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7 DERMAL EXPOSURE FACTORS

7.1 INTRODUCTION

Dermal exposure can occur during a variety of activities in different environmental media and microenvironments (U.S. EPA, 1992a; 1992b; 2004). These include:

- Water (e.g., bathing, washing, swimming);
- Soil (e.g., outdoor recreation, gardening, construction);
- Sediment (e.g., wading, fishing);
- Liquids (e.g., use of commercial products);
- Vapors/fumes (e.g., use of commercial products); and
- Indoor dust (e.g., carpets, floors, counter tops).

Children may be more highly exposed to environmental toxicants through dermal routes than adults. For instance, children may crawl, roll or sit on surfaces treated with chemicals (i.e., carpets and floors) and play with objects such as toys where residues may settle. Children also are more likely to wear less clothing than adults. As a result, children may have higher dermal contact with contaminated media. In addition, young children who wear diapers may be exposed for long periods of time to chemical components of lotions and other products used for diapering. Children also have a higher surface area relative to body weight compared to adults. The surface-area-to-body weight ratio for newborn infants is more than two times greater than that for adults (Cohen-Hubal et al., 1999). Therefore, the dose relative to body weight would be greater for a child than for an adult with an equal amount of skin exposure to a chemical.

This chapter focuses on measurements of body surface area and dermal adherence of solids to the skin. These are only two of a several parameters that influence dermal absorption. Other factors include the concentration of chemical in contact with the skin, characteristics of the chemical (i.e., lipophilicity, polarity, volatility, solubility), the site of application (i.e., the thickness of the stratum corneum varies over parts of the body), absorption of chemical through the skin and factors that affect absorption (i.e, thickness, age, condition), and the amount of chemical delivered to the target organ. For guidance on how to use skin surface area and dermal adherence factors, as well as these other factors to assess dermal exposure, readers are referred to *Dermal Exposure Assessment: Principles and Applications* (U.S. EPA, 1992b) and *Risk Assessment Guidelines for Superfund (RAGs) Part E* (U.S. EPA, 2004). Frequency and duration of contact also affect dermal exposure. Information on activity factors is presented in Chapter 17 of this handbook.

Surface area of the skin can be determined using measurement or estimation techniques. Coating, triangulation, and surface integration are direct measurement techniques that have been used to measure total body surface area and the surface area of specific body parts. The coating method consists of coating either the whole body or specific body regions with a substance of known density and thickness. Triangulation consists of marking the area of the body into geometric figures, then calculating the figure areas from their linear dimensions. Surface integration is performed by using a planimeter and adding the areas. The results of studies conducted using these various techniques have been summarized in *Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments* (U.S. EPA, 1985). Because of the difficulties associated with direct measurements of body surface area, the existing direct measurement data are limited and dated. However, several researchers have developed methods for estimating body surface area from measurements of other body dimensions (DuBois and DuBois, 1916; Boyd, 1935; Gehan and George, 1970). Generally, these formulas are based on the observation that body weight and height are correlated with surface area and are derived using multiple regression techniques. U.S. EPA (1985) evaluated the various formulas for estimating total body surface area. A discussion and comparison of formulas are presented in Appendix 7A. The key studies on body surface area that are presented in Section 7.3 of this chapter are based on these formulas, and weight and height data from the National Health and Nutrition Examination Survey (NHANES).

Several field studies have been conducted to estimate the adherence of solids to skin. These field studies consider factors such as activity, gender, age, field conditions, and clothing worn. These studies are presented in Section 7.4 of this chapter.

The recommendations for skin surface area and dermal adherence of solids to skin are provided in the next section, along with a summary of the confidence ratings for these recommendations. The recommended values are based on key studies identified by U.S. EPA for these factors. Following the recommendations, the two key studies on skin surface area and the three key studies on dermal adherence of solids to skin are summarized. Relevant data on these factors are also presented to provide added perspective on the state-of-knowledge pertaining to dermal exposure factors.

7.2 RECOMMENDATIONS

7.2.1 Body Surface Area

The recommended mean and 95th percentile total body surface area values for children are summarized in Table 7-1. If gender-specific data or data for percentiles other than the mean or 95th percentile are needed, the reader is referred to Tables 7-7 through 7-9 of this chapter. The recommendations for total body surface area are based on the U.S. EPA analysis of NHANES 1999-2006 data and are presented for the standard age groupings recommended by U.S. EPA (2005) for male and female children combined. The U.S. EPA analysis of NHANES 1999-2006 data uses correlations with body weight and height for deriving skin surface area (see Section 7.3.1.2 and Appendix 7A). NHANES 1999-2006 used a statistically-based survey design which should ensure that the data are reasonably representative of the general population. The recommendations for the percentage of total body surface area represented by individual body parts are based on data from U.S. EPA (1985), and are presented in Table 7-2 (See Section 7.3.1). Table 7-2 also provides age-specific body part surface areas (m^2) that were obtained by multiplying the mean body part percentages by the total body surface areas presented in Table 7-1. If gender-specific data or data for percentiles other than the mean and 95th percentile are needed, the body part percentages in Table 7-2 may be applied to the total skin surface area data in Tables 7-7 through 7-9. Table 7-3 presents the confidence ratings for the recommendations for body surface area.

For swimming and bathing scenarios, past exposure assessments have assumed that 75 to 100 percent of the skin surface is exposed (U.S. EPA, 1992b). More recent guidance recommends assuming 100 percent exposure for these scenarios (U.S. EPA, 2004). For other exposure scenarios, it is reasonable to assume that clothing reduces the contact area. However, while it is generally assumed that adherence of solids to skin occurs to only the areas of the body not covered by clothing, it is important to understand that soil and dust particles can get under clothing and be deposited on skin to varying degrees depending on the protective properties of the clothing. Likewise, liquids may soak through clothing and contact covered areas of the skin. Assessors should consider these possibilities for the scenario of concern and select skin areas that are judged appropriate.

7.2.2 Adherence of Solids to Skin

The adherence factor (AF) describes the amount of material that adheres to the skin per unit of surface area. Although most research in this area has focused on soils, a variety of other solid residues can accumulate on skin, including household dust, sediments and commercial powders. Studies on soil adherence have shown that: 1) soil properties influence adherence; 2) soil adherence varies considerably across different parts of the body; and 3) soil adherence varies with activity (U.S. EPA, 2004). It is recommended that exposure assessors use adherence data derived from testing that matches the exposure scenario of concern in terms of solid type, exposed body parts, and activities, as closely as possible. Assessors should refer to the activities described in Table 7-12 to select those that best represent the exposure scenarios of concern and use the corresponding adherence values from Table 7-13. Table 7-12 lists the age ranges covered by each study. This may be used as a general guide to the ages covered by these data. Recommended mean AF values are summarized in Table 7-4 according to common activities involving children. Insufficient data were available to develop distributions or probability functions for these values. Also, the small number of subjects in these studies prevented the development of recommendations for the specific age groups recommended by U.S. EPA (2005).

RAGS Part E (U.S. EPA, 2004) recommends that scenario-specific adherence values be weighted according to the body parts exposed. Weighted adherence factors may be estimated according to the following equation:

$$AF_{wtd} = \frac{(AF_1)(SA_1) + (AF_2)(SA_2) + \ldots . (AF_i)(SA_i)}{SA_1 + SA_2 + \ldots SA_i}$$

(Eqn. 7-1)

where:

AF_{wtd} = weighted adherence factor;
AF = adherence factor; and
SA = surface area.

