TABLE OF CONTENTS

Page No.

6. DERMAL ROUTE 1
   6.1. EQUATION FOR DERMAL DOSE 1
   6.2. SURFACE AREA 2
   6.3. DERMAL ADHERENCE TO SOIL 6
   6.4. RECOMMENDATIONS 8
   6.5. REFERENCES FOR CHAPTER 6 9

APPENDIX 6A
. 3

6. DERMAL ROUTE

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

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

The major factors that must be considered when estimating dermal exposure include: the chemical concentration in contact with the skin, the extent of skin surface area exposed, the duration of exposure, and the rate of absorption of the chemical.

This chapter focuses on measurements of body surface areas and various factors needed to estimate dermal exposure to chemicals in water and soil. Useful information concerning estimates of body surface area can be found in "Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments" (U.S. EPA, 1985). "Dermal Exposure Assessment: Principles and Applications, (U.S. EPA, 1992) provides detailed information concerning dermal exposure using a stepwise guide in the exposure assessment process. Information concerning dermal exposure to pollutants in indoor environments is limited.

The available studies have been classified as either key or relevant based on their applicability to exposure assessment needs and summarized in this chapter. Recommended values are based on the results of the key studies. Relevant studies are presented to provide an added perspective on the state-of-knowledge pertaining to dermal exposure factors. All tables and figures presenting data from each study are shown at the end of this chapter.

6.1. EQUATION FOR DERMAL DOSE

The average daily dose (ADD) is the dose rate averaged over a pathway-specific period of exposure expressed as a daily dose on a per-unit-body-weight basis. The ADD is used for exposure to chemicals with non-carcinogenic non-chronic effects. For compounds with carcinogenic or chronic effects, the lifetime average daily dose (LADD) is used. The LADD is the dose rate averaged over a lifetime.

For dermal contact with chemicals in water, dermally absorbed average daily dose can be estimated by (U.S. EPA, 1992):

$$ADD = \frac{DA_{event} \times EV \times ED \times EF \times SA}{BW \times AT} \qquad \text{(Eqn. 6-1)}$$

where:

ADD	=	average daily dose (mg/kg-day);
DA_{event}	=	absorbed dose per event (mg/cm^2-event);
EV	=	event frequency (events/day);
ED	=	exposure duration (years);
EF	=	exposure frequency (days/year);
SA	=	skin surface area available for contact (cm^2);
BW	=	body weight (kg); and
AT	=	averaging time (days) for noncarcinogenic effects, AT = ED and for carcinogenic effects, AT = 70 years or 25,550 days.

This method is to be used to calculate the absorbed dose of a chemical in water. Total body surface area (SA) is assumed to be exposed to water for a period of time (ED). The DA_{event} is estimated with consideration for the permeability coefficient from water, the chemical concentration in water, and the event duration.

The approach to estimate DA_{event} is different for inorganic and organic compounds. The nonsteady-state approach to estimate the dermally absorbed dose from water is recommended as the preferred approach for organics which exhibit octanol-water partitioning (U.S. EPA, 1992). First, this approach more accurately reflects normal human exposure conditions since the short contact times associated with bathing and swimming generally mean that steady state will not occur. Second, the approach accounts for uptake that can occur after the actual exposure event due to absorption of residual chemical trapped in skin tissue. Use of the nonsteady-state model for organics has implications for selecting permeability coefficient (K_p) values (U.S. EPA, 1992). It is recommended that the traditional steady-state approach be applied to inorganics (U.S. EPA, 1992). Detailed information concerning how to estimate absorbed dose per event (DA_{event}) can be found in "Dermal Exposure Assessment: Principles and Applications" (U.S. EPA, 1992).

For dermal contact with contaminated soil, a variation of Equation 6-1 is used. Dermally absorbed dose is calculated using the equation below:

$$ADD = \frac{DA_{event} \times EF \times ED \times SA}{BW \times AT} \qquad \text{(Eqn. 6-2)}$$

where:

ADD	=	average daily dose (mg/kg-day);
DA_{event}	=	absorbed dose per event (mg/cm^2-event);
SA	=	skin surface area available for contact (cm^2);
EF	=	exposure frequency (events/year);
ED	=	exposure duration (years);
BW	=	body weight (kg); and
AT	=	averaging time (days), for non-carcinogenic effects, AT = ED, and for carcinogenic effects, AT = 70 years or 25,550 days.

