of hygiene habits on other food contaminants such as lead. To obtain more specific information on dietary exposures, data are obtained by collecting duplicate-diet samples. These samples include a duplicate portion of all food and beverages prepared and consumed in the home. Results of duplicate-diet analysis are used in combination with food diaries and supplemental questionnaires to assess exposures by dietary ingestion. More refined protocols to assess dietary exposures of young children caused by contact of foods with contaminated surfaces during eating are currently under development and testing (*43–45*).

For inhalation exposure, a variety of motion detectors and personal monitoring backpacks have been developed to quantify activity levels and to sample air within the individual's breathing zone (*46*). Although motion detectors have been used with some children, most of these studies were designed to evaluate the technique and have not proceeded to thoroughly characterize the level of activity in a large population of children. Breathing zone air monitors have been used with the few children who participated in the National Human Exposure Assessment Survey (NHEXAS) in region V (*47*). Monitoring backpacks that can be worn successfully by children of all ages have not been developed. As a result, personal monitoring is seldom done on infants and preschool children.

Current techniques for measuring dermal exposure are limited in utility. Measures of skin contamination do not reflect changes in dermal loading that occur subsequent to sampling and do not indicate the amount of contamination actually absorbed through the skin (*48,49*). In addition, dermal measurement methods developed for occupational use (where the environment and physical activities are homogenous) may not be useful for measuring children's residential exposures.

Finally, some of the most significant exposures to environmental contaminants experienced by children may be related to nondietary ingestion of contaminant residues, dust, and soil during mouthing of hands subsequent to dermal contact with contaminated surfaces and objects. Reliable methods to monitor nondietary ingestion of environmental contaminants have not been developed (*9*). However, nondietary ingestion of soil and dust has been monitored in fecal samples using tracer elements (*50–54*). These studies require the collection of dietary data and concentrations of contaminants in residential soil and dust to link the tracers to ingested soil and then to estimate ingestion of contaminants.

Biologic monitoring. Biomarkers can serve as a useful measure of direct exposure aggregated over all sources and pathways, measuring integrated exposure from all routes. However, to use biomarkers for this purpose, several important criteria must be met. Biomarkers that can accurately quantify the concentration of an environmental contaminant or its metabolite(s) in easily accessible biologic media (blood, urine, and breath) must be available. The biomarker must be specific to the contaminant of interest, so that its presence can be linked to that contaminant. The pharmacokinetics of absorption, metabolism, and excretion must be known. Finally, the time between exposure and biomarker sample collection must also be known. Although there are a number of biomarkers that meet these criteria, few studies using biomarkers have collected all of the information required to accurately estimate exposure. In addition, significant challenges are associated with collecting biomarker data from children (*55*).

Biomarker data have been collected for children to evaluate environmental exposures to lead (*56*), benzene (*57*), arsenic (*58*), chromium (*59–61*), and pesticides (*62,63*). Most recently, the Minnesota NHEXAS children's pesticide exposure study collected urine samples from children on three alternate days and analyzed them for metabolites of chlorpyrifos, malathion, atrazine, and diazinon. Thus far only the chlorpyrifos values are available (*62*). The children's median levels of the chlorpyrifos biomarker, TCPY, over the three measurements was 8.6 ppb, as compared to 2.2 for the population-based National Health and Nutrition Evaluation Survey (NHANES) III (*62*) adult population. Approximately 60% of the homes in the NHEXAS study were identified as using or storing pesticides in the home within the year, and were considered the user homes (though the data do not show whether pesticides were applied during monitoring or not). Levels for children in these homes were significantly higher than levels for children from homes classified as low-users. However, some of the highest monitored values were found in the low-user children, suggesting that sources of exposure could not be identified based only on categorization of household pesticide use. Similar results were found in a study that attempted to determine whether children who lived near a pesticide-manufacturing plant were exposed to polychlorinated biphenyls (*64*). There was no difference between the proposed exposed children as compared to controls; all children had measurable levels of the metabolite, and no additional sources of exposure were reported. In a study by Loewenherz et al. (*63*), children up to 6 years of age who lived with pesticide applicators in an agricultural region of Washington State were monitored for increased risk of pesticide exposure. Results of this study indicated that applicator children experienced higher pesticide exposures than did reference children in the same community and that proximity to spraying is an important contributor to these exposures.

Children's activity pattern data. As noted previously, a child's exposure is greatly affected by where the child is and what the child is doing. In exposure modeling, the location a child occupies is known as a microenvironment. A microenvironment is a physical three-dimensional space with a well-characterized, relatively homogenous pollutant concentration level over a specified time period (*65*). A child's activity in a microenvironment (e.g., indoors at home) can be described by what the child is doing in a

general sense, such as watching television, eating, playing games, and crawling around on the floor. This type of information has been used since the early 1980s to assess inhalation exposures (*66*). However, in recent years it has become obvious that general activity descriptions do not provide enough information on the specific contacts with exposure media that occur within a microenvironment of interest to estimate dermal and nondietary ingestion exposures.

In response to this need for more detailed information, a distinction is now made between macro- and microactivity information. The general activities described above are macroactivities. Microactivities are detailed actions that occur within a general activity, such as hand-to-surface and hand-to-mouth behavior. The physical activity data, both macro- and microactivity, available to assess exposure are reviewed in the subsequent sections. Activity pattern data requirements are demonstrated in the context of algorithms used to estimate exposure by inhalation, dermal contact, and ingestion. These algorithms for combining the environmental monitoring data with the exposure factors to estimate an exposure or a dose should be used to guide the type of data collected to assess children's exposures.

