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8. DERMAL ROUTE

8.1 INTRODUCTION

Children may be more highly exposed to environmental toxicants through dermal routes than adults. For instance, children often play and crawl on contaminated surfaces and are more likely to wear less clothing than adults. These factors result in higher dermal contact with contaminated media. In addition, children have a higher surface area relative to body weight. In fact, 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).

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
- Indoors (e.g., carpets, floors, counter tops).

The major factors that must be considered when estimating dermal exposure are the chemical concentration in contact with the skin, the extent of skin surface area exposed, the duration of exposure, the absorption of the chemical through the skin, the internal dose, and the amount of chemical that can be delivered to a target organ (i.e., biologically effective dose) (see Figure 8-1). This chapter focuses on measurements of body surface areas and dermal adherence of solids to the skin. For guidance on how to use these factors to assess dermal exposure, readers are referred to *Dermal Exposure Assessment: Principles and Applications* (U.S. EPA, 1992b) and *Risk Assessment Guidelines (RAGs) Part E* (U.S. EPA, 2004).

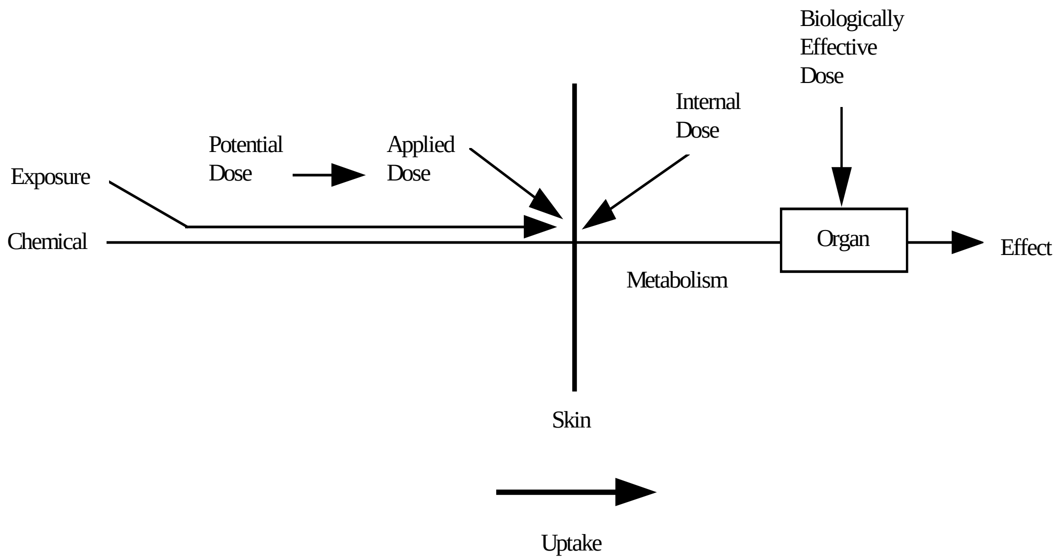

Figure 8-1. Schematic of Dose and Exposure: Dermal Route

Source: U.S. Environmental Protection Agency (1992a).

8.2 SURFACE AREA

8.2.1. Background

The total surface area of skin exposed to a contaminant should be determined using measurement or estimation techniques before conducting a dermal exposure assessment. This section presents estimates of skin surface area for the whole body and individual body parts. Additionally information is presented on the application of skin surface area data to specific exposure scenarios.

8.2.2. Measurement 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. Consideration has been given for differences due to age, gender, and race. The results of the various techniques have been summarized in *Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments* (U.S. EPA, 1985).

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 triangulation measurement technique developed by Boyd (1935) has been found to be highly reliable. It estimates the surface area of the body using geometric approximations that assume that parts of the body resemble geometric solids. More recently, Popendorf and Leffingwell (1976), and Haycock et al. (1978) have developed similar geometric methods that assume body parts correspond to geometric solids, such as the sphere and cylinder. A linear method proposed by DuBois and DuBois (1916) is based on the principle that the surface areas of the parts of the body are proportional, rather than equal to the surface area of the solids they resemble.

In addition to direct measurement techniques, several formulas have been proposed to estimate body surface area from measurements of other major body dimensions (i.e., height and weight) (U.S. EPA, 1985). Generally, the formulas are based on the observation that body weight and height are correlated with surface area and are derived using multiple regression techniques. A discussion and comparison of formulas to determine total body surface area are presented in Appendix 8A.

8.2.3. Body Surface Area Studies

8.2.3.1. Costeff, 1966

Costeff (1966) developed an empirical formula for calculating the surface area of children based on weight only:

$$SA = \frac{4W + 7}{W + 90} \qquad (1)$$

where:

SA	=	surface area (m^2);
Constants	=	4, 7, and 90; and
W	=	weight (kg).

This simple formula applies to the weight range between 1.5 and 100 kg.

8.2.3.2. U.S. EPA, 1985

U.S. EPA (1985) analyzed the direct surface area measurement data of Gehan and George (1970) using the Statistical Processing System (SPS) software package of Buhyoff et al. (1982). For their analysis, Gehan and George (1970) selected 401 measurements made by Boyd (1935) that were complete for surface area, height, weight, and age. Boyd (1935) had reported surface area estimates for 1,114 individuals using coating, triangulation, or surface integration methods (U.S. EPA, 1985).