Estimation of the DA_{event} is based on the concentration of the chemical in soil, the adherence factor of soil to skin, and the absorption fraction.

The apparent simplicity of the absorption fraction (percent absorbed) makes this approach appealing. However, it is not practical to apply it to water contact scenarios, such as swimming, because of the difficulty in estimating the total material contacted (U.S. EPA, 1992). It is assumed that there is essentially an infinite amount of material available, and that the chemical will be replaced continuously, thereby increasing the amount of material (containing the chemical) available by some large unknown amount. Therefore, the permeability coefficient -based approach is recommended over the absorption fraction approach for determining the dermally absorbed dose of chemicals in aqueous media.

Before the absorption fraction approach can be used in soil contact scenarios, the contaminant concentration in soil must be established. Not all of the chemical in a layer of dirt applied to skin may be bioavailable, nor is it assumed to become an absorbed dose. Because of the lack of K_p data for compounds bound to soil, and reduced uncertainty in defining an applied dose, the absorption fraction-based approach is suggested for determining the dermally absorbed dose of chemicals in soil. More detailed explanation of the equations, assumptions, and approaches can be found in "Dermal Exposure Assessment: Principles and Applications" (U.S. EPA. 1992).

6.2. SURFACE AREA

6.2.1. Background

The total surface area of skin exposed to a contaminant must be determined using measurement or estimation techniques before conducting a dermal exposure assessment. Depending on the exposure scenario, estimation of the surface area for the total body or a specific body part can be used to calculate the contact rate for the pollutant. This section presents estimates for total body surface area and for body parts and presents information on the application of body surface area data.

6.2.2. Measurement Techniques

Coating, triangulation, and surface integration are direct measurement techniques that have been used to measure total body surface area and the surface area of specific body parts. Consideration has been given for differences due to age, gender, and race. The results of the various techniques have been summarized in "Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments" (U.S. EPA, 1985). The coating method consists of coating either the whole body or specific body regions with a substance of known or measured area. Triangulation consists of marking the area of the body into geometric figures, then calculating the figure areas from their linear dimensions. Surface integration is performed by using a planimeter and adding the areas.

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

In addition to direct measurement techniques, several formulae have been proposed to estimate body surface area from measurements of other major body dimensions (i.e., height and weight) (U.S. EPA, 1985). Generally, the formulae are based on the principles that body density and shape are roughly the same and that the relationship of surface area to any dimension may be represented by the curve of central tendency of their plotted values or by the algebraic expression for the curve. A discussion and comparison of formulae to determine total body surface area are presented in Appendix 6A.

6.2.3. Key Body Surface Area Studies

U.S. EPA (1985) - Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments - 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 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 then used to calculate body surface area distributions of the U.S. population using the height and weight data obtained from the National Health and Nutrition Examination Survey (NHANES) II and the computer program QNTLS of Rochon and Kalsbeek (1983).

The equation proposed by Gehan and George (1970) was determined by U.S. EPA (1985) to be the best choice for estimating total body surface area. However, the paper by Gehan and George 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 Dubois and Dubois (1916) and SPS to obtain the standard error (U.S. EPA, 1985).

Regression equations were developed for specific body parts using the Dubois and Dubois (1916) formula and using the surface area of various body parts provided by Boyd (1935) and Van Graan (1969) in conjunction with SPS. 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 6-1 presents a summary of the equation parameters developed by the 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.

Percentile estimates of total surface area and surface area of body parts developed by U.S. EPA (1985) using the regression equations and NHANES II height and weight data are presented in Tables 6-2 and 6-3 for adult males and adult females, respectively. The calculated mean surface areas of body parts for men and women are presented in Table 6-4. The standard deviation, the minimum value, and the maximum value for each body part are included. The median total body surface area for men and women and the corresponding standard errors about the regressions are also given. It has been assumed that errors associated with height and weight are negligible (U.S. EPA, 1985). The data in Table 6-5 present the percentage of total body surface by body part for men and women.

Percentile estimates for total surface area of male and female children presented in Tables 6-6 and 6-7 were calculated using the total surface area regression equation, NHANES II height and weight data, and using QNTLS. Estimates are not included for children younger than 2 years old because NHANES height data are not available for this age group. For children, the error associated with height and weight cannot be assumed to be zero because of their relatively small sizes. Therefore, the standard errors of the percentile estimates cannot be estimated, since it cannot be assumed that the errors associated with the exogenous variables (height and weight) are independent of that associated with the model; there are insufficient data to determine the relationship between these errors.

