Children's Behavior and Physiology and How It Affects Exposure to Environmental Contaminants

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ABSTRACT. Infant, child, and adolescent exposures to environmental toxicants are different from those of adults because of differences in behavior and physiology. Because of these differences, there is the potential for quantitatively different exposures at various stages of development. Pediatricians are well aware of these behavioral and physiologic differences from a clinical standpoint—namely, food and water intake, soil ingestion, mouthing behavior, inhalation physiology, and activity level—as they relate to the ratio of these parameters between the adult and the child when considering weight and surface area. Pediatricians recognized the importance of pica as a cause of lead poisoning, the noxious effect of second-hand smoke, and the greater propensity for addiction during the adolescent years. For determining the differences in impact of many environmental toxicants between adults and children, research is needed to document where and whether these differences result in deleterious effects. ***Pediatrics*** **2004;113: 996–1006;** ***children, behaviors, exposure, food intake, water intake, soil intake, inhalation rates, soil adherence.***

ABBREVIATIONS. EPA, Environmental Protection Agency; USDA, US Department of Agriculture; CSFII, Continuing Survey of Food Intakes by Individuals.

It is a child's job to explore his environment. The exploratory behaviors of childhood are the principal ways that children learn. The normal behavioral development of a child will also influence his or her environmental exposures. Children are naturally curious and active. Infants learn about objects by mouthing them (hand-to-mouth behaviors). Toddlers learn by venturing out of doors and testing their physical prowess. As children become adolescents, they gain more and more freedom from parental authority. They learn by trying new things (eg, smoking). Although they are at a stage of development at which physical strength and stamina are at a peak, they are continuing to acquire abstract thinking.[1] Therefore, they may not consider cause and effect, particularly delayed effects, in the same way as adults do. They may place themselves in situations with greater risk as a result of this lack of perception. Although there are tremendous benefits to the exploratory learning that occurs during childhood, it obviously has its risks.

Many factors influence children's health. These factors include genetic background, physiology, nutrition, age, lifestyle, and so forth. Parental exposures that occur before conception can also threaten the health of the fetus either because the maternal or paternal reproductive organs are affected or because chemicals can be stored in the body and excreted during pregnancy. The purpose of this article, however, is to describe the normal childhood behaviors at various life stages and illustrate the ways in which these behaviors and physiologies put them at risk of exposure to environmental contaminants.

BEHAVIORS AND PHYSIOLOGIC NEEDS AT VARIOUS LIFE STAGES

Exposure to an environmental agent is the first step in the sequence of environmentally related health effects. Exposures differ with developmental stage because the environments of fetuses, children, and adolescents are different from those of adults. On a body weight basis, children breathe more air, drink more water, and consume more of certain foods than adults. Children develop in spurts and, at times, discontinuously. For this reason, children's behavioral stages are better defined as a continuum rather than fixed age categories. There is no consistent way to define these age categories. Sometimes the categories selected are driven by the amount of data available. Experts at an Environmental Protection Agency (EPA)-sponsored workshop suggested a set of age categories that may be used while more specific data are developed.[2] Table 1 summarizes the proposed age categories and the behavioral characteristics associated with the different routes of exposure that were proposed.

This article presents data on breast milk intake, water intake, food consumption, soil intake rates, mouthing behavior, inhalation rates, soil adherence factors, and time spent in various activities. Much of the data presented was extracted from the EPA Interim Final Child-Specific Exposure Factors Handbook.[3] A literature search was conducted to identify other relevant data.

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TABLE 1. Behaviors at Various Stages of Childhood

Age Group	Behaviors Relevant to Oral and Dermal Exposure	Behaviors Relevant to Inhalation Exposure
Birth through 2 mo	Breast and bottle feeding. Hand-to-mouth activities.	Time spent sleeping/sedentary.
3 through 5 mo	Solid food may be introduced. Contact with surfaces increases. Object/hand-to-mouth activities increase.	Breathing zone close to the floor. Children spend time in day care.
6 through 11 mo	Food consumption expands. Children's floor mobility increases (surface contact). Children are increasingly likely to mouth nonfood items.	Because children become more mobile and their breathing zone is close to the floor, they may generate and be exposed to dust clouds that contain particulate matter. Children spend time in day care.
12 through 23 mo	Children consume full range of foods. They participate in increased play activities, are extremely curious, and exercise immature judgment. Breast and bottle feeding may cease.	Children walk upright, run, and climb. They occupy a wider variety of breathing zones and engage in more vigorous activities. Children spend time in day care (or preschool/early education).
2 through 5 y	Hand-to-mouth activities begin to moderate.	Occupancy of outdoor spaces increases.
6 through 10 y	There is decreased oral contact with hands and objects as well as decreased dermal contact with surfaces.	Children spend time in school environments and begin playing sports.
11 through 15 y	Smokeless tobacco use may begin. There is an increased rate of food consumption.	Increased independence (more time out of home). Workplace exposure can begin. May begin cigarette smoking.
16 through 20 y	High rate of food consumption begins.	Independent driving begins. Expanded work opportunities. Smoking may begin.