U.S. EPA (1985) used SPS to generate equations to calculate surface area as a function of height and weight. These equations were then used to calculate body surface area distributions of the U.S. population using the height and weight data obtained from the National Health and Nutrition Examination Survey (NHANES) II and the computer program QNTLS of Rochon and Kalsbeek (1983).

The equation proposed by Gehan and George (1970) was determined by U.S. EPA (1985) to be the best choice for estimating total body surface area. However, the paper by Gehan and George (1970) gave insufficient information to estimate the standard error about the regression. Therefore, U.S. EPA (1985) used the direct measurements of 401 individuals and re-analyzed the data using the formula of Dubois and Dubois (1916) and SPS to obtain the standard error.

Regression equations were developed for specific body parts using the Dubois and Dubois (1916) formula and using the surface area of various body parts provided by Boyd (1935) and Van Graan (1969) in conjunction with SPS. Equations to estimate the body part surface area of children were not developed because of insufficient data.

The percentile estimates for total surface area of male and female children presented in Tables 8-1 and 8-2 were calculated using the total surface area regression equation and NHANES II height and weight data, and using QNTLS. Estimates were not included for children younger than 2 years old because NHANES height data were not available for this age group. For children, the error associated with height and weight cannot be assumed to be zero because of their relatively small sample sizes. Therefore, the standard errors of the percentile estimates could not be estimated. This is because it cannot be assumed that the errors associated with the exogenous variables (height and weight) are independent of those associated with the model, i.e. there are insufficient data to determine the relationship between these errors.

Measurements of the surface area of children's body parts are summarized as a percentage of total surface area in Table 8-3. 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.

8.2.3.3. Phillips et al., 1993

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. The authors concluded 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 is more appropriate than treating these factors as independent variables. Direct measurement (coating, triangulation, and surface integration) 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 8-4. The shapes of these SA/BW distributions were determined using D'Agostino's test. 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 should 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.

8.2.3.4. Wong et al. (2000)

Wong et al. (2000) reports on surveys that gathered information on activity patterns related to dermal contact with soil. Two random dialing national phone surveys were conducted. The initial Soil Contact Survey (SCS-I) was conducted in 1996 (also reported on by Garlock et al., 1999) and the second Soil Contact Survey (SCS-II) was conducted in 1999. Information about children were gathered from adults over the age of 18. SCS-I had 450 participants with complete responses and SCS-II had 483 participants with complete responses.

SCS-I gathered 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. An effort was also made to determine the clothing worn while participating in these play activities during warm weather months (April though October). For both groups of children, information was gathered concerning frequency of hand washing and bathing,

Results of SCS-I 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 (Table 8-5).

8.2.3.5. U.S. EPA Analysis of NHANES III Data

The *Third National Health and Nutrition Examination Survey* (NHANES III), 1988-94 was conducted on a nationwide probability sample of approximately 33,994 persons aged 2 months and older. The survey was 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. Unit nonresponse to the household interview was 14 percent, and an additional 8 percent did not participate in the physical examinations (including body weight measurements).

Certain subpopulations were over sampled to ensure a prespecified minimum sample size for each analytic domain. These over sampled subpopulations include children, older persons, Mexican-Americans, African-Americans, and people living in certain geographic areas. 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. The weight for each participant was calculated as the reciprocal of the participant's probability of selection, with adjustments for other variabilities in sampling rates such as changes made to the sampling rates at the time of data collection.

Body weight data from NHANES III study were used to calculate estimated body surface areas for children in the standard age categories using the empirical relationship found in Appendix 8A. The methodology was similar to that used in U.S. EPA (1985), as described in Section 8.2.3.2, but more recent NHANES data were used. The resulting skin surface areas are presented in Tables 8-6 (all children), 8-7 (male children), and 8-8 (female children).

8.2.4. Application of Body Surface Area Data

The skin area studies summarized above address total skin surface area. Application of these data to many exposure scenarios involve some reduction in exposed skin area. This section discusses how this issue has been addressed in EPA guidance.

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% exposure for these scenarios with a central default recommendation of 6,600 cm^2 for children aged 0-6 years in residential settings (U.S. EPA, 2004).

It is generally assumed that adherence of solids to skin occurs only on the areas of the body not covered by clothing. Past guidance has presented clothing scenarios that suggest that roughly 10 to 25 percent of the skin area is uncovered (U.S. EPA, 1992b). Since some studies have suggested that exposure can occur under clothing, the upper end of this range was selected in *Dermal Exposure Assessment: Principles and Applications* (U.S. EPA, 1992b) for deriving defaults. More recent guidance suggests a central default value of 2,800 cm^2 exposed skin area for children aged 0-6 in residential settings (US EPA, 2004). This was derived assuming a clothing scenario that limited exposure to head, hands, forearms, lower legs and feet.

8.3 ADHERENCE OF SOLIDS TO SKIN

8.3.1. Background

A variety of solid residues can accumulate on skin including soil, household dust, sediments and commercial powders. The amount of material adhering to the surface of the skin is a required parameter for calculating dermal dose when the exposure scenario involves dermal contact with a chemical in a solid matrix. A number of studies have measured this factor and they have been used to support EPA guidelines (U.S. EPA 1992b and 2004). This section summarizes the studies that estimate the adherence of solids to skin for use as exposure factors.