Activity data required and available to assess inhalation exposures. For inhalation, exposure is estimated for each of the microenvironments where a child spends time and each macroactivity that would result in a different inhalation rate while engaging in that activity. Exposure over the 24-hr period is then the sum of all of the microenvironmental/macroactivity (*me/ma*) exposures.

For each individual *me/ma,* inhalation exposure over the 24-hr period ($E_{me/ma}$) is defined as

$$E_{me/ma} = T_{me/ma} \times C_{ame} \times IR_{ma} \qquad [1]$$

where

$T_{me/ma}$ = the time spent in that *me/ma* over the 24-hr period (hours per 24 hours); C_{ame} = the air concentration measured in the microenvironment (micrograms per cubic meter); and IR_{ma} = the child's respiration rate representing his or her activity level for that macroactivity (cubic meter per hour).

To apply Equation 1, data are required on the amount of time the child spends in each *me/ma* over a 24-hr period (macroactivity data) and on the child's inhalation rate for each *me/ma.* Inhalation rates are typically estimated based on age and weight of the child and on the macroactivity.

Macroactivity data are obtained using a variety of survey techniques, such as time-budget diaries or recall (yesterday) telephone surveys (*67*). A number of these macroactivity studies have been reviewed by Ott (*68*) and McCurdy (*69*). Macroactivity information relevant to inhalation exposure assessment for an individual contains at least one complete day of sequential location/activity data for every discrete major behavior that is undertaken (and disclosed) by a respondent. This is known as a person-day of information. Nine studies recorded person-day macroactivity data on a flexible-time basis, but not all included data on children. The data from all of these studies are contained in the EPA National Exposure Research Laboratory Consolidated Human Activity Database (CHAD). CHAD is a relational database using a common set of codes for activities, locations, intensity levels, and questionnaire information (*70*). Thus, it allows a user to easily combine information from the nine studies to increase the sample size of the human activity data (*70*). Data from four of these studies are also available in the EPA THERdbASE (*71*).

For children and adolescents younger than 18 years of age, CHAD contains approximately 4,300 person-days of information. An explicit breakdown of these data for children < 12 years of age appears in Table 1. For these children, data are available from only three studies: *a*) the 1990 California children and youth recall survey (*72*); *b*) the 1983 Cincinnati, Ohio, diary study sponsored by the Electric Power Research Institute (*73*); and *c*) the air and water versions of the 1992–1994 National Human Activity Pattern Survey (recall) (*74*). Altogether, there are 3,009 person-days of macroactivity data in CHAD available from 2,640 children < 12 years of age. Another survey of children's activities was just released by the University of Michigan's Institute for Social Research (*75*). This information is being incorporated into CHAD.

The person-days of activity data can be used in exposure assessments in a number of ways. Each person-day of data can be used separately to represent individuals in a modeling exercise, or the person-days can be organized into cohorts (such as female babies < 6 months of age) and used as a pool from which a random sampling routine selects one individual to represent the cohort for a day (*76–79*). Macroactivity data can also be aggregated over the total population or a cohort of the population to obtain average or other statistical measures of activity for some specified time period. This approach is most commonly used in exposure assessment, but it removes the inherent correlations among activity, location, and time—and the pattern of exposures experienced—that truly determine the dose received from an environmental contaminant. In addition, misleading results can occur if the assessor is not careful about how the data are prepared to represent a group.

Specific examples of the type of macroactivity data available for children are presented in Tables 2 and 3. The number of hours per day children spend in various microenvironments is summarized in Table 2. Nearly all of the children in CHAD spent some part of their diary day indoors at home, and the amount of time spent in this microenvironment ranged from 15 to 20 hr/day on average (63–83% of the day) for habitues. Children younger than 2 years of age spend the most time indoors at home, whereas older children spend the least amount of time indoors at home. Variability within each age category was substantial but also fairly consistent across all of the age categories (SDs of approximately 4 hr). This high variability remained when comparing hours spent indoors at home between weekdays and

Table 1. Number of person-days/individuals for children in CHAD[a] database.

Age group	All studies[b]	California (*72*)	Cincinnati[b] (*73*)	NHAPS (*74*) Air	NHAPS (*74*) Water
0 Year	223/199	104	36/12	39	44
0–6 Months	–	50	15/5	–	–
6–12 Months	–	54	21/7	–	–
1 Year	259/238	97	31/11	64	67
12–18 Months	–	57	–	–	–
18–24 Months	–	40	–	–	–
2 Years	317/264	112	81/28	57	67
3	278/242	113	54/18	51	60
4	259/232	91	41/14	64	63
5	254/227	98	40/14	52	64
6	237/199	81	57/19	59	40
7	243/213	85	45/15	57	56
8	259/226	103	49/17	51	55
9	229/195	90	51/17	42	46
10	224/199	105	38/13	39	42
11	227/206	121	32/11	44	30
Total	3,009/2,640	1,200	556/187	619	634

[a]Data from the EPA (*70*). [b]The number of person-days of data are the same as the number of individuals for all studies except for the Cincinnati study. Because up to 3 days of activity pattern data were obtained from each participant in this study, the number of person-days of data is approximately 3 times the number of individuals.

weekends or between seasons, indicating that interchild variability in daily activities within each year of age is significant as compared to trends due to the day of the week or the season when the diary was collected.

Approximately half of the children in CHAD reported spending time outdoors at home, except for children in the youngest age categories (younger than 2 years of age; less than one-third of children under 2 years of age reported being in this microenvironment). Children younger than 2 years of age also spend the least amount of time outdoors at home on average, whereas children 4–7 years of age spend more time in this microenvironment than older children.