For the purposes of this calculation, the surface area of the face may be assumed to be 1/3 that of the head, forearms may be assumed to represent 45 percent of the arms and lower legs may be assumed to represent 40 percent of the legs (U.S. EPA, 2004).

The recommended dermal AFs represent the amount of material on the skin at the time of measurement. U.S. EPA (1992b) recommends interpreting AFs as representative of contact events. Assuming that the amount of solids measured on the skin represents accumulation between washings, and that people wash at least once per day, these adherence values can be interpreted as daily contact rates (U.S. EPA, 1992b). The rate of solids accumulation on skin over time has not been well studied, but probably occurs fairly quickly. Therefore, pro-rating the adherence values for exposure time periods of less than one day is not recommended.

The confidence ratings for these AF recommendations are shown in Table 7-5. It should be noted that while the recommendations are based on the best available estimates of activity-specific adherence, they are based on limited data from studies that have focused primarily on soil. Therefore, they have a high degree of uncertainty and considerable judgment must be used when selecting them for an assessment. It should also be noted that the skin adherence studies have not considered the influence of skin moisture on adherence. Skin moisture varies depending on a number of factors, including activity level and ambient temperature/humidity. It is uncertain how well this variability has been captured in the dermal adherence studies.

Table 7-1. Recommended Values for Total Body Surface Area, Males and Females Combined

Age Group	Mean	95th Percentile	Multiple Percentiles	Source
	m²			
Birth to <1 month	0.29	0.34	See Tables 7-7, 7-8, and 7-9	U.S. EPA Analysis of NHANES 1999-2006 data
1 to <3 months	0.33	0.38		
3 to <6 months	0.38	0.44		
6 to <12 months	0.45	0.51		
1 to <2 years	0.53	0.61		
2 to <3 years	0.61	0.70		
3 to <6 years	0.76	0.95		
6 to <11 years	1.08	1.48		
11 to <16 years	1.59	2.06		
16 to <21 years	1.84	2.33		

Table 7-2. Recommended Values for Surface Area of Body Parts

Age Group	Head	Trunk	Arms	Hands	Legs	Feet	Source
	Mean Percent of Total Surface Area						
Birth to <1 month	18.2	35.7	13.7	5.3	20.6	6.5	U.S. EPA, 1985
1 to <3 months	18.2	35.7	13.7	5.3	20.6	6.5	
3 to <6 months	18.2	35.7	13.7	5.3	20.6	6.5	
6 to <12 months	18.2	35.7	13.7	5.3	20.6	6.5	
1 to <2 years	16.5	35.5	13.0	5.7	23.1	6.3	
2 to <3 years	14.2	38.5	11.8	5.3	23.2	7.1	
3 to <6 years	13.7	31.7	14.2	5.9	27.3	7.3	
6 to <11 years	12.6	34.7	12.7	5.0	27.9	7.2	
11 to <16 years	9.4	33.7	12.9	5.3	31.3	7.5	
16 to <21 years	7.8	32.2	15.3	5.4	32.2	7.1	
	Mean Surface Area by Body Part[a] m^2						
Birth to <1 month	0.053	0.104	0.040	0.015	0.060	0.019	U.S. EPA Analysis of NHANES 1999-2006 data and U.S. EPA, 1985
1 to <3 months	0.060	0.118	0.045	0.017	0.068	0.021	
3 to <6 months	0.069	0.136	0.052	0.020	0.078	0.025	
6 to <12 months	0.082	0.161	0.062	0.024	0.093	0.029	
1 to <2 years	0.087	0.188	0.069	0.030	0.122	0.033	
2 to <3 years	0.087	0.235	0.072	0.032	0.142	0.043	
3 to <6 years	0.104	0.241	0.108	0.045	0.207	0.055	
6 to <11 years	0.136	0.375	0.137	0.054	0.301	0.078	
11 to <16 years	0.149	0.536	0.205	0.084	0.498	0.119	
16 to <21 years	0.144	0.592	0.282	0.099	0.592	0.131	
	95^{th} Percentile Surface Area by Body Part[b] m^2						
Birth to <1 month	0.062	0.121	0.047	0.018	0.070	0.022	U.S. EPA Analysis of NHANES 1999-2006 data and U.S. EPA, 1985
1 to <3 months	0.069	0.136	0.052	0.020	0.078	0.025	
3 to <6 months	0.080	0.157	0.060	0.023	0.091	0.029	
6 to <12 months	0.093	0.182	0.070	0.027	0.105	0.033	
1 to <2 years	0.101	0.217	0.079	0.035	0.141	0.038	
2 to <3 years	0.099	0.270	0.083	0.037	0.162	0.050	
3 to <6 years	0.130	0.301	0.135	0.056	0.259	0.069	
6 to <11 years	0.186	0.514	0.188	0.074	0.413	0.107	
11 to <16 years	0.194	0.694	0.266	0.109	0.645	0.155	
16 to <21 years	0.182	0.750	0.356	0.126	0.750	0.165	

[a] Calculated as mean percentage of body part times mean total body surface area.

[b] Calculated as mean percentage of body part times 95^{th} percentile total body surface area.

Note: Surface area values reported in m^2 can be converted to cm^2 by multiplying by 10,000 cm^2/m^2.

Table 7-3. Confidence in Recommendations for Body Surface Area		
General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of Approach	Total surface area estimates were based on algorithms developed using direct measurements and data from NHANES surveys. The methods used for developing these algorithms were adequate. The NHANES data and the secondary data analyses to estimate total surface areas were appropriate. NHANES included a large sample sizes; sample size varied with age. Body part percentages were based on direct measurements from a limited number of subjects.	
Minimal (or Defined) Bias	The data used to develop the algorithms for estimating surface area from height and weight data were limited. NHANES collected physical measurements of weight and height. Body part data were based on direct measurements from a limited number of subjects.	
Applicability and Utility		Medium
Exposure Factor of Interest	The key studies were directly relevant to surface area estimates.	
Representativeness	The direct measurement data used to develop the algorithms for estimating total body surface area from weight and height may not be representative of the U.S. population. However, NHANES height and weight data were collected using a complex, stratified, multi-stage probability cluster sampling design intended to be representative of the U.S. population. The sample used to derive body part percentages of total surface was not representative of U.S. population.	
Currency	The U.S. EPA analysis used the most current data at the time both studies were conducted. The data on body part percentages were dated; however, the age of the data is not expected to affect its utility.	
Data Collection Period	The U.S. EPA analysis was based on four NHANES data sets covering 1999-2006.	
Clarity and Completeness		Medium
Accessibility	The U.S. EPA analysis of the NHANES data is unpublished, but available upon request. U.S. EPA (1985) is a U.S. EPA-published report.	
Reproducibility	The methodology was clearly presented; enough information was included to reproduce the results.	
Quality Assurance	Quality assurance of NHANES data was good; quality control of secondary data analysis was not well described.	