8.3.2. Adherence of Solids to Skin Studies

8.3.2.1. Kissel et al., 1996a

Kissel et al. (1996a) conducted soil adherence experiments using five soil types obtained locally in the Seattle, WA, area: sand, loamy sand, 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%. Organic carbon content, determined by combustion, ranged from 0.7 to 4.6%. 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.

8.3.2.2. Kissel et al., 1996b

Further experiments were conducted by Kissel et al. to estimate soil adherence associated with various indoor and outdoor activities: greenhouse gardening, tae kwon do karate, soccer, rugby, reed gathering, irrigation installation, truck farming, and playing in mud (Kissel et al., 1996b). Several of the activities studied involved children, as shown in Table 8-9

A summary of field studies by activity, gender, age, field conditions, and clothing worn is presented in Table 8-9. 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. Mass recovered was converted to loading using allometric models of surface area. Geometric means for soil adherence by activity and body region are presented in Table 8-10. The results presented are based on direct measurement of soil loading on the surfaces of skin before and after activities that may be expected to have soil contact (Kissel et al., 1996b). The results indicate that the amount of soil adherence to the hands is higher than for other parts of the body.

8.3.2.3. Holmes et al., 1999

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) and playing indoors in a residential setting (Indoor kids). This study was conducted as a follow up to previous field sampling of soil adherence on individuals participating in various activities (Kissel et al., 1996b). For this round of sampling, soil loading data were collected utilizing the same methods used and described in Kissel et al. (1996b). Information regarding the groups of children studied and their observed activities is presented in Table 8-11.

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 8-12.

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 8-12.

The geometric means and standard deviations of the postactivity soil adherence for each group of children and for each body part are summarized in Table 8-13. 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., 1996b). 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 for 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.

8.3.2.4. Kissel et al., 1998

In this study, 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. For wet soils, both combinations of long sleeves and long pants and short sleeves and short pants were tested. Children only wore short sleeves and short pants during play in the dry soil. Clothing was laundered after each trial. Thus, a total of three trials with children were conducted. The parameters describing each of these trials are summarized in Table 8-14.

Before each trial, each child was washed in order to obtain a preactivity or background gravimetric measurement. Preactivity data are shown in Table 8-15. Body part surface areas were calculated using U.S. EPA (1985) for the range of heights and weights of the study participants.

For wet soil, postactivity fluorescence results indicated that the hand had a much higher fractional coverage than other body surfaces (see Figure 8-2). No fluorescence was detected on the forearms or lower legs of children dressed in long sleeves and pants.

As shown in Figure 8-3, 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 the limited area of contact rather than lower localized loadings. A geometric mean dermal loading of 0.7 mg/cm^2 was 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 for showing soil loadings from soils of different moisture content and providing evidence that dermal exposure to soil is not uniform for various body surfaces. There is also some evidence from this study demonstrating the protective effect of clothing. Disadvantages of the study include a small number of study participants and a short activity duration. Also, no information is provided on the ages of the children involved in the study.

8.3.2.5. Shoaf et al., 2005

The purpose of this study was to obtain sediment adherence data for children playing in a tide flat. The study was conducted on one day in late September 2003 at a tide flat in Jamestown, Rhode Island. Nine subjects (three females and six males) ages 7 to 12 years old participated in the study. This study reports 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 were 0.04 (2.9), 0.17 (3.1), 0.49 (8.2), 0.70 (3.6) and 21 (1.9), respectively. Participants' parents completed questionnaires regarding their child's typical activity patterns during tide flat play, exposure frequency and duration, clothing choices, bathing practices and clothes laundering.

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 tide flat. The limited number of participants (9) and sampling over just one day and one location, make extrapolation to other situations uncertain.

8.4 RECOMMENDATIONS

8.4.1. Body Surface Area

Body surface area estimates have been derived from direct measurements and from correlations with height and weight. Re-analysis of data collected by Boyd (1935) by several investigators (Gehan and George, 1970; U.S. EPA, 1985; ; Phillips et al., 1993) constitutes much of this literature. The U.S. EPA (1985) study summarizes and compares previous reports in the literature, provides statistical distributions for adults, and provides data for total body surface area and body parts by gender for children. The results are based on selected measurements from the original data collected by Boyd (1935). The EPA analysis of NHANES III data uses correlations with body weight and height for deriving skin surface area (see Section 8.2.3.5 and Appendix 8A). NHANES III used a statistically based survey design which should ensure reasonable representativeness of the general population.

The recommendations for body surface area for children are summarized in Table 8-17. The recommendations for total body surface area are based on the EPA analysis of NHANES III data and are presented for the standard age groupings in Tables 8-6 to 8-8. The recommendations in Table 8-17 refer to Table 8-3 for body part percentages which were based on U.S. EPA (1985). Age specific body part areas can be obtained by applying these percentages to the total body part areas in Tables 8-6 to 8-8. Table 8-18 presents the confidence ratings for various aspects of the recommendations for body surface area and indicates an overall confidence rating of medium.