Children also spend a significant amount of time in nonresidential microenvironments, including indoors at school, stores, and restaurants; outdoors at parks and playgrounds; and in vehicles. Approximately 40% of children were in school during their CHAD diary day for each age category of school-aged children (≥ 5 years of age). On average, children spend approximately 6 hr/day in school. Time spent indoors at school was fairly consistent for children ≥ 7 years of age, with lower SDs (1.0–1.5 hr) than for younger children. A small number of children younger than 5 years of age (2–16%) also reported being in school for as much as 6 hr/day on average. This highlights the lack of appropriate microenvironment categories for young children in the CHAD activity pattern studies. Only the California study (*72*) included child-care facility as a separate microenvironment category. In the other studies, the school category may have been used for preschool or other nonresidential child-care facilities, or the nonspecific other indoor category may have been used also.

The number of children in CHAD that reported spending time outdoors at a park or playground also varied significantly with age. Only 10% of the children in the youngest age categories (< 2 years of age) reported being in this microenvironment, whereas approximately 40% of the older children (10–11 years of age) spent time outdoors at a park or playground. For those children that reported being outdoors in this microenvironment, the amount of time spent at a park or playground did not have a trend across age categories. In addition, age differences were least evident in the percentage of children that reported being in vehicles, as well as the amount of time spent in vehicles for those children.

Table 3 summarizes the number of hours that children spend doing various macroactivities while indoors at home; age differences in children's macroactivities are also evident. On average, the number of hours children spend both eating and sleeping decreases gradually with the age of the child, so that children younger than 2 years of age spend the most time doing these macroactivities. Although showering/bathing times are fairly consistent across ages, the other macroactivities in Table 3 show age differences in the number of hours children spend playing games, watching television, and doing other passive activities while indoors at home. Table 3 also illustrates another area where macroactivity data in the CHAD studies are inadequate for characterizing children's activities and exposures. Categories such as playing games do not provide any information on the activity level of the child while playing, which can, for example, significantly affect inhalation exposure. In addition, the CHAD studies did not use appropriate macroactivity categories for infants, so a large percentage of children younger than 1 year of age (62%) have a substantial amount of time (> 3 hr on average) for the nonspecific other passive activity category.

CHAD contains approximately 140 activity codes and 110 location codes, but data generally are not available for all activities or locations for any single respondent. In fact, most of the studies did not use all of the codes. In addition, even though many codes are used in macroactivity studies, many of the activity codes do not adequately capture the richness of what children actually do. They are much too broadly defined and ignore many child-oriented behaviors. Thus, there is a need for more and better focused research into children's activities.

Aggregate human activity data are available from additional sources other than those cited above. Summary and distribution information regarding the time that children spend in various microenvironments and about their activities can be found in the EPA *Exposure Factors Handbook* (*8*) and the American Industrial Health Council *Exposure Factors Sourcebook* (*79*). These are comprehensive source documents. More limited information about American children's activities has been published by Berry et al. (*80*), Harlos et al. (*81*), Roth Associates (*82,83*), Schwab et al. (*27,84,85*), and Silvers et al. (*86,87*). The Silvers et al. (*87*) study is a 1990–1991 survey of 1,000 households with children 5–12 years of age in six states. The results of that survey closely matched those of the California study (*72*).

Activity data required and available to assess exposure by dermal contact and nondietary ingestion. Two main approaches are currently used to assess dermal and nondietary ingestion exposure. These assessment approaches provide different ways of integrating exposure over time and space. In the macroactivity approach, exposure is estimated individually for each of the microenvironments where a child spends time and each macroactivity that the child conducts within that microenvironment. To do this, exposure is modeled using empirically derived transfer coefficients to aggregate the mass transfer associated with a series of contacts with a contaminated medium. In the microactivity approach, exposure is explicitly modeled as a series of discrete transfers resulting from each contact with a contaminated medium. It is important to understand that the temporal and spatial scales of activity patterns, exposure media concentrations, and transfer efficiencies to be measured will depend on the assessment approach that is used.

To estimate dermal exposure using the macroactivity approach, microenvironments are defined by location and surface type (e.g., indoors at home on carpet). The dermal exposure associated with a given macroactivity (e.g., actively playing in the yard) is measured and used to develop an activity- and microenvironment-specific transfer coefficient. Exposure can then be estimated individually for each of the microenvironments where a child spends time and each macroactivity that the child conducts within that microenvironment. Exposure over the 24-hr

Table 2. Number of hours per day children spend in various microenvironments[a] by age.