Adapted from USEPA.[2]

EXPOSURE DATA RELEVANT TO CHILDREN'S BEHAVIOR AND PHYSIOLOGY

Breast Milk Intake

The diets of many newborns are limited to breast milk. The American Academy of Pediatrics advocates breastfeeding as the optimal form of nutrition for infants.[4] Epidemiologic research shows that breast milk and breastfeeding of infants provide advantages with regard to general health, growth, and development while significantly decreasing risk for a large number of acute and chronic diseases.[4]

Breast milk, however, can be a potential source of exposure to toxic chemicals for nursing infants. This is especially true because breastfed infants are at the top of the food chain.[5] Certain chemicals can accumulate in the mother's fatty tissue and may be transferred to an infant during breastfeeding. Studies of breast milk have shown the presence of chlorinated organic contaminants such as polychlorinated biphenyls and dioxins.[6–8] Breast milk contains fat in which these chemicals tend to accumulate.[6] Estimating exposure via this route requires information about the amount of breast milk intake. Average breast milk intake rates range from 427 mL/day to 765 mL/day for children <1 year of age.[9–14] Upper percentile values range from 900 mL/day to 1059 mL/day. Information on the fat content of breast milk may also be necessary to assess exposure when chemical concentrations are indexed to lipid content. Lipid content in breast milk is approximately 4%.[11–16] Although some mothers breastfeed beyond 12 months, data on the prevalence of this behavior or the amount consumed by the child are not currently available.

Food Intake

Toxic chemicals may enter the food supply as a result of environmental contamination. The consumption of a wide variety of foods minimizes the chance of eating large amounts of a particular food that may be contaminated. However, a child's eating habits differ from those of an adult in the choices of food and amounts of a particular food item eaten. As another example, food neophobia, initial reluctance to eat new foods, is a normal behavior among young children. Children with neophobia had a higher intake of saturated fat and less food variety than children without food neophobia.[17]

Also, for many foods, the intake per unit body weight is greater for children than adults. The diet of children contains more milk products and more fruits and vegetables per unit body weight than adults. The primary source of food consumption data are the US Department of Agriculture's (USDA's) Nationwide Food Consumption Survey and the USDA Continuing Survey of Food Intakes by Individuals (CSFII). Analysis of these data shows that, for example, the average consumption of apples for children between birth and 5 months of age is 19 g/kg/day (consumers only). Because the data were broken out by specific age groups and infants at birth are not likely to eat apples, the average apple consumption will probably be higher if one only looks at a finer age group (eg, 3 to 5 months of age). Adults older than 20 years consume approximately 2 g/kg/day of apples (consumers only). When the level of exposure of children to Alar was calculated using a child's daily consumption of apples and apple products, an unacceptable level of risk for cancer was found.[18] This section summarizes food intake data obtained from an EPA analysis of the most recent USDA CSFII (1994–1996). Although data from the 1998 CSFII survey are available, analysis of these data has not been conducted. Table 2 summarizes the per capita consumption of the major food groups. Data for adults older than 20 years are also included for comparison purposes. Definitions of the major food groups can be found in Appendix 1. Table 3 focuses on individual food items that at least 10% of the children in the survey reported having eaten. It is

TABLE 2. Per Capita Intake of the Major Food Groups (g/kg/day as Consumed)

Population Group	Unweighted No. of Observations	% Consuming	Mean	SE	P5	P25	P50	P75	P95	P100
Fruits (age; y)										
<1	359	56.8%	13.2	1.1	0	0	7.6	22.7	41.2	110.2
1–2	1,356	85.5%	19.3	0.52	0	6.4	15.5	27.5	53.9	125.3
3–5	1,435	79.0%	11	0.34	0	2.3	8.1	16.3	32.7	105.2
6–11	1,432	71.2%	5.4	0.2	0	0	3.4	7.9	18	44.6
12–19	1,398	60.7%	2.8	0.13	0	0	1.4	4.1	11	32.2
>20	9,323	69.7%	2.4	0.07	0	0.22	1.5	3.5	8.1	39.9
Vegetables (age; y)										
<1	359	50.1%	6.9	0.72	0	0	2.3	12.2	24.1	102.6
1–2	1,356	95.4%	9.5	0.21	0.57	4.5	8	12.6	23.3	83.3
3–5	1,435	92.7%	7.3	0.16	0	3.4	6.2	9.7	18.3	45.5
6–11	1,432	93.2%	5.4	0.12	0	2.5	4.3	7.1	13.5	52.3
12–19	1,398	97.9%	4	0.09	0.63	2.1	3.4	5.1	9.3	42.4
>20	9,323	97.7%	4.1	0.06	0.64	2.2	3.6	5.4	9.1	31.9
Grains (age; y)										
<1	359	64.9%	4.1	0.42	0	0	1.6	5.4	20.2	40.1
1–2	1,356	95.6%	11.2	0.2	1.7	6.4	9.8	14.3	24.7	48
3–5	1,435	93.1%	10.3	0.2	0	6.3	9.2	13.1	21.1	120.9
6–11	1,432	93.4%	7.2	0.12	0	4.3	6.7	9.4	15.6	36.3
12–19	1,398	98.2%	4.4	0.08	1.1	2.5	3.8	5.5	9.7	34.6
>20	9,323	98.0%	3.3	0.04	0.69	1.8	2.9	4.3	7.5	23.2
Meats (age; y)										
<1	359	32.3%	1.1	0.2	0	0	0	1.4	5.9	12.4
1–2	1,356	94.0%	4.4	0.09	0	1.9	3.8	6.2	10.2	24.4
3–5	1,435	92.2%	4.1	0.08	0	2.1	3.8	5.6	9.4	20.7
6–11	1,432	92.4%	2.9	0.06	0	1.4	2.5	4	6.8	17.6
12–19	1,398	97.3%	2.2	0.05	0.27	1.1	1.9	2.8	4.9	26.8
>20	9,323	96.4%	1.7	0.02	0.16	0.88	1.5	2.2	3.8	12
Fish (age; y)										
<1	359	20.9%	0.11	0.05	0	0	0	0	0.53	4.7
1–2	1,356	58.2%	0.37	0.04	0	0	0.08	0.29	1.8	14.4
3–5	1,435	56.4%	0.32	0.03	0	0	0.07	0.25	1.7	9.6
6–11	1,432	57.5%	0.26	0.03	0	0	0.06	0.18	1.3	6.7
12–19	1,398	62.9%	0.2	0.02	0	0	0.06	0.17	1.1	5.4
>20	9,232	68.3%	0.24	0.01	0	0	0.06	0.18	1.2	8.1
Dairy products (age; y)										
<1	359	83.6%	111.4	4.9	0	63.9	102.2	158.6	235.3	576.3
1–2	1,356	95.7%	37.5	0.78	0.41	17.8	31.8	51.4	90.2	182.8
3–5	1,435	92.9%	20.9	0.4	0	10.2	18.7	29.2	48.8	89.7
6–11	1,432	93.3%	13.9	0.28	0	6.4	12.4	19.3	33.5	80.8
12–19	1,398	96.9%	6.2	0.16	0.17	1.8	4.5	8.8	17.8	38
>20	9,323	96.4%	3.3	0.07	0.08	0.82	2.4	4.7	9.8	37.8

