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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. Environmental Protection Agency (U.S. EPA), (2004, 1992a, b)]. These include:

- water (e.g., bathing, washing, swimming);
- soil (e.g., outdoor recreation, gardening, construction);
- sediment (e.g., wading, fishing);
- other liquids (e.g., use of commercial products);
- vapors/fumes/gases (e.g., use of commercial products); and
- other solids or residues (e.g., soil/dust or chemical residues on carpets, floors, counter tops, outdoor surfaces, or clothing).

Exposure via the dermal route may be estimated in various ways, depending on the exposure media and scenario of interest. For example, dermal exposure to contaminants in soil, sediment, or dust may be evaluated using information on the concentration of contaminant in these materials in conjunction with information on the amount of material that adheres to the skin per unit surface area and the total area of skin surface exposed. An approach for estimating dermal exposure to contaminants in liquids uses information on the concentration of contaminant in the liquid in conjunction with information on the film thickness of liquid remaining on the skin after contact. When assessing dermal exposure to water (e.g., bathing or swimming) or to vapors and fumes, the concentration of chemical in water or vapor with the total exposed skin surface area may be considered. An approach for estimating exposure to surface residues is to use information on the rate of transfer of chemical residues to the skin as a result of contact with the surfaces. Dermal exposure also may result from leaching of chemicals that are impregnated in materials that come into contact with skin. For example, Snodgrass (1992) evaluated transfer of pesticides from treated clothing onto the skin. For information on various methods used to estimate dermal exposure, refer to *Guidelines for Exposure Assessment (U.S. EPA, 1992b)*, *Dermal Exposure Assessment: Principles and Applications (U.S. EPA, 1992a)*, and *Dermal Exposures Assessment: A Summary of EPA Approaches* (U.S. EPA, 2007a). Additional scenario-specific information on dermal exposure assessment is available in *Risk Assessment Guidance for Superfund (RAGS) Part E* (U.S. EPA, 2004), *Standard Operating Procedures for Residential Pesticide Exposure Assessment, draft (U.S. EPA, 2009)*, and *Methods for Assessing Exposure to Chemical Substances: Volume 7, Methods for Assessing Consumer Exposure to Chemical Substances* (U.S. EPA, 1987). In general, these methods for estimating dermal exposure require information on the surface area of the skin that is exposed. Some methods also require information on the adherence of solids to the skin or information on the film thickness of liquids on the skin. Others utilize information on the transfer of residues from contaminated surfaces to the skin surface and/or rate of contact with objects or surfaces. This chapter focuses on measurements of body surface area and non-chemical-specific factors related to dermal exposure (i.e., the deposition of contaminants onto the skin), such as adherence of solids to the skin, film thickness of liquids on the skin, and residue transfer from contaminated surfaces to the skin. However, this chapter only provides recommendations for surface area and solids adherence to skin. According to Riley et al. (2004), numerous factors may affect loading and retention of chemicals on the skin, including the form of the contaminant (particle, liquid, residue), surface characteristics (hard, plush, porous, surface loading, previous transfers), skin characteristics (moisture, age, loading), contact mechanics (pressure, duration, repetition), and environmental conditions (temperature, relative humidity, air exchange). These factors are discussed in this chapter, as reported by the various study authors. Information on other factors that may affect dermal exposure (e.g., contact frequency and duration, and skin thickness) also is provided in this chapter.

Factors that influence dermal uptake (i.e., absorption) and internal dose, including chemical-specific factors, are not provided in this handbook. These include factors such as the concentration of chemical in contact with the skin, weight fraction of chemicals in consumer products, and characteristics of the chemical (i.e., lipophilicity, polarity, volatility, solubility). Also, factors affecting the rate of absorption of the chemical through the skin at the site of application and the amount of chemical delivered to the target organ are not covered in this chapter. Absorption may be affected by the age and condition of the skin, including presence of perspiration (Williams et al., 2005; Williams et al., 2004). Also, the thickness of the stratum corneum (outer layer of the skin) varies over parts of the body and may affect absorption. While not the primary focus of this chapter, some limited information on skin thickness is presented in Section 7.7—Other Factors. For guidance on how to use information on factors needed to assess dermal dose, refer to *Dermal Exposure Assessment: Principles and Applications* (U.S. EPA, 1992a) and *Risk Assessment Guidelines for Superfund (RAGs) Part E* (U.S. EPA, 2004).

Frequency and duration of contact also may affect dermal exposure and dose. Data on dermal contact frequency and duration of hand contact with objects and surfaces are presented in Section 7.7.1 of this chapter. Additional information on consumer products use and activity factors that may affect dermal exposure is presented in Chapters 16 and 17.

Section 7.3 of this chapter provides data on surface area of the human skin. Section 7.4 provides data on adherence of solids to human skin. Information on the film thickness of liquids on the skin is limited. However, studies that estimated film thickness of liquids on the skin are presented in Section 7.5. Section 7.6 presents available information on the transfer of residues from contaminated surfaces to the skin. Section 7.7 provides information on other factors affecting dermal exposure (e.g., frequency and duration of dermal contact with objects and surfaces, and skin thickness).

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. Relevant data on these and other factors also are presented in this chapter to provide added perspective on the state-of-knowledge pertaining to dermal exposure factors.

7.2. RECOMMENDATIONS

7.2.1. Body Surface Area

Table 7-1 summarizes the recommended mean and 95th percentile total body surface area values. For children under 21 years of age, the recommendations for total body surface area are based on the U.S. EPA analysis of 1999–2006 data from the National Health and Nutrition Examination Survey (NHANES). These data are presented for the standard age groupings recommended by U.S. EPA (2005) for male and female children combined. For adults 21 years and over, the recommendations for total body surface area are based on the U.S. EPA analysis of NHANES (2005–2006) data. The U.S. EPA analysis of NHANES data uses correlations with body weight and height for deriving skin surface area (see Section 7.3.1.3 and Appendix 7A). NHANES (1999–2006) used a statistically based survey design that should ensure that the data are reasonably representative of the general population for each 2-year interval (e.g., 1999 to 2000, 2001 to 2002). Multiple NHANES study years, supplying a larger sample size, were necessary for estimating surface area for children given the multiple stratifications by age. The advantage of using the NHANES data sets to derive the total surface area recommendations is that data are nationally representative and remain the principal source of body-weight and height data collected nationwide from a large number of subjects. Note that differences between the surface area recommendations presented here and those in the previous *Exposure Factors Handbook* (U.S. EPA, 1997) reflect changes in the body weights used in calculating these surface areas. If sex-specific data for children, sex-combined data for adults, or data for statistics other than the mean or 95th percentile are needed, refer to Table 7-9 through Table 7-13 of this chapter.

Table 7-2 presents the recommendations for the percentage of total body surface area represented by individual body parts for children based on data from U.S. EPA (1985) and Boniol et al. (2008) (see Section 7.3.1). The data from Boniol et al. (2008) are used for the recommendations for children greater than 2 years of age because they are based on a larger sample size than those in U.S. EPA (1985) for the same age groups. Because the Boniol et al. (2008) study does not include data for children less than 2 years of age, recommendations for this age group are based on the data from U.S. EPA (1985). It should be noted, however, that the sample size for the percentages of the total body represented by various body parts in this age group is very small. Table 7-2 also provides age-specific body part surface areas (m^2) for children. These values were obtained by multiplying the age-specific mean body part percentages (for males and females combined) by the total body surface areas presented in Table 7-1. If sex-specific data are needed for children equal to or greater than 2 years of age, or if data for additional body parts not summarized in Table 7-2 are needed, refer to Table 7-8. The body part data in this table may be applied to data in Table 7-9 through Table 7-11 to calculate surface area for the various body parts.

The recommendations for surface area of adult body parts are based on the U.S. EPA Analysis of NHANES 2005–2006 data and algorithms from U.S. EPA (1985). The U.S. EPA Analysis of the NHANES data was used to develop recommendations for body parts because the data are nationally representative and based on a large number of subjects. Table 7-2 presents the data for adult males and adult females (21+ years of age). If sex-combined data for adults or data for statistics other than the mean and 95th percentile are needed, refer to Table 7-12 and Table 7-13. These tables present the surface area of body parts for males and females, respectively, 21 years of age and older. 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% of the skin surface is exposed (U.S. EPA, 1992a). More recent guidance recommends assuming 100% 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 only occurs to 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 or chemical residues on surfaces 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. Also, surface area of the body and body weight are highly correlated (Phillips et al., 1993). The relationship between these factors, therefore, should be considered when selecting body weights for use with the surface area data for estimating dermal exposure.

7.2.2. Adherence of Solids to Skin

The adherence factor (AF) describes the amount of solid 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. Refer to the activities described in Table 7-19 to select those that best represent the exposure scenarios of concern and use the corresponding adherence values from Table 7-20. Table 7-19 also lists the age ranges covered by each study. This may be used as a general guide to the ages covered by these data.

Table 7-4 summarizes recommended mean AF values according to common activities. The key studies used to develop the recommendations for adherence of solids to skin are those based on field studies in which specific activities relevant to dermal exposure were evaluated (compared to relevant studies that evaluated adherence in controlled laboratory trials using sieved or standardized soil). Insufficient data were available to develop activity-specific distributions or probability functions for these studies. Also, the small number of subjects in these studies prevented the development of recommendations for the childhood specific age groups recommended by U.S. EPA (2005).

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:

$$AF_{wtd} = \frac{(AF_1)(SA_1) + (AF_2)(SA_2) + \ldots (AF_i)(SA_i)}{SA_1 + SA_2 + \ldots SA_i} \qquad \text{(Eqn. 7-1)}$$

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% of the arms, and lower legs may be assumed to represent 40% 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 (1992a) 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, 1992a). The rate of solids accumulation on skin over time has not been well studied but probably occurs fairly quickly. Therefore, prorating the adherence values for exposure time periods of less than 1 day is not recommended.

Table 7-5 shows the confidence ratings for these AF recommendations. 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 also should be noted that the skin-adherence studies on which these recommendations are based have generally 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 used for the recommendations.

7.2.3. Film Thickness of Liquids on Skin

The film thickness of liquids on skin represents the amount of material that remains on the skin after contact with a liquid (e.g., consumer product such as cleaning solution or soap). The data on film thickness of liquids on the hand are limited, and recommended values are not provided in this chapter. Refer to Section 7.5 for a description of the available data that may be used to assess dermal contact with liquid using the film thickness approach.

7.2.4. Residue Transfer

Several studies have developed methods for quantifying the rates of transfer of chemical residues to the skin of individuals performing activities on contaminated surfaces. These studies have been conducted primarily for the purpose of estimating exposure to pesticides. Section 7.6 describes studies that have estimated residue transfer to human skin. Because use of residue transfer depends on the specific conditions under which exposure occurs (e.g., activity, contact surfaces, age), general recommendations are not provided. Instead, refer to Section 7.6 for a description of the available data from which appropriate values may be selected.

Table 7-1. Recommended Values for Total Body Surface Area, for Children (sexes combined) and Adults by Sex

Age Group	Mean (m²)	95th Percentile (m²)	Multiple Percentiles	Source
Male and Female Children Combined				
Birth to <1 month	0.29	0.34	See Table 7-9, Table 7-10, and Table 7-11 (for sex-specific data)	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		
Adult Male				
21 to 30 years	2.05	2.52	See Table 7-9 (for sex-combined data) and Table 7-10	U.S. EPA Analysis of NHANES 2005−2006 data
30 to <40 years	2.10	2.50		
40 to <50 years	2.15	2.56		
50 to <60 years	2.11	2.55		
60 to <70 years	2.08	2.46		
70 to <80 years	2.05	2.45		
80 years and over	1.92	2.22		
Adult Female				
21 to 30 years	1.81	2.25	See Table 7-9(for sex-combined data) and Table 7-11	U.S. EPA Analysis of NHANES 2005−2006 data
30 to <40 years	1.85	2.31		
40 to <50 years	1.88	2.36		
50 to <60 years	1.89	2.38		
60 to <70 years	1.88	2.34		
70 to <80 years	1.77	2.13		
80 years and over	1.69	1.98		

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

Age Group	Head	Trunk[a]	Arms[b]	Hands	Legs[c]	Feet	Source
	Mean Percent of Total Surface Area						
Male and Female Children Combined							
Birth to <1 month[d]	18.2	35.7	13.7	5.3	20.6	6.5	U.S. EPA (1985)
1 to <3 months[d]	18.2	35.7	13.7	5.3	20.6	6.5	U.S. EPA (1985)
3 to <6 months[d]	18.2	35.7	13.7	5.3	20.6	6.5	U.S. EPA (1985)
6 to <12 months[d]	18.2	35.7	13.7	5.3	20.6	6.5	U.S. EPA (1985)
1 to <2 years[d]	16.5	35.5	13.0	5.7	23.1	6.3	U.S. EPA (1985)
2 to <3 years[e]	8.4	41.0	14.4	4.7	25.3	6.3	Boniol et al. (2008) (average of data for males and females)
3 to <6 years[f]	8.0	41.2	14.0	4.9	25.7	6.4	Boniol et al. (2008) (average of data for males and females)
6 to <11 years[g]	6.1	39.6	14.0	4.7	28.8	6.8	Boniol et al. (2008) (average of data for males and females)
11 to <16 years[h]	4.6	39.6	14.3	4.5	30.4	6.6	Boniol et al. (2008) (average of data for males and females)
16 to <21 years[i]	4.1	41.2	14.6	4.5	29.5	6.1	Boniol et al. (2008) (average of data for males and females)
Adult Male							
21+ years	6.6	40.1	15.2	5.2	33.1	6.7	U.S. EPA Analysis of NHANES 2005−2006 data and U.S. EPA (1985)
Adult Female							
21+ years	6.2	35.4	12.8	4.8	32.3	6.6	U.S. EPA Analysis of NHANES 2005−2006 data and U.S. EPA (1985)
	Mean Surface Area by Body Part[j] m^2						
Male and Female Children Combined							
Birth to <1 month[d]	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[d]	0.060	0.118	0.045	0.017	0.068	0.021	U.S. EPA Analysis of NHANES 1999−2006 data and U.S. EPA (1985)
3 to <6 months[d]	0.069	0.136	0.052	0.020	0.078	0.025	U.S. EPA Analysis of NHANES 1999−2006 data and U.S. EPA (1985)
6 to <12 months[d]	0.082	0.161	0.062	0.024	0.093	0.029	U.S. EPA Analysis of NHANES 1999−2006 data and U.S. EPA (1985)
1 to <2 years[d]	0.087	0.188	0.069	0.030	0.122	0.033	U.S. EPA Analysis of NHANES 1999−2006 data and U.S. EPA (1985)
2 to <3 years[e]	0.051	0.250	0.088	0.028	0.154	0.038	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
3 to <6 years[f]	0.061	0.313	0.106	0.037	0.195	0.049	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
6 to <11 years[g]	0.066	0.428	0.151	0.051	0.311	0.073	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
11 to <16 years[h]	0.073	0.630	0.227	0.072	0.483	0.105	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
16 to <21 years[i]	0.075	0.759	0.269	0.083	0.543	0.112	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
Adult Male							
21+ years	0.136	0.827	0.314	0.107	0.682	0.137	U.S. EPA Analysis of NHANES 2005−2006 data and U.S. EPA (1985)
Adult Female							
21+ years	0.114	0.654	0.237	0.089	0.598	0.122	U.S. EPA Analysis of NHANES 2005−2006 data and U.S. EPA (1985)

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

Age Group	Head	Trunk[a]	Arms[b]	Hands	Legs[c]	Feet	Source
	95th Percentile Surface Area by Body Part[k] m²						
Male and Female Children Combined							
Birth to <1 month[d]	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[d]	0.069	0.136	0.052	0.020	0.078	0.025	
3 to <6 months[d]	0.080	0.157	0.060	0.023	0.091	0.029	
6 to <12 months[d]	0.093	0.182	0.070	0.027	0.105	0.033	
1 to <2 years[d]	0.101	0.217	0.079	0.035	0.141	0.038	
2 to <3 years[e]	0.059	0.287	0.101	0.033	0.177	0.044	U.S. EPA Analysis of NHANES 1999−2006 data and Boniol et al. (2008)
3 to <6 years[f]	0.076	0.391	0.133	0.046	0.244	0.061	
6 to <11 years[g]	0.090	0.586	0.207	0.070	0.426	0.100	
11 to <16 years[h]	0.095	0.816	0.295	0.093	0.626	0.136	
16 to <21 years[i]	0.096	0.960	0.340	0.105	0.687	0.142	
Adult Male							U.S. EPA Analysis of NHANES 2005−2006 data and U.S. EPA (1985)
21+ years	0.154	1.10	0.399	0.131	0.847	0.161	
Adult Female							
21+ years	0.121	0.850	0.266	0.106	0.764	0.146	

a For children, ages 2 to <21 years, data from Boniol et al. (2008) for the neck, bosom, shoulders, abdomen, back, genitals, and buttocks were combined to represent the trunk.
b For children, ages 2 to <21 years, data from Boniol et al. (2008) for the upper and lower arms were combined to represent the arms.
c For children, ages 2 to <21 years, data from Boniol et al. (2008) for the thigh and legs were combined to represent the legs.
d Percentages based on a small number of observations for this age group.
e Based on data for 2 year olds from Boniol et al. (2008).
f Based on data for 4 year olds from Boniol et al. (2008).
g Based on average of data for 6, 8, and 10 year olds from Boniol et al. (2008).
h Based on average of data for 12 and 14 year olds from Boniol et al. (2008).
i Based on average of data for 16 and 18 year olds from Boniol et al. (2008).
j Children’s values calculated as mean percentage of body part times mean total body surface area.
k Children’s values calculated as mean percentage of body part times 95th 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 large sample sizes; sample size varied with age. Body-part percentages for children <2 years of age were based on direct measurements from a very small number of subjects (*N* = 4). Percentages for children ≥2 years were based on 2,050 children; adult values were based on 89 adults.	
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 for a large sample of the population.	
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. Body part percentages for children <2 years of age were based on direct measurements from a very small number of subjects (*N* = 4). Percentages for children ≥2 years were based on 2,050 children from various states in the United States and are assumed to be representative of U.S. children; adult values were based on 89 adults.	
Currency	The U.S. EPA analysis used the most current NHANES data to generate surface area data using algorithms based on older direct measurements. The data on body part percentages were dated. However, the age of the percentage data is not expected to affect its utility if the percentages are applied to total surface area data that has been updated based on the most recent NHANES body-weight and height data.	
Data Collection Period	The U.S. EPA analysis was based on four NHANES data sets covering 1999−2006 for children and one NHANES data set, 2005−2006, for adults.	

Table 7-3. Confidence in Recommendations for Body Surface Area (continued)		
General Assessment Factors	Rationale	Rating
Clarity and Completeness		Medium
Accessibility	The U.S. EPA analysis of the NHANES data is unpublished, but used the same methodology as that described in the 1997 *Exposure Factors Handbook* (U.S. EPA, 1997). U.S. EPA (1985) is a U.S. EPA-published report. Boniol et al. (2008) is a published paper.	
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.	
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 for some ages, there is uncertainty in the body part percentage estimates for these age groups.	
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, but used the same methodology as that described in the 1997 *Exposure Factors Handbook* (U.S. EPA, 1997).	
Number and Agreement of Studies	There is one key study for total surface area and two key studies 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					
Children						
Residential (indoors)[a]	-	0.0041	0.011	0.0035	0.010	Holmes et al. (1999)
Daycare (indoors and 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. (1996b)
Indoor sports[d]	-	0.0019	0.0063	0.0020	0.0022	Kissel et al. (1996b)
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. (1996b)
Playing in sediment[g]	0.040	0.17	0.49	0.70	21	Shoaf et al. (2005b)
Adults						
Outdoor sports[h]	0.0314	0.0872	0.1336	0.1223	-	Holmes et al. (1999); Kissel et al. (1996b)
Activities with soil[i]	0.0240	0.0379	0.1595	0.0189	0.1393	Holmes et al. (1999); Kissel et al. (1996b)
Construction activities[j]	0.0982	0.1859	0.2763	0.0660	-	Holmes et al. (1999)
Clamming[k]	0.02	0.12	0.88	0.16	0.58	Shoaf et al. (2005a)

[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 8 children (ages 13 to 15 years) playing soccer.