Table 7-3. Confidence in Recommendations for Body Surface Area (continued)		
General Assessment Factors	Rationale	Rating
Variability and Uncertainty		Medium
Variability in Population	The full distributions were given for total surface area.	
Uncertainty	A source of uncertainty in total surface areas resulted from the limitations in data used to develop the algorithms for estimating total surface from height and weight. Because of the small sample size, there is uncertainty in the body part percentage estimates.	
Evaluation and Review		Medium
Peer Review	The NHANES surveys received a high level of peer review. The U.S. EPA analysis was not published in a peer-reviewed journal.	
Number and Agreement of Studies	There is one key study for total surface area and one key study for the surface area of body parts.	
Overall Rating		**Medium** for Total Surface Area and **Low** for Surface Area of Individual Body Parts

Table 7-4. Recommended Values for Mean Solids Adherence to Skin

	Face	Arms	Hands	Legs	Feet	Source
	mg/cm^2					
Residential (indoors)[a]	-	0.0041	0.011	0.0035	0.010	Holmes et al., 1999
Daycare (indoors & outdoors)[b]	-	0.024	0.099	0.020	0.071	Holmes et al., 1999
Outdoor sports[c]	0.012	0.011	0.11	0.031	-	Kissel et al., 1996a
Indoor sports[d]	-	0.0019	0.0063	0.0020	0.0022	Kissel et al., 1996a
Activities with soil[e]	0.054	0.046	0.17	0.051	0.20	Holmes et al., 1999
Playing in mud[f]	-	11	47	23	15	Kissel et al., 1996a
Playing in sediment[g]	0.040	0.17	0.49	0.70	21	Shoaf et al., 2005

[a] Based on weighted average of geometric mean soil loadings for 2 groups of children (ages 3 to13 years; N = 10) playing indoors.

[b] Based on weighted average of geometric mean soil loadings for 4 groups of daycare children (ages 1 to 6.5 years; N = 21) playing both indoors and outdoors.

[c] Based on geometric mean soil loadings of 6 children (ages ≥8 years) and 1 adult engaging in Tae Kwon Do.

[d] Based on geometric mean soil loadings of 8 children (ages 13 to 15 years) playing soccer.

[e] Based on weighted average of geometric mean soil loadings for gardeners and archeologists (ages 16 to 35 years).

[e] Based on weighted average of geometric mean solids loading of 2 groups of children (age 9 to 14 years; N= 12) playing in mud.

[f] Based on geometric mean solids loading of 9 children (ages 7 to 12 years) playing in tidal flats.

\- = No data.

Table 7-5. Confidence in Recommendations for Solids Adherence to Skin		
General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of Approach	The approach was adequate; the skin rinsing technique is widely employed for purposes similar to this. Small sample sizes (4 to 9 children) were used in the studies; the key studies directly measured soil adherence to skin.	
Minimal (or Defined) Bias	The studies attempted to measure soil adherence for selected activities and conditions. The number of activities and study participants was limited.	
Applicability and Utility		Low
Exposure Factor of Interest	The studies were relevant to the factor of interest; the goal was to determine soil adherence to skin.	
Representativeness	The soil/dust studies were limited to the State of Washington and the sediment study was limited to Rhode Island. The data may not be representative of other locales.	
Currency	The studies were published between 1996 and 2005	
Data Collection Period	Short-term data were collected. Seasonal factors may be important, but have not been studied adequately.	
Clarity and Completeness		Medium
Accessibility	Articles were published in widely circulated journals/reports.	
Reproducibility	The reports clearly describe the experimental methods, and enough information was provided to allow for the study to be reproduced.	
Quality Assurance	Quality control was not well described.	
Variability and Uncertainty		Low
Variability in Population	Variability in soil adherence is affected by many factors including soil properties, activity and individual behavior patterns. Not all age groups were represented in the sample.	
Uncertainty	The estimates are highly uncertain; the soil adherence values were derived from a small number of observations for a limited set of activities.	
Evaluation and Review		Medium
Peer Review	The studies were reported in peer reviewed journal articles.	
Number and Agreement of Studies	There are three key studies that evaluated different activities in children.	
Overall Rating		**Low**

7.3 SURFACE AREA

7.3.1 Key Body Surface Area Studies

7.3.1.1 *U.S. EPA, 1985 - Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments*

The U.S. EPA (1985) summarized the direct measurements of the surface area of children's body parts provided by Boyd (1935) and Van Graan (1969) as a percentage of total surface area. A total of 21 children less than 18 years of age were included. These percentages are presented in Table 7-6. Because of the small sample size, it is unclear how accurately these estimates represent averages for the age groups. Note that the proportion of total body surface area contributed by the head decreases from childhood to adulthood, whereas the proportion contributed by the leg increases.

7.3.1.2 *U.S. EPA Analysis of NHANES 1999-2006 Data*

The U.S. EPA estimated total body surface areas for children in U.S. EPA's standard age categories, using the empirical relationship shown in Appendix 7A and U.S. EPA (1985), and body weight and height data from the 1999-2006 NHANES. NHANES is conducted annually by the Center for Disease Control (CDC), National Center of Health Statistics (NCHS). The survey's target population is the civilian, noninstitutionalized U.S. population. The NHANES 1999-2006 survey was conducted on a nationwide probability sample of approximately 40,000 persons for all ages, of which approximately 20,000 were children. The survey is designed to obtain nationally representative information on the health and nutritional status of the population of the United States through interviews and direct physical examinations. A number of anthropometrical measurements were taken for each participant in the study, including body weight and height. Unit nonresponse to the household interview was 19 percent, and an additional 4 percent did not participate in the physical examinations (including body weight measurements).

The NHANES 1999-2006 survey includes over-sampling of low-income persons, adolescents 12-19 years, persons 60+ years of age, African Americans, and Mexican Americans. Sample data were assigned weights to account both for the disparity in sample sizes for these groups and for other inadequacies in sampling, such as the presence of non-respondents. Because the U.S. EPA utilized four NHANES data sets in its analysis (NHANES 1999-2000, 2001-2002, 2003-2004, and 2005-2006), sample weights were developed for the combined data set in accordance with CDC guidance from the NHANES' web site (http://www.cdc.gov/nchs/about/major/nhanes/nhanes2005-2006/faqs05_06.htm#question%2012).

Table 7-7 presents the mean and percentile estimates of body surface area by age category for male and female children, combined. Tables 7-8 and 7-9 present mean and percentiles of body surface area by age category for male and female children, respectively. An advantage of using the NHANES datasets to derive surface area estimates is that data are available for infants from birth and older. In addition, the NHANES data are nationally representative and remain the principal source of body weight and height data collected nationwide from a large number of subjects. It should be noted that in the NHANES surveys height measurements for children under 2 years of age were based on recumbent length while standing height information was collected for children aged 2 years and older. Some studies have reported differences between recumbent length and standing height measurements for the same individual, ranging from 0.5 to 2 cm, with recumbent length being the larger of the two measurements (Buyken et al., 2005). The use of height data obtained from two different types of height measurements to estimate surface area of children may potentially introduce errors into the estimates.

7.3.2 Relevant Body Surface Area Studies

7.3.2.1 *Phillips et al., 1993 - Distributions of Total Skin Surface Area to Body Weight Ratios*

Phillips et al. (1993) observed a strong correlation (0.986) between body surface area and body weight and studied the effect of using these factors as independent variables in the lifetime average daily dose (LADD) equation (See Chapter 1). The authors suggested that, because of the correlation between these two variables, the use of body surface area to body weight (SA/BW) ratios in human exposure assessments may be more appropriate than treating these factors as independent variables. Direct measurement data from the scientific literature were used to calculate SA/BW ratios for two age groups of children (infants aged 0 to 2 years and children aged 2.1 to 17.9 years). These ratios were calculated by dividing body surface areas by corresponding body weights for the 401 individuals analyzed by Gehan and George (1970) and summarized by U.S. EPA (1985). Distributions of SA/BW ratios were developed, and summary statistics were calculated for the two age groups and the combined data set.