SE indicates standard error; P, percentile of the distribution. Based on EPA's analyses of the 1994–1996 CSFII.[3]

important to note that the CSFII survey is conducted over a period of 2 nonconsecutive days and is based on a 24-hour recall. Therefore, these estimates of intake may not reflect long-term consumption patterns.

Tap Water Intake

Microbiologic and chemical contaminants can enter water supplies. Tap water may be a source of human exposure to these contaminants. The source of the pollution can be the result of human activity or naturally occurring chemicals. Contaminants may enter water sources by seeping through the soil to the ground water or entering streams as surface runoff. For instance, fertilizers and pesticides used in agricultural sites can migrate in the runoff from crops and contaminate sources of drinking water. Waste disposal sites can contaminate sources of drinking water through surface runoff or through infiltration to the ground water. In addition, animal wastes may be carried to lakes and streams by rainfall runoff or snow melt.

Consumption of drinking water may vary depending on levels of physical activity and changes in temperature and humidity. On a body weight basis, children drink more water than adults. For instance, the mean consumption rate of tap water by adults 20 years old and older is approximately 17 mL/kg/day. Tap water intake for children younger than 6 months is approximately 88 mL/kg/day. Table 4 presents tap water intake for various age groups. These values are based on consumers only and represent plain water directly ingested by the individual and indirect water that was added to foods and beverages during final preparation at home or by local food service establishments (eg, school cafeterias, restaurants).[19] For this reason, these values exclude infants who are completely breastfed and infants who drink ready-to-use formula and are not consuming any tap water. Indirect water does not include water that was added by the manufacturer during processing of a food or water that is intrinsic in food.

TABLE 3. Per Capita Intake of Individual Food (g/kg/day as Consumed)[3]