Measurements of the surface area of children's body parts are summarized as a percentage of total surface area in Table 6-8. Because of the small sample size, the data cannot be assumed to represent the average percentage of surface area by body part for all children. Note that the percent of total body surface area contributed by the head decreases from childhood to adult, while the percent contributed by the leg increases.

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. They studied the effect of using these factors as independent variables in the LADD equation. They concluded that, because of the correlation between these two variables, the use of body surface area to body weight (SA/BW) ratios in human exposure assessments is more appropriate than treating these factors as independent variables. Direct measurement (coating, triangulation, and surface integration) data from the scientific literature were used to calculate body surface area to body weight (SA/BW) ratios for three age groups (infants aged 0 to 2 years, children aged 2.1 to 17.9 years, and adults 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 each of the three age groups and the combined data set. Summary statistics for these populations are presented in Table 6-9. The shapes of these SA/BW distributions were determined using D'Agostino's test. The results indicate that the SA/BW ratios for infants are lognormally distributed and the SA/BW ratios for adults and all ages combined are normally distributed (Figure 6-1). SA/BW ratios for children were neither normally nor lognormally distributed. According to Phillips et al. (1993), SA/BW ratios should be used to calculate LADDs by replacing the body surface area factor in the numerator of the LADD equation with the SA/BW ratio and eliminating the body weight factor in the denominator of the LADD equation.

The effect of gender and age on SA/BW distribution was also analyzed by classifying the 401 observations by gender and age. Statistical analyses indicated no significant differences between SA/BW ratios for males and females. SA/BW ratios were found to decrease with increasing age.

6.2.4. Relevant Surface Area Studies

Murray and Burmaster (1992) - Estimated Distributions for Total Body Surface Area of Men and Women in the United States - In this study, distributions of total body surface area for men and women ages 18 to 74 years were estimated using Monte Carlo simulations based on height and weight distributions. Four different formulae for estimating body surface area as a function of height and weight were employed: Dubois and Dubois (1916); Boyd (1935); U.S. EPA (1989); and Costeff (1966). The formulae of Dubois and Dubois (1916); Boyd (1935); and U.S. EPA (1989) are based on height and weight. They are discussed in Appendix 6A. The formula developed by Costeff (1966) is based on 220 observations that estimate body surface area based on weight only. This formula is:

$$SA = 4W + 7/W + 90 \qquad \text{(Eqn. 6-3)}$$

where:

SA = Surface Area (m^2); and
W = Weight (kg).

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 above. 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 (Table 6-10). 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 percent. Body surface area was found to have lognormal distribution for both men and women (Figure 6-2). It was also found that assuming correlation between height and weight influences the final distribution by less than 1 percent.

AICH (1994) - Exposure Factors Sourcebook - The Exposure Factors Sourcebook (AIHC, 1994) provides similar body surface area data as presented here. Consistent with this document, average and percentile values are presented on the basis of age and gender. In addition, the Sourcebook presents point estimates of exposed skin surface areas for various scenarios on the basis of several published studies. Finally, the Sourcebook presents probability distributions based on U.S. EPA (1989) and as derived by Brainard and Burmaster et al. (1991); Versar (1991); and Brorby and Finley (1993). For each distribution, the @Risk formula is provided for direct use in the @Risk simulation software (Palisade, 1992). The organization of this document, makes it very convenient to use in support of Monte Carlo analysis. The reviews of the supporting studies are very brief with little analysis of their strengths and weaknesses. The Sourcebook has been classified as a relevant rather than key study because it is not the primary source for the data used to make recommendations in this document. The Sourcebook is very similar to this document in the sense that it summarizes exposure factor data and recommends values. As such, it is clearly relevant as an alternative information source on body surface area as well as other exposure factors.