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

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

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

[g] Based on geometric mean soil loadings of 9 children (ages 7 to 12 years) playing in tidal flats.

[h] Based on weighted average of geometric mean soil loadings of 3 groups of adults (ages 23 to 33 years) playing rugby and 2 groups of adults (ages 24 to 34) playing soccer.

[i] Based on weighted average of geometric mean soil loadings for 69 gardeners, farmers, groundskeepers, landscapers and archeologists (ages 16 to 64 years) for faces, arms and hands; 65 gardeners, farmers, groundskeepers, and archeologists (ages 16 to 64 years) for legs; and 36 gardeners, groundskeepers and archeologists (ages 16 to 62) for feet.

[j] Based on weighted average of geometric mean soil loadings for 27 construction workers, utility workers and equipment operators (ages 21 to 54) for faces, arms and hands; and based on geometric mean soil loadings for 8 construction workers (ages 21 to 30 years) for legs.

[k] Based on geometric mean soil loadings of 18 adults (ages 33 to 63 years) clamming 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 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. All three studies were conducted by researchers from a laboratory where a similar methodology was used. This may limit the representativeness of the data in terms of a wider population.	
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.	

Table 7-5. Confidence in Recommendations for Solids Adherence to Skin (continued)		
General Assessment Factors	Rationale	Rating
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 and adults.	
Overall Rating		**Low**

7.3. SURFACE AREA

Surface area of the skin can be determined by 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 (Du Bois and Du Bois, 1989; Gehan and George, 1970; Boyd, 1935). 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. Appendix 7A presents a discussion and comparison of formulas. The key studies on body surface area that are presented in Section 7.3.1 are based on these formulas, as well as weight and height data from NHANES.

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*

U.S. EPA (1985) summarized the direct measurements of the surface area of adults' and children's body parts provided by Boyd (1935) and USDA (1969) as a percentage of total surface area. Table 7-6 presents these percentages. A total of 21 children less than 18 years of age were included. Because of the small sample size, it is unclear how accurately these estimates represent averages for the age groups. A total of 89 adults, 18 years and older, were included in the analysis of body parts, providing greater accuracy for the adult estimates. 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.

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). Gehan and George (1970) selected 401 measurements made by Boyd (1935) that were complete for surface area, height, weight, and age for their analysis. 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 subsequently used by U.S. EPA 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, 1999–2006 [CDC (2006); see Section 7.3.1.3].

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 401 direct measurements of children and adults and reanalyzed the data using the formula of Du Bois and Du Bois (1989) and SPS to obtain the standard error (U.S. EPA, 1985).

Regression equations were developed for specific body parts using the Du Bois and Du Bois (1989) formula and using the surface area of various body parts provided by Boyd (1935) and USDA (1969) in conjunction with SPS. Regression equations for adults were developed for the head, trunk (including the neck), upper extremities (arms and hands, upper arms, and forearms) and lower extremities (legs and feet, thighs, and lower legs) (U.S. EPA, 1985). Table 7-7 presents a summary of the equation parameters developed by U.S. EPA (1985) for calculating surface area of adult body parts. Equations to estimate the body part surface area of children were not developed because of insufficient data.

7.3.1.2. *Boniol et al. (2008)—Proportion of Skin Surface Area of Children and Young Adults from 2 to 18 Years Old*

Boniol et al. (2008) applied measurement data for 87 body parts to a computer model to estimate the surface area of body parts of children. The measurement data were collected in the late 1970s by Snyder et al. (1978) for the purpose of product safety design (e.g., toys and ergonomics) and represent

1,075 boys and 975 girls from various states in the United States. A surface area module of the computer model MAN3D was used to construct models of the human body for children (ages 2, 4, 6, 8, 10, 12, 14, 16, and 18 years) to estimate surface area of 13 body parts for use in treating skin lesions. The body parts included head, neck, bosom, shoulders, abdomen, back, genitals and buttocks, thighs, legs, feet, upper arms, lower arms, and feet. The proportion of the skin surface area of these body parts relative to total surface area was computed. Table 7-8 presents these data for the various ages of male and female children. Except for the head, for which the percentages are much lower in this study than in U.S. EPA (1985), the body part proportions in this study appear to be similar to those presented in U.S. EPA (1985). For example, the proportions for hands range from 4.2 to 4.9% in this study and from 5.0 to 5.9% in U.S. EPA (1985). Because this study provides additional body parts that were not included in the U.S. EPA (1985) study, it is necessary to combine some body parts for the purpose of comparing their results. For example, upper arms and lower arms can be combined to represent total arms, and thighs plus legs can be combined to represent total legs. Upper arms plus lower arms for 4-year-olds from this study represent 14% of the total body surface, compared to 14.2% for arms for 3- to 6-year-olds from U.S. EPA (1985). Thighs plus legs for 2-year-olds from this study represent 25.3% of the total surface, compared to 23.2% for 2- to 3-year-olds from U.S. EPA (1985). Likewise, neck, bosom, shoulders, abdomen, back, and genitals/buttocks can be combined to represent the trunk.

The advantages of this study are that the data represent a larger sample size of children and are more recent than those used in U.S. EPA (1985). This study also provides data for more body parts than U.S. EPA (1985). However, the age groups presented in this study differ from those recommended in U.S. EPA (2005) and used elsewhere in this handbook, and no data are available for children 1 year of age and younger.

7.3.1.3. *U.S. EPA Analysis of NHANES 2005−2006 and 1999–2006 Data*

The U.S. EPA estimated total body surface areas by using the empirical relationship shown in Appendix 7A and U.S. EPA (1985), and body-weight and height data from the 1999–2006 NHANES for children and the 2005–2006 NHANES for adults. NHANES is conducted annually by the Centers for Disease Control (CDC) National Center of Health Statistics. The survey's target population is the civilian, non-institutionalized U.S. population. The NHANES 1999–2006 survey was conducted on a nationwide probability sample of approximately 40,000 people 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 non-response to the household interview was 19%, and an additional 4% did not participate in the physical examinations (including body-weight measurements).

The NHANES 1999–2006 survey includes oversampling of low-income persons, adolescents 12 to 19 years of age, 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. For children's estimates, the U.S. EPA utilized four NHANES data sets in its analysis (NHANES 1999–2000, 2001–2002, 2003−2004, and 2005–2006) to ensure adequate sample size for the age groupings of interest. 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/nhanes20052006/faqs05_06.htm#question%2012). For adult estimates, the U.S. EPA utilized NHANES 2005–2006 in its estimates for currency and the same analytical methodology as in the earlier version of the *Exposure Factors Handbook* (U.S. EPA, 1997).

Table 7-9 presents the mean and percentile estimates of total body surface area by age category for males and females combined. Table 7-10 and Table 7-11 present the mean and percentiles of total body surface area by age category for males and females, respectively. Table 7-12 and Table 7-13 present the mean and percentile estimates of body surface area of specific body parts for males and females 21 years and older, respectively.

An advantage of using the NHANES data sets to derive total 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 less than 2 years of age were based on recumbent length whereas 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. *Murray and Burmaster (1992)—Estimated Distributions for Total Body Surface Area of Men and Women in the United States*

Murray and Burmaster (1992) generated distributions of total body surface area for men and women ages 18 to 74 years using Monte Carlo simulations based on height and weight distribution data. Four different formulae for estimating body surface area as a function of height and weight were employed: Du Bois and Du Bois (1989), Boyd (1935), U.S. EPA (1985), and Costeff (1966). The formulae of Du Bois and Du Bois (1989), Boyd (1935), and U.S. EPA (1985) are based on height and weight. The formula developed by Costeff (1966) is based on 220 observations that estimate body surface area based on weight only. Formulae were compared, and the effect of the correlation between height and weight on the body surface area distribution was analyzed.

Monte Carlo simulations were conducted to estimate body surface area distributions. They were based on the bivariate distributions estimated by Brainard and Burmaster (1992) for height and natural logarithm of weight and the formulae described previously. A total of 5,000 random samples each for men and women were selected from the two correlated bivariate distributions. Body surface area calculations were made for each sample, and for each formula, resulting in body surface area distributions. Murray and Burmaster (1992) found that the body surface area frequency distributions were similar for the four models (see Table 7-14). Using the U.S. EPA (1985) formula, the median surface area values were calculated to be 1.96 m^2 for men and 1.69 m^2 for women. The median value for women is identical to that generated by U.S. EPA (1985) but differs for men by approximately 1%. Body surface area was found to have lognormal distributions for both men and women (see Figure 7-1). It also was found that assuming correlation between height and weight influences the final distribution by less than 1%.

The advantages of this study are that it compared the various formulae for computing surface area and confirmed that the formula used by the U.S. EPA in its analysis—as described in Section 7.3.1.3—is appropriate. This study is considered relevant because the height and weight data used in this analysis predates the height and weight data used in the more recent U.S. EPA analysis (see Section 7.3.1.3).

7.3.2.2. *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 three age groups of the population (infants age 0 to 2 years, children age 2.1 to 17.9 years, and adults age 18 years and older). 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 three age groups and the combined data set.

Table 7-15 presents summary statistics for both adults and children. 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 were lognormally distributed. The SA/BW ratios for adults and all ages combined were normally 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 sex and age on SA/BW distribution also was analyzed by classifying the 401 observations by sex 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.

7.3.2.3. *Garlock et al. (1999)—Adult Responses to a Survey of Soil Contact Scenarios*

Garlock et al. (1999) reported on a survey conducted during the summer of 1996. The objective of the study was to evaluate behaviors relevant to dermal contact with soil and dust. Garlock et al. (1999) conducted computer-aided telephone interviews designed to be nationally representative of the U.S. population. The survey response rate was 61.4%, with a sample size of 450. Adult respondents were asked to provide information on what they usually wore while engaging in the following activities during warm or cold weather: gardening, outdoor team sports (e.g., soccer, softball, football), and home construction projects that include digging, as well as whether they washed or bathed following these activities. Information also was collected on frequency and duration of these activities (see Chapter 16). Similar information was collected for children's outdoor activities and is reported in Wong et al. (2000). Using the activity-specific clothing choices reported for each survey participant and body surface area data from U.S. EPA (1985), Garlock et al. (1999) estimated the percentages of adult total body surface areas that would be uncovered for each of the warm weather and cold weather activities (see Table 7-16). The median ranged from 28 to 33% for warm weather activities and 3 to 8% for cold weather activities.

The advantages of this study are that it provides information on the percentage of adult total surface area that may be exposed to soil during a variety of outdoor activities. These data represent outdoor activities only (no data are provided for exposure to indoor surface dusts).

7.3.2.4. *Wong et al. (2000)—Adult Proxy Responses to a Survey of Children's Dermal Soil Contact Activities*

Wong et al. (2000) reported on two national phone surveys that gathered information on activity patterns related to dermal contact with soil. The first [also reported on by Garlock et al. (1999)] was conducted in 1996 using random digit dialing. Information about 211 children was gathered from adults more than 18 years of age. 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 of age, 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 through October) was obtained. The results of this survey indicated 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 7-17 provides these estimates.

The advantage of this study is that it provides information on the percentage of children's bodies exposed to soil. These data reflect exposed skin areas during warm weather for outdoor activities only.

7.3.2.5. *AuYeung et al. (2008)—The Fraction of Total Hand Surface Area Involved in Young Children's Outdoor Hand-to-Mouth Contacts*

AuYeung et al. (2008) videotaped a total of 38 children (20 girls and 18 boys) between the ages of 1 and 6 years while they engaged in unstructured play activities in outdoor residential locations. The data were reviewed, and contact information was recorded according to the objects contacted and the associated contact configurations (e.g., full palm press, closed hand grip, open hand grip, side hand contact, partial palm, fingers only). The fraction of the hand associated with each of the various configuration categories then was estimated for a convenience sample of children and adults using hand traces and handprints consistent with the various contact configurations. Statistical distributions of the fraction of children's total hand surface associated with outdoor contacts were estimated by combining the information on occurrence and configuration of contacts from the videotaped activity study with the data on the fraction of the hand associated with the various contact configurations. Table 7-18 provides the per-contact fractional surface areas for the various types of objects contacted and for all objects combined. For all objects contacted, fractional surface areas ranged from 0.13 to 0.27. AuYeung et al. (2008) suggested that "the majority of children's outdoor contacts with objects involve a relatively small fraction of the hand's total surface area."

The advantage of this study is that it provides information on the fraction of the hand that contacts various surfaces and objects. However, the data are for a relatively small sample size of children (ages 1 to 6 years). Similar data for adults and older children were not provided.

7.4. ADHERENCE OF SOLIDS TO SKIN

Several field studies have been conducted to estimate the adherence of solids to skin. These field studies consider factors such as activity, sex, age, field conditions, and clothing worn. Section 7.4.1 provides information on key studies that measured adherence of solids to skin according to specific activities. Section 7.4.2 provides relevant information. Relevant studies provide additional perspective on adherence, including information on loading per contact event and the effects of soil/dust type, particle size, soil organic and moisture content, skin condition, and contact pressure and duration. This information may be useful for models based on individual contact events.

7.4.1. Key Adherence of Solids to Skin Studies

7.4.1.1. *Kissel et al. (1996b)—Field Measurements of Dermal Soil Loading Attributable to Various Activities: Implications for Exposure Assessment*

Kissel et al. (1996b) 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, soccer, rugby, reed gathering, irrigation installation, truck farming, outdoor gardening and landscaping (groundskeepers), and playing in mud. Skin-surface areas monitored included hands, forearms, lower legs, faces, and feet (Kissel et al., 1996b).

Table 7-19 provides the activities, information on their duration, sample size, and clothing worn by participants. The subjects' body surfaces (forearms, hands, lower legs for all sample groups; faces and/or feet 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 by using allometric models of surface area.

Table 7-20 presents geometric means for post-activity soil adherence by activity and body region for the four groups of volunteers evaluated. 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.

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 removing historical artifacts from a site ("Archeologists"), individuals erecting a corrugated metal wall ("Construction Workers"), heavy equipment operators ("Equipment Operators"), individuals playing rugby ("Rugby Players"), utility workers jack-hammering and excavating trenches ("Utility Workers"), individuals conducting landscaping and rockery ("Landscape/Rockery"), and individuals performing gardening work ("Gardeners"). The 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). Table 7-19 presents information regarding the groups studied and their observed activities.

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. Table 7-19 describes the number of children within each day's group and the clothing worn. For the second observation day ("Daycare Kids No. 2"), post-activity 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. The play area was described by the authors as being primarily carpeted. Table 7-19 describes the clothing worn by the children within each day's group.

Seven individuals ("Archeologists") were monitored while excavating, screening, sorting, and cataloging historical artifacts from an ancient Native American site during a single event. Eight rugby players were monitored on two occasions after playing or practicing rugby. Eight volunteers from a construction company were monitored for 1 day while erecting corrugated metal walls. Four volunteers ("Landscape/Rockery") were monitored while relocating a rock wall in a park. Four excavation workers ("Equipment Operators") were monitored twice after operation of heavy equipment. Utility workers were monitored while cleaning and fixing water mains, jack-hammering, and excavating trenches ("Utility Workers") on 2 days; five participated on the 1st day and four on the 2nd. 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). Table 7-19 describes the clothing worn by these groups.

Table 7-20 summarizes the geometric means and standard deviations (SDs) of the post-activity soil adherence for each group of individuals and for each body part. 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 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. (2005b)—Child Dermal Sediment Loads Following Play in a Tide Flat*

The purpose of the Shoaf et al. (2005b) study was to obtain sediment adherence data for children playing in a tidal flat ("Shoreline Play"). The study was conducted 1 day in late September 2003 at a tidal flat in Jamestown, RI. A total of nine subjects (three females and six males) ages 7 to 12 years participated in the study. Table 7-19 presents information on activity duration, sample size, and clothing worn by participants. Participants' parents completed questionnaires on 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 7-20, were 0.04 (2.9), 0.17 (3.1), 0.49 (8.2), 0.70 (3.6), and 21 (1.9), respectively. Event duration did not appear to be associated with sediment loading on the skin.

The primary advantage of this study is that it provides adherence data specific to children and sediments, which previously had 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 (nine) and sampling during just 1 day and at one location, make extrapolation to other situations uncertain.

7.4.1.4. *Shoaf et al. (2005a)—Adult Dermal Sediment Loads Following Clam Digging in Tide Flats*

The purpose of this study was to obtain sediment adherence data for adults engaged in unscripted clam digging activities in a tidal flat. The study was conducted over three days in late August 2003 at a tide flat near Narragansett, RI. Eighteen subjects (nine females and nine males) ages 33 to 63 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). Pre- and post-activity sediment loading data were collected using skin rinsing techniques. The data from this study are presented along with the other field studies in Table 7-19 (populations and field conditions) and Table 7-20 (soil adherence results). Activity time was found not to be a good indicator of skin loading.

The primary advantage of this study is that it provides adherence data for sediments which had previously been largely unavailable. Results will be useful to risk assessors considering exposure scenarios involving adult activities at a coastal shoreline or tide flat. The limited number of participants (18) and sampling over just 3 days and one location, make extrapolation to other situations uncertain.

7.4.2. Relevant Adherence of Solids to Skin Studies

7.4.2.1. *Harger (1979)—A Model for the Determination of an Action Level for Removal of Curene Contaminated Soil*

U.S. EPA (1992a, 1988, 1987) reported on experimental values for (soil-related) dust adherence as estimated by Harger (1979). According to U.S. EPA (1992a), "these estimates are based on unpublished experiments by Dr. Rolf Hartung (University of Michigan) as reported in a 1979 memorandum from J. Harger to P. Cole (both from Michigan Toxic Substance Control Commission in Lansing, MI). According to this memo, Dr. Hartung measured adherence using his own hands and found: 2.77 mg/cm^2 for kaolin with a SD of 0.66 and $N = 6$; 1.45 mg/cm^2 for potting soil with SD = 0.36 and $N = 6$; and 3.44 mg/cm^2 for sieved vacuum cleaner dust (mesh 80) with SD = 0.80 and $N = 6$. The details of the experimental procedures were not reported. Considering the informality of the study and lack of procedural details, the reliability of these estimates cannot be evaluated." Accordingly, these data are not considered to be key for the purpose of developing recommendations for soil adherence to the skin.

7.4.2.2. *Que Hee et al. (1985)—Evolution of Efficient Methods to Sample Lead Sources, Such as House Dust and Hand Dust, in the Homes of Children*

Que Hee et al. (1985) used house dust having particle sizes ranging from 44 to 833 µm in diameter, fractionated into six size ranges, to estimate the amount that adhered to the palm of the hand of a small adult. The amount of dust that adhered to skin was determined by applying approximately 5 grams of dust for each size fraction, removing excess dust by shaking the hands, and then measuring the difference in weight before and after application. Que Hee et al. (1985) found no relationship between particle size and adherence for house dusts with particle sizes <246 µm. For all six particle sizes, an average of 63 ± 42 percent of applied dust adhered to the palm of the hand. This represents 31.2 ± 16.6 mg of soil. Excluding the two largest size fractions, 58 ± 29% of the applied dust adhered to the hand, representing 28.9 ± 1.9 mg.