For bathing and swimming exposure scenarios, an assumption of 100% skin area exposure is recommended. For exposure scenarios involving contact with solids, it is reasonable to assume that clothing reduces the contact area. RAGS Part E (US EPA, 2004) presents default assumptions for exposed skin areas of children in a residential setting. The child resident was assumed to wear a short-sleeved shirt and shorts (no shoes). Therefore, the exposed skin was limited to face, hands, forearms (45% of total arms), lower legs (40% of total legs), and feet. The percentages of total skin area for these body parts can be obtained from Table 8-3 and applied to the total skin area in Tables 8-6 to 8-8, to derive age specific exposure areas. This clothing scenario is characteristic of warm weather situations and should be adjusted based on judgement to represent other climatic conditions. Although, 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. Assessors should consider this possibility for the scenario of concern and use larger skin areas if judged appropriate.

8.4.2. 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). Ideally exposure assessors should 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. It is recommended that assessors use Tables 8-9 and 8-10 for this purpose. These tables provide body-part specific adherence values for a variety of solids (garden soils, indoor dust, sediment, etc.) and activities. Table 8-9 lists the age range covered by each study. This should be used as a general guide to the ages covered by these data. The small number of subjects in these studies prevents the development of recommendations for narrower age groups.

EPA guidance under RAGS Part E (US EPA, 2004) provides body part area-weighted adherence factors that can facilitate dermal exposure calculations. These values were derived by adding the mass of solid adhering to various body parts and dividing by the total exposed skin area. These values as summarized in Table 8-16 can be directly applied to the total exposed skin surface area.

The solids adherence recommendations are summarized in Table 8-17. The overall confidence rating for the adherence recommendations is medium as shown in Table 8-19. Insufficient data are available to develop distributions or probability functions. Note also that the skin adherence studies have not considered the influence of skin moisture on adherence. Skin moisture varies for an individual depending on factors such as activity and ambient temperature/humidity. It also varies across individuals. It is uncertain how well this variability has been captured in the adherence studies.

The dermal adherence value represents the amount of material on the skin at the time of measurement. EPA, 1992b recommends interpreting adherence values as representative of contact events. Assuming that the amount measured on the skin represents its 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.

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Table 8-1. Total Body Surface Area of Male Children in Square Meters[a]

Age (yr)[b]	Percentile								
	5	10	15	25	50	75	85	90	95
2 < 3	0.527	0.544	0.552	0.569	0.603	0.629	0.643	0.661	0.682
3 < 4	0.585	0.606	0.620	0.636	0.664	0.700	0.719	0.729	0.764
4 < 5	0.633	0.658	0.673	0.689	0.731	0.771	0,796	0.809	0.845
5 < 6	0.692	0.721	0.732	0.746	0.793	0.840	0.864	0.895	0.918
6 < 7	0.757	0.788	0.809	0.821	0.866	0.915	0.957	1.01	1.06
7 < 8	0.794	0.832	0.848	0.877	0.936	0.993	1.01	1.06	1.11
8 < 9	0.836	0.897	0.914	0.932	1.00	1.06	1.12	1.17	1.24
9 < 10	0.932	0.966	0.988	1.00	1.07	1.13	1.16	1.25	1.29
10 < 11	1.01	1.04	1.06	1.10	1.18	1.28	1.35	1.40	1.48
11 < 12	1.00	1.06	1.12	1.16	1.23	1.40	1.47	1.53	1.60
12 < 13	1.11	1.13	1.20	1.25	1.34	1.47	1.52	1.62	1.76
13 < 14	1.20	1.24	1.27	1.30	1.47	1.62	1.67	1.75	1.81
14 < 15	1.33	1.39	1.45	1.51	1.61	1.73	1.78	1.84	1.91
15 < 16	1.45	1.49	1.52	1.60	1.70	1.79	1.84	1.90	2.02
16 < 17	1.55	1.59	1.61	1.66	1.76	1.87	1.98	2.03	2.16
17 < 18	1.54	1.56	1.62	1.69	1.80	1.91	1.96	2.03	2.09
3 < 6	0.616	0.636	0.649	0.673	0.728	0.785	0.817	0.842	0.876
6 < 9	0.787	0.814	0.834	0.866	0.931	1.01	1.05	1.09	1.14
9 < 12	0.972	1.00	1.02	1.07	1.16	1.28	1.36	1.42	1.52
12 < 15	1.19	1.24	1.27	1.32	1.49	1.64	1.73	1.77	1.85
15 < 18	1.50	1.55	1.59	1.65	1.75	1.86	1.94	2.01	2.11

[a]Lack of height measurements for children <2 years in NHANES II precluded calculation of surface areas for this age group.
[b]Estimated values calculated using NHANES II data.

Source: U.S. EPA (1985).