Summary statistics for the two children's age groups are presented in Table 7-10. The shapes of these SA/BW distributions were determined using D'Agostino's test, as described in D'Agostino et al. (1990). The results indicate that the SA/BW ratios for infants are lognormally distributed. SA/BW ratios for children were neither normally nor lognormally distributed. According to Phillips et al. (1993), SA/BW ratios may be used to calculate LADDs by replacing the body surface area factor in the numerator of the LADD equation with the SA/BW ratio and eliminating the body weight factor in the denominator of the LADD equation.

The effect of gender and age on SA/BW distribution was also analyzed by classifying the 401 observations by gender and age. Statistical analyses indicated no significant differences between SA/BW ratios for males and females. SA/BW ratios were found to decrease with increasing age. The advantage of this study is that it studied correlations between surface area and body weight. However, data could not be broken out by finer age categories.

7.3.2.2 *Wong et al., 2000 - Adult Proxy Responses to a Survey of Children's Dermal Soil Contact Activities*

Wong et al. (2000) reported on two surveys that gathered information on activity patterns related to dermal contact with soil. The first of these national phone surveys (also reported on by Garlock et al., 1999) was conducted in 1996 using random digit dialing. Information about children was gathered from adults over the age of 18, and obtained information on 211 children. For older children (those between the ages of 5 and 17 years), information was gathered on their participation in "gardening and yardwork," "outdoor sports," and "outdoor play activities." For children less than 5 years old, information was gathered on "outdoor play activities," including whether the activity occurred on a playground or yard with "bare dirt or mixed grass and dirt" surfaces. Information on the types of clothing worn while participating in these play activities during warm weather months (April though October) was obtained. The results of this survey indicate that most children wore short pants, a dress or skirt, short sleeve shirts, no socks, and leather or canvas shoes during the outdoor play activities of interest. Using the survey data on clothing and total body surface area data from U.S. EPA (1985), estimates were made of the skin area exposed (expressed as percentages of total body surface area) associated with various age ranges and activities. These estimates are provided in Table 7-11.

7.4 ADHERENCE OF SOLIDS TO SKIN

7.4.1 Key Adherence of Solids to Skin Studies

7.4.1.1 *Kissel et al., 1996a - Field Measurements of Dermal Soil Loading Attributable to Various Activities: Implications for Exposure Assessment*

Kissel et al. (1996a) collected direct measurements of soil loading on the surface of the skin of volunteers, before and after activities expected to result in soil contact. Soil adherence associated with the following indoor and outdoor activities were estimated: greenhouse gardening, tae kwon do karate, soccer, rugby, reed gathering, irrigation installation, truck farming, and playing in mud. Skin surface areas monitored included hands, forearms, lower legs, faces and/or feet (Kissel et al., 1996a).

Several of the activities studied by Kissel et al. (1996a) involved children, as shown in Table 7-12. A group of young male soccer players (Soccer) was monitored before and after 40 minutes of practice on a field consisting of half grass and half bare earth. Six children were monitored after 10 and 20 minutes of playing in the mud at a lake with an exposed shoreline (Kids-in-mud No. 1 and No. 2). For indoor activities, soil loadings were estimated from six children and one adult practicing tae kwon do (Tae Kwon Do); the activity lasted 90 minutes including a 30-min warm up. Information on activity duration, sample size and clothing worn by participants is provided in Table 7-12. The subjects' body surfaces (forearms, hands, lower legs for all sample groups; faces and/or feet pairs in some sample groups) were washed before and after the monitored activities. Paired samples were pooled into single ones. The mass recovered was converted to soil loading using allometric models of surface area.

Geometric means for post-activity soil adherence by activity and body region for the four groups of volunteers evaluated are presented in Table 7-13. Children playing in the mud had the highest soil loadings among the groups evaluated. The results also indicate that, in general, the amount of soil adherence to the hands is higher than for other parts of the body during the same activity.

An advantage of this study is that it provides information on soil adherence to various body parts resulting from unscripted activities. However, the study authors noted that, because the activities were unstaged, "control of variables such as specific behaviors within each activity, clothing worn by participants, and duration of activity was limited." In addition, soil adherence values were estimated based on a small number of observations and very young children and indoor activities were under-represented in the study.

7.4.1.2 *Holmes et al., 1999 - Field Measurements of Dermal Loadings in Occupational and Recreational Activities*

Holmes et al. (1999) collected pre- and post-activity soil loadings on various body parts of individuals within groups engaged in various occupational and recreational activities. These groups included: children at a daycare center (Daycare Kids), children playing indoors in a residential setting (Indoor Kids), individuals (aged 16 to 35) removing historical artifacts from a site (Archeologists), and individuals (aged 16 to 35) performing gardening work (Gardeners). This study was conducted as a follow up to previous field sampling of soil adherence on individuals participating in various activities (Kissel et al., 1996a). For this round of sampling, soil loading data were collected utilizing the same methods used and described in Kissel et al. (1996a). Information regarding the groups studied and their observed activities is presented in Table 7-12.

The daycare children studied were all at one location, and measurements were taken on three different days. The children freely played both indoors in the house and outdoors in the backyard. The backyard was described as having a grass lawn, shed, sand box, and wood chip box. In this setting, the children engaged in typical activities including: playing with toys and each other, wrestling, sleeping, and eating. The number of children within each day's group and the clothing worn is described in Table 7-12. The five children measured on the first day were washed first thing in the morning to establish a preactivity level. They were next washed at noon to determine the postactivity soil loading for the morning (Daycare Kids No. 1a). The same children were washed once again at the close of the day for measurement of soil adherence from the afternoon play activities (Daycare Kids No. 1b). For the second observation day (Daycare Kids No. 2), postactivity data were collected for five children. All the activities on this day occurred indoors. For the third daycare group (Daycare Kids No. 3), four children were studied.

On two separate days, children playing indoors in a home environment were monitored. The first group (Indoor Kids No. 1) had four children while the second group (Indoor Kids No. 2) had six children. The play area was described by the authors as being primarily carpeted. The clothing worn by the children within each day's group is described in Table 7-12.

Seven individuals (Archeologists), ages 16 to 35 years, were monitored while excavating, screening, sorting, and cataloging historical artifacts from an ancient Native American site during a single event. Eight volunteers (Gardeners), ages 16 to 35 years, were monitored while performing gardening activities (i.e., weeding, pruning, digging small irrigation trenches, picking and cleaning fruit). The clothing worn by these groups is described in Table 7-12.

The geometric means and standard deviations of the postactivity soil adherence for each group of individuals and for each body part are summarized in Table 7-13. According to the authors, variations in the soil loading data from the daycare participants reflect differences in the weather and access to the outdoors.

An advantage of this study is that it provides a supplement to soil loading data collected in a previous round of studies (Kissel et al., 1996a). Also, the data support the assumption that hand loading can be used as a conservative estimate of soil loading on other body surfaces for the same activity. The activities studied represent normal child play both indoors and outdoors, as well as different combinations of clothing. The small number of participants is a disadvantage of this study. Also, the children studied and the activity setting may not be representative of the U.S. population.