The limitation of these data is that they were based on one adult hand and a single house dust sample. Also, the data are for hands only and are not linked to specific activities.

7.4.2.3. *Driver et al. (1989)—Soil Adherence to Human Skin*

Driver et al. (1989) conducted experiments to evaluate the conditions that may affect soil adherence to the skin of adult hands. Both top soils and subsoils of five soil types (Hyde, Chapanoke, Panorama, Jackland, and Montalto) were collected from sites in Virginia. The organic content, clay mineralogy, and particle size distribution of the soils were characterized, and the soils were dry sieved to obtain particle sizes of ≤250 µm and ≤150 µm. For each soil type, the amount of soil adhering to adult male hands when using both sieved and unsieved soils was determined gravimetrically (i.e., measuring the difference in soil sample weight before and after soil application to the hands). An attempt was made to measure only the minimal or "monolayer" of soil adhering to the hands. This was done by mixing a preweighed amount of soil over the entire surface area of the hands for a period of approximately 30 seconds, followed by removing excess soil by gently rubbing the hands together after contact with the soil. Excess soil that was removed from the hands was collected, weighed, and compared to the original soil sample weight. Driver et al. (1989) measured average adherence of 1.40 mg/cm^2 for particle sizes less than 150 µm, 0.95 mg/cm^2 for particle sizes less than 250 µm, and 0.58 mg/cm^2 for unsieved soils. Analysis of variance statistics showed that the most important factor affecting adherence variability was particle size ($p < 0.001$). The next most important factor was soil type and subtype ($p < 0.001$), but the interaction of soil type and particle size also was significant ($p < 0.01$).

Driver et al. (1989) found statistically significant increases in soil adherence with decreasing particle size, whereas Que Hee et al. (1985) found that different size particles of house dust <246 µm adhered equally well to hands.

The advantages of this study are that it provides additional perspective on the effects of particle size on adherence and that it evaluated several different soil types. However, it is based on data for hands only for a limited number of experimental observations (i.e., one subject). Also, the data are not activity based.

7.4.2.4. *Sedman (1989)—The Development of Applied Action Levels for Soil Contact: A Scenario for the Exposure of Humans to Soil in a Residential Setting*

Sedman (1989) used estimates from Lepow et al. (1975), Roels et al. (1980), and Que Hee et al. (1985) to develop a maximum soil load that could occur on the skin. Lepow et al. (1975) estimated that approximately 0.5 mg of soil adhered to 1 cm^2 of skin. Roels et al. (1980) estimated that 159 mg of soil adhered to the hand of an 11-year-old child. Assuming that approximately 60% (185 cm^2) of the surface area of the hand was sampled, the amount of soil adhering per unit area of skin was estimated to be 0.9 mg/cm^2. Que Hee et al. (1985) estimated that approximately 31.2 mg of housedust adhered to the palm of a small adult. Assuming a hand surface area of 160 cm^2, Sedman (1989) estimated a soil loading of 0.2 mg/cm^2. A rounded arithmetic mean of 0.5 mg/cm^2 was calculated from these three studies. According to Sedman (1989), this was near the maximum load of soil that could occur on the skin, but it is unlikely that most skin surfaces would be covered with this amount of soil (Sedman, 1989).

This study is considered relevant and not key because it does not provide any new data, but uses data from other studies and various assumptions to estimate soil adherence.

7.4.2.5. *Finley et al. (1994)—Development of a Standard Soil-to-Skin Adherence Probability Density Function for Use in Monte Carlo Analyses of Dermal Exposure*

Using data from several existing studies, Finley et al. (1994) developed probability density functions of soil-to-skin adherence. Finley et al. (1994) reviewed studies that estimated adherence among adults and children based on various gravimetric and hand wiping/rinsing methods. Several of these studies were originally conducted for the purpose of estimating lead exposure from soil contact. By combining data from four studies [Charney et al. (1980); Roels et al. (1980); Gallacher et al. (1984); and Duggan et al. (1985)], Finley et al. (1994) estimated a mean ± standard deviation soil adherence value for children of 0.65 ± 1.2 mg soil/cm^2-skin. (50^{th} percentile = 0.36 and 95^{th} percentile = 2.4 mg soil/cm^2-skin). Using data from three studies [Gallacher et al. (1984); Que Hee et al. (1985); and Driver et al. (1989)], Finley et al. (1994) estimated a mean ± standard deviation soil adherence value for adults of 0.49 ± 0.54 mg soil/cm^2-skin. (50^{th} percentile = 0.06 and 95^{th} percentile = 1.6 mg soil/cm^2-skin). Because the distributions of soil-to-skin adherence were similar for children and adults, Finley et al. (1994) developed a probability density function based on the combined data for children and adults. The probability density function is lognormally distributed with a mean ± standard deviation of 0.52 ± 0.9 mg soil/cm^2-skin (50^{th} percentile = 0.25 and 95^{th} percentile = 1.7 mg soil/cm^2-skin).

The advantage of this study is that it provides distributions of soil adherence for children, adults, and children and adults combined. However, it is based on some older, relevant studies that are not activity- or body-part specific.

7.4.2.6. *Kissel et al. (1996a)—Factors Affecting Soil Adherence to Skin in Hand-Press Trials: Investigation of Soil Contact and Skin Coverage*

Kissel et al. (1996a) conducted soil adherence experiments to evaluate the effect of particle size and soil moisture content on adherence to the skin. Five soil types were obtained in the Seattle, WA, area (sand, two types of loamy sand, sandy loam, and silt loam) and were analyzed to determine composition. Clay content ranged from 0.5 to 7.0%, and organic carbon content 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 when 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 the total surface area of one hand, 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. For dry soil, mean adherence was the lowest for the largest particle sizes (i.e., >250 µm) of dry soil (0.06 to 0.34 mg/cm^2) and highest for the smallest particle sizes (0.42 to 0.76 mg/cm^2). Adherence values based on moisture content ranged from 0.22 to 0.54 mg/cm^2 for soils with moisture contents of 9% or less, 0.39 to 3.09 mg/cm^2 for soils with moisture contents of 10 to 19%, and 1.64 to 14.8 mg/cm^2 for soils with moisture contents of 21 to 27%.

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.

7.4.2.7. *Holmes et al. (1996)—Investigation of the Influence of Oil on Soil Adherence to Skin*

Holmes et al. (1996) conducted experiments to evaluate differences in adherence of soil to skin based on soil type, moisture content, and the presence of oil (i.e., petroleum contaminants) in the soil. Three soil types (loamy sand, silt loam, and sand) treated with three concentrations (0, 1, and 10%) of motor oil were used, and the experiments were conducted under wet and dry soil conditions. A single subject pressed the right hand, palm down, into a pan containing soil. The soil adhering to the hand was collected by washing and then weighed. For dry soil containing no oil, adherence values ranged from 0.29 mg/cm^2 for sandy soil to 0.59 mg/cm^2 for silt loam. For wet soil containing no oil (13 to 15% moisture), adherence values were 0.25 mg/cm^2 for silt loam, 1.6 mg/cm^2 for sand, and 3.7 mg/cm^2 for loamy sand. According to Holmes et al. (1996), "high concentrations of petroleum contaminants can increase the dermal adherence of soil, but the magnitude of the effect is likely to be modest."

The advantage of this study is that it provides additional perspective on the factors that affect soil adherence to skin. However, it is based on limited observations (i.e., one subject) for only the hand under experimental conditions (i.e., not activity-based).

7.4.2.8. *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 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 pre-activity and post-activity were obtained from the different body parts examined. The studied groups included adults transplanting 14 plants for 9 to 18 minutes, children playing for 20 minutes in a soil bed of varying moisture content representing wet and dry soils, and adults laying plastic pipes for 15, 30, or 45 minutes. Table 7-21 summarizes the parameters describing each of these activities. Before each trial, each participant was washed to obtain a preactivity or background gravimetric measurement.

For wet soil, post-activity fluorescence results indicated that the hand had a much higher fractional coverage than other body surfaces (see Figure 7-2). As shown in Figure 7-3, post-activity gravimetric measurements for children playing and adults transplanting showed higher soil loading on hands and much lower soil loading on other body surfaces. This also was observed in adults laying pipe. The arithmetic mean percent of hand surface area fluorescing was 65% after 15 minutes laying pipe in wet soil and 85% after 30 and 45 minutes laying pipe in wet soil. The arithmetic mean percent of lower leg surface area fluorescing was ~20% after 15 minutes of laying pipe in wet soil, 25% after 30 minutes, and 40% after 45 minutes. 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. Kissel et al. (1998) observed geometric means of up to about 3 mg/cm^2 on adults' hands after the 30-minute pipelaying activity with wet soil. After children played and adults transplanted in wet soil, geometric mean soil loadings were 0.7 and 1.1 mg/cm^2, respectively. 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 the short activity duration.

7.4.2.9. *Rodes et al. (2001)—Experimental Methodologies and Preliminary Transfer Factor Data for Estimation of Dermal Exposure to Particles*

Rodes et al. (2001) conducted a study using the fluorescein-tagged Arizona Test Dust (ATD) as a surrogate for house dust and evaluated particle mass transfer from surfaces to the human skin of three test subjects (one female and two males). Transfers to wet and dry skin from stainless steel, vinyl, and carpeted surfaces that had been preloaded with tagged ATD were quantified. For carpets, experiments were conducted in which particles were either embedded in the carpet fibers or not embedded. Particles were embedded into carpet by dragging a steel cylinder across the carpet after loading. Controlled hand (palm) press experiments were conducted, and the amount of tagged ATD that had transferred to the skin of the palm was measured using fluorometry. Surface loadings that represented typical indoor conditions were used in the study. Rodes et al. (2001) used defined dust fractions (<80 µm) to evaluate the influence of particles size on transfer. For the experiments with wet hands, a surrogate saliva solution was used. The portion of the hand that contacted the material also was estimated.

Dermal transfer factors were calculated as the mass of particles on the hand (µg on hand/cm^2 of dermal contact area) divided by the mass of particles on the surface contacts (µg on surface/cm^2 of surface contact). Table 7-22 shows the dermal transfer factors (based on the mean of left and right hand presses) for the various surface types and hand moisture contents. The results indicate that for dry hands, transfer from smooth surfaces (i.e., stainless steel) was higher than for other materials (58.2 to 76.0%; mean = 69 $\pm$ 9%). Skin moisture content was shown to be a critical factor in the proportion of particles to transfer (wet hands resulted in 100% transfer from stainless steel). As surface roughness increased, transfer tended to decrease, with carpet surfaces having the lowest transfer factors (3.4 to 16.9%). Embedding particles into the carpet significantly reduced particle transfer. Rodes et al. (2001) also observed that "only about 1/3rd of the projected hand surface typically came in contact with the smooth test surfaces during a press….[and] consecutive presses decreased the particle transfer by a factor of three as the skin became loaded, requiring ~100 presses to reach an equilibrium transfer rate."

The advantage of this study is that it evaluated particle transfer for a variety of surface types and skin conditions. However, a small number of subjects were involved in the study, and Rodes et al. (2001) suggested that when using these data, the similarities and differences in characteristics between ATD and real house dust should be considered.

7.4.2.10. *Edwards and Lioy (2001)—Influence of Sebum and Stratum Corneum Hydration on Pesticide/Herbicide Collection Efficiencies of the Human Hand*

Edwards and Lioy (2001) studied the effects of sebum/sweat and skin hydration on the transfer of pesticide residues in dust to the hands. Under normal conditions, the skin on the hand is covered by a layer of sebum, a mixture of lipids secreted from the sebaceous glands, and sweat that is secreted from sweat ducts. Edwards and Lioy (2001) measured the levels of sebum and moisture on the palm of the hand of one subject prior to conducting hand press experiments using house dust treated with a mixture of four pesticides (atrazine, diazinon, malathion, and chlorpyrifos). The house dust sample was obtained from vacuum cleaner bags and was sieved to <250 µm. The dust was settled onto the sample surfaces and sprayed with the pesticide mixture, and the subject pressed one hand to the surface in a series of trials conducted approximately 1 week apart. The hand was rinsed with solvent to extract any transferred pesticide/dust, and the solution was analyzed for pesticide residues. Transfer efficiencies (percentage) were calculated as the concentration of residues measured in the hand rinse solution divided by the concentration of pesticide on the sampling surface times 100. The results of this study indicated that the transfer efficiencies of two pesticides in dust were negatively correlated with sebum levels (i.e., increased sebum levels resulted in a 13% reduction in atrazine transfer and an 8% reduction in malathion transfer) and transfer efficiencies of two pesticides in dust were negatively correlated with skin hydration [i.e., increased skin moisture resulted in a 7% reduction in diazinon transfer and 5% reduction in chlorpyrifos transfer; Edwards and Lioy (2001)].

The advantage of this study is that it provides additional perspective on factors that can affect adherence of solids to the skin. However, it is considered relevant and not key because the transfer of dust was studied for the hands only and used experimental conditions not based on exposure-related activities.

7.4.2.11. *Choate et al. (2006)—Dermally Adhered Soil: Amount and Particle Size Distribution*

Choate et al. (2006) investigated the soil characteristics that affect particle adherence to human skin. The factors considered included particle size, organic carbon content, and soil moisture. Day-to-day variability and differences based on whether or not hands were washed before contacting the soil also were examined. A total of 108 subjects (1/3 female) between 18 and 30 years of age participated in one or more of a series of soil adherence experiments. Some of the experiments were conducted using clay loam soil collected in Colorado, while others were conducted using silty-clay loam soil collected in Iowa. Soil moisture contents ranged from 1 to 10%. Choate et al. (2006) used either preweighed adhesive tape or hand washing with distilled water to remove and collect soil that had adhered to the palm of subjects' hands after contact with bulk soil under controlled experimental conditions. Removed soil was weighed, and the mass of soil per area of skin surface was calculated for each sample.

Based on the adhesive tape tests, an average of 0.7 mg/cm^2 of the Colorado soil adhered to the hand ($N = 6$ subjects each sampled using the right or left hand on 10–12 study days). There were no significant differences between the left and right hands, but there were "large average variabilities . . . both between subjects on a given day (±52%) and for an individual subject on different days (±50%)." Differences between soil adherence to hands that had or had not been washed prior to soil contact were observed, with hand washing resulting in a lower mean adherence value (0.51 mg/cm^2; $N = 76$) than non-washing (1.1 mg/cm^2; $N = 72$), when soil with a moisture content of 4.7% was used. The authors suggested that this is "probably due to the removal [during washing] of oils from the skin that aid in the adherence of soil particles." Soil adherence for the two types of soils (i.e., from Colorado and Iowa) with low moisture content (i.e., <2%) averaged 0.64 and 0.69 mg/cm^2, compared to 1.47 and 1.36 mg/cm^2 for those with high moisture content (9% to 10%). Large particle fractions of the soils with higher moisture content adhered more readily than those in soils with low or medium moisture content. The "adhered fractions of dry or moderately moist soils with wide distribution of particle sizes generally consist[ed] of particles of diameters <63 µm." The organic carbon content of the soils did not appear to be an important contributor to soil adherence.

The advantage of this study is that it provides additional perspective on factors that affect soil adherence to skin by using a larger number of subjects compared to some of the earlier studies. However, the data are based only on controlled experimental conditions and may not be representative of the specific types of activities in which dermal exposure may occur.

7.4.2.12. *Yamamoto et al. (2006)—Size Distribution of Soil Particles Adhered to Children's Hands*

Yamamoto et al. (2006) conducted both laboratory and field experiments that showed finer soil particles adhered more readily to children's hands than coarse particles. In the laboratory, one female subject pressed her hand into a tray containing reference soil. Her hand then was washed in ultrapure water that was analyzed to determine the size distributions and the amount of soil that had adhered to the hand. Yamamoto et al. (2006) observed that the mode diameter of soil adhering to the hand (22.8 ± 0.0 µm) was less than that of the reference soil (36.9 ± 4.9 µm), indicating that finer particles adhered more efficiently to the hand. The effect of hand moisture was tested by moistening the hand prior to pressing it onto the tray of soil. Yamamoto et al. (2006) observed that while the amount of soil that adhered to the hand increased with hand moisture, the size distributions were not greatly changed.

A separate field experiment was conducted in which ten 4-year-old children (five males and five females) attending a nursery school in Japan participated. After playing in the playground and sandbox for a morning or afternoon, the children's hands were washed in bottles containing 500 mL ultrapure water, and aliquots of the water were analyzed to determine the size distributions and amounts of particles that had adhered to the hands. The particles sizes of soil samples collected from the children's playing area (i.e., playground, field, and sandbox) also were analyzed. The mean, median, and maximum amounts of soil adhering to the children's hands were 26.2, 15.2, and 162.5 mg/hand, respectively. Assuming a surface area of the hand of 210 cm^2, the amounts are equivalent to 0.125, 0.73, and 0.774 mg/cm^2, respectively. Compared to the soil in the children's play area, the soil adhering to the children's hands was composed primarily of the finer particles.

The advantage of this study is that both laboratory and field measurements were used to evaluate particle sizes of soil that adheres to the hands. However, only one subject participated in the laboratory study, and the children's activities in the field portion were not indexed to the amount of time spent performing soil contact activities.

7.4.2.13. *Ferguson et al. (2009a; 2009c; 2009b; 2008)—Soil-Skin Adherence: Computer-Controlled Chamber Measurements*

Ferguson et al. (2009a; 2009c; 2009b; 2008) conducted a series of soil adherence experiments by using a mechanical chamber designed to control and measure pressure and time of contact with surfaces loaded with soil. Adherence of play sand and lawn soil to human cadaver skin and cotton sheet samples was measured after contact with either loaded carpet or aluminum surfaces. Multiple pressure levels (20 to 50 kPa), durations of contact (10 to 50 seconds), and particle sizes (<139.7 µm and $\geq$139.7 to <381.0 µm) were evaluated (Ferguson et al., 2009a; Ferguson et al., 2009b; Beamer et al., 2008). Also, both single- and multiple-contact experiments were conducted (Ferguson et al., 2009c). Soil adherence was estimated by weighing the carpet or aluminum samples loaded with play sand or lawn soil both before and after controlled contacts occurred and calculating the weight differences. Each experiment, using different combinations of pressure, contact duration, particle size, soil type, surface, and contact material, was repeated multiple times. Table 7-23 presents a comparison of the adherence values for contact with carpet and aluminum surfaces. Mean soil to skin adherence from contact with aluminum surfaces (1.18 mg/cm^2) was higher than from carpet (0.71 mg/cm^2). In general, soil transfer increased as pressure increased, and contact durations of 30 seconds or more did not appear to result in higher adherence. For carpets, larger particle size was associated with higher adherence, while smaller particle size was associated with higher adherence from aluminum (Ferguson et al., 2009a), Based on a comparison of data from experiments with multiple contacts, Ferguson et al. (2009c) found that, "on average, 8% of the original transfer amount will transfer during a second contact. Therefore, attaching a soil/adherence transfer of the original magnitude for every contact may result in overestimates for exposure."

The advantages of these studies are that they provide data from controlled experiments in which a variety of conditions were tested. However, a single carpet type was used, and transfer may differ based on carpet type. Also, adherence may be different for different types of soil or house dust, as well as for different skin types and conditions. Differences in the nature of contact and the initial surface soil loadings also may affect adherence.