Age (years)	Microenvironment[b] Indoors at home	Outdoors at home	Indoors at school	Outdoors at park	In vehicle
0	19.6 ± 4.3 (99)	1.4 ± 1.5 (20)	3.5 ± 3.7 (2)	1.6 ± 1.5 (9)	1.2 ± 1.0 (65)
1	19.5 ± 4.1 (99)	1.6 ± 1.3 (35)	3.4 ± 3.8 (5)	1.9 ± 2.7 (10)	1.1 ± 0.9 (66)
2	17.8 ± 4.3 (100)	2.0 ± 1.7 (46)	6.2 ± 3.3 (9)	2.0 ± 1.7 (17)	1.2 ± 1.5 (76)
3	18.0 ± 4.2 (100)	2.1 ± 1.8 (48)	5.7 ± 2.8 (14)	1.5 ± 0.9 (17)	1.4 ± 1.9 (73)
4	17.3 ± 4.3 (100)	2.4 ± 1.8 (42)	4.9 ± 3.2 (16)	2.3 ± 1.9 (20)	1.1 ± 0.8 (78)
5	16.3 ± 4.0 (99)	2.5 ± 2.1 (52)	5.4 ± 2.5 (39)	1.6 ± 1.5 (28)	1.3 ± 1.8 (80)
6	16.0 ± 4.2 (98)	2.6 ± 2.2 (48)	5.8 ± 2.2 (34)	2.1 ± 2.4 (32)	1.1 ± 0.8 (79)
7	15.5 ± 3.9 (99)	2.6 ± 2.0 (48)	6.3 ± 1.3 (40)	1.5 ± 1.0 (28)	1.1 ± 1.1 (77)
8	15.6 ± 4.1 (99)	2.1 ± 2.5 (44)	6.2 ± 1.1 (41)	2.2 ± 2.4 (37)	1.3 ± 2.1 (82)
9	15.2 ± 4.3 (99)	2.3 ± 2.8 (49)	6.0 ± 1.5 (39)	1.7 ± 1.5 (34)	1.2 ± 1.2 (76)
10	16.0 ± 4.4 (96)	1.7 ± 1.9 (40)	5.9 ± 1.5 (39)	2.2 ± 2.3 (40)	1.1 ± 1.1 (82)
11	14.9 ± 4.6 (98)	1.9 ± 2.3 (45)	5.9 ± 1.5 (41)	2.0 ± 1.7 (44)	1.6 ± 1.9 (74)

[a]Percent of children reporting > 0 hr in microenvironment. [b]Values are average ± SD; values in parentheses are percentages.

period is the sum of all of the microenvironment/macroactivity (*me/ma*) exposures. For each *me/ma*, dermal exposure over the 24-hr period ($E_{dme/ma}$) is defined as

$$E_{dme/ma} = C_{surf} \times TC_{der} \times ED \quad [2]$$

where C_{surf} = total contaminant loading on surface (micrograms per square centimeter), TC_{der} = dermal transfer coefficient for the *me/ma* (square centimeters per hour), and *ED* = exposure duration that represents the time spent in the *me/ma* (hours per day).

To apply the macroactivity approach to assess dermal and nondietary ingestion exposure, data are required on the amount of time the child spends in each *me/ma* over a 24-hr period. Although the CHAD activity pattern studies can provide data on time spent in various *me/ma*, the types of surfaces associated with each *me/ma* are not included in the database. Alternatively, CHAD does include information on time spent in different rooms within a home, which may be useful in the macroactivity approach to modeling dermal and nondietary exposures. According to data in CHAD, children spend the majority of their time indoors at home in the bedroom (an average of 65–75%) and in the living room (15–25%). These rooms are likely to contain textured surfaces such as carpet and upholstery, as compared to the kitchen and bathroom, which are likely to have hard smooth surfaces (linoleum and tile). Because surface types are required to estimate dermal exposures, these additional data should be collected in future activity pattern studies.

To assess dermal exposure and nondietary ingestion using the microactivity approach, exposure is estimated individually for each of the microactivities or events (e.g., each time a child touches a given object) from which dermal contact or nondietary ingestion occurs. Exposure over the 24-hr period is then the sum of all of the individual exposures. For each microactivity, dermal exposure over the 24-hr period ($E_{der/mi}$) can be defined as

$$E_{der/mi} = C_{surf} \times TE \times SA \times EF \quad [3]$$

where $E_{der/mi}$ = dermal exposure for a given microactivity over a 24-hr period (micrograms per day), C_{surf} = total contaminant loading on surface (micrograms per square centimeter), *TE* = transfer efficiency, fraction transferred from surface to skin (unitless), *SA* = area of surface that is contacted (square centimeters per event), and *EF* = frequency of contact event over a 24-hr period (events per day).

For each microactivity resulting in nondietary ingestion, exposure over the 24-hr period ($E_{nding/mi}$) can be defined as

$$E_{nding/mi} = C_x \times TE_{xm} \times SA_x \times EF \quad [4]$$

where $E_{nding/mi}$ = nondietary ingestion exposure for a given microactivity over a 24-hr period (micrograms per day); x = hand or object that is mouthed; C_x = total contaminant loading on hand or object (micrograms per square centimeter); TE_{xm} = transfer efficiency, fraction transferred from object or hand to mouth (unitless); SA_x = area of object or hand that is mouthed (square centimeters per event), and *EF* = frequency of mouthing event over a 24-hr period (events per day).

To use the microactivity approach, a greater level of detail (i.e., microactivity data) is needed to characterize people's dermal contact with chemical residues in their environments and to quantify subsequent dermal absorption and nondietary ingestion. Microactivities required to estimate dermal and nondietary ingestion exposure include frequency and duration of contact between skin surfaces (including the mouth) and objects and parameters describing the nature of contact, such as pressure, motion type, and exposed surface area.

Literature about children's activities from the fields of child development and psychology tends to focus on social development and peer interactions of infants, toddlers, and kindergarten children. The literature seldom reports how children act on, or move about in, their physical space (*88,89*). In 1998 the EPA (*90*) published a review of the child behavior and psychology literature. Frequency and duration of handling and mouthing events were documented in several of the reviewed studies. However, in these studies, caretakers introduced objects to children sitting on their laps. Handling and mouthing behaviors will differ for a child in his or her own environment under normal conditions.

Because of the age dependencies and labor-intensive nature of gathering microactivity data, few data sets relevant to exposure assessments currently exist. Two general approaches to gathering such data have been used: *a*) real-time hand recording, in which trained observers watch an individual and write down the information of interest on a score sheet; and *b*) videotaping, in which trained videographers videotape an individual and then subsequently extract the data of interest by hand or by computerized software.