7.4.1.3 *Shoaf et al., 2005 - Child Dermal Sediment Loads Following Play in a Tide Flat*

The purpose of this study was to obtain sediment adherence data for children playing in a tidal flat (Shoreline Play). The study was conducted on one day in late September 2003 at a tidal flat in Jamestown, Rhode Island. Nine subjects (three females and six males) ages 7 to 12 years old participated in the study. Information on activity duration, sample size and clothing worn by participants is provided in Table 7-12. Participants' parents completed questionnaires regarding their child's typical activity patterns during tidal flat play, exposure frequency and duration, clothing choices, bathing practices and clothes laundering.

This study reported direct measurements of sediment loadings on five body parts (face, forearms, hands, lower legs, and feet) after play in a tide flat. Each of nine subjects participated in two timed sessions and pre- and post-activity sediment loading data were collected. Geometric mean (geometric standard deviations) dermal loadings (mg/cm^2) on the face, forearm, hands, lower legs, and feet for the combined sessions, as shown in Table 7-13, were 0.04 (2.9), 0.17 (3.1), 0.49 (8.2), 0.70 (3.6) and 21 (1.9), respectively.

The primary advantage of this study is that it provides adherence data specific to children and sediments which had previously been largely unavailable. Results will be useful to risk assessors considering exposure scenarios involving child activities at a coastal shoreline or tidal flat. The limited number of participants (9) and sampling during just one day and at one location, make extrapolation to other situations uncertain.

7.4.2 Relevant Adherence of Solids to Skin Studies

7.4.2.1 *Kissel et al., 1996b - Factors Affecting Soil Adherence to Skin in Hand-press Trials: Investigation of Soil Contact and Skin Coverage*

Kissel et al. (1996b) conducted soil adherence experiments using five soil types obtained locally in the Seattle, WA, area: sand, 2 types of loamy sand, sandy loam, and silt loam. All soils were analyzed by hydrometer (settling velocity) to determine composition. Clay content ranged from 0.5 to 7.0 percent. Organic carbon content, determined by combustion, ranged from 0.7 to 4.6 percent. Soils were dry-sieved to obtain particle size ranges of <150, 150-250, and >250 µm. For each soil type, the amount of soil adhering to an adult female hand, using both sieved and unsieved soils, was determined by measuring the soil sample weight before and after the hand was pressed into a pan containing the test soil. Loadings were estimated by dividing the recovered soil mass by total hand area, although loading occurred primarily on only one side of the hand. Results showed that generally, soil adherence to hands was directly correlated with moisture content, inversely correlated with particle size, and independent of clay content or organic carbon content. The advantage of this study is that it provides information on how soil type can affect adherence to the skin. However, the soil adherence data are for a single subject and the data are limited to five soil samples.

7.4.2.2 *Kissel et al., 1998 - Investigation of Dermal Contact with Soil in Controlled Trials*

Kissel et al. (1998) measured dermal exposure to soil from staged activities conducted in a greenhouse. A fluorescent marker was mixed in soil so that soil contact for a particular skin surface area could be identified. The subjects, which included a group of children, were video-imaged under a long-wave ultraviolet (UV) light before and after soil contact. In this manner, soil contact on hands, forearms, lower legs, and faces was assessed by presence of fluorescence. In addition to fluorometric data, gravimetric measurements for preactivity and postactivity were obtained from the different body parts examined.

The studied group of children played for 20 minutes in a soil bed of varying moisture content representing wet and dry soils. Three trials with children were conducted, each representing a different clothing/soil moisture scenario. For wet soils, both combinations of long sleeves and long pants, and short sleeves and short pants were tested. For dry soil, only short sleeves and short pants were worn during play. Clothing was laundered after each trial. The parameters describing each of these trials are summarized in Table 7-14. Before each trial, each child was washed in order to obtain a preactivity or background gravimetric measurement.

For wet soil, postactivity fluorescence results indicated that the hand had a much higher fractional coverage than other body surfaces (see Figure 7-1). No fluorescence was detected on the forearms or lower legs of children dressed in long sleeves and pants. As shown in Figure 7-2, postactivity gravimetric measurements showed higher soil loading on hands and much lower amounts on other body surfaces, as was observed with fluorescence data. According to Kissel et al. (1998), the relatively low loadings observed on non-hand body parts may be a result of a more limited area of contact for the body part rather than lower localized loadings. The highest soil loading observed was a geometric mean dermal loading of 0.7 mg/cm^2, found on the children's hands following play in wet soil. Mean loadings were lower on hands in the dry soil trial and on lower legs, forearms, and faces in both the wet and dry soil trials. Higher loadings were observed for all body surfaces with the higher moisture content soils.

This report is valuable in showing soil loadings from soils of different moisture content and providing evidence that dermal exposure to soil is not uniform for various body surfaces. This study also provides some evidence of the protective effect of clothing. Disadvantages of the study include the small number of study participants and a short activity duration.

7.5 REFERENCES FOR CHAPTER 7

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Table 7-6. Percentage of Total Body Surface Area by Body Part For Children
Males and Females Combined

Age (years)	N M:F	Percent of Total											
		Head		Trunk		Arms		Hands		Legs		Feet	
		Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max
< 1	2:0	18.2	18.2-18.3	35.7	34.8-36.6	13.7	12.4-15.1	5.3	5.2-5.4	20.6	18.2-22.9	6.5	6.5-6.6
1 < 2	1:1	16.5	16.5-16.5	35.5	34.5-36.6	13.0	12.8-13.1	5.7	5.6-5.8	23.1	22.1-24.0	6.3	5.8-6.7
2 < 3	1:0	14.2		38.5		11.8		5.3		23.2		7.1	
3 < 4	0:5	13.6	13.3-14.0	31.9	29.9-32.8	14.4	14.2-14.7	6.1	5.8-6.3	26.8	26.0-28.6	7.2	6.8-7.9
4 < 5	1:3	13.8	12.1-15.3	31.5	30.5-32.4	14.0	13.0-15.5	5.7	5.2-6.6	27.8	26.0-29.3	7.3	6.9-8.1
5 < 6													
6 < 7	1:0	13.1		35.1		13.1		4.7		27.1		6.9	
7 < 8													
8 < 9													
9 < 10	0:2	12.0	11.6-12.5	34.2	33.4-34.9	12.3	11.7-12.8	5.3	5.2-5.4	28.7	28.5-28.8	7.6	7.4-7.8
10 < 11													
11 < 12													
12 < 13	1:0	8.7		34.7		13.7		5.4		30.5		7.0	
13 <14	1:0	10.0		32.7		12.1		5.1		32.0		8.0	
14 < 15													
15 < 16													
16 < 17	1:0	8.0		32.7		13.1		5.7		33.6		6.9	
17 < 18	1:0	7.6		31.7		17.5		5.1		30.8		7.3	

N = Number of subjects, (M:F = males:females).
Min. = Minimum percent.
Max. = Maximum percent.

Source: U.S. EPA, 1985.