6.2.5. Application of Body Surface Area Data

In many settings, it is likely that only certain parts of the body are exposed. All body parts that come in

contact with a chemical must be considered to estimate the total surface area of the body exposed. The data in Table 6-4 may be used to estimate the total surface area of the particular body part(s). For example, to assess exposure to a chemical in a cleaning product for which only the hands are exposed, surface area values for hands from Table 6-4 can be used. For exposure to both hands and arms, mean surface areas for these parts from Table 6-4 may be summed to estimate the total surface area exposed. The mean surface area of these body parts for men and women is as follows:

	Surface Area (m^2)	
	Men	Women
Arms (includes upper arms and forearms)	0.228	0.210
Hands	0.084	0.075
Total area	0.312	0.285

Therefore, the total body part surface area that may be in contact with the chemical in the cleaning product in this example is 0.312 m^2 for men and 0.285 m^2 for women.

A common assumption is that clothing prevents dermal contact and subsequent absorption of contaminants. This assumption may be false in cases where the chemical may be able to penetrate clothing, such as in a fine dust or liquid suspension. Studies using personal patch monitors placed beneath clothing of pesticide workers exposed to fine mists and vapors show that a significant proportion of dermal exposure may occur at anatomical sites covered by clothing (U.S. EPA, 1992). In addition, it has been demonstrated that a "pumping" effect can occur which causes material to move under loose clothing (U.S. EPA, 1992). Furthermore, studies have demonstrated that hands cannot be considered to be protected from exposure even if waterproof gloves are worn (U.S. EPA, 1992). This may be due to contamination to the interior surface of the gloves when donning or removing them during work activities (U.S. EPA, 1992). Depending on the task, pesticide workers have been shown to experience 12 percent to 43 percent of their total exposure through their hands, approximately 20 percent to 23 percent through their heads and necks, and 36 percent to 64 percent through their torsos and arms, despite the use of protective gloves and clothing (U.S. EPA, 1992).

For swimming and bathing scenarios, past exposure assessments have assumed that 75 percent to 100 percent of the skin surface is exposed (U.S. EPA, 1992). As shown in Table 6-4, total adult body surface areas can vary from about 17,000 cm^2 to 23,000 cm^2. The mean is reported as approximately 20,000 cm^2.

For default purposes, adult body surface areas of 20,000 cm^2 (central estimate) to 23,000 cm^2 (upper percentile) are recommended in U.S. EPA (1992). Tables 6-2 and 6-3 can also be used when the default values are not preferred. Central and upper-percentile values for children should be derived from Table 6-6 or 6-7.

Unlike exposure to liquids,clothing may or may not be effective in limiting the extent of exposure to soil. The 1989 Exposure Factors Handbook presented two adult clothing scenarios for outdoor activities (U.S. EPA, 1989):

> **Central tendency mid range:** Individual wears long sleeve shirt, pants, and shoes. The exposed skin surface is limited to the head and hands (2,000 cm^2).
>
> **Upper percentile:** Individual wears a short sleeve shirt, shorts, and shoes. The exposed skin surface is limited to the head, hands, forearms, and lower legs (5,300 cm^2).

The clothing scenarios presented above, suggest that roughly 10 percent to 25 percent of the skin area may be exposed to soil. Since some studies have suggested that exposure can occur under clothing, the upper end of this range was selected in *Dermal Exposure Assessment: Principles and Applications* (U.S. EPA, 1992) for deriving defaults. Thus, taking 25 percent of the total body surface area results in defaults for adults of 5,000 cm^2 to 5,800 cm^2. These values were obtained from the body surface areas in Table 6-2 after rounding to 20,000 cm^2 and 23,000 cm^2, respectively. The range of defaults for children can be derived by multiplying the 50th and 95th percentiles by 0.25 for the ages of interest.

When addressing soil contact exposures, assessors may want to refine estimates of surface area exposed on the basis of seasonal conditions. For example, in moderate climates, it may be reasonable to assume that 5 percent of the skin is exposed during the winter, 10 percent during the spring and fall, and 25 percent during the summer.

The previous discussion, has presented information about the area of skin exposed to soil. These estimates of exposed skin area should be useful to assessors using the traditional approach of multiplying the soil adherence factor by exposed skin area to estimate the total amount of soil on skin. The next section recommends a new form of the soil adherence factor which is specific to activity and

body part and is designed to be combined with the total surface area of that body part. No reduction of body part area is made for clothing coverage using this approach. Thus, assessors who adopt this approach, should not use the defaults presented above for soil exposed skin area. Rather, they should use Table 6-4 to obtain total surface areas of specific body parts. See detailed discussion below.