A recent study used the first approach to quantify duration of mouthing in awake infants 3–36 months of age in The Netherlands (*22*). Five parents were asked to observe eight children (10 times, 15 min/day on 2 days) and measure mouthing time with a stopwatch. There were no differences between the two observed days, across different periods of the day, or between boys and girls; however, the total mouthing time differed among age groups. The mean daily extrapolated mouthing times (in minutes) for children 3–6, 6–12, 12–18, and 18–36 months of age were 36.9 (SD 19.1), 44 (SD 44.7), 16.4 (SD 18.2), and 9.3 (SD 9.8), respectively. The youngest children mouthed mainly their fingers, whereas children 6–12 months of age mouthed toys not meant for mouthing. The older age groups mouthed mostly nontoys and their fingers. On average, children sucked or bit on objects two-thirds of the time and licked objects the other one-third of the time. The children 12–18 months of age sucked or bit the most, and the percentage of licking was highest in the youngest age group. This study reported difficulties in parent training and compliance; these difficulties may have influenced the reliability of the reported data.

Several studies have used the videotaping approach to quantify children's microactivity data. The U.S. EPA NHEXAS included videotaping 19 children 3–12 years of age in Minnesota with a hand-held camera. Observers then replayed the videotapes and recorded the frequency of object-to-mouth contact, hand-to-mouth contact, and hand

Table 3. Average number of hours per day children spend doing various macroactivities while indoors at home by age (percent of children reporting > 0 hr for microenvironment/macroactivity).

	Macroactivity in home microenvironment[a]						
Age (year)	Eat	Sleep or nap	Shower or bathe	Play games	Watch TV or listen to radio	Read, write, homework	Think, relax, passive
0	1.9 (96)	12.6 (99)	0.4 (44)	4.3 (29)	1.1 (9)	0.4 (4)	3.3 (62)
1	1.5 (97)	12.1 (99)	0.5 (56)	3.9 (68)	1.8 (41)	0.6 (19)	2.3 (20)
2	1.3 (92)	11.5 (100)	0.5 (53)	2.5 (59)	2.1 (69)	0.6 (27)	1.4 (18)
3	1.2 (95)	11.3 (99)	0.4 (53)	2.6 (59)	2.6 (81)	0.8 (27)	1.0 (19)
4	1.1 (93)	10.9 (100)	0.5 (52)	2.6 (54)	2.5 (82)	0.7 (31)	1.1 (17)
5	1.1 (95)	10.5 (98)	0.5 (54)	2.0 (49)	2.3 (85)	0.8 (31)	1.2 (19)
6	1.1 (94)	10.4 (98)	0.4 (49)	1.9 (35)	2.3 (82)	0.9 (38)	1.1 (14)
7	1.0 (93)	9.9 (99)	0.4 (56)	2.1 (38)	2.5 (84)	0.9 (40)	0.6 (10)
8	0.9 (91)	10.0 (96)	0.4 (51)	2.0 (35)	2.7 (83)	1.0 (45)	0.7 (7)
9	0.9 (90)	9.7 (96)	0.5 (43)	1.7 (28)	3.1 (83)	1.0 (44)	0.9 (17)
10	1.0 (86)	9.6 (94)	0.4 (43)	1.7 (38)	3.5 (79)	1.5 (47)	0.6 (10)
11	0.9 (89)	9.3 (94)	0.4 (45)	1.9 (27)	3.1 (85)	1.1 (47)	0.6 (10)

TV, television.
[a]Values in parentheses are percentages.

contact with the following object categories: clothing, dirt, smooth surface, textured surface, and hand-held object (*91*). Reed (*92*) videotaped 30 children between the ages of 18 months and 5 years in New Jersey (20 in a day-care facility and 10 in their homes) for a total of 168 hr and then recorded hand and mouthing behaviors in the same way as Freeman (*91*). As in NHEXAS, observers in the Reed (*92*) study recorded the frequencies of hand-to-object contacts over 5-min intervals. Objects recorded included clothing, dirt, another hand, mouth, object, other items, smooth surfaces, and textured surfaces. Zartarian et al. (*14,93*) reported results for the left hand, right hand, and mouth from a videotape study of four children in an agricultural setting (2–4 years of age) in California (31 hr of videotape). This study used a computer software application (*94*) rather than a scorecard to obtain the sequence of a wide array of objects contacted and the duration of each contact. Table 4 summarizes the type of microactivity data collected in these studies.

Comparing results among these studies is difficult because the children's ages, the reported summary statistics, and the categories of body parts and objects contacted were different among the studies. Despite these differences and the small sample sizes, some interesting observations can be drawn. The children studied exhibited short average duration of mouthing and surface contacts (on the order of seconds) and high contact frequencies. Average contact frequencies across the studies for the same object categories were reasonably similar, but the variability for a particular object category was high in each study. Object categories contacted the most frequently by hands were smooth surfaces (e.g., wood furniture), bedding, clothes, plastic toys, and paper. The only variable that was statistically different across age groups in the NHEXAS (children 3–4, 5–6, 7–8, and 10–12 years of age) was object-to-mouth contacts, which were greater for the 3-year olds (6 ± 7/hr) than the other groups. For age-matched boys and girls, girls exhibited higher object-to-mouth contacts. However, this may be related to the fact that boys spent substantially more time outdoors in active play (*91*). In the New Jersey study (*92*), contacts with another hand (either the child's own hand or another person's hand) were higher for children 1–3 years of age (25/hr) than for children 4–6 years of age (13.5/hr); hand-to-mouth contacts were significantly higher in the spring (10.4/hr) than in the winter (4.6/hr); no variables were significantly different by sex; and some variables (contact with dirt, objects-to-mouth, other items, and textured surfaces) were statistically significant between day-care and residential children. Some microactivities appeared to be setting dependent (e.g., contact with dirt, grass, and toys), whereas others (e.g., contact with clothes, body parts, and mouths) did not. In general, nondietary object-to-mouth contacts were less frequent than hand-to-mouth contacts. All of these results, -however, may reflect the types of behaviors quantified, the small sample size, and the setting and conditions under which the observations were made.