7.5. FILM THICKNESS OF LIQUIDS ON SKIN

Information on the thickness of liquids on human skin is sometimes used to estimate dermal exposure to contaminants in liquids that come into contact with the skin. For example, these data are used to estimate exposure to consumer products in U.S. EPA's Exposure and Fate Assessment Screening Tool [EFAST; U.S. Environmental Protection Agency (2007b)]. Section 7.5.1 provides the available data on film thickness of liquids on the skin. However, these data are limited; therefore, studies related to this factor have not been categorized as key or relevant in this chapter, and specific recommendations are not provided for this factor.

7.5.1. U.S. EPA (1987)—Methods for Assessing Consumer Exposure to Chemical Substances; and U.S. EPA (1992c)—A Laboratory Method to Determine the Retention of Liquids on the Surface of Hands

U.S. EPA (1992c, 1987) reported on experiments that were conducted to measure the retention of liquids on hands after contact with six different types of liquids (mineral oil, cooking oil, water soluble bath oil, 50:50 oil/water emulsion, water, and 50:50 water ethanol). These liquids were selected because they were non-toxic and represented a range of viscosities and likely retention on the hands. Five exposure conditions were tested to simulate activities in which consumers' hands may be exposed to liquids, including (1) contact with dry skin (initial contact), (2) contact with skin previously exposed to the liquid and still wet (secondary contact), (3) immersion of a hand into a liquid, (4) contact from handling a wet rag, and (5) contact during spill cleanup. For the initial contact scenario, a cloth saturated with liquid was rubbed over the front and back of both clean, dry hands for the first time during an exposure event. For the secondary contact scenario, a cloth saturated with liquid was rubbed over the front and back of both hands for a second time, after as much as possible of the liquid that adhered to skin during the first contact event was removed using a clean cloth. For the immersion scenario, one hand was immersed in a container of liquid and then removed; the liquid was allowed to drip back into the container for 30 seconds (60 seconds for cooking oil). For the scenario involving the handling of a rag, a cloth saturated with liquid was rubbed over the palms of both hands in a manner simulating handling of a wet cloth. For the spill cleanup scenario, a subject used a clean cloth to wipe up 50 mL of liquid poured onto a plastic laminate countertop. For each of the five scenarios, retention was measured immediately after applying the liquid to the hands and after partial and full removal by wiping. Partial wiping was defined as "lightly [wiping with a removal cloth] for 5 seconds (superficially)." Full wiping was defined as "thoroughly and completely as possible within 10 seconds removing as much liquid as possible." Four human subjects were used in the experiments, and multiple replicates (four to six) were conducted for each subject and type of liquid and exposure condition. Retention of liquids on the skin was estimated by taking the difference between the weight of the cloth(s) before and after wiping and dividing by skin surface area. For the immersion scenario, retention was estimated as the weight difference in the immersion container before and after immersion. Film thickness (cm) was estimated as the amount of liquid retained on the skin (g/cm^2) divided by the density of the liquid (g/cm^3) used in the experiment.

Table 7-24 presents the estimated film thickness data from these experiments. Film thickness data may be used with information on the density of a liquid and the weight fraction of the chemical in the liquid to estimate the amount of contaminant retained on the skin (i.e., amount retained on skin [g/cm^2] = film thickness of liquid on skin [cm] × density of liquid [g/cm^3] × weight fraction [unitless]). Dermal exposure (g/event) may be estimated as the amount retained on the skin (g/cm^2) times the skin surface area exposed (cm^2/event).

The advantage of this study is that it provides data for a factor for which information is very limited. Data are provided for various types of liquids under various conditions. However, the data are based on a limited number of observations and may not be representative of all types of exposure scenarios.

7.6. RESIDUE TRANSFER

Several methods have been developed to quantify rates of residue transfer to the human skin of individuals performing activities on treated surfaces. These methods have been used to either develop transfer efficiencies or estimate residue transfer coefficients. Transfer efficiencies are the fraction (or percentage) of surface residues transferred to the skin. Transfer coefficients (cm^2/hour) represent the ratio of the dermal exposure during a specified time period (mg/hour) based on a specific exposure activity (e.g., harvesting a crop or performing indoor or outdoor activities) to the environmental concentration of the pesticide (mg/cm^2). Transfer coefficients are estimated in studies in which environmental residue levels are measured concurrently with exposure levels for particular job functions or activities. These studies have been conducted primarily for the purpose of estimating exposure to pesticides. Exposure levels are typically measured using dosimeter clothing that is worn by study subjects during the conduct of specific activities and then removed and analyzed for pesticide residues. Sometimes biomonitoring studies (i.e., urine analyses) or other methods (e.g., hand wash) are used to estimate exposure levels. Environmental residues are estimated using various techniques, including use of deposition coupons, wipe samples, or a residue collection tool such as a "drag sled" or roller on indoor or outdoor surfaces, as described in U.S. EPA (1998).

Although chemical-specific transfer coefficients are typically preferred for estimating exposure, U.S. EPA (2009) has used data from published and unpublished residue transfer studies to develop some generic activity-specific transfer coefficient assumptions to use in exposure assessments when chemical-specific data are unavailable. Use of these generic transfer coefficients for pesticides is based on the assumption that the transfer of residues to human skin is based primarily on the types of activities being performed rather than on the specific characteristics of the pesticide. This section presents data for published residue transfer studies only (i.e., unpublished data are not included here).

A transfer coefficient, expressed in units of cm^2/hour, is used to estimate exposure to chemical residues by combining it with the environmental concentration (in units of mg/cm^2) and an exposure time in hours/days (e.g., exposure [mg/day] = transfer coefficient [cm^2/hour] × environmental concentration [mg/cm^2] × exposure time [hours/day]). When using transfer co-efficients, it is important to ensure that the residue levels used are consistent with the method for developing the transfer coefficient (e.g., residue levels based on deposition coupons should be used with transfer co-efficients based on deposition coupons; residue levels based on a residue collection tool such as the California Roller should be used with transfer coefficients based on the same type of tool). Information on methods that may be used to estimate transferrable residues from indoor surfaces and dislodgeable residues from turf may be found in Hsu et al. (1990), Geno et al. (1996), Camann et al. (1996), Fortune (1998a, b), and Fortune et al. (2000). U.S. EPA (2009) describes the use of generic transfer coefficients for a variety of activities involving pesticides. Section 7.6.1 discusses the published data on transfer efficiencies and transfer coefficients gathered from the scientific literature. Because residue transfer depends on the specific conditions under which exposure occurs (e.g., activity, contact surfaces, age), the studies described in Section 7.6.1 have not been categorized as key or relevant, and specific recommendations are not provided for this factor.

7.6.1. Residue Transfer Studies

7.6.1.1. *Ross et al. (1990)—Measuring Potential Dermal Transfer of Surface Pesticide Residue Generated From Indoor Fogger Use: An Interim Report*

Ross et al. (1990) utilized choreographed exercise routines to measure the amount of pesticide residues that may be transferred from carpets to adult skin. Five adult volunteers wore dosimeter clothing (i.e., cotton tight, shirt, gloves, and socks) over the skin areas that normally would be exposed and conducted exercise routines for 18.2 minutes in hotel rooms where pesticides (i.e., chlorpyrifos and d-trans-allethrin) were applied (20 minutes total exposure to account for entry and exit from the treated rooms). The exercise routines were performed at times ranging from 0 to 13 hours after pesticide application. The routines included “substantial body contact between the subject and treated carpet” and were “intended to represent a person’s day-long (16 hours]) contact with pesticide-treated surfaces in a home in which a total discharge fogger had been used” (Krieger et al., 2000). The dosimeter clothing was assumed to retain the same amount of pesticide as the skin (Krieger et al., 2000). It was collected and analyzed for pesticide residues to estimate the amount of residues that had been transferred from the carpet the skin. Environmental concentrations of the pesticides were measured in the rooms where the exercise routines took place by using gauze coupons placed in the rooms prior to pesticide application.

Ross et al. (1990) found that the transfer of pesticides (i.e., potential dermal exposure) differed according to the body part exposed and declined with time after pesticide application with a rapid decline in pesticide transfer between 6 and 12 hours. Some of the possible factors attributed to this decline were loss of formulation inerts, absorption by or adsorption to the carpet, breakdown to non-detected materials, downward migration into non-contact areas of the carpet or adsorption to dust particles, and volatilization. Table 7-25 provides the mean transfer efficiencies (i.e., percent of pesticide residues transferred to the various body parts from carpet), based on the time after application. These percentages represent the clothing residues divided by the environmental concentrations—based on deposition coupons—times 100 (Ross, 1990).

The study demonstrated the efficacy of using choreographed activities to estimate pesticide residue transfer. A limitation of this study is that the exercise routines used may not be representative of other types of indoor activities.

7.6.1.2. *Ross et al. (1991)—Measuring Potential Dermal Transfer of Surface Pesticide Residue Generated From Indoor Fogger Use: Using the CDFA Roller Method: Interim Report II*

Ross et al. (1991) reported on the use of the California Food and Drug Administration (CDFA) roller to estimate pesticide transfer from carpet. This study was conducted in parallel with the Ross et al. (1990) study. The roller device was tested as a surrogate for human subjects for measuring residue transfer from indoor surfaces. The roller was a 12-kg, foam-covered rolling cylinder equipped with stationary handles. A cotton cloth covered with plastic was placed over a pesticide-treated carpet, and the device was rolled over it 10 times. The cloth then was collected and analyzed for pesticide residues. Environmental residue levels were measured using gauze coupons placed on the carpet prior to pesticide application. Mean gauze dosimeter residues were compared to the amount of material transferred to the roller sheet. The results showed that the carpet roller method transferred 1 to 3% of carpet residue to the roller sheet. As in the 1990 study, pesticide transferability decreased with time and with contact with the treated surface. Using the data from Ross et al. (1990), which involved the collection of pesticide residues on dosimeter clothing worn by human subjects who engaged in choreographed exercise routines, and the roller data from this study, Ross et al. (1991) calculated residue transfer coefficients as the total µg of residues transferred to dosimetry clothing times hours of exposure/µg/cm^2 residue transferred to the roller sheet. Mean transfer coefficients were 200,000 ± 50,000 cm^2/hr for chlorpyrifos and 140,000 ± 30,000 cm^2/hr for d-trans allethrin. Ross et al. (1991) concluded that the use of a carpet roller was a good surrogate for measuring residue transfer.

A limitation of this study is that transfer of surface residues from the carpet to CDFA roller may not be representative of transfer of residues based on various human activities.

7.6.1.3. *Formoli (1996)—Estimation of Exposure of Persons in California to Pesticide Products That Contain Propetamphos*

Formoli (1996) conducted a study to estimate exposure to propetamphos that was applied to carpets. Five adult subjects (two men and three women) wore whole body dosimeters and performed structured exercise routines for 20 minutes on the treated carpet. The subjects’ clothing was cut up and analyzed for pesticide residues. Transferable residues also were collected from the carpet by moving a roller device over cotton cloth that was subsequently analyzed for pesticide residues. Using the dermal exposure data from the dosimeters and the transferable residue data from the roller device, Formoli (1996) calculated a transfer coefficient of 43,800 cm^2/hr.

These data are useful because they provide perspective on residue transfer data based on controlled experimental conditions. However, the limitations of this study are that the exercise routines used may not be representative of all types of activities in which transfer of surface residues occurs, and the data are based on a single pesticide and a limited number of observations.

7.6.1.4. *Krieger et al. (2000)—Biomonitoring and Whole Body Dosimetry to Estimate Potential Human Dermal Exposure to Semi-Volatile Chemicals*

Krieger et al. (2000) conducted a study similar to the Ross et al. (1991; 1990) studies. The purpose of the Krieger et al. (2000) study was to compare dermal exposure estimated by four different methods. The methods included (1) measurement of residues deposited onto foil coupons that had been placed on the carpet prior to pesticide application; (2) measurement of residues transferred to cotton cloth using the CDFA roller method, as described by Ross et al. (1991); (3) measurement of residues transferred to whole body cotton dosimeters during structured exercise routines; and (4) analysis of biomonitoring (urine) from subjects who participated in structured activities wearing either cotton whole body dosimeters or swimsuits. A total of 13 subjects wore whole body dosimeters while 21 subjects wore bathing suits. Foggers containing the pesticide chlorpyrifos were discharged from the centers of two identical rectangular meeting rooms at the University of California, Riverside. The rooms were kept unventilated for 2 hours and then were opened with a room divider removed during 30 minutes of ventilation. Surface deposition and dislodgeable residues were measured with three aluminum foil coupons and cotton sheets placed at two, four, and six feet from each fogger. The exercise routines were the same as those used in Ross et al. (1990). Biomonitoring was conducted by collecting four successive 24-hour urine samples from each subject 1 day prior to exposure and 3 days after exposure to chlorpyrifos.

The average amounts of pesticide transferred to the dosimeters were 0.27 μg/cm^2 based on the CDFA roller method and 0.73 μg/cm^2 based on the whole body dosimetry method. These transfer amounts represent 7.5% and 20.2%, respectively, of the average concentration of pesticide on the surface of the carpet (3.6 μg/cm^2) based on the deposition coupons. Calculating the transfer coefficient in the same way as Ross et al. (1991), the mean transfer coefficient would be approximately 154,000 cm^2/hr (13,758 μg of residues transferred to dosimetry clothing per 0.33 hour of exposure/0.27 μg/cm^2 residue transferred to the roller sheet). Using the concentration of residues on the deposition coupons instead of those transferred to the roller cloth as the environmental concentration would give a transfer coefficient of approximately 12,000 cm^2/hr (13,758 μg of residues transferred to dosimetry clothing per 0.33 hour of exposure/3.6 μg/cm^2 residue deposited on the carpet). Absorbed doses and biomonitoring data reported by Krieger et al. (2000) are not summarized because the data are specific to the pesticide (chlorpyrifos) studied. However, the biomonitoring data indicate that "both types of dosimeters [roller cloth and whole body] removed substantially more [pesticide] than was transferred and absorbed by human skin" (Krieger et al., 2000).

The advantage of this study is that it compared estimates of pesticide residue transfer using a variety of methods. However, the results are based on a single pesticide and may not be representative of other chemicals or activities that may result in exposure.

7.6.1.5. *Clothier (2000)—Dermal Transfer Efficiency of Pesticides From New, Vinyl Sheet Flooring to Dry and Wetted Palms*

Clothier (2000) compared the transfer of pesticide residues from vinyl flooring to dry, water-wetted, and saliva-wetted hands. Three different pesticides were used in the study (chlorpyrifos, piperonyl butoxide, and pyrethrin). Three male subjects participated in the study by pressing their hand palm down on the vinyl surface. Prior to performing the hand presses, the hands were either treated with a sample of their own saliva or water or received no pretreatment (dry hands). Transferable residues also were collected using the polyurethane foam (PUF) roller method described by Camann et al. (1996). Deposition coupons also were used to measure the amount of pesticide applied to the flooring. Transfer efficiencies were estimated as the rate of transfer to hands or PUF roller (μg/cm^2) /mean surface loading (μg/cm^2) times 100. Table 7-26 presents the transfer efficiencies from this study. Transfer efficiencies were higher for wetted palms than for dry palms and for the PUF roller than for dry hands.

The advantage of this study is that it provides perspective on the effects of hand moisture on residue transfer. The data are based on three pesticides applied to vinyl surfaces and a limited number of subjects under controlled experimental conditions. However, the data may not reflect transfer associated with other chemicals or activities.

7.6.1.6. *Bernard et al. (2001)—Environmental Residues and Biomonitoring Estimates of Human Insecticide Exposure From Treated Residential Turf*

Bernard et al. (2001) conducted a study similar to those conducted by Ross et al. (1990) and Krieger et al. (2000), except that the exercise routines were conducted on pesticide-treated turf instead of on pesticide-treated carpets. Exposure was measured by analyzing whole body dosimeters worn by female participants during 20 minutes of exercise that occurred approximately 3.5 hours after pesticide had been applied to the turf. Pesticide deposition was estimated by collecting and analyzing cotton coupons present at the time of application. Dislodgeable residues were measured by collecting and rinsing foliage samples in an aqueous solution, and transferable turf residues were estimated using the CDFA roller 0, 1, and 3 days after application. Turf residues based on spray deposition (i.e., coupons), dislodgeable (aqueous wash) residues, and transferable (roller) residues were 12, 3.4, and 0.085 μg/cm^2, respectively. This suggests that dislodgeable residues were approximately 28% of the deposition residues, and transferable residues were less than 1% of the deposition residues. Bernard et al. (2001) estimated that exposures based on transferable residues and those based on whole body dosimetry would be similar because transferable residues based on whole body dosimetry and those based on the roller technique were similar.

This study provides perspective on residue transfer from treated turf. However, the data are for a single pesticide and may not be representative of other chemical substances or exposure conditions.

7.6.1.7. *Cohen Hubal et al. (2005)—Characterizing Residue Transfer Efficiencies Using a Fluorescent Imaging Technique*

Cohen Hubal et al. (2005) used a fluorescent tracer method to evaluate the factors that affect the transfer of residues from indoor surfaces to the hands. The non-toxic fluorescent tracer vitamin B_2 riboflavin was applied to carpet and laminate flooring. Two levels of analyte loading were evaluated in the study (2 μg/cm^2 and 10 μg/cm^2). Three adult subjects participated in a series of controlled experiments in which the hands contacted the treated surfaces using one of two different levels of pressure for one of two different durations. Transfer as a result of multiple sequential contacts also was evaluated. The hands were characterized as dry, moist, or sticky prior to conducting the hand presses on the treated flooring materials. To simulate moist hands, the hands were placed under a cool mist vaporizer for 20 seconds; to simulate sticky conditions, 1.2 grams of Karo Syrup was applied to the hands. Dermal loading on the hands was measured by using a fluorescence imaging system. Transfer efficiencies were estimated by dividing the mass of tracer on the hand per unit surface area (μg/cm^2) divided by the loading of tracer on the carpet or laminate surface (μg/cm^2) times 100. Incremental transfer efficiency was calculated separately for each individual contact, whereas overall transfer efficiency was calculated cumulatively for the series of contacts. Table 7-27 provides the incremental and overall transfer efficiencies based on the hand conditions, the surface type, the surface loading, and the number of contacts. Based on the data in Table 7-27, the mean transfer efficiency after a single contact ranged from 3 to 14% for dry and sticky hands, respectively. According to Cohen Hubal et al. (2005), surface loading and skin condition were important parameters in characterizing transfer efficiency, but duration of contact and pressure did not have a significant effect on transfer.

An advantage of this study is that it uses a tracer method to estimate transfer efficiency from surfaces to human skin. It also provides perspective on various conditions that may affect transfer efficiency. A limitation is that the data may not reflect transfer associated with specific chemicals or activities.

7.6.1.8. *Hubal et al. (2008)—Comparing Surface Residue Transfer Efficiencies to Hands Using Polar and Non-Polar Fluorescent Transfer*

As a follow up to the Cohen Hubal et al. (2005) study, Hubal et al. (2008) conducted a study using a second fluorescent tracer, Uvitex OB, which has different physical-chemical properties than riboflavin. The fluorescent tracer, which was used as a surrogate for pesticide residues, was applied to carpet or laminate surfaces at two different loading levels, and controlled hand transfer experiments were conducted by using various pressures and motions (i.e., press and smudge), numbers of contacts, and different hand conditions (i.e., dry or moist). The mass of tracer transferred to the hands was measured using a fluorescent tracer imaging system. The results indicated that "overall percent transfer ranged from 0.8 to 45.5% for the first contact and 0.6 to 19.4% for the seventh contact," and dermal loadings increased in a near linear fashion through the seventh contact. "Transfer was greater for laminate (over carpet), smudge (over press), and moist (over dry)" (Hubal et al., 2008). For lower surface loadings, dermal transfer increased through the seventh contact, suggesting that multiple contacts may be required to reach an effective equilibrium with the surface.