Population Group (Age; Years)	Apples			Bananas			Carrots			Corn			Cucumbers		
	% Consuming	Mean	SE	% Consuming	Mean	SE	% Consuming	Mean	SE	% Consuming	Mean	SE	% Consuming	Mean	SE
0–5 mo	24.3%	4.7	1.7	8.0%	0.38	0.33	7.9%	0.68	0.7	0.0%	0	0	0.0%	0	0
6–12 mo	64.4%	9.7	1.2	39.2%	2	0.52	18.5%	0.67	0.35	8.4%	0.35	0.51	0.2%	0	0.02
<1	43.1%	7	0.98	22.6%	1.2	0.34	12.9%	0.68	0.35	3.9%	0.16	0.36	0.1%	0	0.01
1–2	55.0%	8	0.45	34.7%	1.7	0.14	14.7%	0.34	0.18	17.6%	0.46	0.1	6.9%	0.09	0.05
3–5	47.2%	4.1	0.27	21.0%	0.71	0.1	15.2%	0.18	0.04	18.6%	0.43	0.07	11.6%	0.13	0.06
6–11	34.7%	1.4	0.14	15.4%	0.35	0.07	19.4%	0.15	0.03	20.8%	0.32	0.05	15.0%	0.12	0.04
12–19	21.3%	0.58	0.09	9.5%	0.12	0.04	12.9%	0.06	0.02	12.9%	0.14	0.04	15.6%	0.09	0.04
>20	22.2%	0.38	0.04	26.1%	0.28	0.02	20.0%	0.09	0.01	14.7%	0.12	0.04	20.0%	0.07	0.01
	Lettuce			Onions			Peaches			Pears			Peas		
0–5 mo	0.0%	0	0	0.0%	0	0	5.3%	0.28	0.45	12.9%	0.93	0.67	7.3%	0.28	0.39
6–12 mo	0.0%	0	0	0.5%	0.01	0.2	23.3%	1.5	0.58	25.9%	1.8	0.71	20.9%	0.97	0.46
<1	0.0%	0	0	0.3%	0.01	0.14	13.7%	0.86	0.39	19.0%	1.4	0.49	13.7%	0.6	0.31
1–2	12.4%	0.11	0.04	3.9%	0.02	0.02	9.7%	0.45	0.15	9.0%	0.39	0.16	12.0%	0.26	0.07
3–5	19.8%	0.17	0.03	4.8%	0.02	0.02	6.5%	0.25	0.12	4.7%	0.18	0.11	10.1%	0.16	0.05
6–11	24.7%	0.18	0.03	6.5%	0.03	0.02	5.5%	0.13	0.08	5.1%	0.11	0.07	8.4%	0.11	0.05
12–19	35.9%	0.18	0.02	13.5%	0.04	0.02	4.5%	0.06	0.05	1.8%	0.02	0.04	5.5%	0.06	0.04
>20	42.0%	0.07	0.01	23.4%	0.06	0.01	7.3%	0.08	0.03	4.7%	0.06	0.03	11.6%	0.11	0.03
	Snap Beans			Tomatoes			White Potatoes			Breads			Breakfast Foods (Grains)		
0–5 mo	5.1%	0.26	0.43	4.6%	0.16	0.36	7.4%	0.12	0.19	0.9%	0.1	0.08	0.0%	0	0
6–12 mo	26.7%	1	0.36	66.2%	0.93	0.12	62.1%	1	0.21	30.2%	0.53	0.16	4.2%	0.1	0.24
<1	15.2%	0.62	0.27	33.5%	0.52	0.12	33.0%	0.54	0.15	14.6%	0.26	0.11	1.7%	0.05	0.16
1–2	20.1%	0.49	0.09	88.9%	2.1	0.08	77.3%	2.2	0.1	77.2%	2	0.06	20.4%	0.43	0.07
3–5	15.6%	0.24	0.05	88.3%	1.7	0.06	78.2%	2	0.09	86.5%	2.3	0.05	20.8%	0.39	0.06
6–11	12.0%	0.16	0.06	90.2%	1.2	0.04	79.2%	1.5	0.06	87.1%	1.7	0.04	23.7%	0.37	0.05
12–19	7.9%	0.06	0.02	95.1%	1	0.03	84.9%	1.2	0.05	86.2%	1.1	0.03	13.0%	0.13	0.03
>20	15.8%	0.12	0.02	90.7%	0.82	0.02	83.0%	0.89	0.02	89.9%	0.94	0.02	9.6%	0.07	0.02
	Baby Cereals			Cereals (Cooked)			Cereals (Ready-to-Eat)			Pasta			Rice		
0–5 mo	40.8%	0.83	0.24	0.9%	.05	.54	0.0%	0	0	0.0%	0	0	0.2%	0.01	0.24
6–12 mo	67.8%	2.5	0.45	16.6%	1.9	1.2	19.9%	0.13	0.07	7.5%	0.14	0.22	9.2%	0.35	0.42
<1	53.4%	1.6	0.27	8.3%	0.93	0.82	9.3%	0.06	0.05	3.5%	0.07	0.15	4.4%	0.17	0.28
1–2	6.2%	0.16	0.1	18.4%	1.6	0.29	64.9%	0.97	0.04	16.0%	0.8	0.15	19.2%	0.91	0.17
3–5	0.3%	0	0.06	16.0%	1.3	0.28	69.8%	1.1	0.04	12.8%	0.55	0.13	17.0%	0.8	0.18
6–11	0.1%	0	0	8.7%	0.47	0.17	64.0%	0.79	0.03	13.4%	0.49	0.12	15.8%	0.49	0.1
12–19	0.0%	0	0	5.6%	0.16	0.09	45.7%	0.36	0.02	11.7%	0.26	0.09	17.1%	0.46	0.11
>20	0.0%	0	0	14.1%	0.32	0.01	36.7%	0.2	0.01	12.2%	0.22	0.04	17.0%	0.34	0.06
	Snacks (Grains)			Sweets (Grains)			Beef								
0–5 mo	1.0%	0.02	0.11	2.5%	0.01	0.04	5.3%	0.07	0.1						
6–12 mo	29.0%	0.27	0.08	23.0%	0.32	0.14	66.6%	1	0.15						
<1	14.1%	0.14	0.06	12.1%	0.16	0.1	34.0%	0.51	0.11						
1–2	58.1%	0.74	0.04	53.2%	1.2	0.07	88.9%	1.4	0.05						
3–5	56.7%	0.7	0.04	62.1%	1.3	0.06	86.7%	1.3	0.04						
6–11	51.3%	0.46	0.03	64.2%	1.2	0.06	88.7%	1.1	0.04						
12–19	45.0%	0.29	0.02	54.3%	0.62	0.03	93.3%	0.92	0.03						
>20	40.0%	0.14	0	52.9%	0.48	0.02	86.8%	0.66	0.01						
	Pork			Poultry			Eggs								
0–5 mo	4.6%	0.01	0.01	4.6%	0.03	0.05	5.5%	0.02	0.07						
6–12 mo	68.5%	0.19	0.04	70.6%	0.72	0.15	66.6%	0.84	0.21						
<1	34.6%	0.09	0.03	35.5%	0.35	0.1	34.1%	0.41	0.14						
1–2	86.6%	0.4	0.03	89.9%	1.4	0.05	88.6%	1.2	0.06						
3–5	84.4%	0.38	0.02	89.0%	1.3	0.05	84.8%	0.7	0.04						
6–11	85.9%	0.27	0.02	88.5%	0.83	0.03	86.1%	0.4	0.03						
12–19	90.9%	0.21	0.01	94.1%	0.62	0.02	91.6%	0.29	0.02						
>20	86.0%	0.2	0.01	87.9%	0.48	0.01	85.9%	0.28	0.01						