Table 8-2. Total Body Surface Area of Female Children in Square Meters[a]

	Percentile								
Age (yr)[b]	5	10	15	25	50	75	85	90	95
2 < 3	0.516	0.532	0.544	0.557	0.579	0.610	0.623	0.637	0.653
3 < 4	0.555	0.570	0.589	0.607	0.649	0.688	0.707	0.721	0.737
4 < 5	0.627	0.639	0.649	0.666	0.706	0.758	0.777	0.794	0.820
5 < 6	0.675	0.700	0.714	0.735	0.779	0.830	0.870	0.902	0.952
6 < 7	0.723	0.748	0.770	0.791	0.843	0.914	0.961	0.989	1.03
7 < 8	0.792	0.808	0.819	0.854	0.917	0.977	1.02	1.06	1.13
8 < 9	0.863	0.888	0.913	0.932	1.00	1.05	1.08	1.11	1.18
9 < 10	0.897	0.948	0.969	1.01	1.06	1.14	1.22	1.31	1.41
10 < 11	0.981	1.01	1.05	1.10	1.17	1.29	1.34	1.37	1.43
11 < 12	1.06	1.09	1.12	1.16	1.30	1.40	1.50	1.56	1.62
12 < 13	1.13	1.19	1.24	1.27	1.40	1.51	1.62	1.64	1.70
13 < 14	1.21	1.28	1.32	1.38	1.48	1.59	1.67	1.75	1.86
14 < 15	1.31	1.34	1.39	1.45	1.55	1.66	1.74	1.76	1.88
15 < 16	1.38	1.49	1.43	1.47	1.57	1.67	1.72	1.76	1.83
16 < 17	1.40	1.46	1.48	1.53	1.60	1.69	1.79	1.84	1.91
17 < 18	1.42	1.49	1.51	1.56	1.63	1.73	1.80	1.84	1.94
3 < 6	0.585	0.610	0.630	0.654	0.711	0.770	0.808	0.831	0.879
6 < 9	0.754	0.790	0.804	0.845	0.919	1.00	1.04	1.07	1.13
9 < 12	0.957	0.990	1.03	1.06	1.16	1.31	1.38	1.43	1.56
12 < 15	1.21	1.27	1.30	1.37	1.48	1.61	1.68	1.74	1.82
15 < 18	1.40	1.44	1.47	1.51	1.60	1.70	1.76	1.82	1.92

[a]Lack of height measurements for children <2 years in NHANES II precluded calculation of surface areas for this age group.
[b]Estimated values calculated using NHANES II data.

Source: U.S. EPA (1985).

Table 8-3. Percentage of Total Body Surface Area by Body Part For Children

Age (yr)	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	5.21-5.39	20.6	18.2-22.9	6.54	6.49-6.59
1 < 2	1:1	16.5	16.5-16.5	35.5	34.5-36.6	13.0	12.8-13.1	5.68	5.57-5.78	23.1	22.1-24.0	6.27	5.84-6.70
2 < 3	1:0	14.2		38.5		11.8		5.30		23.2		7.07	
3 < 4	0:5	13.6	13.3-14.0	31.9	29.9-32.8	14.4	14.2-14.7	6.07	5.83-6.32	26.8	26.0-28.6	7.21	6.80-7.88
4 < 5	1:3	13.8	12.1-15.3	31.5	30.5-32.4	14.0	13.0-15.5	5.70	5.15-6.62	27.8	26.0-29.3	7.29	6.91-8.10
5 < 6													
6 < 7	1:0	13.1		35.1		13.1		4.71		27.1		6.90	
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	5.30	5.15-5.44	28.7	28.5-28.8	7.58	7.38-7.77
10 < 11													
11 < 12													
12 < 13	1:0	8.74		34.7		13.7		5.39		30.5		7.03	
13 <14	1:0	9.97		32.7		12.1		5.11		32.0		8.02	
14 < 15													
15 < 16													
16 < 17	1:0	7.96		32.7		13.1		5.68		33.6		6.93	
17 < 18	1:0	7.58		31.7		17.5		5.13		30.8		7.28	

N: Number of subjects, (males and females)

Source: U.S. EPA (1985).

Table 8-4. Descriptive Statistics For Surface Area/body Weight (SA/BW) Ratios (m^2/kg)

Age (yrs.)	Mean	Range Min-Max	SD[a]	SE[b]	Percentiles						
					5	10	25	50	75	90	95
0-2	0.0641	0.0421-0.1142	0.0114	7.84e-4	0.0470	0.0507	0.0563	0.0617	0.0719	0.0784	0.0846
2.1 - 17.9	0.0423	0.0268-0.0670	0.0076	1.05e-3	0.0291	0.0328	0.0376	0.0422	0.0454	0.0501	0.0594

[a]Standard deviation.

[b]Standard error of the mean.

Source: Phillips et al. (1993).

Table 8-5. Estimated skin surface exposed during warm weather outdoor activities

	Skin area exposed (% of total)		
	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
S.D.	6.0	8.3	10.5

Source: Wong et al. (2000).