In summary, the current database on children's microactivities is sparse. More data for different ages and body parts over a wide range of scenarios are needed to reduce uncertainty in modeled estimates of dermal and nondietary ingestion exposure and dose and to identify important objects for measuring pollutant concentrations. However, before these data can be collected, the important activities and contact parameters (e.g., surface type, contact duration, and skin condition) need to be identified to determine the type of microactivity data that should be collected. A standard protocol for collecting and reporting relevant children's microactivity data could then be developed.

Activity data required and available to assess dietary exposure. Young children do not consume foods in a structured manner. While eating, their foods contact surfaces (hands, floors, eating surfaces, etc.) that may be contaminated. Thus, dietary exposures of young children are difficult to accurately assess or measure. A young child's dietary exposure to environmental contaminants is characterized by the sum of three major terms (*43*) (Equation 5): term 1, the original contaminant residue on foods before they are handled by the child; term 2, surface-to-food contamination as the foods come into contact with contaminated surfaces before being consumed by the child; and term 3, surface-to-hand-to-food contamination as the child touches contaminated surfaces and then handles and eats the foods.

To assess dietary ingestion, exposure is estimated individually for each item of food consumed by the child. Total dietary exposure is then the sum of exposures for all food items consumed over a 24-hr period. For each food item, dietary exposure (E_{diet}) can be defined as the sum of the three terms. The intake of a contaminant associated with one food item, i, specific eating activities resulting in that food item's contact with contaminated surfaces, and j, specific activities resulting in the food item's contact with the child's hands before it is eaten, can be described as in Equation 5.

$$E_{diet} = \underbrace{C_{food} W_T}_{\text{Term 1}} + \underbrace{\sum_i \left[C_{surf} TE_{S/F} SA_{S/F} EF_{S/F}\right]}_{\text{Term 2}} + \underbrace{\sum_j \left[C_{hand} TE_{H/F} SA_{H/F} EF_{H/F}\right]}_{\text{Term 3}} \quad [5]$$

where E_{diet} = the total dietary exposure to the environmental contaminant for one food eaten (micrograms per food item); C_{food} = the contaminant concentration of food item after preparation for consumption (micrograms per gram food); W_T = the total amount of the individual food consumed (grams food per food item); C_{surf} = contaminant loading on a contacted surface (micrograms per square centimeter); $TE_{S/F}$ = surface-to-food contaminant transfer efficiency (where transfer efficiency is a function of duration of

Table 4. Summary of studies containing children's microactivity data.

Reference	Children (*n*)	Children (ages)	Study location	Type(s) of data collected	Method used
Groot et al. (*22*)	8	3–36 months	Netherlands	Mouthing duration	Children's mothers; real-time observation with stopwatches; 15 min intervals
Freeman (*91*)	19	3–12 years	Minnesota	Hand-to-object, hand-to-mouth, object-to-mouth contact frequency	Videotape observation by researchers with scorecards; 5 min intervals
Reed et al. (*92*)	30	18 months–5 years	Urban New Jersey: 20 day care, 10 residential	Hand-to-object, hand-to-mouth, object-to-mouth contact frequency	Videotape observation by researchers with scorecards; 5 min intervals
Zartarian et al. (*14*)	4	2–4 years	Agricultural California	Left hand-to-object, right hand-to-object contact frequency and duration	Videotape observation by researchers with computerized translation software
Zartarian et al. (*93*)	4	2–4 years	Agricultural California	Object-to-mouth contact frequency and duration	Videotape observation by researchers with computerized translation software

contact, surface type, moisture, etc.) (unitless); $SA_{S/F}$ = the area of contaminated surface that is contacted by the food item (square centimeters per event); $EF_{S/F}$ = frequency of surface-to-food contact events that occur during consumption of the food item (events per food item); C_{hand} = contaminant loading on child's hand (micrograms per square centimeter); $TE_{H/F}$ = hand-to-food contaminant transfer efficiency (unitless); $SA_{H/F}$ = the area of the contaminated hand that is contacted by the food (square centimeters per event); and $EF_{H/F}$ = the frequency of hand-to-food contact events that occur during consumption of the food item (events per food item).

In measurable quantities, term 1 summed for all foods consumed over the day may be obtained by duplicate-diet sampling procedures, which provide total daily dietary intake of contaminants that are present on the foods themselves, plus those that were introduced during its preparation. Terms 2 and 3 are much more difficult to quantify even for the simplest eating scenario, and require measurements of specific factors (e.g., surface concentrations, contact areas, and transfer efficiencies) in the eating environment of the child and an analysis of eating activities.

Recent studies on dietary exposure of children to lead (*25,95*) and to pesticides (*43–45*) have begun to explore potential pathways of dietary contamination caused by the child's eating activities, and ways to measure them. These studies are focused on young children (1–3 years of age). In the Barlion (*25*) study, children's dietary exposure to lead was evaluated by collecting a 24-hr duplicate of all foods plus sentinel foods (i.e., individual food items used to represent foods contaminated during handling) from 48 children 2–3 years of age. Sentinel foods were contacted with the child's hands and other surfaces to represent ways the child might handle the foods while eating. Additional information collected included lead concentrations from hand wipes, floor wipes, and venous blood, and questionnaire responses on activities related to exposure. Results showed that children's dietary exposure to lead may potentially increase by a factor of 4–20 when foods are handled by a child in a contaminated environment.