Based on EPA's analyses of the 1994–1996 CSFII.[3]

TABLE 4. Estimate of Direct and Indirect Community Water Ingestion, Consumers Only[19]

Age, Years	Sample Size	Mean	Water Intake, Percentile (mL/kg/day)				
			5th	25th	50th	75th	95th
<0.5	106	88	5*	27	85	131	204*
0.5–0.9	128	56	3*	14	52	83	127*
1–3	1548	26	2	9	20	35	68
4–6	1025	23	2	9	18	31	65
7–10	820	16	1	6	12	22	39
11–14	736	13	1	5	10	17	36
15–19	771	12	1	4	9	16	32

Source of Data: 1994–1996 USDA CSFII.
* Sample size was insufficient for minimum reporting requirements according to "Third Report on Nutritional Monitoring in the U.S. (1994-96)."

Soil Intake

Children often put their hands, toys, and other objects in their mouths during normal exploration of their environment. This hand-to-mouth or object-to-mouth behavior may result in the ingestion of soil and dust. This behavior may present a risk to children when the soil and dust are contaminated. Children with "pica"—the habitual eating of nonfood objects—are at even greater risk as they may consume larger amounts of soil per day. To set soil cleanup standards, health officials need data on the amount of soil expected to be ingested by a child. Soil intake studies of young children have been conducted using methods that measure trace elements in feces and soil that are believed to be poorly absorbed in the gut. These measurements are used to estimate the amount of soil ingested over a specified time period by doing a mass balance using the measured amounts of tracer elements found in the various media. Soil ingestion studies conducted thus far included children between 2 and 6 years of age. Although children younger than 2 years are of concern because they are more likely to display hand-to-mouth behavior, data for this age group do not exist. Likewise, data do not exist for children older than 6 years. In addition, these studies have not been able to differentiate successfully between ingestion of soil and ingestion of dust. Children with pica may exhibit unusually high levels of soil ingestion. Data on ingestion rates by children with pica are very limited, and the behavior is considered to be relatively uncommon.

Children's mean soil ingestion values ranged from 39 mg/day to 271 mg/day with an average of 138 mg/day for soil ingestion and 193 mg/day for soil and dust ingestion.[20–25] Upper percentile values ranged from 104 mg/day to 1432 mg/day with an average of 358 mg/day for soil and 790 mg/day for soil and dust combined.[20–25] Limitations of these data do not permit the derivation of a distribution of soil intake rates by children. Individuals were not studied for sufficient periods of time to get a good estimate of long-term behavior. In addition, inconsistencies among tracers and input/output misalignment errors indicate a fundamental problem with the methods currently used to estimate soil intake rates.

Mouthing Behavior

Young children, during normal exploration of their environment, mouth objects or their fingers.[26] Children play close to the ground and are constantly licking their fingers or mouthing toys or objects. This mouthing behavior may result in exposure to toxic chemicals in the environment. For example, pesticide residues that have been transferred from treated surfaces to the hands or objects may be mouthed by children. This route of exposure may exceed other ingestion routes (eg, food, pica, drinking water, breast milk) and dermal exposure because nondietary ingestion may result in higher ingestion rates of contaminated material.[27] In addition, because young children spend a lot of time indoors, contaminants that are deposited on surfaces in the home may be a concern. Mouthing behavior is intermittent and nonuniform, which makes it difficult to measure and model.[28] For this reason, data on mouthing behavior are limited.

Some researchers express mouthing behavior in terms of frequency of occurrence (eg, contacts/hour, contacts/min). Others express mouthing behavior as a rate in units of minutes per hour of mouthing time. Four studies have examined mouthing behavior in children (Table 5).

Inhalation Rates

Infants and young children have a higher resting metabolic rate and rate of oxygen consumption per unit body weight than adults because they have a larger surface per unit body weight and because they are growing rapidly. Therefore, their exposure to any air pollutant may be greater. An additional consideration is the smaller lung surface area/kg in the early stages of development. Thus, the higher amount of inspired air will affect a relatively smaller area of lung tissue.

Although oxygen consumption is a physiologic factor, it is affected by the level of activity. The oxygen consumption of a resting infant aged between 1 week and 1 year is 7 mL/kg body weight per minute. The rate for an adult under the same conditions is 3 to 5 mL/kg/min.[29] Thus, on a body weight basis, the volume of air passing through the lungs of a resting infant is twice that of a resting adult under the same conditions, and therefore twice as much of any chemical in the atmosphere could reach the lungs of an infant. In addition to an increased need for oxygen relative to their size, children have narrower airways than those of adults. Thus, irritation caused by air pollution that would produce only a

TABLE 5. Summary of Mouthing Behavior Data

Age	No. of Children	Mouthing Frequency/Time	Reference
3–6 mo	5	1 min/d	Groot et al[26]
6–12 mo	14	44 min/d	
12–18 mo	12	16 min/d	
18–36 mo	11	9 min/d	
2–6 y		9.5 contacts/h (hand to mouth)	Reed et al[47]
	30	16.3 contacts/h (object to mouth)	
2.5–4.2 y	4	9 contacts/h	Zartarian[28]
10–60	92	55 min/d	US EPA[3]
<24	30	76 ± 5 contacts/h	
>24	56	38 ± 3 contacts/h	

slight response in an adult can result in potentially significant obstruction in the airways of a young child. In addition, they often spend more time engaged in vigorous activities than adults.[30] Table 6 summarizes studies conducted in California. Layton[31] calculated breathing rates on the basis of oxygen consumption associated with energy expenditures. Energy expenditures were obtained from data collected in the USDA 1977–1978 food consumption survey. Table 7 summarizes inhalation rate data for various age categories. These data represent average values for the US population.