Table 8-6. Mean and Percentile Skin Surface Area (m^2) Derived from EPA Analysis of NHANES III (All Children)

Age Group	N	mean	percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
2 to <3 months	234	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
3 to <5 months	556	0.4	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
6 to <11 months	1163	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
1 to <2 years	1230	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
2 to <3 years	1224	0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7
3 to <5 years	3214	0.7	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9
6 to <11 years	2694	1.1	0.8	0.8	0.9	0.9	1.0	1.2	1.3	1.3	1.4
11 to <16 years	2181	1.5	1.2	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.0
16 to <21 years	1891	1.8	1.5	1.5	1.5	1.6	1.8	1.9	2.0	2.1	2.2

Source: EPA Analysis of NHANES III data

Table 8-7. Mean and Percentile Skin Surface Area (m^2) Derived from EPA Analysis of NHANES III (Male Children)

Age Group	N	mean	percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
2 to <3 months	103	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
3 to <5 months	287	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
6 to <11 months	589	0.5	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5
1 to <2 years	613	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
2 to <3 years	627	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7
3 to <5 years	1556	0.7	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9
6 to <11 years	1373	1.1	0.8	0.8	0.9	0.9	1.0	1.2	1.3	1.3	1.4
11 to <16 years	1037	1.6	1.2	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.0
16 to <21 years	890	1.9	1.6	1.6	1.7	1.7	1.8	2.0	2.0	2.1	2.3

Source: EPA Analysis of NHANES III data

Table 8-8. Mean and Percentile Skin Surface Area (m^2) Derived from EPA Analysis of NHANES III (Female Children)

Age Group	N	mean	percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
2 to <3 months	131	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
3 to <5 months	269	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
6 to <11 months	574	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
1 to <2 years	617	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
2 to <3 years	597	0.6	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7
3 to <5 years	1658	0.7	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9
6 to <11 years	1321	1.1	0.8	0.8	0.9	0.9	1.0	1.2	1.3	1.3	1.4
11 to <16 years	1144	1.5	1.2	1.3	1.3	1.4	1.5	1.6	1.8	1.8	1.9
16 to <21 years	1001	1.7	1.4	1.5	1.5	1.5	1.6	1.8	1.9	2.0	2.1

Source: EPA Analysis of NHANES III data

Table 8-9. Summary of Field Studies

Activity	Month	Event[a] (hrs)	N[b]	M	F	Age (yrs)	Conditions	Clothing
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
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
Indoor Kids No. 2	Feb.	2	6	4	2	3-13	Playing on carpeted floor	5of 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, 4 of 6 short sleeves, 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 in long pants, 4 of 6 short sleeves, no shoes
Daycare Kids No.2c	Sept.	8	5	4	1	1-4	Indoors, low napped carpeting, linoleum surfaces	4 of 5 long pants, 3of 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 No. 1	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
Gardeners No. 1	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
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
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
Shoreline Play	Sept	0.33-1.0	9	6	3	7-12	Tidal flat	No shirt or short sleeve T-shirts, shorts, barefoot

[a]Event duration
[b]Number of subjects
[c]Activities were confined to the house

Sources: Kissel et al. (1996b); Holmes et al. (1996), Shoaf et al. (2005).

Table 8-10. Geometric Mean and Geometric Standard Deviations of Solids Adherence by Activity and Body Region[a]

Activity	N[b]	Post-activity Dermal Solids 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
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.
[b]Number of subjects.

Sources: Kissel et al. (1996b); Holmes et al. (1996); Shoaf et al. (2005).

Table 8-11. Summary of Groups Assayed in Round 2 of Field Measurements

Activity	Month	Event[a] (hrs)	*n*[b]	Males	Females	Ages
Daycare kids No. 1a	Aug.	3.5	6	5	1	1 - 6.5
Daycare kids No. 1b	Aug.	4	6	5	1	1 - 6.5
Daycare kids No. 2	Sept.	8	5	4	1	1 - 4
Daycare kids No. 3	Nov.	8	4	3	1	1 - 4.5
Indoor kids No. 1	Jan.	2	4	3	1	6 - 13
Indoor kids No. 2	Feb.	2	6	4	2	3 - 13

[a] Event duration.
[b] Number of subjects.

Source: Holmes et al. (1999).

Table 8-12. Attire for Individuals within Children's Groups Studied

Activity	n^a	Pants		Sleeves		Socks		Shoes
		Long	Short	Long	Short	High	Low	
Daycare kids No. 1a	6	4	2	1	5	1	5	low leather or canvas shoes - 6
Daycare kids No. 1b	6	4	2	1	5	1	5	barefoot - 3 low leather or canvas shoes - 3
Daycare kids No. 2	5	4	1	2	3	NA	NA	barefoot - 2 shoes/socks ½ day and barefoot ½ day - 3
Daycare kids No. 3[b]	4	4	0	3	1	0	4	low shoes - 4
Indoor kids No. 1	4	1	3	2	2	0	4	no shoes (socks only) - 4
Indoor kids No. 2	6	5	1	5	1	0	6	no shoes (socks only) - 6

[a] Number of subjects.
[b] All children wore jackets when engaged in outdoor activities.
NA - "Not Available": 3 children wore socks for ½ day in the morning but no specific information is provided on the type of socks worn.

Source: Holmes et al. (1999).

Table 8-13. Geometric Means (Geometric Standard Deviations) of Round 2 Post-activity Loadings

Activity	n[a]	Postactivity Dermal Soil Loadings (mg/cm2)				
		Hands	Forearms	Lower legs	Faces[b]	Feet
Daycare kids No. 1a	4	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	6	0.073 (1.6)	0.023 (1.4)	0.011 (1.4)		0.044 (1.3)
Daycare kids No. 3	6	0.036 (1.3)	0.012 (1.2)	0.014 (3.0)		0.0053 (5.1)
Indoor kids No. 1	5	0.0073 (1.9)	0.0042 (1.9)	0.0041 (2.3)		0.012 (1.4)
Indoor kids No. 2	4	0.014 (1.5)	0.0041 (2.0)	0.0031 (1.5)		0.0091 (1.7)

[a] Number of subjects (number of data points for specific non-hand body parts may deviate slightly).
[b] Children’s feet rather than faces were washed in order to reduce the chance of a child’s refusal to participate.