Akland et al. (*44*) videotaped the eating activities of young children to determine the frequency and duration of activities that may lead to contamination, including hand-to-surface, hand-to-food, and food-to-surface contacts. The frequency and duration of hand and food contacts with different surfaces, types, and amounts of foods consumed, and other location factors were recorded for 10 children 1–3 years of age, eating both at home and in day-care facilities. Summary results from the analysis show that there is a wide range of time and contact frequency between children. A specific food item contacting the child's hands during an eating event depended on the type of food eaten and the age. Bread, cereal, and banana were the food items most commonly handled while being eaten by these children. Food is in contact with a plate or eating utensil for the longest period of time (approximately 10 min on average); food and hand contact, and food and surface contact each occur for approximately 2 min. Food items come in contact with plate, hands, and mouth about the same number of times on average during an eating event.

Field testing is being conducted to collect additional activity pattern data and to measure other input parameters required for the dietary exposure model (Equation 5) under realistic conditions to improve dietary exposure assessments for young children. The field testing will also provide indirect confirmation of the dietary exposure model through comparisons of dietary exposures estimated by the model with measurements of handled foods and child biomarkers (*43*).

Total Exposure Studies

An important component of current exposure and risk characterization is the consideration of aggregate exposures. When assessing exposure and health risk to children, exposure information should be aggregated from all potential exposure media including the air that children breathe, the foods that children eat, groundwater or surface water that is consumed as drinking water or used for bathing, and other contaminated media contacted under nonoccupational circumstances (i.e., dermal or nondietary contact with contaminated residential surfaces).

Table 5 presents several examples to demonstrate the type of data required to assess aggregate exposure to a variety of environmental contaminants. The first two examples, depicting exposure to methylmercury and lead, might be considered simple systems, each with one chemical and typically only one route of exposure. The final two examples, depicting exposure to chloroform and pesticides, require consideration of multiple exposure media and routes. As shown in Table 5, some of the most useful studies for assessing exposure collect a combination of personal and biologic monitoring data, environmental concentration data, and activity pattern data. These types of studies are required to assess aggregate exposure by the indirect approach. Some examples of studies for which a combination of children's exposure data were (or are currently being) collected are presented in Table 6.

Conclusions

Currently, data on children's exposures and activities are insufficient to adequately assess exposures to environmental contaminants. As a result, regulators use a series of default assumptions and exposure factors when conducting exposure assessments. The more uncertain the assumptions and exposure factors used, the more conservative they must be to protect children's health. Data to reduce uncertainty in the assumptions and exposure estimates are needed to ensure chemicals are regulated appropriately. To improve the database available to assess children's exposures, three areas of research are required.

Table 5. Example scenarios of children's exposure to environmental pollutants.

Media contaminant	Exposure media	Significant routes of exposure	Data required to assess exposure
Methylmercury	Contaminated fish or mother's milk	Dietary ingestion	Concentrations of methylmercury in fish Fish consumption rates Resulting concentrations in mother's milk Consumption rates of mother's milk
Lead	Dust, soil, paint chips	Nondietary ingestion	Concentrations of lead in dust, soil, paint chips Activity patterns (mouthing behavior, finger sucking, dirt ingestion, eating behavior, hand washing, outdoor play, etc.) Nutritional status Blood lead measurements (direct assessment of exposure)
Chloroform	Water, air	Inhalation Dermal contact Nondietary ingestion	Concentrations of chloroform in water Bathing, showering, and swimming activities Breath concentrations (direct assessment of exposure)
Pesticides	Food, air, water, soil, plants/turf, house dust, surfaces/objects, clothes	Dietary ingestion Inhalation Dermal contact Nondietary ingestion	Pesticide use patterns Concentrations of pesticides in all relevant exposure media Activity patterns Biomarkers of exposure (direct assessment of exposure)

Identification of appropriate age/developmental benchmarks for categorizing children in exposure assessments. The physiologic characteristics and behavioral patterns of children not only result in differences in exposures between children and adults, but also result in differences in exposures among children of different developmental stages. Classification of children by age group should be based on estimates of when developmental changes most commonly occur. Both physiologic and behavioral development need to be considered in developing appropriate age classifications. Protocols for addressing variability in development need to be established to ensure that exposure patterns of specific individuals who are delayed or advanced in development can be adequately characterized. In addition, methods need to be developed for addressing developmental characteristics, such as teething, that will likely span age classifications, yet may have a very significant influence on a child's exposure.

Development and improvement of methods for monitoring children's exposures and activities. Significant challenges are associated with developing and verifying exposure factors for young children, such as contaminant contact rates and transfer rates. Novel methods must be developed and validated in the manner of Sheldon et al. (*42*), Noland et al. (*107*), Kissel et al. (*108*), and Gurunathan et al. (*15*) to elicit information from or about young children who are nonverbal or who lack a well-developed sense of time about their activities and exposures. New and improved methods are needed to monitor personal exposures, measure biomarkers, and survey activities in these young children. Methods that can be used with infants should also be developed.

Collection of physical activity data for children (especially young children) required to assess exposure by all routes. The data available for conducting exposure assessments for children are highly variable, depending on the route of exposure considered. The data that are available for assessing inhalation exposures are the most complete. However, even for inhalation, limited data are available for very young children. For all routes of exposure, sufficient population-based data are needed to better characterize children's exposures and behaviors as a function of age, sex, setting (residence, school, or day care), socioeconomic status, race/ethnicity, location (urban, suburban, or rural), region, and season. These data gaps are particularly significant for children younger than 4 years of age.