6.3. DERMAL ADHERENCE TO SOIL

6.3.1. Background

Soil adherence to the surface of the skin is a required parameter to calculate dermal dose when the exposure scenario involves dermal contact with a chemical in soil. A number of studies have attempted to determine the magnitude of dermal soil adherence. These studies are described in detail in U.S. EPA (1992). This section summarizes recent studies that estimate soil adherence to skin for use as exposure factors.

6.3.2. Key Dermal Adherence to Soil Study

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 using five soil types (descriptor) obtained locally in the Seattle, Washington, area: sand (211), loamy sand (CP), loamy sand (85), sandy loam (228), and silt loam (72). All soils were analyzed by hydrometer (settling velocity) to determine composition. Clay contents ranged from 0.5 to 7.0 percent. Organic carbon content, determined by combustion, ranged from 0.7 to 4.6 percent. Soils were dry sieved to obtain particle size ranges of <150, 150-250, and >250 μm. For each soil type, the amount of soil adhering to an adult female hand, using both sieved and unsieved soils, was determined by measuring the difference in soil sample weight before and after the hand was pressed into a pan containing the test soil. Loadings were estimated by dividing the recovered soil mass by total hand area, although loading occurred primarily on only one side of the hand. Results showed that generally, soil adherence to hands could be directly correlated with moisture content, inversely correlated with particle size, and independent of clay content or organic carbon content.

Kissel et al. (1996a) used a fluorescent marking technique and video imaging to assess the percentage of skin coverage in several soil contact trials in a greenhouse setting, and an irrigation pipe laying trial (Table 6-11). The investigators concluded that adjusted loadings, averaged over fluorescing areas only, may be two to three orders of magnitude larger than average loadings, if average loadings are small.

Further experiments by Kissel et al. (1996a) estimated soil adherence associated with various indoor and outdoor activities: greenhouse gardening, tae kwon do karate, soccer, rugby, reed gathering, irrigation installation, truck farming, and playing in mud. A summary of field studies by activity, gender, age, field conditions, and clothing worn is presented in Table 6-12. Subjects body surfaces (forearms, hands, lower legs in all cases, faces, and/or feet; pairs in some cases) were washed before and after monitored activities. Paired samples were pooled into single ones. Mass recovered was converted to loading using allometric models of surface area. These data are presented in Table 6-13.

6.3.3. Relevant Dermal Adherence to Soil Studies

Lepow et al. (1975) - Investigations into Sources of Lead in the Environment of Urban Children - This study was conducted to identify the behavioral and environmental factors contributing to elevated lead levels in ten preschool children. The study was performed over 6-25 months. Samples of dirt from the hands of subjects were collected during the course of play around the areas where they lived. Preweighed self-adhesive labels were used to sample a standard area on the palm of the hands of 16 male and female children. The labels were pressed on a single area, often pressed several times, to obtain an adequate sample. In the laboratory, labels were equilibrated in a desiccant cabinet for 24 hours (comparable to the preweighed desiccation), then the total weight was recorded. The mean weight of dirt from the 22 hand sample labels was 11 mg. This corresponds to 0.51 mg/cm^2. Lepow et al. (1975) reported that this amount (11 mg) represented only a small fraction (percent not specified) of the total amount of surface dirt present on the hands, because much of the dirt may be trapped in skin folds and creases or there may be a patchy distribution of dirt on hands.

Roels et al. (1980) - Exposure to Lead by the Oral and the Pulmonary Routes of Children Living in the Vicinity of a Primary Lead Smelter - Roels et al. (1980) examined blood lead levels among 661 children, 9-14 years old, who lived in the vicinity of a large lead smelter in Brussels, Belgium. During five different study periods, lead levels were assessed by rinsing the childrens' hands in 500 mL dilute nitric acid. The amount of lead on the hands was divided by the concentration of lead in soil to estimate the amount of soil adhering to the hands. The mean soil amount adhering to the hands was 0.159 grams.

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 the estimate from Roels et al. (1980), 0.159 g, and the average surface area of the hand of an 11 year old, 307 cm^2 to estimate the amount of soil adhering per unit area of skin to be 0.9 mg/cm^2. This assumed that approximately 60 percent (185 cm^2) of the lead on the hands was recovered by the method employed by Roels et al. (1980).

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. 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).