Source: Holmes et al. (1999).

Table 8-14. Summary of Controlled Green House Trials - Children Playing

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

[a] L, long sleeves and long pants; S, short sleeves and short pants.

Source: Kissel et al. (1998).

Table 8-15. Preactivity Loadings Recovered from Greenhouse Trial Children Volunteers

Area	n	Body part surface area (cm^2)	Geometric mean (95% C.I.) ($\mu g/cm^2$)
Hands	12	420-798	9.4 (5.4 - 15.8)
Forearms	12	584-932	3.4 (2.3 - 5.2)
Lower legs	12	1,206-2,166	1.0 (0.7 - 1.5)
Face	12	388-602	0.8 (0.5 - 1.5)

Source: Kissel et al. (1998).

Table 8-16. Area Weighted Adherence Factors

Exposure Scenario	Age (years)	Geometric Mean Area Weighted Adherence Factor (mg/cm2)
Indoor Children	1-13	0.01
Daycare Children (playing indoors and outdoors)	1-6.5	0.04
Children Playing (dry soil)	8-12	0.04
Children Playing (wet soil)	8-12	0.2
Children-in-mud	9-14	21

Source: U.S. EPA, 2004

Table 8-17. Summary of Recommended Values for Skin Surface Area and Solids Adherence

Factor	Central Tendency	Upper Percentile	Multiple Percentiles
Whole body surface area	—	see Tables 8-6, 8-7, and 8-8	see Tables 8-6, 8-7, and 8-8
Body part surface areas	---	see Table 8-3	see Table 8-3
Solids adherence	see Tables 8-9, 8-10, 8-16		

Table 8-18. Confidence in Body Surface Area Measurement Recommendations

Considerations	Rationale	Rating
Study Elements		
• Level of Peer Review	Studies were from peer reviewed journal articles. EPA report was peer reviewed before distribution.	High
• Accessibility	The journals used have wide circulation. EPA report available from National Technical Information Service.	High
• Reproducibility	Experimental methods are well-described.	High
• Focus on factor of interest	Experiments measured skin area directly.	High
• Data pertinent to U.S.	Experiments conducted in the U.S.	High
• Primary data	Re-analysis of primary data in more detail by two different investigators .	Low
• Currency	Neither rapidly changing nor controversial area; estimates made in 1935 deemed to be accurate and subsequently used by others.	Low
• Adequacy of data collection period	Not relevant to exposure factor; parameter not time dependent.	NA
• Validity of approach	Approach used by other investigators; not challenged in other studies.	High
• Representativeness of the population	Not statistically representative of U.S. population.	Medium
• Characterization of variability	Individual variability due to age, race, or gender not studied.	Low
• Lack of bias in study design	Objective subject selection and measurement methods used; results reproduced by others with different methods.	High
• Measurement error	Measurement variations are low; adequately described by normal statistics.	Low/Medium
Other Elements		
• Number of studies	1 experiment; two independent re-analyses of this data set.	Medium
• Agreement among researchers	Consistent results obtained with different analyses; but from a single set of measurements.	Medium
Overall Rating	This factor can be directly measured. It is not subject to dispute. Influence of age, race, or gender have not been detailed adequately in these studies.	**Medium**

Table 8-19. Confidence in Solids Adherence to Skin Recommendations

Considerations	Rationale	Rating
Study Elements		
• Level of Peer Review	Studies were from peer reviewed journal articles.	High
• Accessibility	Articles were published in widely circulated journals.	High
• Reproducibility	Reports clearly describe experimental method.	High
• Focus on factor of interest	The goal of the studies was to determine soil adherence to skin.	High
• Data pertinent to U.S.	Experiments were conducted in the U.S.	High
• Primary data	Experiments were used to directly measure soil adherence to skin;	High
• Currency	New studies were presented.	High
• Adequacy of data collection period	Seasonal factors may be important, but have not been studied adequately.	Medium
• Validity of approach	Skin rinsing technique is a widely employed procedure.	High
• Representativeness of the population	Soil/dust studies were limited to the State of Washington and sediment study limited to Rhode Island. May not be representative of other locales.	Low
• Characterization of variability	Variability in soil adherence is affected by many factors including soil properties, activity and individual behavior patterns.	Low
• Lack of bias in study design	The studies attempted to measure soil adherence in selected activities and conditions to identify important activities and groups.	High
• Measurement error	The experimental error is low and well controlled.	High
Other Elements		
• Number of studies	The experiments were controlled as they were conducted by a few laboratories; activity patterns were studied by only one laboratory.	Medium
• Agreement among researchers	Results from key study were consistent with earlier estimates from relevant studies and assumptions, but are limited to hand data.	Medium
Overall Rating	Data are limited, therefore it is difficult to extrapolate from experiments and field observations to general conditions. Application of results to other similar activities may be subject to variation.	Medium