Table 7-7. Mean and Percentile Skin Surface Area (m^2) Derived from U.S. EPA Analysis of NHANES 1999-2006
Males and Females Combined

Age Group	N	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
Birth to <1 month	154	0.29	0.24	0.25	0.26	0.27	0.29	0.31	0.31	0.33	0.34
1 to <3 months	281	0.33	0.27	0.29	0.29	0.31	0.33	0.35	0.37	0.37	0.38
3 to <6 months	488	0.38	0.33	0.34	0.35	0.36	0.38	0.40	0.42	0.43	0.44
6 to <12 months	923	0.45	0.38	0.39	0.40	0.42	0.45	0.48	0.49	0.50	0.51
1 to <2 years	1159	0.53	0.45	0.46	0.47	0.49	0.53	0.56	0.58	0.59	0.61
2 to <3 years	1122	0.61	0.52	0.54	0.55	0.57	0.61	0.64	0.67	0.68	0.70
3 to <6 years	2303	0.76	0.61	0.64	0.66	0.68	0.74	0.81	0.85	0.89	0.95
6 to <11 years	3590	1.08	0.81	0.85	0.88	0.93	1.05	1.21	1.31	1.36	1.48
11 to <16 years	5294	1.59	1.19	1.25	1.31	1.4	1.57	1.75	1.86	1.94	2.06
16 to <21 years	4843	1.84	1.47	1.53	1.58	1.65	1.80	1.99	2.10	2.21	2.33

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999-2006 data.

Table 7-8. Mean and Percentile Skin Surface Area (m^2) Derived from U.S. EPA Analysis of NHANES 1999-2006
Males

Age Group	N	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
Birth to <1 month	85	0.29	0.24	0.25	0.26	0.27	0.29	0.31	0.33	0.34	0.36
1 to <3 months	151	0.33	0.28	0.29	0.30	0.31	0.34	0.36	0.37	0.37	0.38
3 to <6 months	255	0.39	0.34	0.35	0.36	0.37	0.39	0.41	0.42	0.43	0.44
6 to <12 months	471	0.45	0.39	0.41	0.42	0.43	0.46	0.48	0.49	0.50	0.51
1 to <2 years	620	0.53	0.46	0.47	0.48	0.50	0.53	0.57	0.58	0.59	0.62
2 to <3 years	548	0.62	0.54	0.56	0.56	0.58	0.62	0.65	0.67	0.68	0.70
3 to <6 years	1150	0.76	0.61	0.64	0.66	0.69	0.75	0.82	0.86	0.89	0.95
6 to <11 years	1794	1.09	0.82	0.86	0.89	0.94	1.06	1.21	1.29	1.34	1.46
11 to <16 years	2593	1.61	1.17	1.23	1.28	1.39	1.60	1.79	1.90	1.99	2.12
16 to <21 years	2457	1.94	1.61	1.66	1.7	1.76	1.91	2.08	2.22	2.30	2.42

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999-2006 data.

Table 7-9. Mean and Percentile Skin Surface Area (m^2) Derived from U.S. EPA Analysis of NHANES 1999-2006 Females

Age Group	N	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
Birth to <1 month	69	0.28	0.24	0.25	0.26	0.27	0.28	0.30	0.30	0.31	0.33
1 to <3 months	130	0.32	0.27	0.28	0.29	0.30	0.31	0.35	0.36	0.37	0.37
3 to <6 months	233	0.38	0.32	0.33	0.34	0.35	0.38	0.40	0.40	0.41	0.43
6 to <12 months	452	0.44	0.38	0.39	0.40	0.41	0.44	0.47	0.48	0.49	0.51
1 to <2 years	539	0.52	0.44	0.46	0.47	0.48	0.52	0.56	0.57	0.58	0.59
2 to <3 years	574	0.60	0.51	0.53	0.54	0.56	0.59	0.63	0.66	0.67	0.70
3 to <6 years	1153	0.75	0.61	0.64	0.66	0.68	0.74	0.80	0.84	0.88	0.94
6 to <11 years	1796	1.08	0.80	0.85	0.87	0.92	1.04	1.21	1.33	1.39	1.51
11 to <16 years	2701	1.57	1.20	1.28	1.34	1.42	1.55	1.69	1.8	1.88	2.00
16 to <21 years	2386	1.73	1.42	1.47	1.51	1.57	1.69	1.85	1.98	2.06	2.17

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999-2006 data.

Table 7-10. Descriptive Statistics For Surface Area/Body Weight (SA/BW) Ratios (m^2/kg)											
Age (years)	Mean	Range Min-Max	SD	SE	Percentiles						
					5th	10th	25th	50th	75th	90th	95th
0 to 2	0.064	0.042-0.114	0.011	0.001	0.047	0.051	0.056	0.062	0.072	0.0784	0.0846
2.1 to 17.9	0.042	0.027-0.067	0.008	0.001	0.029	0.033	0.038	0.042	0.045	0.0501	0.0594

SD = Standard deviation.
SE = Standard error of the mean.

Source: Phillips et al., 1993.

Table 7-11. Estimated Skin Surface Exposed During Warm Weather Outdoor Activities

	Skin Area Exposed (% of total body surface area)		
	Play	Gardening/yardwork	Organized Team Sport
Age (years)	<5	5-17	5-17
N	41	437	65
Mean	38.0	33.8	29.0
Median	36.5	33.0	30.0
SD	6.0	8.3	10.5

N = Number of observations.
SD = Standard deviation.

Source: Wong et al., 2000.

Table 7-12. Summary of Field Studies

Activity	Month	Event[a] (hrs)	N	M	F	Age (years)	Conditions	Clothing	Study
Indoor									
Tae Kwon Do	Feb.	1.5	7	6	1	8-42	Carpeted floor	All in long sleeve-long pants martial arts uniform, sleeves rolled back, barefoot	Kissel et al., 1996a
Indoor Kids No. 1	Jan.	2	4	3	1	6-13	Playing on carpeted floor	3 of 4 short pants, 2 of 4 short sleeves, socks, no shoes	Holmes et al., 1999
Indoor Kids No. 2	Feb.	2	6	4	2	3-13	Playing on carpeted floor	5 of 6 long pants, 5 of 6 long sleeves, socks, no shoes	
Daycare Kids No. 1a	Aug.	3.5	6	5	1	1-6.5	Indoors: linoleum surface; Outdoors: grass, bare earth, barked area	4 of 6 in long pants, 5 of 6 short sleeves, socks, shoes	
Daycare Kids No. 1b	Aug.	4	6	5	1	1-6.5	Indoors: linoleum surface; Outdoors: grass, bare earth, barked area	4 of 6 long pants, 5 of 6 short sleeves, 3 of 6 barefoot all afternoon, others barefoot half the afternoon	
Daycare Kids No. 2[b]	Sept.	8	5	4	1	1-4	Indoors: low napped carpeting, linoleum surfaces	4 of 5 long pants, 3 of 5 long sleeves, all barefoot for part of the day	
Daycare Kids No. 3	Nov.	8	4	3	1	1-4.5	Indoors: linoleum surface, Outside: grass, bare earth, barked area	All long pants, 3 of 4 long sleeves, socks and shoes	
Outdoor									
Soccer	Nov.	0.67	8	8	0	13-15	Half grass-half bare earth	6 of 8 long sleeves, 4 of 8 long pants, 3 of 4 short pants and shin guards	Kissel et al., 1996a
Kids-in-mud No. 1	Sept.	0.17	6	5	1	9-14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot	
Kids-in-mud No. 2	Sept.	0.33	6	5	1	9-14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot	
Gardeners	Aug.	4	8	1	7	16-35	Weeding, pruning, digging a trench	6 of 8 long pants, 7 of 8 short sleeves, 1 sleeveless, socks, shoes, intermittent use of gloves	Holmes et al., 1999
Archeologists	July	11.5	7	3	4	16-35	Digging with trowel, screening dirt, sorting	6 of 7 short pants, all short sleeves, 3 no shoes or socks, 2 sandals	
Shoreline Play	Sept.	0.33-1.0	9	6	3	7-12	Tidal flat	No shirt or short sleeve T-shirts, shorts, barefoot	Shoaf et al., 2005

a Event duration.
b Activities were confined to the house.
N = Number of subjects.
M = Male.
F = Female.