Similar to the previous study, the advantage of these data is that they are based on tracers and provide information on factors affecting residue transfer. However, the data may or may not accurately reflect transfer for specific chemicals or activities.

7.6.1.9. *Beamer et al. (2009)—Developing Probability Distributions for Transfer Efficiencies for Dermal Exposure*

Beamer et al. (2009) combined data from nine residue transfer studies and developed distributions for three pesticides (chlorpyrifos, pyrethrin I, and piperonyl butoxide) and three surface types (foil, vinyl, and carpet). The studies used for developing these distributions included Hsu et al. (1990), Ross et al. (1991), Camann et al. (1996; 1995), Geno et al. (1996), Fortune (1998a, b), Clothier (2000), and Krieger et al. (2000). Beamer et al. (2009) stratified the data by chemical and surface type. Statistical methods were used to develop the distributions, based on combined data from studies that used different sampling methods, surface concentrations, formulations, sampling time, and skin conditions (i.e., dry or wet). Transfer efficiencies were defined as the amount transferred to skin or a transfer media used as a surrogate for skin divided by the amount of pesticide applied to the surface.

Table 7-28 presents the lognormal parameter values for the three chemicals and three surface types evaluated. The results of statistical analyses indicated that the distributions of transfer efficiencies were statistically different for the surface types and chemicals shown in Table 7-28. Transfer efficiency was highest for foil for all chemicals, followed by vinyl and carpet. For example, the geometric mean transfer efficiencies ranged from 0.01 to 0.02 (i.e., 1 to 2%) for carpet, 0.03 to 0.04 (3 to 4%) for vinyl, and 0.83 to 0.86 (83 to 86%) for foil. According to Beamer et al. (2009), these distributions can be used for modeling transfer efficiencies.

An advantage of this data set is that it uses data from several of the studies described in this chapter to develop distributions for three pesticides and three surface types. However, there is some uncertainty with regard to the representativeness of these data for other chemicals or exposure conditions.

7.7. OTHER FACTORS

7.7.1. Frequency and Duration of Dermal (Hand) Contact

This section provides information from studies that evaluated activities that may affect dermal exposure. This includes information on the frequency and duration of dermal contact with objects and surfaces. Additional information on activities patterns and consumer product use that affect the frequency and duration of dermal contact is provided in Chapters 16 and 17. Information on hand-to-mouth contact frequency in presented in Chapter 4.

7.7.1.1. *Zartarian et al. (1997)—Quantified Dermal Activity Data From a Four-Child Pilot Field Study*

Zartarian et al. (1997) conducted a pilot field study in California in 1993 to estimate children's dermal contact with objects in their environment. Four Mexican American farm worker children ages 2 to 4 years were videotaped to record their activities over a 1-day period. Five to 30% of the children's time was spent outdoors, while the remainder was spent indoors. Videotape data were obtained over 6 to 11 waking hours for the four children (i.e., a total of 33 hours of videotape). The videotapes were translated to provide information about the objects that the children contacted, as well as the frequency and duration of contact. The data indicated that most objects were contacted for approximately 2 to 3 seconds in duration, and hard surfaces and hard toys were touched by children's hands for the longest percent of the time (Zartarian et al., 1997). Table 7-29 provides the average contact frequency for the left and right hands of the four children who participated in the study. Frequency of contact was highest for hard surfaces and hard toys (see Table 7-29).

The advantage of this study is that it was the first in a series of papers that used video-transcription methods to evaluate children's micro-activities relative to potential dermal exposure. However, the number of participants in this study (four children) was small, and the results may not be representative of all U.S. children.

7.7.1.2. *Reed et al. (1999)—Quantification of Children's Hand and Mouthing Activities Through a Videotaping Methodology*

Reed et al. (1999) used a videotaping methodology similar to that used by Zartarian et al. (1997) to quantify the hand contact activities of 30 children in New Jersey. A total of 20 children ages 3 to 6 years were observed in daycare facilities, while an additional 10 children, ages 2 to 5 years were observed in residential settings. Total videotaping time ranged from 3 to 7 hours for the daycare children and 5 to 6 hours for the residential children. Frequency of hand contact with objects and surfaces was quantified by recording touches with clothing, dirt, objects, and smooth or textured surfaces, as observed on video. According to Reed et al. (1999), "comparison of activities of children in home settings and daycare showed that rates of many of the activities did not differ significantly between venues and therefore, data from homes and daycare were combined." Table 7-30 presents the hand contact frequency data for the 30 children observed in this study. High contact frequencies were observed for clothing, objects, other, and smooth surfaces.

The advantages of this study are that more children were observed than in the previous study, and both daycare and residential children were included. However, the children were from a single location and may not be representative of all U.S. children.

7.7.1.3. *Freeman et al. (2001)—Quantitative Analysis of Children's Micro-Activity Patterns: The Minnesota Children's Pesticide Exposure Study*

Freeman et al. (2001) conducted a survey response and video-transcription study of some of the respondents in a phased study of children's pesticide exposures in the summer and early fall of 1997. A probability-based sample of 168 families with children ages 3 to <14 years old in urban (Minneapolis/St. Paul) and non-urban (Rice and Goodhue Counties) areas of Minnesota answered questions about children's behaviors that might contribute to exposure via dermal contact or non-dietary ingestion. Of these 168 families, 19 agreed to videotaping of the study children's activities for a period of 4 consecutive hours. The videotaped children ranged in age from 3 to 12 years of age but were divided into four age groups (3 to 4 years, 5 to 6 years, 7 to 8 years, and 10 to 12 years) for the purposes of quantifying microactivities. The frequency of touching clothing, textured surfaces (e.g., carpets and upholstered furniture), smooth surfaces (e.g., wood or plastic furniture, hardwood floor), or objects (e.g., toys, pencils, or other things that could be manipulated) was quantified by observing the behaviors on the videotapes during a 4-hour observation period. Table 7-31 shows the frequency of hand contacts per hour for the 19 children.

An advantage to this study is that it included results for various ages of children. However, the children in this study may not be representative of all U.S. children. Also, the presence of unfamiliar persons following the children with a video camera may have influenced the video-transcription methodology results.

7.7.1.4. *Freeman et al. (2005)—Contributions of Children's Activities to Pesticide Hand Loadings Following Residential Pesticide Application*

Freeman et al. (2005) gathered data on hand contacts with surfaces and objects as part of a study to evaluate pesticide exposure in residential settings. A convenience sample of 10 children between the ages of 24 and 55 months was selected for videotape observation on the 2nd day after their homes were treated with pesticides. The children were videotaped during a 4-hour period (only three children spent time outside the house, with outdoor times ranging from 21 to 57 minutes). The videotapes were transcribed to quantify contact rates in terms of frequency and duration. According to Freeman et al. (2005), "the duration of contact of most contact events was very short (2−3 seconds)," but contact with bottles, food, and objects tended to be somewhat longer (median durations ranged from 4.5 to 7.5 seconds for these items). Table 7-32 presents the right-hand contact rates (contacts per hour) for the various objects and surfaces. High contact items include objects and smooth surfaces.

The advantage of this study is that it provides additional information on hand contact frequency. However, the data are based on a limited number of children and were collected over a relatively short time period. Also, the presence of a video camera may have affected the children's behavior.

7.7.1.5. *AuYeung et al. (2006)—Young Children's Hand Contact Activities; an Observational Study via Videotaping in Primarily Outdoor Residential Settings*

AuYeung et al. (2006) gathered data on children's hand contact activities by videotaping them in outdoor residential settings in 1998–1999. A total of 38 children ages 1 to 6 years from middle class suburban families were recruited from the San Francisco Bay peninsula area to participate in the study. Each child was videotaped during 2 hours of natural (i.e., unstructured) play in an outdoor location (i.e., park, playground, outdoor residential area). Videotapes then were translated using a software package specially designed for this use. Contacts were tabulated for 15 object surface categories and for all non-dietary objects and all objects and surfaces combined. Hourly contact frequency, median duration per contact, and hourly contact duration were calculated for each child for the left hand, right hand, and both hands combined, and summary statistics were developed for all children combined. Table 7-33 provides the data for outdoor locations. According to AuYeung et al. (2006), these data suggest that children have a large number of short-duration contacts with outdoor objects and surfaces. AuYeung et al. (2006) also collected some limited data for indoor locations. These data are based on nine children who were videotaped for 15 minutes or more indoors. Table 7-34 provides summary data for these children.

The advantage of this study is that it provides dermal (hand) contact data for a wide variety of outdoor objects and surfaces. The data for indoor environments were limited, however, and the presence of unfamiliar persons following the children with a video camera may have influenced the video-transcription methodology results.

7.7.1.6. *Ko et al. (2007)—Relationships of Video Assessments of Touching and Mouthing Behaviors During Outdoor Play in Urban Residential Yards to Parental Perceptions of Child Behaviors and Blood Lead Levels*

Ko et al. (2007) used video observation and transcription methods to assess children's hand contacts with outdoor surfaces as part of a study to assess the relationship between blood level levels and children's activities in urban environments. During the summers of 2000 and 2001, a total of 37 children ages 1 to 5 years were videotaped during 2-hour periods while playing in outdoor urban residential settings. The children were primarily from low-income, Hispanic families. Ko et al. (2007) tabulated surface contacts by reviewing the videotapes and counting the number of times a child's hands touched one of the following surfaces: (1) cement, stone, or steel on the ground (cement); (2) porch floor or porch steps (porch); (3) grass; and (4) bare soil. Distributions of contact frequency (contacts per hour) were developed using the data for the 37 children for the four surface types and for all surfaces combined. According to Ko et al. (2007), the median contact frequency for all surfaces was 81 contacts per hour (geometric mean = 70 contacts per hour), with several children touching surfaces approximately 400 contacts per hour (see Table 7-35).

Similar to the AuYeung et al. (2006) study described in the previous section, the advantage of this study is that it provides data for outdoor dermal (hand) contacts with a variety of objects and surfaces. These surface types are somewhat different from those in AuYeung et al. (2006) but provide additional perspective on contact with outdoor surfaces. As with all studies that use videotape methods, however, the presence of unfamiliar persons following the children with a video camera may have influenced the results.

7.7.1.7. *Beamer et al. (2008)—Quantified Activity Pattern Data From 6 to 27-Month-Old Farm Worker Children for Use in Exposure Assessment*

Beamer et al. (2008) conducted a study in which children were videotaped to estimate contacts with objects and surfaces in their environment. A convenience sample of 23 children residing in the farm worker community of Salinas Valley, CA, participated in the study. Participants were 6- to 13-month-old infants and 20- to 26-month-old toddlers. Two researchers videotaped each child's activities for a minimum of 4 hours and kept a detailed written log of locations visited and objects and surfaces contacted by the child. A questionnaire was administered to an adult in the household to acquire demographic data, housing and cleaning characteristics, eating patterns, and other information pertinent to the child's potential pesticide exposure.

Table 7-36 presents the mean and median object and surface contact frequency in events per hour. The most frequently contacted objects included toys (121 contacts per hour) and clothing/towels (114 contacts per hour). The mean frequency of hand contact of all objects and surfaces for both hands combined was 686.3 contacts per hour. Table 7-36 also provides information on the duration of contact with these objects and surfaces in minutes per hour and in seconds per contact.

The advantage of this study is that it included both infants and toddlers. Also, it provided data for a wide variety of objects and surfaces. Differences between the two age groups, as well as sex differences, were observed. As with other video-transcription studies, however, the presence of non-family-member videographers and a video camera may have influenced the children's behavior.

7.7.2. Thickness of the Skin

Although factors that influence dermal uptake (i.e., absorption) and internal dose are not the focus of this chapter, limited information on the physiological characteristics of the skin (i.e., thickness of the skin on various body parts) is presented here to provide some perspective on this topic. It should be noted that this is only one factor that may influence dermal uptake. Others include the condition of the skin (e.g., Williams et al. (2005; 2004), suggested that the presence of perspiration on the skin may affect uptake of contaminants) and chemical-specific factors (e.g., concentration of chemical in contact with the skin and characteristics of the chemical that affect its rate of absorption).

The skin consists of two distinct layers: the epidermis (outermost layer) and dermis. The outermost layer of the epidermis is the stratum corneum or horny layer. Because the stratum corneum serves as the body's outermost boundary, it is the layer where chemical exposures may occur. According to the International Commission on Radiological Protection (ICRP, 1975), the thickness of the stratum corneum of adults is "approximately one-tenth that of the epidermis except for palms [of hands] and soles [of feet] where it may be much thicker." Over most parts of the body, the stratum corneum is estimated to range in thickness from about 13 to 15 µm, but it may vary by region of the body, with the certain parts (e.g., the "horny pads") of the palms and soles being as high as 600 µm (ICRP, 1975). Holbrook and Odland (1974) used electron microscopy to measure the thickness of the stratum corneum from fixed tissues collected from the abdomen, back, forearm, and thigh of six subjects (three men and three women) ages 25 to 31 years old. The mean thicknesses for these four body regions were 8.2, 9.4, 12.9, and 10.9 µm, respectively. Schwindt et al. (1998) estimated thickness using skin at the same four sites in six women with a mean age of 33.2 years. Based on calculations from measurements of transepidermal water loss during tape stripping, mean thicknesses were estimated to be 7.7 ± 1.7, 11.2 ± 2.6, 12.3 ± 3.6, and 13.1 ± 4.7 µm for the abdomen, back, forearm, and thigh, respectively (Schwindt et al., 1998). Using two methods of calculating thickness, Pirot et al. (1998) estimated the thickness of the stratum corneum on the forearms of 13 subjects (2 men and 11 women) between the ages of 23 and 60 years. The mean ± standard deviation values were 11.3 ± 5.1 and 12.6 ± 5.3 µm. Russell et al. (2008) estimated the thickness of the stratum corneum on the forearm to be approximately 10 µm, based on 18 adults (3 men and 15 women) between the ages of 22 and 43 years. Egawa et al. (2007) estimated the stratum corneum thickness on five body parts of 15 Japanese adults (6 men and 9 women) ages 23 to 49 years old. Mean ± standard deviation thicknesses were 16.8 ± 2.8, 21.8 ± 3.6, 22.6 ± 4.3, 29.3 ± 6.8, and 173 ± 37.0 for the cheek, upper arm, forearm, back of hand, and palm of hand, respectively (Egawa et al., 2007).

For newborn infants, the stratum corneum "is extremely thin, but grows rapidly during the first month" (ICRP, 1975). Based on measurements of newborn skin that was fixed in formalin, thickness of the stratum corneum was about 10 µm on the back and about 80 to 140 µm on the sole of the foot of newborns. Based on measurement using non-fixed, fresh, frozen newborn skin, the thickness of the stratum corneum ranged from 10 to 50 µm for portions of the buttocks and abdomen and most other regions of the body except the hands and feet (ICRP, 1975).

7.8. REFERENCES FOR CHAPTER 7

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Table 7-6. Percentage of Total Body Surface Area by Body Part for Children (sexes combined) and Adults by Sex

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
Male and Female Children Combined													
<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	
Male, 18+ years	32	7.8	6.1−10.6	35.9	30.5−41.4	14.1	12.5−15.5	5.2	4.6−7.0	31.2	26.1−33.4	7.0	6.0−7.9
Female, 18+ years	57	7.1	5.6−8.1	34.8	32.8−41.7	14.0[a]	12.4−14.8	5.1[b]	4.4−5.4	32.4[a]	29.8−35.3	6.5[a]	6.0−7.0

[a] Sample size = 13.
[b] Sample size = 12.
N = Number of subjects, (M:F = male:female).
Min = Minimum percent.
Max = Maximum percent.

Source: U.S. EPA (1985).

Table 7-7. Summary of Equation Parameters for Calculating Adult Body Surface Area[a]

		Equation for surface areas (m^2)					
Body Part	*N*	a_o	W^{a1}	H^{a2}	P	R^2	SE
Head							
Female	57	0.0256	0.124	0.189	0.01	0.302	0.00678
Male	32	0.0492	0.339	−0.0950	0.01	0.222	0.0202
Trunk							
Female	57	0.188	0.647	−0.304	0.001	0.877	0.00567
Male	32	0.0240	0.808	−0.0131	0.001	0.894	0.0118
Upper Extremities							
Female	57	0.0288	0.341	0.175	0.001	0.526	0.00833
Male	48	0.00329	0.466	0.524	0.001	0.821	0.0101
Arms							
Female	13	0.00223	0.201	0.748	0.01	0.731	0.00996
Male	32	0.00111	0.616	0.561	0.001	0.892	0.0177
Upper Arms							
Male	6	8.70	0.741	−1.40	0.25	0.576	0.0387
Forearms							
Male	6	0.326	0.858	−0.895	0.05	0.897	0.0207
Hands							
Female	12[b]	0.0131	0.412	0.0274	0.1	0.447	0.0172
Male	32	0.0257	0.573	−0.218	0.001	0.575	0.0187
Lower Extremities[c]	105	0.00286	0.458	0.696	0.001	0.802	0.00633
Legs	45	0.00240	0.542	0.626	0.001	0.780	0.0130
Thighs	45	0.00352	0.629	0.379	0.001	0.739	0.0149
Lower legs	45	0.000276	0.416	0.973	0.001	0.727	0.0149
Feet	45	0.000618	0.372	0.725	0.001	0.651	0.0147

[a] $SA = a_o W^{a1} H^{a2}$ where: W = Weight in kilograms; H = Height in centimeters; P = Level of significance; R^2 = Coefficient of determination; SA = Surface Area; SE = Standard error; *N* = Number of observations.

[b] One observation for a female whose body weight exceeded the 95 percentile was not used.

[c] Although two separate regressions were marginally indicated by the F test, pooling was done for consistency with individual components of lower extremities.

Source: U.S. EPA (1985).

Table 7-8. Mean Proportion (%) of Children's Total Skin Surface Area, by Body Part									
	Age (years)								
	2	4	6	8	10	12	14	16	18
	Males								
N	115	118	117	104	124	154	155	100	88
Head	8.4	8.1	7.0	6.0	5.4	4.9	4.3	4.0	3.9
Neck	3.9	3.8	3.2	2.7	2.6	2.3	2.2	2.0	2.0
Bosom	12.3	12.3	12.2	12.2	12.2	12.4	12.3	12.3	12.8
Shoulders	1.9	2.1	1.9	1.9	1.8	1.8	1.8	1.8	1.9
Abdomen	2.7	2.9	2.7	2.8	2.7	2.8	2.8	2.8	2.9
Back	12.9	13.2	13.1	13.1	13.1	13.4	13.4	13.3	13.9
Genitals and Buttocks	7.1	6.9	6.9	6.8	7.1	7.0	7.2	7.2	6.8
Thighs	14.9	15.0	16.2	16.6	17.6	17.4	18.2	18.1	18.3
Legs	10.3	10.3	10.9	11.7	11.8	11.9	11.9	11.9	11.2
Feet	6.5	6.5	6.7	7.2	6.8	7.0	6.6	6.7	6.1
Upper Arms	8.7	8.5	8.6	8.6	8.8	8.7	8.9	9.6	9.6
Lower Arms	5.8	5.6	5.7	5.7	5.5	5.5	5.7	5.8	5.9
Hands	4.5	4.8	4.9	4.7	4.6	4.7	4.7	4.7	4.7
	Females								
N	97	110	126	93	134	133	116	98	68
Head	8.4	7.8	6.9	6.1	5.3	4.8	4.5	4.3	4.3
Neck	3.8	3.6	3.2	2.8	2.5	2.3	2.1	2.1	2.0
Bosom	12.4	12.6	12.4	12.2	12.1	12.0	12.3	13.3	14.3
Shoulders	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.8	1.8
Abdomen	3.0	2.9	2.8	2.8	2.7	2.7	2.8	2.9	3.0
Back	13.2	13.4	13.2	13.1	13.0	12.9	13.2	13.9	14.1
Genitals and Buttocks	6.8	6.6	6.6	6.6	7.0	7.3	8.0	7.9	8.1
Thighs	14.2	15.6	16.5	18.4	18.4	18.5	18.9	17.8	17.4
Legs	11.2	10.4	11.4	11.3	12.2	12.5	12.1	11.9	11.5
Feet	6.0	6.3	6.6	6.5	6.7	6.5	6.1	6.1	5.6
Upper Arms	8.6	8.4	8.3	8.1	8.4	8.8	8.8	8.6	8.5
Lower Arms	5.6	5.5	5.3	5.5	5.3	5.5	5.3	5.3	5.1
Hands	4.8	4.9	4.9	4.7	4.5	4.5	4.2	4.2	4.4

N = Number of observations.