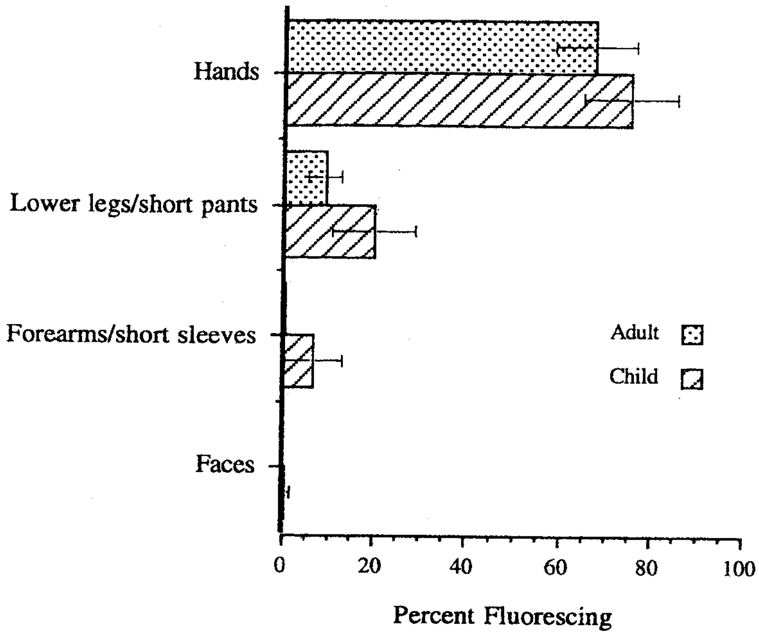

Figure 8-2. Skin Coverage as Determined by Fluorescence vs. Body Part for Adults Transplanting Plants and for Children Playing in Wet Soils

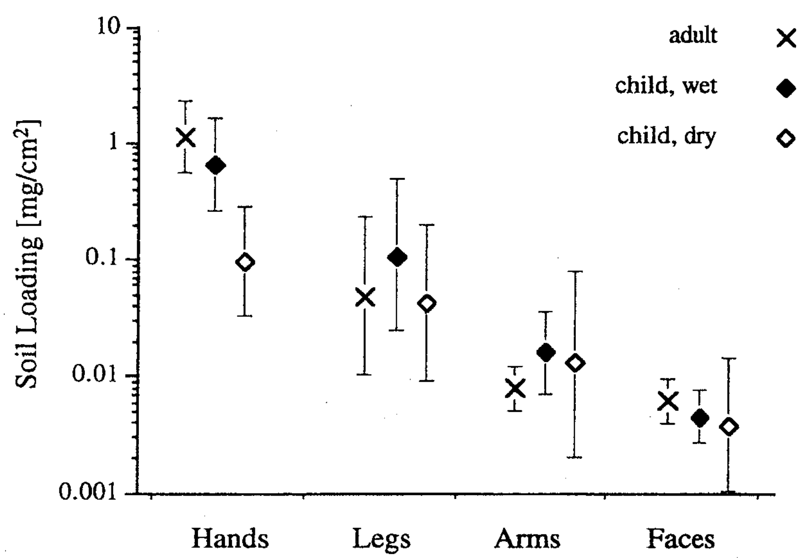

Figure 8-3. Gravimetric Loading vs. Body Part for Adult Transplanting Plants in Wet Soil and for Children Playing in Wet and Dry Soils

APPENDIX 8A

Formulas FOR TOTAL BODY SURFACE AREA

APPENDIX 8A

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):

$$SA = KW^{2/3} \qquad (8A\text{-}1)$$

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. Their model can be written:

where:

$$SA = a_0 H^{a1} W^{a2} \qquad (8A\text{-}2)$$

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.

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:

$$SA = 0.02350\ H^{0.42246} W^{0.51456} \qquad (8A\text{-}3)$$

or in logarithmic form:

$$\ln SA = -3.75080 + 0.42246 \ln H + 0.51456 \ln W \qquad (8A\text{-}4)$$

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:

$$SA_i = a_0 H_i^{a_1} W_i^{a_2} e_i \qquad (8A\text{-}5)$$

or in logarithmic form:

$$\ln(SA)_i = \ln a_0 + a_1 \ln H_i + a_2 \ln W_i + \ln e_i \quad (8A\text{-}6)$$

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	=	parameters to be estimated; and
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:

$$SA = 0.0239\, H^{0.417} W^{0.517} \quad (8A\text{-}7)$$

or in logarithmic form:

$$\ln SA = 3.73 + 0.417 \ln H + 0.517 \ln W \quad (8A\text{-}8)$$

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 below:

Table 8A-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 - <20 years old	42	0.03050	0.35129	0.54375
$ 20 years old	30	0.01545	0.54468	0.46336

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:

$$SA = 0.024265 H^{0.3964} W^{0.5378} \quad \text{(8A-9)}$$

expressed logarithmically as:

$$\ln SA = \ln 0.024265 + 0.3964 \ln H + 0.5378 \ln W \quad \text{(8A-10)}$$

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:

$$\ln SA = \ln a_0 + a_1 \ln H + a_2 \ln W \qquad (8A\text{-}11)$$

The values for a_0, a_1, and a_2 obtained by the various authors discussed in this section are presented to follow:

Table 8A-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

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.