Table 7-13. Geometric Mean and Geometric Standard Deviations of Solids Adherence by Activity and Body Region[a]

Activity	N	Post-activity Dermal Solids Loadings (mg/cm²)				
		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	8	0.11 1.8	0.011 2.0	0.031 3.8	0.012 1.5	
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
Gardeners	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
Shoreline Play	9	0.49 8.2	0.17 3.1	0.70 3.6	0.04 2.9	21 1.9

[a] Means are presented above the standard deviations. The standard deviations generally exceed the means by large amounts indicating high variability in the data.

N = Number of subjects.

Sources: Kissel et al., 1996a; Holmes et al., 1999; Shoaf et al., 2005.

Table 7-14. Summary of Controlled Greenhouse Trials - Children Playing

Activity	Ages (years)	Duration (min)	Soil Moisture (%)	Clothing[a]	N	Male	Female
Playing	8 to 12	20	17-18	L	4	3	1
			16-18	S	9	5	4
			3-4	S	5	3	2

[a] L, long sleeves and long pants; S, short sleeves and short pants.
N = Number of subjects.

Source: Kissel et al., 1998.

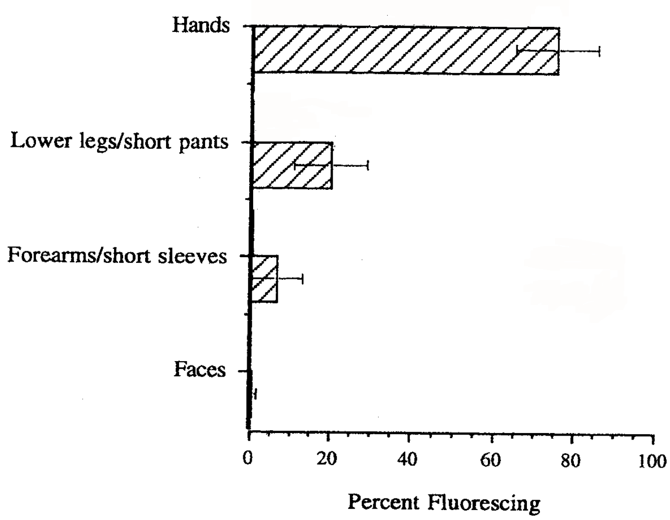

Figure 7-1. Skin Coverage as Determined by Fluorescence vs. Body Part for Children Playing in Wet Soils (bars are arithmetic means and corresponding 95% confidence intervals)

Source: Kissel et al., 1998.

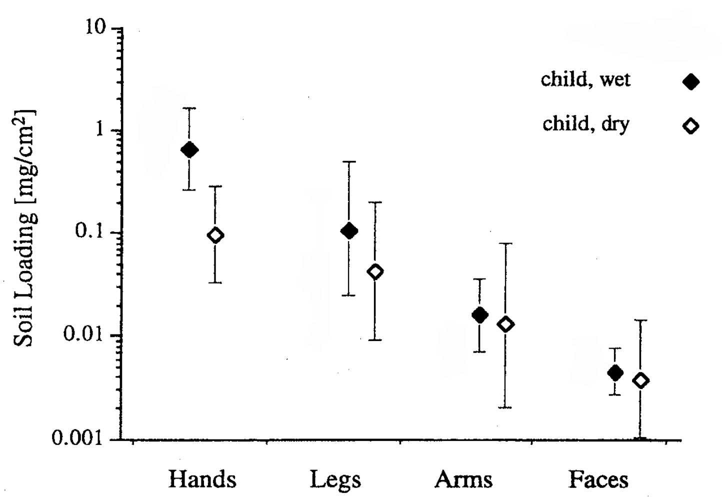

Figure 7-2. Gravimetric Loading vs. Body Part for Children Playing in Wet and Dry Soils (symbols are geomettric means and 95% confidence intervals)

Source: Kissel et al., 1998.

APPENDIX 7A

FORMULAS FOR TOTAL BODY SURFACE AREA

APPENDIX 7A - FORMULAS FOR TOTAL BODY SURFACE AREA

Most formulas for estimating surface area (SA) relate height to weight to surface area. The following formula was proposed by Gehan and George (1970):

$$SA = KW^{2/3} \qquad \text{(Eqn. 7A-1)}$$

where:

SA = surface area in square meters;
W = weight in kg; and
K = constant.

While the above equation has been criticized because human bodies have different specific gravities and because the surface area per unit volume differs for individuals with different body builds, it gives a reasonably good estimate of surface area.

A formula published in 1916 that still finds wide acceptance and use is that of DuBois and DuBois (1916). Their model can be written:

$$SA = a_0 H^{a_1} W^{a_2} \qquad \text{(Eqn. 7A-2)}$$

where:

SA = surface area in square meters;
H = height in centimeters; and
W = weight in kg.

The values of a_0 (0.007182), a_1 (0.725), and a_2 (0.425) were estimated from a sample of only nine individuals for whom surface area was directly measured. Boyd (1935) stated that the Dubois formula was considered a reasonably adequate substitute for measuring surface area. Nomograms for determining surface area from height and mass presented in Volume I of the Geigy Scientific Tables (1981) are based on the DuBois and DuBois formula. In addition, a computerized literature search conducted for this report identified several articles written in the last 10 years in which the DuBois and DuBois formula was used to estimate body surface area.

Boyd (1935) developed new constants for the DuBois and DuBois model based on 231 direct measurements of body surface area found in the literature. These data were limited to measurements of surface area by coating methods (122 cases), surface integration (93 cases), and triangulation (16 cases). The subjects were Caucasians of normal body build for whom data on weight, height, and age (except for exact age of adults) were complete. Resulting values for the constants in the DuBois and DuBois model were a_0 = 0.01787, a_1 = 0.500, and a_2 = 0.4838. Boyd also developed a formula based exclusively on weight, which was inferior to the DuBois and DuBois formula based on height and weight.

Gehan and George (1970) proposed another set of constants for the DuBois and DuBois model. The constants were based on a total of 401 direct measurements of surface area, height, and weight of all postnatal subjects listed in Boyd (1935). The methods used to measure these subjects were coating (163 cases), surface integration (222 cases), and triangulation (16 cases).

Gehan and George (1970) used a least-squares method to identify the values of the constants. The values of the constants chosen are those that minimize the sum of the squared percentage errors of the predicted values of surface area. This approach was used because the importance of an error of 0.1 square meter depends on the surface area of the individual. Gehan and George (1970) used the 401 observations summarized in Boyd (1935) in the least-squares method. The following estimates of the constants were obtained: a_0 = 0.02350, a_1 = 0.42246, and a_2 = 0.51456. Hence, their equation for predicting SA is:

$$SA = 0.02350\ H^{0.42246} W^{0.51456} \qquad \text{(Eqn. 7A-3)}$$

or in logarithmic form:

$$\ln SA = -3.75080 + 0.42246 \ln H + 0.51456 \ln W \qquad \text{(Eqn. 7A-4)}$$

where:

SA = surface area in square meters;
H = height in centimeters; and
W = weight in kg.