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 soil having particle sizes ranging from $\leq$ 44 to 833 µm diameters, fractionated into six size ranges, to estimate the amount that adhered to the palm of the hand assumed to be approximately 160 cm^2 (test subject approximately 14 years old with an average total body surface area of 16,000 cm^2 and a total hand surface area of 400 cm^2). The amount of soil that adhered to skin was determined by applying approximately 5 g of soil for each size fraction, removing excess soil by shaking the hands, and then measuring the difference in weight before and after application. Several assumptions were made to apply these results to other soil types and exposure scenarios: (a) the soil is composed of particles of the indicated diameters; (b) all soil types and particle sizes adhere to the skin to the degree observed in this study; and an equivalent weight of particles of any diameter adhere to the same surface area of skin. On average, 31.2 mg of soil adhered to the palm of the hand. From this experiment it was assumed that 0.2 mg of soil adhered to 1 cm^2 of skin.

Driver et al. (1989) - Soil Adherence to Human Skin - Driver et al. (1989) conducted soil adherence experiments using various soil types collected from sites in Virginia. A total of five soil types were collected: Hyde, Chapanoke, Panorama, Jackland, and Montalto. Both top soils and subsoils were collected for each soil type. The soils were also characterized by cation exchange capacity, organic content, clay mineralogy, and particle size distribution. The soils were dry sieved to obtain particle sizes of $\leq$250 µm and $\leq$150 µm. For each soil type, the amount of soil adhering to adult male hands, 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 pre-weighed amount of soil over the entire surface area of the hands for a period of approximately 30 seconds, followed by removal of 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. The authors 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 is soil type and subtype ($p < 0.001$). The interaction of soil type and particle size was also significant, but at a lower significance level ($p < 0.01$).

Driver et al. (1989) found statistically significant increases in soil adherence with decreasing particle size; whereas, Que Hee et al. (1985) found relatively small changes with changes in particle size. The amount of soil adherence found by Driver et al. (1989) was greater than that reported by Que Hee et al. (1985).

Yang et al. (1989) - In vitro and In vivo Percutaneous Absorption of Benzo[a]pyrene from Petroleum Crude - Fortified Soil in the Rat - Yang et al. (1989) evaluated the percutaneous absorption of benzo[a]pyrene (BAP) in petroleum crude oil sorbed on soil using a modified in vitro technique. This method was used in preliminary experiments to determine the minimum amount of soil adhering to the skin of rats. Based on these results, percutaneous absorption experiments with the crude-sorbed soil were conducted with soil particles of < 150 μm only. This particle size was intended to represent the composition of the soil adhering to the skin surface. Approximately 9 mg/cm^2 of soil was found to be the minimum amount required for a "monolayer" coverage of the skin surface in both in vitro and in vivo experiments. This value is larger than the < 1 mg/cm^2 of soil (dust) reported for human skin in the studies of Lepow et al., 1975; Roels et al., 1980; and Que Hee et al., 1985. Differences between the rat and human soil adhesion findings may be the result of differences in rat and human skin texture, the types of soils used, soil

moisture content or possibly the methods of measuring soil adhesion (Yang et al., 1985).

6.4. RECOMMENDATIONS

6.4.1. Body Surface Area

Body surface area estimates are based on direct measurements. Re-analysis of data collected by Boyd (1935) by several investigators (Gehan and George, 1970; U.S. EPA, 1985; Murray and Burmaster, 1992; Phillips et al., 1993) constitutes much of this literature. Methods are highly reproducible and the results are widely accepted. The representativeness of these data to the general population is somewhat limited since variability due to race or gender have not been systematically addressed.

Individual body surface area studies are summarized in Table 6-14 and the recommendations for body surface area are summarized in Table 6-15. Table 6-16 presents the confidence ratings for various aspects of the recommendations for body surface area. The U.S. EPA (1985) study is based on generally accepted measurements that enjoy widespread usage, summarizes and compares previous reports in the literature, provides statistical distributions for adults, and provides data for total body surface area and body parts by gender for adults and children. However, the results are based on 401 selected measurements from the original 1,114 made by Boyd (1935). More than half of the measurements are from children. Therefore, these estimates may be subject to selection bias and may not be representative of the general population nor specific ethnic groups. Phillips et al. (1993) analyses are based on direct measurement data that provide distributions of body surface area to calculate LADD. Results are consistent with previous efforts to estimate body surface area. Analyses are based on 401 measurements selected from the original 1,114 measurements made by Boyd (1935) and data were not analyzed for specific body parts. The study by Murray and Burmaster (1992) provides frequency distributions for body surface area for men and women and produces results that are similar to those obtained by the U.S. EPA (1985), but do not provide data for body parts nor can results be applied to children.