Soil Adherence

Children may be involved in several activities that may put them in contact with soil and dust. In addition to the ingestion and inhalation of soil and dust particles, children may be exposed to soil and dust through the dermal route. Soil can adhere to the skin, and contaminants found in soil can penetrate the dermal barrier. Although soil adherence itself is not a behavior, studies show that soil adherence is highly dependent on the type of activity[3,32–35] (see Table 8). Soil adherence is expressed in units of milligrams of

TABLE 6. Summary of Inhalation Rate Studies Conducted in California

Age Group	Location	Activity Level	Inhalation Rate				
			Mean (m^3/h)	50th (m^3/h)	99th (m^3/h)	Average Daily (m^3/day)	Study
Healthy		Slow	0.84		1.98		Linn et al[48]
Elementary school		Medium	0.96				
		Fast	1.14				
		Mean	0.90				
High school		Slow	0.78		2.22		
		Medium	1.14				
		Fast	1.62				
		Mean	0.84				
Asthmatics		Slow	1.2		2.40		
Elementary and high school		Medium	1.2				
		Fast	1.5				
		Mean	1.2				
10–12 y	Indoor	Slow	0.84	0.78	2.34*	21.4† (mean)	Spier et al[49]
		Medium	0.96	0.84	2.58*	19.3† (50th)	
		Fast	1.02	0.84	3.42*	64† (99.9th)	
	Outdoor	Slow	0.96	0.78	4.32*		
		Medium	1.08	0.96	3.36*		
		Fast	1.14	0.96	3.60*		
13–17 y	Indoor	Slow	0.78	0.72	3.24*	19.9† (mean)	
		Medium	0.96	0.84	4.02*	18.2† (50th)	
		Fast	1.26	1.08	6.84*	85.5† (99.9th)	
	Outdoor	Slow	0.96	0.90	5.28*		
		Medium	1.26	1.08	5.70*		
		Fast	1.44	1.02	5.94*		
3–5.9 y		Resting	0.37				Adams[50]
		Sedentary	0.40				
		Light	0.65				
6–12.9 y		Resting	0.45				
		Sedentary	0.47				
		Light	0.95				
		Moderate	1.74				
		Heavy	2.23				
<12 y						0.452‡	OEHHA[51]
						0.581*§	

* 99.9th percentile.
† Calculated using data on hours spent at each activity and inhalation rates for each activity type.
‡ m^3/kg/day.
§ High end.

TABLE 7. Summary of Mean Daily and Activity-Specific Inhalation Rates

Population	Mean*
Daily	
Infants	
<1 y	4.5 m^3/day (0.54 m^3/kg/day)
Children	
1–2 y	6.8 m^3/day (0.56 m^3/kg/day)
3–5 y	8.3 m^3/day (0.48 m^3/kg/day)
6–8 y	10 m^3/day (0.40 m^3/kg/day)
9–11 y	
Boys	14 m^3/day (0.39 m^3/kg/day)
Girls	13 m^3/day (0.35 m^3/kg/day)
12–14 y	
Boys	15 m^3/day (0.28 m^3/kg/day)
Girls	12 m^3/day (0.22 m^3/kg/day)
15–18 y	
Boys	17 m^3/day (0.24 m^3/kg/day)
Girls	12 m^3/day (0.20 m^3/kg/day)
Activity specific	
Children (18 y and under)	
Rest	0.3 m^3/h
Sedentary activities	0.4 m^3/h
Light activities	1.0 m^3/h
Moderate activities	1.2 m^3/h
Heavy activities	1.9 m^3/h

Source: Layton.[31]
* Converted to body weight basis using data from US EPA.[3]

soil divided by surface area of the skin exposed. Experiments to determine soil loadings have been conducted on children engaged in various physical activities. These activities can be grouped into some general classes of low, moderate, or high soil contact. In general, the hands have the highest soil loadings. Likewise, activities involving high soil contact with wet soil result in high soil loadings. Exposure to environmental contaminants may be reduced by handwashing after active play outdoors.

Activity Factors

When considering exposures, one must look at the exposures of an individual over the course of time. Children move through several environments during the course of a day: going to school, going to child care, going to play, and sleeping. What is needed is a sum total of all of the exposures and/or an idea of the total exposure, but we are usually not able to put monitors on children to measure their total exposure. Usually our estimates of exposure are from retrospective estimates.