This prediction explains more than 99 percent of the variations in surface area among the 401 individuals measured (Gehan and George, 1970).

The equation proposed by Gehan and George (1970) was determined by the U.S. EPA (1985) as the best choice for estimating total body surface area. However, the paper by Gehan and George gave insufficient information to estimate the standard error about the regression. Therefore, the 401 direct measurements of children and adults (i.e., Boyd, 1935) were reanalyzed in U.S. EPA (1985) using the formula of Dubois and Dubois (1916) and the Statistical Processing System (SPS) software package to obtain the standard error.

The Dubois and Dubois (1916) formula uses weight and height as independent variables to predict total body surface area (SA), and can be written as:

$$SA_i = a_0 H_i^{a_1} W_i^{a_2} e_i \qquad \text{(Eqn. 7A-5)}$$

or in logarithmic form:

$$\ln(SA)_i = \ln a_0 + a_1 \ln H_i + a_2 \ln W_i + \ln e_i \qquad \text{(Eqn. 7A-6)}$$

where:

SA_i	=	surface area of the i-th individual (m^2);
H_i	=	height of the i-th individual (cm);
W_i	=	weight of the i-th individual (kg);
a_0, a_1, and a_2 and	=	parameters to be estimated;
e_i	=	a random error term with mean zero and constant variance.

Using the least squares procedure for the 401 observations, the following parameter estimates and their standard errors were obtained:

a_0 = -3.73 (0.18), a_1 = 0.417 (0.054), a_2 = 0.517 (0.022)

The model is then:

$$SA = 0.0239\ H^{0.417} W^{0.517} \qquad \text{(Eqn. 7A-7)}$$

or in logarithmic form:

$$\ln SA = 3.73 + 0.417 \ln H + 0.517 \ln W \qquad \text{(Eqn. 7A-8)}$$

with a standard error about the regression of 0.00374. This model explains more than 99 percent of the total variation in surface area among the observations, and is identical to two significant figures with the model developed by Gehan and George (1970).

When natural logarithms of the measured surface areas are plotted against natural logarithms of the surface predicted by the equation, the observed surface areas are symmetrically distributed around a line of perfect fit, with only a few large percentage deviations. Only five subjects differed from the measured value by 25 percent or more. Because each of the five subjects weighed less than 13 pounds, the amount of difference was small. Eighteen estimates differed from measurements by 15 to 24 percent. Of these, 12 weighed less than 15 pounds each, 1 was overweight (5 feet 7 inches, 172 pounds), 1 was very thin (4 feet 11 inches, 78 pounds), and 4 were of average build. Since the same observer measured surface area for these 4 subjects, the possibility of some bias in measured values cannot be discounted (Gehan and George 1970).

Gehan and George (1970) also considered separate constants for different age groups: less than 5 years old, 5 years old to less than 20 years old, and greater than 20 years old. The different values for the constants are presented in Table 7A-1.

The surface areas estimated using the parameter values for all ages were compared to surface areas estimated by the values for each age group for subjects at the 3rd, 50th, and 97th percentiles of weight and height. Nearly all differences in surface area estimates were less than 0.01 square meter, and the largest difference was 0.03 m^2 for an 18-year-old at the 97th percentile. The authors concluded that there is no advantage in using separate values of a_0, a_1, and a_2 by age interval.

Haycock et al. (1978) without knowledge of the work by Gehan and George (1970), developed values for the parameters a_0, a_1, and a_2 for the DuBois and DuBois model. Their interest in making the DuBois and DuBois model more accurate resulted from their work in pediatrics and the fact that DuBois and DuBois (1916) included only one child in their study group, a severely undernourished girl who weighed only 13.8 pounds at age 21 months. Haycock et al. (1978) used their own geometric method for estimating surface area from 34 body measurements for 81 subjects. Their study included newborn infants (10 cases), infants (12 cases), children (40 cases), and adult members of the medical and secretarial staffs of 2 hospitals (19 cases). The subjects all had grossly normal body structure, but the sample included subjects of widely varying physique ranging from thin to obese. Black, Hispanic, and white children were included in their sample. The values of the model parameters were solved for the relationship between surface area and height and weight by multiple regression analysis. The least squares best fit for this equation yielded the following values for the three coefficients: a_0 = 0.024265, a_1 = 0.3964, and a_2 = 0.5378. The result was the following equation for estimating surface area:

$$SA = 0.024265 H^{0.3964} W^{0.5378} \qquad \text{(Eqn. 7A-9)}$$

expressed logarithmically as:

$$\ln SA = \ln 0.024265 + 0.3964 \ln H + 0.5378 \ln W \qquad \text{(Eqn. 7A-10)}$$

The coefficients for this equation agree remarkably with those obtained by Gehan and George (1970) for 401 measurements.

George et al. (1979) agree that a model more complex than the model of DuBois and DuBois for estimating surface area is unnecessary. Based on samples of direct measurements by Boyd (1935) and Gehan and George (1970), and samples of geometric estimates by Haycock et al. (1978), these authors have obtained parameters for the DuBois and DuBois model that are different than those originally postulated in 1916. The DuBois and DuBois model can be written logarithmically as:

$$\ln SA = \ln a_0 + a_1 \ln H + a_2 \ln W \qquad \text{(Eqn. 7A-11)}$$

The values for a_0, a_1, and a_2 obtained by the various authors discussed in this section are presented in Table 7A-2.

The agreement between the model parameters estimated by Gehan and George (1970) and Haycock et al. (1978) is remarkable in view of the fact that Haycock et al. (1978) were unaware of the previous work. Haycock et al. (1978) used an entirely different set of subjects, and used geometric estimates of surface area rather than direct measurements. It has been determined that the Gehan and George model is the formula of choice for estimating total surface area of the body since it is based on the largest number of direct measurements.

Sendroy and Cecchini (1954) proposed a method of creating a *nomogram*, a diagram relating height and weight to surface area. However, they do not give an explicit model for calculating surface area. The nomogram was developed empirically based on 252 cases, 127 of which were from the 401 direct measurements reported by Boyd (1935). In the other 125 cases the surface area was estimated using the linear method of DuBois and DuBois (1916). Because the Sendroy and Cecchini method is graphical, it is inherently less precise and less accurate than the formulas of other authors discussed above.

REFERENCES FOR APPENDIX 7A

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Table 7A-1. Estimated Parameter Values for Different Age Intervals

Age Group	Number of persons	a_0	a_1	a_2
All ages	401	0.02350	0.42246	0.51456
<5 years old	229	0.02667	0.38217	0.53937
≥5 to <20 years old	42	0.03050	0.35129	0.54375
≥20 years old	30	0.01545	0.54468	0.46336

Table 7A-2. Summary of Surface Area Parameter Values for the Dubois and Dubois Model

Author (year)	Number of persons	a_0	a_1	a_2
DuBois and DuBois (1916)	9	0.007184	0.725	0.425
Boyd (1935)	231	0.01787	0.500	0.4838
Gehan and George (1970)	401	0.02350	0.42246	0.51456
Haycock et al. (1978)	81	0.024265	0.3964	0.5378