Note: Sums of columns may equal slightly more or less than 100% due to rounding.

Source: Boniol et al. (2008).

Table 7-9. Mean and Percentile Skin Surface Area (m^2)
Derived From U.S. EPA Analysis of NHANES 1999−2006
Males and Females Combined for Children <21 Years and NHANES 2005–2006 for Adults >21 Years

Age Group	*N*	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
Males and Females Combined											
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	1,159	0.53	0.45	0.46	0.47	0.49	0.53	0.56	0.58	0.59	0.61
2 to <3 years	1,122	0.61	0.52	0.54	0.55	0.57	0.61	0.64	0.67	0.68	0.70
3 to <6 years	2,303	0.76	0.61	0.64	0.66	0.68	0.74	0.81	0.85	0.89	0.95
6 to <11 years	3,590	1.08	0.81	0.85	0.88	0.93	1.05	1.21	1.31	1.36	1.48
11 to <16 years	5,294	1.59	1.19	1.25	1.31	1.4	1.57	1.75	1.86	1.94	2.06
16 to <21 years	4,843	1.84	1.47	1.53	1.58	1.65	1.80	1.99	2.10	2.21	2.33
21 to <30 years	914	1.93	1.51	1.56	1.62	1.73	1.91	2.09	2.21	2.29	2.43
30 to <40 years	813	1.97	1.55	1.63	1.67	1.77	1.95	2.16	2.26	2.31	2.43
40 to <50 years	806	2.01	1.59	1.66	1.71	1.80	1.99	2.21	2.31	2.40	2.48
50 to <60 years	624	2.00	1.57	1.63	1.69	1.80	1.97	2.19	2.29	2.37	2.51
60 to <70 years	645	1.98	1.58	1.63	1.70	1.78	1.98	2.15	2.26	2.33	2.43
70 to <80 years	454	1.89	1.48	1.56	1.64	1.72	1.90	2.05	2.15	2.22	2.30
80 years and over	330	1.77	1.45	1.53	1.56	1.62	1.76	1.92	2.00	2.05	2.12

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999–2006 data (children) NHANES 2005–2006 data (adults).

Table 7-10. Mean and Percentile Skin Surface Area (m^2) Derived From U.S. EPA Analysis of NHANES 1999–2006 for Children <21 Years and NHANES 2005–2006 for Adults >21 Years, Male

Age Group	*N*	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
					Male						
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	1,150	0.76	0.61	0.64	0.66	0.69	0.75	0.82	0.86	0.89	0.95
6 to <11 years	1,794	1.09	0.82	0.86	0.89	0.94	1.06	1.21	1.29	1.34	1.46
11 to <16 years	2,593	1.61	1.17	1.23	1.28	1.39	1.60	1.79	1.90	1.99	2.12
16 to <21 years	2,457	1.94	1.61	1.66	1.7	1.76	1.91	2.08	2.22	2.30	2.42
21 to 30 years	361	2.05	1.70	1.76	1.81	1.87	2.01	2.18	2.30	2.39	2.52
30 to <40 years	390	2.10	1.74	1.81	1.85	1.93	2.08	2.24	2.31	2.39	2.50
40 to <50 years	399	2.15	1.78	1.86	1.90	1.97	2.12	2.29	2.41	2.47	2.56
50 to <60 years	310	2.11	1.68	1.81	1.86	1.94	2.12	2.26	2.34	2.46	2.55
60 to <70 years	323	2.08	1.72	1.78	1.84	1.94	2.08	2.25	2.33	2.37	2.46
70 to <80 years	249	2.05	1.71	1.80	1.84	1.92	2.05	2.18	2.23	2.31	2.45
80 years and older	163	1.92	1.67	1.71	1.74	1.80	1.92	2.02	2.08	2.13	2.22

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999–2006 data (children) NHANES 2005–2006 data (adults).

Table 7-11. Mean and Percentile Skin Surface Area (m^2) Derived From U.S. EPA Analysis of NHANES 1999–2006 for Children <21 Years and NHANES 2005–2006 for Adults >21 Years, Females

Age Group	*N*	Mean	Percentiles								
			5th	10th	15th	25th	50th	75th	85th	90th	95th
						Female					
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	1,153	0.75	0.61	0.64	0.66	0.68	0.74	0.80	0.84	0.88	0.94
6 to <11 years	1,796	1.08	0.80	0.85	0.87	0.92	1.04	1.21	1.33	1.39	1.51
11 to <16 years	2,701	1.57	1.20	1.28	1.34	1.42	1.55	1.69	1.8	1.88	2.00
16 to <21 years	2,386	1.73	1.42	1.47	1.51	1.57	1.69	1.85	1.98	2.06	2.17
21 to 30 years	553	1.81	1.45	1.51	1.54	1.60	1.79	1.94	2.08	2.17	2.25
30 to <40 years	423	1.85	1.50	1.55	1.61	1.67	1.82	2.00	2.13	2.23	2.31
40 to <50 years	407	1.88	1.54	1.59	1.63	1.70	1.83	2.04	2.19	2.27	2.36
50 to <60 years	314	1.89	1.54	1.58	1.62	1.70	1.85	2.005	2.19	2.26	2.38
60 to <70 years	322	1.88	1.49	1.59	1.62	1.70	1.85	2.04	2.14	2.20	2.34
70 to <80 years	205	1.77	1.44	1.48	1.55	1.62	1.77	1.91	1.99	2.03	2.13
80 years and older	167	1.69	1.41	1.46	1.51	1.56	1.68	1.80	1.86	1.92	1.98

N = Number of observations.

Source: U.S. EPA Analysis of NHANES 1999–2006 data (children) NHANES 2005–2006 data (adults).

Table 7-12. Surface Area of Adult Males (21 years and older) in Square Meters										
Body Part	Percentile									
	Mean	5th	10th	15th	25th	50th	75th	85th	90th	95th
Adult Males										
Total	2.06	1.73	1.80	1.84	1.93	2.07	2.23	2.34	2.41	2.52
Head	0.136	0.123	0.126	0.128	0.131	0.136	0.143	0.147	0.149	0.154
Trunk[a]	0.827	0.636	0.672	0.701	0.74	0.820	0.918	0.984	1.02	1.10
Upper Extremities	0.393	0.332	0.346	0.354	0.369	0.395	0.425	0.442	0.456	0.474
Arms	0.314	0.253	0.265	0.274	0.289	0.316	0.346	0.364	0.379	0.399
Upper arms	0.172	0.139	0.145	0.149	0.156	0.169	0.185	0.196	0.205	0.220
Forearms	0.148	0.115	0.121	0.125	0.132	0.146	0.163	0.173	0.181	0.197
Hands	0.107	0.090	0.093	0.096	0.100	0.107	0.115	0.121	0.124	0.131
Lower Extremities	0.802	0.673	0.703	0.721	0.752	0.808	0.868	0.903	0.936	0.972
Legs	0.682	0.560	0.587	0.603	0.634	0.686	0.746	0.780	0.811	0.847
Thighs	0.412	0.334	0.349	0.360	0.379	0.4113	0.452	0.478	0.495	0.523
Lower Legs	0.268	0.225	0.234	0.241	0.252	0.271	0.292	0.302	0.312	0.324
Feet	0.137	0.118	0.123	0.125	0.130	0.138	0.147	0.152	0.156	0.161

[a] Trunk includes neck.

Source: Based on U.S. EPA (1985) and NHANES 2005–2006.

Table 7-13. Surface Area of Adult Females (21 years and older) in Square Meters

Body Part	Percentile									
	Mean	5th	10th	15th	25th	50th	75th	85th	90th	95th
Adult Females										
Total	1.85	1.49	1.55	1.59	1.66	1.82	1.99	2.12	2.21	2.33
Head	0.114	0.108	0.109	0.110	0.111	0.114	0.116	0.118	0.119	0.121
Trunk[a]	0.654	0.511	0.530	0.544	0.571	0.633	0.708	0.765	0.795	0.850
Upper Extremities	0.304	0.266	0.272	0.277	0.284	0.301	0.320	0.333	0.342	0.354
Arms	0.237	0.213	0.218	0.221	0.227	0.237	0.248	0.254	0.259	0.266
Hands	0.089	0.076	0.078	0.079	0.082	0.087	0.094	0.099	0.102	0.106
Lower Extremities	0.707	0.579	0.599	0.616	0.643	0.698	0.761	0.805	0.835	0.875
Legs	0.598	0.474	0.494	0.509	0.533	0.588	0.649	0.693	0.724	0.764
Thighs	0.364	0.281	0.294	0.303	0.319	0.356	0.397	0.428	0.450	0.479
Lower Legs	0.233	0.191	0.198	0.204	0.213	0.230	0.250	0.263	0.273	0.286
Feet	0.122	0.103	0.106	0.109	0.113	0.121	0.130	0.136	0.140	0.146

[a] Trunk includes neck.

Source: Based on U.S. EPA (1985) and NHANES 2005–2006.

Table 7-14. Statistical Results for Total Body Surface Area Distributions (m^2), for Adults				
	Males			
	U.S. EPA	Boyd	Du Bois and Du Bois	Costeff
Mean	1.97	1.95	1.94	1.89
Median	1.96	1.94	1.94	1.89
Mode	1.96	1.91	1.90	1.90
Standard Deviation	0.19	0.18	0.17	0.16
Skewness	0.27	0.26	0.23	0.04
Kurtosis	3.08	3.06	3.02	2.92
	Females			
	U.S. EPA	Boyd	Du Bois and Du Bois	Costeff
Mean	1.73	1.71	1.69	1.71
Median	1.69	1.68	1.67	1.68
Mode	1.68	1.62	1.60	1.66
Standard Deviation	0.21	0.20	0.18	0.21
Skewness	0.92	0.88	0.77	0.69
Kurtosis	4.30	4.21	4.01	3.52
Source: Murray and Burmaster (1992).				

Table 7-15. Descriptive Statistics for Surface Area/Body-Weight (SA/BW) Ratios (m^2/kg)											
Age (year)	Mean	Range Min–Max	SD	SE	Percentiles						
					5th	10th	25th	50th	75th	90th	95th
Male and Female Combined											
0 to 2	0.064	0.042−0.114	0.011	0.001	0.047	0.051	0.056	0.062	0.072	0.078	0.085
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	0.050	0.059
≥18	0.028	0.020−0.031	0.003	7.68e-6	0.024	0.024	0.027	0.029	0.030	0.032	0.033
All Ages	0.049	0.020−0.114	0.019	9.33e-4	0.025	0.027	0.030	0.050	0.063	0.074	0.079

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

Source: Phillips et al. (1993).

Table 7-16. Estimated Percent of Adult Skin Surface Exposed During Outdoor Activities				
	Skin Area Exposed (% of total body surface area)			
	N	5th percentile	50th percentile	95th percentile
Gardening				
Cold months	31	3	8	33
Warm months	212	3	33	69
Other Yard Work	73	3	3	31
Cold months	245	8	33	68
Team Sports				
Cold months	26	3	8	33
Warm months	71	14	33	43
Repair/Digging	15	3	3	14
Cold months	65	9	28	67

N = Number of observations.

Source: Garlock et al. (1999).

Table 7-17. Estimated Skin Surface Exposed During Warm Weather Outdoor Activities			
	Skin Area Exposed (% of total body surface area)		
	Play	Gardening/Yardwork	Organized Team Sport
Age (year)	<5	5 to 17	5 to 17
N	41	47	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 7-18. Median per Contact Outdoor Fractional Surface Areas of the Hands, by Object, Both Hands Combined

	Animal	Body	Clothes	Fabric	Floor	Food	Footwear	Metal	Non-Dietary Water	Paper	Plastic	Rock /Brick	Toy	Vegetation /Grass	Wood	All Objects
N	12	38	38	19	37	26	30	38	9	27	36	16	37	37	38	38
Minimum	0.02	0.06	0.11	0.05	0.13	0.02	0.02	0.00	0.08	0.02	0.08	0.06	0.08	0.02	0.07	0.13
Maximum	0.27	0.27	0.30	0.30	1.00	1.00	0.25	0.27	1.00	0.30	0.30	0.30	0.27	0.30	0.30	0.27
Mean	0.18	0.15	0.22	0.16	0.24	0.16	0.11	0.14	0.52	0.13	0.17	0.20	0.15	0.17	0.20	0.16
5th percentile	0.04	0.07	0.14	0.11	0.13	0.03	0.03	0.11	0.10	0.03	0.13	0.07	0.13	0.03	0.11	0.13
25th percentile	0.12	0.13	0.19	0.14	0.19	0.05	0.06	0.14	0.19	0.08	0.14	0.18	0.14	0.12	0.15	0.14
50th percentile	0.20	0.16	0.22	0.15	0.24	0.11	0.10	0.14	0.31	0.13	0.15	0.23	0.14	0.16	0.18	0.15
75th percentile	0.24	0.19	0.26	0.15	0.27	0.14	0.14	0.15	1.00	0.17	0.19	0.24	0.15	0.24	0.25	0.17
95th percentile	0.26	0.24	0.30	0.24	0.30	0.80	0.21	0.19	1.00	0.25	0.28	0.28	0.24	0.30	0.30	0.26
95th percentile	0.26	0.26	0.30	0.29	0.75	1.00	0.25	0.26	1.00	0.29	0.30	0.30	0.26	0.30	0.30	0.27

N = Number of subjects.

Source: AuYeung et al. (2008).

Table 7-19. Summary of Field Studies That Estimated Activity-Specific Adherence Rates

Activity	Month	Event[a] (hours)	*N*	M	F	Age (years)	Conditions	Clothing	Study
Indoor									
Tae Kwon Do	Feb.	1.5	7	6	1	8 to 42	Carpeted floor	All in long sleeve-long pants martial arts uniform, sleeves rolled back, barefoot	Kissel et al. (1996b)
Greenhouse Worker	Mar.	5.25	2	1	1	37 to 39	Plant watering, spraying, soil blending, sterilization	Long pants, elbow length short sleeve shirt, no gloves	
Indoor Kid No. 1	Jan.	2	4	3	1	6 to 13	Playing on carpeted floor	3 or 4 short pants, 2 of 4 short sleeves, socks, no shoes	Holmes et al. (1999)
Indoor Kid No. 2	Feb.	2	6	4	2	3 to 13	Playing on carpeted floor	5 of 6 long pants, 5 of 6 long sleeves, socks, no shoes	
Daycare Kid No. 1a	Aug.	3.5	6	5	1	1 to 6.5	Indoors: linoleum surface; Outdoors: grass, bare earth, barked area	4 of 6 long pants, 5 of 6 short sleeves, socks, shoes	
Daycare Kid No. 1b	Aug.	4	6	5	1	1 to 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 Kid No. 2[b]	Sept.	8	5	4	1	1 to 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 Kid No. 3	Nov.	8	4	3	1	1 to 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 to 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. (1996b)
Soccer No. 2	Mar.	1.5	8	0	8	24 to 34	All weather field (sand-ground tires)	All in short sleeve shirts, shorts, knee socks, shin guards	
Soccer No. 3	Nov.	1.5	7	0	7	24 to 34	All weather field (sand-ground tires)	All in short sleeve shirts, shorts, knee socks, shin guards	
Groundskeeper No. 1	Mar.	1.5	2	1	1	29 to 52	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves	
Groundskeeper No. 2	Mar.	4.25	5	3	2	22 to 37	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves	
Groundskeeper No. 3	Mar.	8	7	5	2	30 to 62	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves	

Table 7-19. Summary of Field Studies That Estimated Activity-Specific Adherence Rates (continued)

Activity	Month	Event[a] (hours)	*N*	M	F	Age (years)	Conditions	Clothing	Study
Outdoor (continued)									
Groundskeeper No. 4	Aug.	4.25	7	4	3	22 to 38	Campus grounds, urban horticulture center, arboretum	5 of 7 in short sleeve shirts, intermittent use of gloves	Kissel et al. (1996b)
Groundskeeper No. 5	Aug.	8	8	6	2	19 to 64	Campus grounds, urban horticulture center, arboretum	5 of 8 in short sleeve shirts, intermittent use of gloves	
Irrigation Installer	Oct.	3	6	6	0	23 to 41	Landscaping, surface restoration	All in long pants, 3 of 6 short sleeve or sleeveless shirts	
Rugby No. 1	Mar.	1.75	8	8	0	20 to 22	Mixed grass-bare wet field	All in short sleeve shirts, shorts, variable sock lengths	
Farmer No. 1	May	2	4	2	2	39 to 44	Manual weeding, mechanical cultivation	All in long pants, heavy shoes, short sleeve shirts, no gloves	
Farmer No. 2	July	2	6	4	2	18 to 43	Manual weeding, mechanical cultivation	2 of 6 short, 4 of 6 long pants, 1 of 6 long sleeve shirt, no gloves	
Reed Gatherer	Aug.	2	4	0	4	42 to 67	Tidal flats	2 of 4 short sleeve shirts/knee length pants, all wore shoes	
Kid-in-Mud No. 1	Sept.	0.17	6	5	1	9 to 14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot	
Kid-in-Mud No. 2	Sept.	0.33	6	5	1	9 to 14	Lake shoreline	All in short sleeve T-shirts, shorts, barefoot	
Gardener No. 1	Aug.	4	8	1	7	16 to 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)
Gardener No. 2	Aug.	4	7	2	5	26 to 52	Weeding, pruning, digging a trench, picking fruit, cleaning	3 of 7 long pants, 5 of 7 short sleeves, 1 sleeveless, socks, shoes, no gloves	
Rugby No. 2	July	2	8	8	0	23 to 33	Grass field (80% of time) and all-weather field (mix of gravel, sand, and clay) (20% of time)	All in shorts, 7 of 8 in short sleeve shirts, 6 of 8 in low socks	
Rugby No. 3	Sept.	2.75	8	7	0	24 to 30	Compacted mixed grass and bare earth field	All short pants, 7 of 8 short or rolled up sleeves, socks, shoes	
Archeologist	July	11.5	7	3	4	16 to 35	Digging with trowel, screening dirt, sorting	6 of 7 short pants, all short sleeves, 3 no shoes or socks, 2 sandals	
Construction Worker	Sept.	8	8	8	0	21 to 30	Mixed bare earth and concrete surfaces, dust and debris	5 of 8 pants,7 of 8 short sleeves, all socks and shoes	
Landscape/Rockery	June	9	4	3	1	27 to 43	Digging (manual and mechanical), rock moving	All long pants, 2 long sleeves, all socks and boots	

Activity	Month	Event[a] (hours)	*N*	M	F	Age (years)	Conditions	Clothing	Study
Outdoor (continued)									
Utility Worker No. 1	July	9.5	5	5	0	24 to 45	Cleaning, fixing mains, excavation (backhoe and shovel)	All long pants, short sleeves, socks, boots, gloves sometimes	Holmes et al. (1999)
Utility Worker No. 2	Aug.	9.5	6	6	0	23 to 44	Cleaning, fixing mains, excavation (backhoe and shovel)	All long pants, 5 of 6 short sleeves, socks, boots, gloves sometimes	
Equip. Operator No. 1	Aug.	8	4	4	0	21 to 54	Earth scraping with heavy machinery, dusty conditions	All long pants, 3 of 4 short sleeves, socks, boots, 2 of 4 gloves	
Equip. Operator No. 2	Aug.	8	4	4	0	21 to 54	Earth scraping with heavy machinery, dusty conditions	All long pants, 3 of 4 short sleeves, socks, boots, 1 gloves	
Shoreline Play (children)	Sept.	0.33−1.0	9	6	3	7 to 12	Tidal flat	No shirt or short sleeve T-shirts, shorts, barefoot	Shoaf et al. (2005b)
Clamming (adults)	Aug.	1−2	18	9	9	33 to 63	Tidal flat	T-shirt, shorts, shoes	Shoaf et al. (2005a)

Table 7-19. Summary of Field Studies That Estimated Activity-Specific Adherence Rates (continued)

[a] Event duration.
[b] Activities were confined to the house.
N = Number of subjects.
M = Males.
F = Females.