In addition, route-specific data on dietary ingestion, inhalation, and dermal contact and nondietary ingestion are required to improve assessment of children's exposures.

Improved information on the foods children eat and the residues on them is needed. Those foods most frequently consumed by infants and children need to be identified, and distributions of amounts consumed need to be quantified more specifically. Because of the changing nature of children's diets, food consumption surveys should include adequate sample sizes of children 0–6, 6–12, 12–24, and 24–36 months of age and 3–5, 5–10, and 11–18 years of age. The residues associated with a child's diet (before food preparation and handling by the child) need to be better characterized. Methods to assess exposures caused by the contamination of foods during consumption by the child need to be evaluated. Activities specifically related to the way children consume foods need to be categorized. Current information is not specific enough to

Table 6. Summary of available children's aggregate exposure data.

Study	Participants	Exposure Data	Reference
Children's exposure to persistent organic pollutants	Nine preschoolers 2–5 years of age Pilot study	Indoor air, outdoor air, food and beverages, indoor dust, and outdoor play area soil, handwipes and urine samples were collected both at home and at day-care center and analyzed for persistent organic pollutants including 20 target PAHs and several pesticides	Wilson et al. (*96*); Wilson and Morgan (*97*)
PAH exposures of children in low-income families	24 children 2–4 years of age Three separate pilot studies	Indoor air, outdoor air, house dust, soil, duplicate diet, and urine samples collected and analyzed for persistent organic pollutants	Chuang et al. (*98*)
Multimedia concentrations of PAHs in day-care centers	Nine day-care centers	Indoor air, outdoor air, food and beverages, indoor dust, and outdoor play area soil were sampled and analyzed for persistent organic pollutants including 20 target PAHs and several pesticides	Wilson et al. (*99*); Wilson et al. (*41*).
Housedust/Infant Pesticide Exposure Study (HIPES)	Nine toddlers, pilot study	Indoor air, outdoor air, personal air, house dust, soil, handwipe, dislodgeable residue samples collected and analyzed for 31 pesticides	Lewis et al. (*100*)
Total OP pesticide exposure among children in rural and urban environments	Children 1–5 years of age Number unknown	Environmental and biologic samples to account for all exposure routes; indoor air, outdoor air, house dust, surface wipes, handwipes, and urine samples collected and analyzed for selected pesticides	Lu et al. (*101*)
NHEXAS	Children older than 8 years of age	Indoor air, outdoor air, house dust, soil, dislodgeable residue, duplicate diet, and urine samples collected and analyzed for VOCs, pesticides, metals, and PAHs	Pellizzari et al. (*47*); Sexton et al. (*102*)
Children's pesticide exposure study	100 children 3–12 years of age	Indoor air, outdoor air, water, house dust, soil, dislodgeable residue, handwipe, duplicate diet, urine, and blood samples collected and analyzed for selected pesticides	Quackenboss et al. (*62*)[a]
Agricultural Health Pilot Study	Farm workers, spouses, children Six farms in North Carolina and Iowa; pilot study	Indoor air, outdoor air, housedust, soil, dislodgeable residue, handwipe, duplicate diet, blood, and urine samples collected and analyzed for selected pesticides	Melnyk et al. (*103*); Streicher et al. (*104*); Camann et al. (*105*)
School-based study of complex environmental exposures and related health effects in children	800 children attending elementary school in two low-income neighborhoods in south Minneapolis	Outdoor, in-home, in-school, personal, and human tissue monitoring for volatile organic compounds, metals, environmental tobacco smoke, PAHs, and pesticides	Principal investigator: K. Sexton[a,b]
Exposure of children to pesticides in Yuma County, Arizona	100–300 children, primarily low income Hispanic and Cocopah	Indoor air, surfaces, house dust, hands, and other media sampled for pyrethroids and OPs; blood sampled for cholinesterase inhibitors	Principal investigator: M. Lebowitz[b]

Abbreviations: OP, organophosphates; PAH, polycyclic aromatic hydrocarbon.
[a]Abstracts describing these studies can be found on the EPA web site (*106*). [b]Recently funded study.

determine the relative magnitude of the child-handling component to the total dietary intake of a contaminant.

There is a need for more and better-focused research into children's activities. The seemingly extensive current database is deficient from an exposure modeling perspective because many of the activity codes do not adequately capture the richness of what children actually do. They are too broadly defined and ignore many child-oriented behaviors, limiting the utility of these data for assessing the frequency and duration of children's contact with contaminated air, children's activity levels, and, consequently, inhalation rates.

Currently, there are no methods available to directly assess dermal and nondietary ingestion exposures. Therefore, it is particularly important that studies be performed to identify the most important exposure factors for assessing dermal exposures. Characteristics of surfaces and objects contacted by children are important in assessing children's dermal and nondietary ingestion exposures. Consequently, the definition used to identify microenvironments in which children spend time must be modified to include the surface type. In addition, more survey and observational studies across all ages of children are required to characterize both macro- and microactivities that contribute to dermal exposure in these microenvironments, as well as contact and transfer necessary for nondietary ingestion and contamination of food.

The research needed to better characterize and quantify children's exposures to environmental contaminants is best conducted by carefully considering the data needed to assess aggregate exposure. The algorithms for combining the environmental monitoring data with the exposure factors to estimate an exposure or a dose should be used to guide the type of data collected. In this way, future research efforts will most efficiently provide the knowledge base needed to improve exposure assessments for children.

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