Understanding children's activity patterns and time spent in various microenvironments is important to understand exposure to potentially harmful environmental pollutants. Microenvironment is defined as the location that the child occupies (eg, indoors, outdoors, home, school). The physical location of children changes as they grow. The newborn frequently spends more time in a single environment for prolonged periods of time (eg, a crib) rather than in several different environments. Infants and toddlers are frequently placed on the floor, carpet, or grass. Therefore, they may have much more exposure to chemicals associated with these surfaces, such as formaldehyde and volatile organic chemicals from synthetic carpet and pesticide residues from flea bombs.[36,37] In addition, the breathing zone for an adult is typically 4 to 6 feet above the floor. However, for a child, it will be closer to the floor and dependent on the height and mobility of the child. Within lower breathing zones, chemicals that are heavier

TABLE 8. Geometric Mean and Geometric Standard Deviations of Soil Adherence by Activity and Body Region

Activity	*N*	Postactivity Dermal Soil Loadings (mg/cm^2)*				
		Hands	Arms	Legs	Faces	Feet
Indoor						
Tae Kwon Do	7	0.0063 (1.9)	0.0019 (4.1)	0.0020 (2.0)		0.0022 (2.1)
Indoor kids no. 1	4	0.0073 (1.9)	0.0042 (1.9)	0.0041 (2.3)		0.012 (1.4)
Indoor kids no. 2	6	0.014 (1.5)	0.0041 (2.0)	0.0031 (1.5)		0.0091 (1.7)
Daycare kids no. 1a	6	0.11 (1.9)	0.026 (1.9)	0.030 (1.7)		0.079 (2.4)
Daycare kids no. 1b	6	0.15 (2.1)	0.031 (1.8)	0.023 (1.2)		0.13 (1.4)
Daycare kids no. 2	5	0.073 (1.6)	0.023 (1.4)	0.011 (1.4)		0.044 (1.3)
Daycare kids no. 3	4	0.036 (1.3)	0.012 (1.2)	0.014 (3.0)		0.0053 (5.1)
Outdoor						
Soccer no. 1	8	0.11 (1.8)	0.011 (2.0)	0.031 (3.8)	0.012 (1.5)	
Gardeners no. 1	8	0.20 (1.9)	0.050 (2.1)	0.072 —	0.058 (1.6)	0.17 —
Archeologists	7	0.14 (1.3)	0.041 (1.9)	0.028 (4.1)	0.050 (1.8)	0.24 (1.4)
Kids-in-mud no. 1	6	35 (2.3)	11 (6.1)	36 (2.0)		24 (3.6)
Kids-in-mud no. 2	6	58 (2.3)	11 (3.8)	9.5 (2.3)		6.7 (12.4)

Sources: Kissel et al,[34] Holmes et al.[35]
* Geometric means (first row) and geometric standard deviation (second row in parentheses).

TABLE 9. Summary of Mean Time Spent Indoors and Outdoors From Several Studies

Age (Years)	Time Indoors (Hours/Day)	Time Outdoors (Hours/Day)*	Population	Study
3–5	19	2.8	US population; children were studied during school months (n = 922)	Timmer et al[52]
6–8	20	2.2		
9–11	20	1.8		
12–14	20	1.8		
15–17	19	1.9		
12 and older	21 (national)	1.2 (national)	Children in California were studied (n = 1762) and compared with national data (n = 2762)	Robinson and Thomas[53]
	21 (California)	1.4 (California)		
0–2	20	4	Children in California were studied (n = 1200)	Wiley[54]
3–5	18.8	5.2		
6–8	19.7	4.4		
9–11	19.9	4.1		
1–4	—	6	US population (n = 1789)	Tsang and Kleipeis[55]
5–11	—	6		
12–17	—	5		

* Mean of weekday and weekend rounded up to 2 significant figures.

than air, such as mercury vapor, may concentrate.[38] This is 1 factor that may have accounted for a case of acrodynia in a Michigan child who was exposed to mercury vapor from latex house paint.[39]

Preambulatory children also may experience sustained exposure to noxious agents because they cannot remove themselves from their environment. An example is the infant who is badly sunburned as a result of the inability to protect him- or herself. It has been shown that the risk of skin cancer is most closely related to the amount of sun damage that the skin sustains during the first 18 years of life.[40]

Certain activities and behaviors specific to children place them at higher risk of exposure to certain environmental agents.[41] An activity or time spent will vary on the basis of culture, hobbies, location, gender, age, and personal preferences. It is difficult to collect/record accurately data on a child's activity patterns.[42] Because children engage in more contact activities than adults, a much wider distribution of activities needs to be considered when assessing exposure.[42] Behavioral patterns and preferred activities result in different exposures for children in different developmental stages.[41]

This section summarizes information on various activities, length of time spent performing these activities, and locations and length of time spent by individuals within those various microenvironments. We focus on those activities that are deemed the most important in assessing children's exposures. Young children spend most of their time indoors at home.[3] Because infants and toddlers spend a significant amount of time in the house, they may use only 1 source of tap water. Information about the amount of time spent indoors is necessary to assess exposures related to indoor air environments. Older children spend a significant part of their lives at school. Schools are frequently near highways (auto emissions and lead), under power lines (electromagnetic fields), or on old industrial sites (benzene, arsenic). Schools made frequent use of asbestos as a building material and commonly use pesticides for ground and building management.[43] Because child care facilities range from private homes to institutional facilities and the environments of child care facilities are less regulated than schools, little is known about these physical environments.

Adolescents not only have a new school environment but also begin to self-determine physical environments, often misjudging or ignoring the risks to themselves.[44] In addition, many adolescents have part-time jobs that place them in physical environments that may be hazardous as a result of occupational exposures.[45]

Other activities, such as time spent showering, bathing, swimming, and playing in grass or gravel, may also be important. Because young children tend to take baths rather than showers and bathing generally takes more time than showering, their exposure may be higher because the duration may be longer. Swimming may be another source of dermal, inhalation, and ingestion exposures. Water may be inadvertently swallowed during swimming. Children may be exposed to chemicals found in swimming pools or contaminants found in water bodies.