Table 7-20. 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	0.0019	0.0020		0.0022
		1.9	4.1	2.0		2.1
Greenhouse Worker	2	0.043	0.0064	0.0015	0.0050	
		--	--	--	--	
Indoor Kid No. 1	4	0.0073	0.0042	0.0041		0.012
		1.9	1.9	2.3		1.4
Indoor Kid No. 2	6	0.014	0.0041	0.0031		0.0091
		1.5	2.0	1.5		1.7
Daycare Kid No. 1a	6	0.11	0.026	0.030		0.079
		1.9	1.9	1.7		2.4
Daycare Kid No. 1b	6	0.15	0.031	0.023		0.13
		2.1	1.8	1.2		1.4
Daycare Kid No. 2	5	0.073	0.023	0.011		0.044
		1.6	1.4	1.4		1.3
Daycare Kid No. 3	4	0.036	0.012	0.014		0.0053
		1.3	1.2	3.0		5.1
Outdoor						
Soccer No. 1	8	0.11	0.011	0.031	0.012	
		1.8	2.0	3.8	1.5	
Soccer No. 2	8	0.035	0.0043	0.014	0.016	
		3.9	2.2	5.3	1.5	
Soccer No. 3	7	0.019	0.0029	0.0081	0.012	
		1.5	2.2	1.6	1.6	
Groundskeeper No. 1	2	0.15	0.005		0.0021	0.018
		--	--		--	--
Groundskeeper No. 2	5	0.098	0.0021	0.0010	0.010	
		2.1	2.6	1.5	2.0	
Groundskeeper No. 3	7	0.030	0.0022	0.0009	0.0044	0.0040
		2.3	1.9	1.8	2.6	
Groundskeeper No. 4	7	0.045	0.014	0.0008	0.0026	0.018
		1.9	1.8	1.9	1.6	--
Groundskeeper No. 5	8	0.032	0.022	0.0010	0.0039	
		1.7	2.8	1.4	2.1	
Irrigation Installer	6	0.19	0.018	0.0054	0.0063	
		1.6	3.2	1.8	1.3	

Table 7-20. Geometric Mean and Geometric Standard Deviations of Solids Adherence by Activity and Body Region[a] (continued)

Activity	*N*	Post-Activity Dermal Solids Loadings (mg/cm²)				
		Hands	Arms	Legs	Faces	Feet
Rugby No. 1	8	0.40	0.27	0.36	0.059	
		1.7	1.6	1.7	2.7	
Farmers No. 1	4	0.41	0.059	0.0058	0.018	
		1.6	3.2	2.7	1.4	
Farmers No. 2	6	0.47	0.13	0.037	0.041	
		1.4	2.2	3.9	3.0	
Reed Gatherer	4	0.66	0.036	0.16		0.63
		1.8	2.1	9.2		7.1
Kid-in-Mud No. 1	6	35	11	36		24
		2.3	6.1	2.0		3.6
Kid-in-Mud No. 2	6	58	11	9.5		6.7
		2.3	3.8	2.3		12.4
Gardener No. 1	8	0.20	0.050	0.072	0.058	0.17
		1.9	2.1	--	1.6	--
Gardener No. 2	7	0.18	0.054	0.022	0.047	0.26
		3.4	2.9	2.0	1.6	--
Rugby No. 2	8	0.14	0.11	0.15	0.046	
		1.4	1.6	1.6	1.4	
Rugby No. 3	7	0.049	0.031	0.057	0.020	
		1.7	1.3	1.2	1.5	
Archeologist	7	0.14	0.041	0.028	0.050	0.24
		1.3	1.9	4.1	1.8	1.4
Construction Worker	8	0.24	0.098	0.066	0.029	
		1.5	1.5	1.4	1.6	
Landscape/Rockery	4	0.072	0.030		0.0057	
		2.1	2.1		1.9	
Utility Worker No.1	5	0.32	0.20		0.10	
		1.7	2.7		1.5	
Utility Worker No. 2	6	0.27	0.30		0.10	
		2.1	1.8		1.5	
Equip. Operator No. 1	4	0.26	0.089		0.10	
		2.5	1.6		1.4	
Equip. Operator No. 2	4	0.32	0.27		0.23	
		1.6	1.4		1.7	
Shoreline Play	9	0.49	0.17	0.70	0.04	21
(children)		8.2	3.1	3.6	2.9	1.9
Clamming (adults)	18	0.88	0.12	0.16	0.02	0.58
		17	1.1	4.7	0.10	12

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. (1996b); Holmes et al. (1999); Shoaf et al. (2005a, b).

Table 7-21. Summary of Controlled Greenhouse Trials							
Activity	Ages (years)	Duration (min)	Soil Moisture (%)	Clothing[a]	*N*	Male	Female
Transplanting	Adult	~12[b]	17−19	L	4	2	2
			15−18	S	13	6	7
Playing	8 to 12	20	17−18	L	4	3	1
			16−18	S	9	5	4
			3−4	S	5	3	2
Pipe Laying	Adult	15, 30, 45	9−12	S	7	4	3
			5−7	S	6	3	3

[a] L = long sleeves and long pants; S = short sleeves and short pants.
[b] Arithmetic mean (range was 9 to 18 minutes). Activity was terminated after completion of the task rather than at a fixed time.
N = Number of subjects.

Source: Kissel et al. (1998).

Table 7-22. Dermal Transfer Factors for Selected Contact Surface Types and Skin Wetness, Using <80 µm Tagged ATD				
Mean surface Loading $\mu g/cm^2$	Test Subject[a]	Contact Surface Type[b]	Skin Moisture Level[c]	Dermal Transfer Factor[d]
36.3	F1	SS	Dry	0.760 (0.000)
39.1	M1	SS	Dry	0.716 (NA)
32.0	M1	SS	Damp	1.222 (NA)
45.0	M1	SS	Wet	1.447 (NA)
42.6	M2	SS	Dry	0.582 (0.059)
23.8	M2	SS	Damp	0.970 (NA)
30.6	M2	SS	Wet	1.148 (NA)
30.5	M2	Vinyl	Dry	0.554 (0.052)
32.7	M2	Vinyl	Damp	0.485 (0.068)
38.9 (not embedded)	M2	Carpet	Dry	0.087 (0.000)
36.4 (embedded)	M2	Carpet	Dry	0.034 (0.007)
33.8 (not embedded)	M2	Carpet	Damp	0.190 (0.002)
33.3 (embedded)	M2	Carpet	Damp	0.169 (0.11)

[a] F1 = female subject; M1 and M2 = male subjects.
[b] SS = stainless steel; vinyl linoleum; nylon carpet.
[c] Dry = no added moisture; wet = synthetic saliva moistened (moisture visible but not excessive).
[d] Dermal transfer factor = µg on hand/cm^2 of dermal contact area/µg on surface/cm^2 of surface contact. Based on mean of left and right hand presses. Standard deviation (SD) in parenthesis; NA = not available.

Source: Rodes et al. (2001).

Table 7-23. Comparison of Adherence (mg/cm^2) for Contact With Carpet and Aluminum Surfaces, Averaged Across Pressure, Contact Time, Soil Type, and Soil Particle Size[a]

	Carpet Transfer	Hard Surface (aluminum) Transfer	Combined (carpet/aluminum) Transfer
Mean Soil Adherence	0.37 ± 0.4	0.42 ± 0.6	0.39 ± 0.4
Mean Soil-Skin Adherence	0.71 ± 0.5	1.18 ± 0.4	0.92 ± 0.5
Mean Soil-Cloth Adherence	0.20 ± 0.3	0.15 ± 0.4	0.17 ± 0.4

[a] Soil adherence values averaged across pressure, time, soil type, and soil size.

Source: Ferguson et al. (2009a).

Table 7-24. Film Thickness Values of Selected Liquids Under Various Experimental Conditions (10^{-3}cm)

	Mineral Oil[a]	Cooking Oil[b]	Bath Oil[c]	Oil/ Water[d]	Water[e]	Water/ Ethanol[f]
Initial Contact[g]						
No wipe[h]	1.56	2.25	1.74	2.03	2.34	3.25
Partial wipe[i]	0.62	0.82	0.59	1.55	1.83	2.93
Full wipe[j]	0.27	0.34	0.20	1.38	1.97	3.12
Secondary Contact[k]						
No wipe[h]	1.40	1.87	1.56	1.60	2.05	2.95
Partial wipe[i]	0.47	0.52	0.48	1.19	1.39	2.67
Full wipe[j]	0.06	0.07	0.08	0.92	1.32	2.60
Immersion[l]						
No wipe[h]	11.87	6.55	6.90	9.81	4.99	6.55
Partial wipe[i]	2.00	1.46	1.55	2.42	2.14	2.93
Full wipe[j]	-	-	-	-	-	-
Handling Rag[m]						
No wipe[h]	1.64	1.50	2.04	1.88	2.10	4.17
Partial wipe[i]	0.44	0.34	0.53	1.21	1.48	3.70
Full wipe[j]	0.13	0.01	0.21	0.96	1.37	3.58
Spill Cleanup[n]						
No wipe[h]	1.23	0.73	0.89	1.19	-	-
Partial wipe[i]	0.55	0.51	0.48	1.36	-	-
Full wipe[j]	-	-	-	-	-	-

[a] Density = 0.8720 g/cm^3.
[b] Density = 0.9161 g/cm^3.
[c] Density = 0.8660 g/cm^3.
[d] Density = 0.9357 g/cm^3; 50% water and 50% oil.
[e] Density = 0.9989 g/cm^3.
[f] Density = 0.9297 g/cm^3; 50% water and 50% ethanol.
[g] Initial contact = cloth saturated with liquid was rubbed over the front and back of both clean, dry hands for the first time during an exposure event.
[h] Retention of liquid on the skin was estimated without any intentional removal of liquid by wiping.
[i] Retention was measured after ‘partial’ removal of liquids on the skin by wiping. Partial wiping was defined as “lightly [wiping with a removal cloth] for 5 seconds (superficially).”
[j] Retention was measured after ‘full’ removal of liquids on the skin by wiping. Full wiping was defined as “ thoroughly and completely as possible within 10 seconds removing as much liquid as possible.”
[k] Secondary contact = cloth saturated with liquid was rubbed over the front and back of both hands for a second time, after as much as possible of the liquid that adhered to skin during the first contact event was removed using a clean cloth.
[l] Immersion = one hand immersed in a container of liquid, removed, and liquid allowed to drip back into container for 30 seconds (60 seconds for cooking oil).
[m] Handling rag = cloth saturated with liquid was rubbed over the palms of both hands for the first time during an exposure event in a manner simulating handling of a wet cloth.
[n] Spill cleanup = subject used a clean cloth to wipe up 50 mL of liquid poured onto a plastic laminate countertop.
\- = no data.
Note: Data for mineral oil, cooking oil, and bath oil for initial contact, secondary contact, and immersion from U.S. EPA (1992c). All other data from U.S. EPA (1987).

Source: U.S. EPA (1987) and U.S. EPA (1992c).

Table 7-25. Mean Transfer Efficiencies (%)[a]				
Time After Application[b]	Legs (tights)	Torso and Arms (shirt)	Feet (socks)	Hands (gloves)
0 hours				
chlorpyrifos	6.6 ± 1.6	5.6 ± 2.6	32.1 ± 13.4	17.4 ± 8.6
allethrin	5.9 ± 1.5	5.4 ± 2.4	34.3 ± 18.3	22.4 ± 12.6
6 hours				
chlorpyrifos	7.5 ± 4.6	6.3 ± 5.8	33.3 ± 12.9	16.9 ± 11.0
allethrin	5.3 ± 2.0	4.8 ± 2.5	27.1 ± 8.8	17.9 ± 9.1
12.5 hours				
chlorpyrifos	4.0 ± 1.3	3.1 ± 0.5	20.3 ± 3.5	8.1 ± 1.9
allethrin	3.0 ± 0.8	2.8 ± 0.5	13.7 ± 4.7	8.3 ± 2.7

[a] Clothing residue values divided by floor residues and multiplied by 100.
[b] After room was vented.

Source: Ross et al. (1990).

Table 7-26. Transfer Efficiencies (%) for Dry, Water-Wetted, and Saliva-Wetted Palms and PUF Roller				
	Dry Palms	Water-Wetted Palms	Saliva-Wetted Palms	PUF Roller
Chlorpyrifos				
Mean	1.53	5.22	4.38	4.19
SD	0.73	3.02	2.83	2.87
Pyrethrin				
Mean	3.64	11.87	8.89	5.66
SD	2.21	7.25	4.66	3.60
Piperonyl Butoxide				
Mean	1.41	4.85	4.06	4.28
SD	0.73	2.95	2.64	3.33

SD = Standard deviation.
PUF = Polyurethane foam.

Source: Clothier (2000).

Table 7-27. Incremental and Overall Surface-to-Hand Transfer Efficiencies (%)

Contact	Hand Condition			Surface Type		Surface Loading	
	Dry	Moist	Sticky	Carpet	Laminate	High	Low
Incremental transfer %, average (SD)							
1	3.0 (2.7)	7.1 (6.1)	14 (18)	6.4 (7.0)	10 (16)	3.9 (4.0)	13 (16)
2	2.5 (4.0)	7.7 (5.7)	7.5 (18)	8.0 (9.5)	3.6 (13)	3.7 (3.5)	8.1 (16)
3	2.0 (5.4)	4.0 (7.3)	6.9 (7.3)	3.8 (7.2)	4.8 (6.8)	1.7 (1.7)	7.0 (9.0)
4	0.9 (3.1)	1.9 (2.5)	2.3 (8.0)	1.1 (6.3)	2.3 (4.2)	0.9 (1.8)	2.7 (7.4)
5	1.3 (2.2)	1.0 (3.7)	2.0 (5.3)	1.7 (2.4)	1.3 (4.9)	0.3 (1.1)	2.5 (5.0)
Incremental transfer %, average (SD) without sticky hands							
1	3.0 (2.7)	7.1 (6.1)	-	4.9 (5.3	5.2 (4.9)	2.6 (2.1)	7.5 (6.0)
2	2.5 (4.0)	7.7 (5.7)	-	5.8 (6.0)	4.2 (4.9)	2.8 (3.0)	7.3 (6.6)
3	2.0 (5.4)	4.0 (7.3)	-	2.1 (6.4)	4.0 (6.4)	1.4 (1.3)	4.7 (8.8)
4	0.9 (3.1)	1.9 (2.5)	-	0.9 (3.0)	1.9 (2.6)	1.0 (1.8)	1.8 (3.8)
5	1.3 (2.3)	1.0 (3.7)	-	1.6 (1.6)	0.7 (3.8)	0.4 (1.2)	1.9 (3.9)
Overall transfer %, average (SD)							
1	3.0 (2.7)	7.1 (6.1)	14 (18)	6.4 (7.0)	10 (16)	3.9 (4.0)	13 (16)
2	2.8 (2.5)	7.4 (5.2)	11 (9.7)	7.2 (7.6)	6.9 (7.1)	3.8 (3.1)	10 (8.8)
3	2.5 (2.9)	6.2 (4.7)	9.7 (7.6)	6.1 (6.3)	6.2 (6.0)	3.1 (2.2)	9.3 (7.2)
4	2.1 (2.4)	5.3 (4.0)	7.9 (7.0)	5.0 (5.7)	5.4 (5.4)	2.5 (1.7)	8.2 (6.6)
5	1.6 (0.8)	4.2 (3.4)	8.2 (6.9)	4.6 (5.3)	4.6 (5.1)	1.8 (1.0)	7.1 (6.0)
Overall transfer %, average (SD) without sticky hands							
1	3.0 (2.7)	7.1 (6.1)	-	4.9 (5.3)	5.2 (4.9)	2.6 (2.1)	7.5 (6.0)
2	2.8 (2.5)	7.4 (5.2)	-	5.4 (5.0)	4.7 (4.3)	2.7 (2.1)	7.4 (5.3)
3	2.5 (2.9)	6.2 (4.7)	-	4.3 (4.0)	4.4 (4.6)	2.3 (1.4)	6.5 (5.1)
4	2.1 (2.4)	5.3 (4.0)	-	3.3 (3.3)	3.9 (4.0)	1.9 (1.1)	5.7 (4.4)
5	1.6 (0.8)	4.2 (3.4)	-	2.8 (2.4)	2.8 (3.0)	1.4 (0.5)	4.2 (3.2)

SD = Standard deviation.

Source: Cohen Hubal et al. (2005).

Table 7-28. Lognormal Distributions for Modeling Transfer Efficiencies (fraction)[a]					
Chemical	Surface	μ	σ	GM	GSD
Chlorpyrifos	Carpet	−4.26	0.54	0.01	1.70
	Vinyl	−3.30	0.85	0.04	2.34
	Foil	−0.15	0.08	0.86	1.08
Pyrethrin I	Carpet	−3.86	0.68	0.02	1.97
	Vinyl	−3.66	0.96	0.03	2.61
	Foil	−0.19	0.10	0.83	1.11
Piperonyl butoxide	Carpet	−4.00	0.51	0.02	1.67
	Vinyl	−3.63	0.81	0.03	2.25

[a] Distributions should be truncated at 1.0.

GM = Geometric mean.

GSD = Geometric standard deviation.

Source: Beamer et al. (2009).

Table 7-29. Hand-to-Object/Surface Contact—Frequency (contacts/hour)		
Object/Surface	Left Hand Average[a]	Right Hand Average[a]
Bedding/Towel	13.0	13.8
Carpet/Rug	4.3	6.0
Dirt	5.3	6.5
Food	9.3	9.3
Footwear	2.0	3.0
Grass/Vegetation	6.3	5.0
Hair	4.5	3.5
Hard Floor	10.0	9.5
Hard Surface	36.0	40.3
Hard Toy	27.3	29.3
Paper/Card	8.8	14.5
Plush Toy	4.0	4.0
Upholstered Furniture	17.0	15.5
Water/Beverage	1.3	1.8

[a] Average = mean of average hourly contact rates of 4 children of farm workers, ages 2 to 4 years.

Source: Zartarian et al. (1997).

Table 7-30. Hand-to-Objects/Surfaces—Frequency (contacts/hour)				
Object/Surface	Both Hands[a]			
	Range	Mean	Median	90th Percentile
Clothing	22.8−129.2	66.6	65.0	103.3
Dirt	0−146.3	11.4	0.3	56.4
Object	56.2−312.0	122.9	118.7	175.8
Other[b]	8.3−243.6	82.9	64.3	199.6
Smooth Surface	13.6−190.4	83.7	80.2	136.9
Textured Surface	0.2−68.7	22.1	16.3	52.2

[a] Based on data for 30 children (20 daycare children and 10 residential children) ages 2 to 6 years.
[b] Other includes items such as paper, grass, and pets.

Source: Reed et al. (1999).

Table 7-31. Median (mean ± SD) Hand Contact Frequency With Clothing, Surfaces, or Objects (contacts/hour)[a]				
Age	3 to 4 years	5 to 6 years	7 to 8 years	10 to 12 years
N	3	7	4	5
Touch Clothing	26 (34 ± 21)	22 (26 ± 23)	50 (54 ± 43)	35 (53 ± 66)
Touch Textured Surface	40 (52 ± 61)	20 (32 ± 40)	22 (58 ± 88)	16 (24 ± 31)
Touch Smooth Surface	134 (151 ± 62)	111 (120 ± 77)	120 (155 ± 119)	94 (96 ± 50)
Touch Object	130 (153 ± 108)	117 (132 ± 88)	111 (164 ± 148)	127 (179 ± 126)

[a] Based on 4-hour observation period.
SD = Standard deviation.
N = Number of children observed.

Source: Freeman et al. (2001).

Table 7-32. Hand Contact with Objects/Surfaces—Frequency (contacts/hour)		
Object/Surface	Right Hand[a]	
	Mean (SD)	Median (range)
Bottle	14.6 (17.9)	11.5 (1.3−63.0)
Carpet/Rug	6.3 (9.3)	1.1 (0−23.0)
Clothes	38.0 (16.4)	41.9 (12.8−66.8)
Food	9.2 (6.6)	7.3 (3.0−20.8)
Hair	5.1 (3.6)	4.1 (1.3−11.8)
Hard Floor	9.5 (6.2)	10.3 (1.3−17.5)
Object	97.7 (45.8)	96.8 (25.0−176.4)
Paper	22.9 (18.0)	21.8 (1.3−54.3)
Skin	31.5 (15.3)	26.4 (16.0−63.5)
Smooth Surface	83.9 (38.0)	88.0 (32.0−158.4)
Textured Surface	6.5 (5.7)	4.1 (1.0−20.7)
Upholstered Furniture	20.7 (15.2)	19.3 (6.8−55.5)

[a] Only data for the right hand were reported; data for 10 children, ages 24 to 55 months.
SD = Standard deviation.

Source: Freeman et al. (2005).

Table 7-33. Outdoor Hand Contact With Objects/Surfaces, Children 1 to 6 Years[a]

Object/Surface	Both Hands											
	Range	Mean	Median	95th Percentile	Range	Mean	Median	95th Percentile	Range	Mean	Median	95th Percentile
	Frequency (contacts/hour)				Duration (seconds/contact)				Duration (minutes/hour)			
Animal	0−23.3	2.6	0	13.8	1.5−7	3.2	2.5	6.5	0−2	0.2	0	1.6
Body	17−191.7	74.8	65.1	150.4	1−4	2	2	3.2	0.6−17.8	5	4.1	11.2
Clothes/Towel	17−199.1	73.7	65.7	132	1−5	2.5	2	4.6	1.4−26.3	6.7	4.8	18.2
Fabric	0−31.5	3.7	0.4	14.7	0.5−23.5	5.9	3	15.4	0−6.6	0.7	0	3.9
Floor	0−940.4	65.8	27.9	182.7	0−13	3	2	6.5	0−16.4	4	2.4	12.2
Food	0−88.7	14.5	4.9	56.2	0−28	7.6	6	20.8	0−17.3	3.9	0.4	17
Footwear	0−23.1	3.6	1.5	11.4	0−12	3.3	2.5	8.1	0−5.6	0.5	0	2
Metal	0.6−466.2	58.3	16	206.4	0−109.5	7.3	3	15.8	0−36.3	7.4	3.2	27.3
Non-Dietary Water	0.7.4	0.5	0	2.9	0.5−9	3.3	2	8.2	0−1	0.1	0	0.6
Paper/Wrapper	0−103.8	7.3	1.5	21.4	0−53.5	9.4	4.3	28.1	0−27	1.8	0.4	7.8
Plastic	0−324.6	56.7	47	121.1	1−21.5	5.1	4	12.8	0−26.3	8	6	20.6
Rock/Brick	0−28	2.4	0	10.3	1−9	2.8	2	7.5	0−3.7	0.2	0	1
Toy	0−657.8	161.3	129.4	372.8	0−25.5	6.5	6	13.5	0−63.1	29.8	28.4	57
Vegetation/Grass	0−138.7	40.6	27.8	128.1	0−11	3.7	3	9.1	0−21.5	5.1	2.9	17.9
Wood	0.6−100.9	22.4	12.7	79.8	0−9	3.7	3	8	0−27.8	3.2	1.2	12.8
Non-Dietary Object	225.1−1,512.6	575.3	526.3	889.2	0−5	3	3	4	42.6−101.7	72.9	72.3	94.2
All Objects/Surfaces	229.9−1,517.7	589.8	540.8	889.2	0−5	3	3	4.2	42.6−102.2	76.8	77.5	99.3

[a] Based on 38 children aged 1 to 6 years in parks, playgrounds, and outdoor residential areas in California.

Source: AuYeung et al. (2006).

Table 7-34. Indoor Hand Contact With Objects/Surfaces—Frequency, Children 1 to 6 Years[a] (median contacts/hour)

Object/Surface	Left Hand	Right Hand
Carpet	7.9	8.5
Clothing	41	25.2
Hard Floor	3.2	3.9
Paper	3.8	7.4
Skin	11.6	9.9
Upholstered Furniture	13.1	7.7
Smooth Surface	61.9	62.7
Textured Surfaces	18.2	22.1

[a] Based on 9 children aged 1 to 6 years in indoor residential settings in California.

Source: AuYeung et al. (2006).

Table 7-35. Outdoor Hand Contact With Surfaces—Frequency, Children 1 to 5 Years[a] (contacts/hour)

Object/Surface	Both Hands					
	N	Range	Geometric Mean	SD	Median	90th Percentile
Cement	37	0−240	27	0.59	36	107
Porch	22	0−104	12	0.74	16	86
Grass	34	0−183	8	0.71	7	71
Bare Soil	27	0−81	6	0.67	5	71
All Surfaces	37	3−405	70	0.44	81	193

[a] Based on observations of a total of 37 children aged 1 to 5 years (primarily low-income, Hispanic) in outdoor residential areas in Illinois.

N = Number of subjects.

SD = Standard deviation of log-transformed contacts/hour.

Source: Ko et al. (2007).

Table 7-36. Hand Contact With Objects/Surfaces, Infants and Toddlers[a]

Object/Surface	Both Hands								
	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
	Frequency (contacts/hour)			Duration (minutes/hour)[b]			Duration (seconds/contact)		
Animal	0.0−4.3	0.2	0.0	0.0−0.2	0.0	0.0	1.5−2.0	1.8	1.8
Body	16.6−147.1	76.8	70.5	1.6−21.9	7.5	5.9	1.0−3.0	2.3	2.0
Clothes/Towel	39.2−237.9	113.8	100.9	4.5−31.0	13.1	12.4	1.0−4.0	2.9	3.0
Fabric	0.0−134.4	45.6	37.6	2.1−21.6	10.3	9.1	2.0−9.0	3.6	3.0
Floor	0.0−594.5	96.0	41.5	0.0−32.2	7.0	4.3	0.5−5.0	2.3	2.5
Food	0.0−170.7	51.8	42.7	0.0−37.1	14.2	12.1	2.0−24.0	7.1	7.0
Footwear	0.0−47.0	7.8	2.4	0.0−7.7	1.1	0.3	1.0−11.0	3.8	3.0
Metal	0.0−52.4	17.3	14.5	0.0−5.2	2.0	1.9	0.8−9.0	3.4	3.0
Non-Dietary Water	0.0−2.6	0.2	0.0	0.0−0.0	0.0	0.0	0.5−1.0	0.8	0.8
Paper/Wrapper	0.0−75.3	18.1	18.7	0.0−13.9	3.7	3.1	1.5−11.5	4.4	4.0
Plastic	10.9−294.9	87.1	76.1	0.9−50.6	13.5	10.9	0.5−8.0	3.8	4.0
Rock/Brick	0.0−17.4	3.4	1.6	0.0−1.8	0.3	0.1	1.0−5.0	2.7	3.0
Toy	28.3−300.4	121.2	98.8	9.8−54.1	25.2	9.8	3.0−11.5	5.8	5.0
Vegetation	0.0−16.3	3.8	0.3	0.0−2.2	0.3	0.0	0.5−4.0	2.7	3.0
Wood	0.0−65.4	24.9	27.2	0.0−10.6	3.5	3.9	1.5−8.0	3.8	3.0
Non-Dietary Object	266.8−1,180.0	600.8	568.7	62.6−106.2	83.1	83.2	2.0−5.0	3.2	3.0
All Objects/Surfaces	303.1−1,206.0	686.3	689.4	76.4−124.1	99.1	100.5	2.0−5.0	3.3	3.0

[a] Based on 23 farm worker children (ages 6 to 26 months) from California.

[b] Hourly contact duration for both hands is the sum of the hourly contact durations for the left and right hands independently.

Source: Beamer et al. (2008).

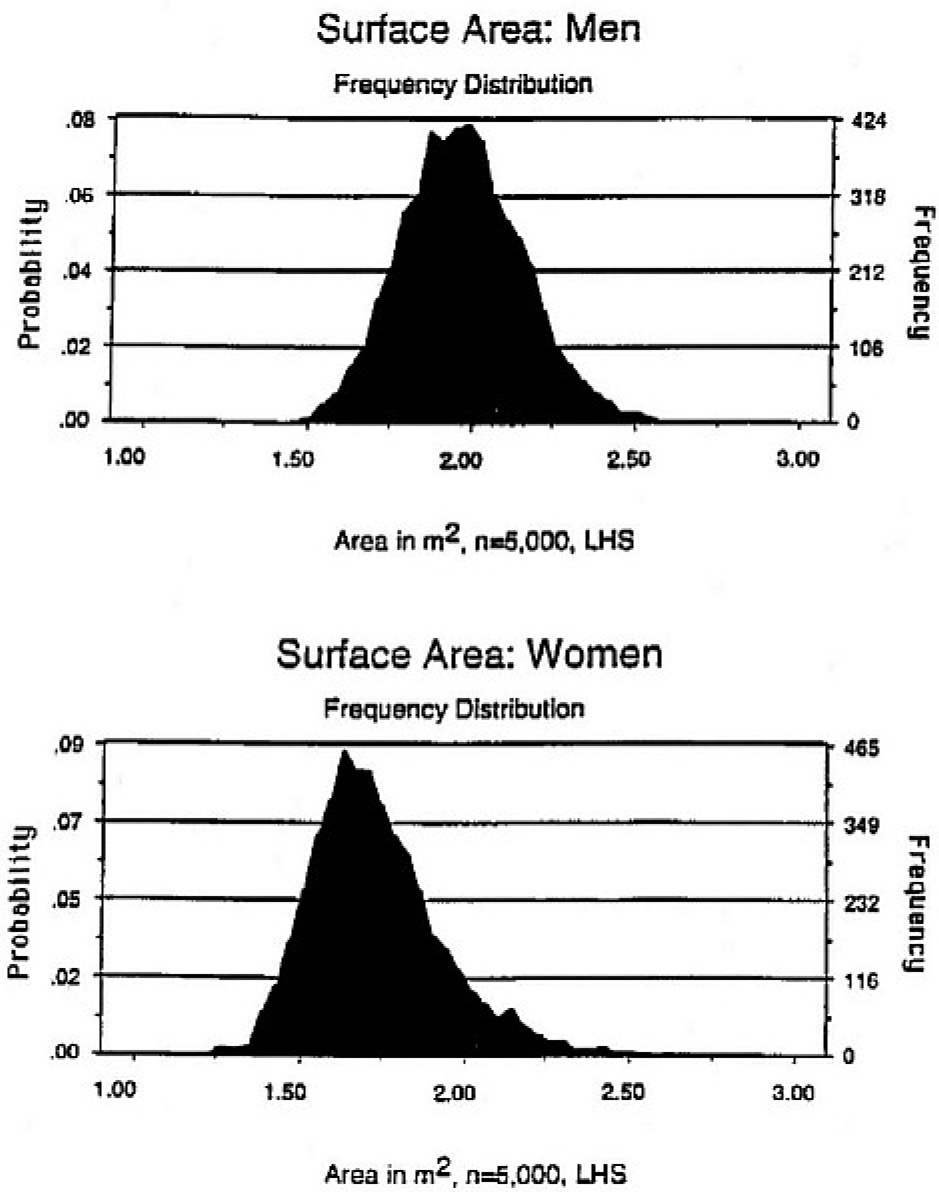

Figure 7-1. Frequency Distributions for the Surface Area of Men and Women.

Source: Murray and Burmaster (1992)

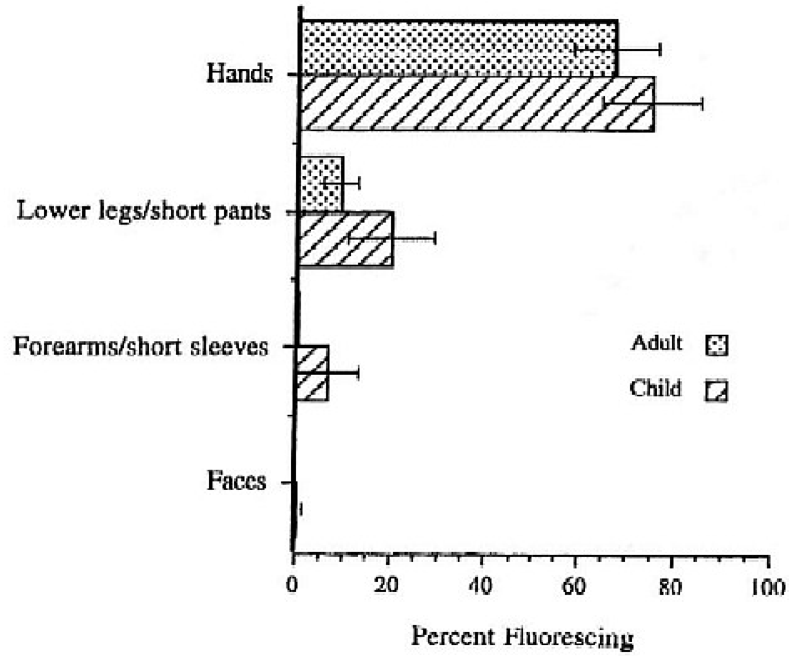

Figure 7-2. Skin Coverage as Determined by Fluorescence Versus Body Part for Adults Transplanting Plants and Children Playing in Wet Soils (bars are arithmetic means and corresponding 95% confidence intervals).
Source: Kissel et al. (1998).

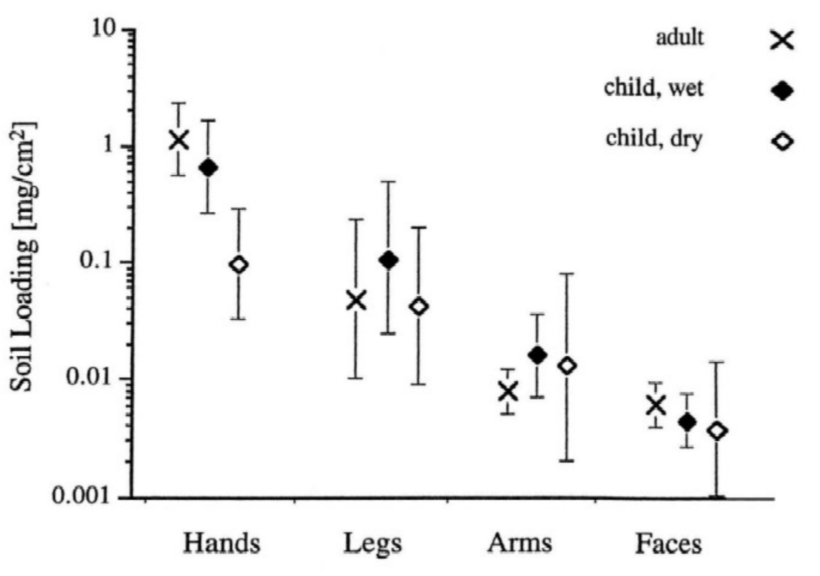

Figure 7-3. Gravimetric Loading Versus Body Part for Adults Transplanting Plants in Wet Soil and Children Playing in Wet and Dry Soils (symbols are geometric means and 95% confidence intervals).
Source: Kissel et al. (1998).

APPENDIX 7A

FORMULAS FOR TOTAL BODY SURFACE AREA

APPENDIX 7A—FORMULAS FOR TOTAL BODY SURFACE AREA

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

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

where:

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

While this 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 Du Bois and Du Bois (1989). Their model can be written:

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

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 Du Bois 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 (Lentner, 1981) are based on the Du Bois and Du Bois formula.

Boyd (1935) developed new constants for the Du Bois and Du Bois 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 Du Bois and Du Bois 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 Du Bois and Du Bois formula based on height and weight.

Gehan and George (1970) proposed another set of constants for the Du Bois and Du Bois 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 surface area is:

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

or in logarithmic form:

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

where:

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

This prediction explains more than 99% 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) to be 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 Du Bois and Du Bois (1989) and the

Statistical Processing System (SPS) software package to obtain the standard error.

The Du Bois and Du Bois (1989) formula uses weight and height as independent variables to predict total body surface area and can be written as:

$$SA_1 = a_0 H_i^{a_1} W_i^{a_2} e_i \qquad \text{(Eqn. 7A-5)}$$

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	=	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:

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

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% of the total variation in surface area among the observations, and it 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% 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%. Of these, 12 weighed less than 15 pounds each, one was overweight (5 feet 7 inches, 172 pounds), one was very thin (4 feet 11 inches, 78 pounds), and four were of average build. Because the same observer measured surface area for these four 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. Table 7A-1 presents the different values for the constants.

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 m^2, 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 Du Bois and Du Bois model. Their interest in making the Du Bois and Du Bois model more accurate resulted from their work in pediatrics and the fact that Du Bois and Du Bois (1989) 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 two 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 Caucasian 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 co-efficients: a_0 = 0.024265, a_1 = 0.3964, and a_2 = 0.5378. The result was the following equation for estimating surface area:

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

expressed logarithmically as:

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

The co-efficients 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 Du Bois and Du Bois 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 Du Bois and Du Bois model that are different than those originally postulated in 1916. The Du Bois and Du Bois model can be written logarithmically as:

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

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

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 because 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 Du Bois and Du Bois (1989). Because the Sendroy and Cecchini method is graphical, it is inherently less precise and less accurate than the formulas of other authors discussed in this section.

7A.1. 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

Source: Gehan and George (1970).

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

Author (year)	Number of Persons	a_0	a_1	a_2
Du Bois and Du Bois (1989)	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