A comprehensive list of activities, locations, and length of time spent on these activities is available.[3] Several studies have been conducted to obtain data on children's time use. Most of these studies have been done using time diary methods. Tables 9 and 10 provide a summary of a selected group of activities in which children are engaged. Activities can vary significantly with differences in age.

DATA GAPS AND CONCLUSIONS

Although much information is available in the published literature and there has been a recent increased emphasis on children's environmental research, large data gaps still exist. For example, fetal exposure may occur through maternal exposure to environmental chemicals as substances cross the placenta.[46] Exposure factors data related to fetal exposures are limited. Other areas in which research related to childhood exposures is needed are[3]

- Breast milk consumption and the incidence and duration of breastfeeding

TABLE 10. Summary of Data on Activity Factors

Type	Value			Study
Time indoors	At residence			
	Age, y	Mean, h	95th percentile, h	Tsang and Klepeis[55]
	1–4	20	24	
	5–11	17	24	
	12–17	16	23	
	Total time indoors			
	Ages	Mean, h*		Timmer et al[52]
	3–5	19		
	6–8	20		
	9–11	20		
	12–14	20		
	15–17	19		
Time outdoors	At residence			
	Age, y	Mean, h	95th percentile, h	Tsang and Klepeis[55]
	1–4	3	9	
	5–11	3	8	
	12–17	2	8	
	Total time outdoors			
	Ages, y	Mean, h†		Timmer et al[52]
	3–5	3		
	6–8	2		
	9–11	2		
	12–14	2		
	15–17	2		
Time in school	Age, y	Mean, min/day		Timmer et al[52]
	3–5	137		
	6–8	292		
	9–11	315		
	12–14	344		
	15–17	314		
Taking showers	10 min/day shower duration			Tsang and Klepeis[55]
	1 shower event/day			Tsang and Klepeis[55]
	20 min/day bath duration			
Swimming	1 event/month			Tsang and Klepeis[55]
	60 min/event			
Playing on sand or gravel	60 min/day			Tsang and Klepeis[55]
Playing on grass	60 min/day			Tsang and Klepeis[55]

* Mean of weekday and weekend rounded up to 2 significant figures.
† Mean of weekday and weekend rounded up to 1 significant figure.

- Children's food handling practices that might exacerbate exposure
- Fish intake among children, particularly recreational and subsistence populations
- Consumption of ethnic foods by children. The term "ethnic" here refers to foods pertaining to a group of people recognized as a class on the basis of certain distinctive characteristics such as religion, language, ancestry, culture, or national origin.
- Better estimates of soil intake rates, particularly at the upper percentiles. Research is also needed to refine the methods to calculate soil intake rates and to better understand the relative contribution of soil versus dust ingestion.
- Nondietary ingestion and dermal exposure factors, such as the microenvironments in which children spend time and the types of materials with which they come in contact, as well as information on the rate at which they come in contact with contaminated surfaces, the fraction of the contaminants that are transferred to skin and object surfaces, and the amount of the object/skin entering the mouth
- Better soil adherence rates for additional activities involving children
- Frequency and duration of use and kinds of consumer products used by children
- Derivation of new surface areas based on newer body weight data
- Inhalation rates that are specific to children's activities and overall 24-hour breathing rates
- Biomarkers of exposure need to be developed to improve estimates of exposure
- Methods to extrapolate from short-term to long-term or chronic exposures
- Studies that link exposures to specific health outcomes

Children's physiology and behavior during various life stages may put them at higher risk from environmental exposures. On a body weight basis, children breathe more air, drink more water, and consume more of certain foods than adults. Children also engage in activities that may put them in contact with contaminants in the environment (eg, crawling, mouthing behavior). Understanding these differences between adults and children is important when assessing environmental health risks to children.

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Appendix 1. Food Definitions for the Major Food Groups[3]

Food Product	Food Codes	
Total dairy	Milk and milk products; milk and milk drinks; cream and cream substitutes; milk desserts, sauces, and gravies; cheeses	Includes regular fluid milk, human milk, imitation milk products, yogurt, milk-based meal replacements, and infant formulas. Also includes the average portion of grain mixtures (13.48%) and the average portion of meat mixtures (5.56%) made up by dairy. Includes soy-based milk or formula.
Total meats	Meat, type not specified; beef; pork; lamb, veal, game, carcass meat; poultry; organ meats, sausages, lunchmeats, meat spreads	Also includes the average portion of grain mixtures (7.87%) and the average portion of meat mixtures (31.11%) made up by meats.
Total fish	Fish, all types	Also includes the average portion of meat mixtures (4.44%) made up by fish.
Total grains	Flour, breads, tortillas, sweets, snacks, breakfast foods, pasta, cooked cereals and rice, ready-to-eat and baby cereals	Also includes the average portion of grain mixtures (31.46%) and the average portion of meat mixtures (13.33%) made up by grain.
Total fruits	Fruits, citrus fruits and juices, dried fruits, other fruits, fruits/juices and nectar, fruit/juices baby food	Includes baby foods.
Total vegetables	Vegetables (all forms), white potatoes and Puerto Rican starchy, dark green vegetables, deep yellow vegetables, tomatoes and tomato mixtures, other vegetables, veg. and mixtures/baby food, veg. with meat mixtures, beans/legumes, soybeans, bean dinners and soups, meatless items, soyburgers	Includes baby foods; mixtures, mostly vegetables; does not include nuts and seeds. Also includes the average portion of grain mixtures (25.84%) and the average portion of meat mixtures (30.00%) made up by vegetables.

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