For most dermal exposure scenarios concerning adults, it is recommended that the body surface areas presented in Table 6-4 be used after determining which body parts will be exposed. Table 6-4 was selected because these data are straightforward determinations for most scenarios. However, for others, additional considerations may need to be addressed. For example, (1) the type of clothing worn could have a significant effect on the surface area exposed, and (2) climatic conditions will also affect the type of clothing worn and, thus, the skin surface area exposed.

Frequency, event, and exposure duration for water activities and soil contact are presented in Activity Patterns, Volume III, Chapter 14 of this report. For each parameter, recommended values were derived for average and upper percentile values. Each of these considerations are also discussed in more detail in U.S. EPA (1992). Data in Tables 6-2 and 6-3 can be used when surface area distributions are preferred. A range of recommended values for estimates of the skin surface area of children may be taken from Tables 6-6 and 6-7 using the 50th and 95th percentile values for age(s) of concern. The recommended 50th and 90th percentile values for adult skin surface area provided in U.S. EPA (1992) are:

Water Contact		
	50th	95th
Bathing and Swimming	20,000 cm^2	23,000 cm^2
Soil Contact		
	50th	95th
Outdoor Activities	5,000 cm^2	5,800 cm^2

6.4.2. Dermal Adherence to Soil

Table 6-18 summarizes the relevant and key studies addressing soil adherence to skin. Both Lepow et al. (1975) and Roels et al. (1980) monitored typical exposures in children over long periods of time. They attempted to estimate typical exposure by recovery of accumulated soil from hands at specific time intervals. The efficiency of their sample collection methods is not known and may be subject to error. Only children were studied which may limit generalizing these results to adults. Later studies (Que Hee et al., 1985 and Driver et al., 1989) attempted to characterize both soil properties and sample collection efficiency to estimate adherence of soil to skin. However, the experimental conditions used to expose skin to soil may not reflect typical dermal exposure situations. This provides useful information about the influence of soil characteristics on skin adherence, but the intimate contact of skin with soil required under the controlled experimental conditions in the studies by Driver et al. (1989) and Que Hee et al. (1985) may have exaggerated the amount of adherence over what typically occurs.

More recently, Kissel et al. (1996a; 1996b) have related dermal adherence to soil characteristics and to specific activities. In all cases, experimental design and measurement methods are straightforward and reproducible, but application of results is limited. Both controlled experiments and field studies are based on a limited number of measurements. Specific situations have been selected to assess soil adherence to skin. Consequently, variation due to individuals, protective clothing, temporal, or seasonal factors remain to be studied in more detail. Therefore, caution is required in interpretation and application of these results for exposure assessments.

The studies all have uncertainties, but suggest the following generalizations about soil adherence:

- Soil properties influence adherence. Adherence increases with moisture content, decreases with particle size, but is relatively unaffected by clay or organic carbon content.

- Adherence levels vary considerably across different parts of the body. The highest levels were found on common contact points such as hands, knees, and elbows; the least was detected on the face.

- Adherence levels vary with activity. In general, the highest levels of soil adherence were seen in outdoor workers such as farmers and irrigation system installers, followed by outdoor recreation, and gardening activities. Very high adherence levels were seen in individuals contacting wet soils such as might occur during wading or other shore area recreational activities.

In consideration, of these general observations and the recent data from Kissel et al. (1996a, 1996b), this document recommends a new approach for estimating soil adherence to skin. First use Table 6-12 to select the activity which best approximates the exposure scenario of concern. Next, use Table 6-13 to select soil loadings on exposed skin surfaces which correspond to the activity of interest. This table contains soil loading estimates for various body parts. The estimates were derived from soil adherence measurements of body parts of individuals engaged in specific activities described in Table 6-12. These results provide the best estimate of central loadings, but are based on limited data. Therefore, they have a high degree of uncertainty such that considerable judgment must be used when selecting them for an assessment. The confidence ratings for various aspects of this recommendation are summarized in Table 6-17. Insufficient data are available to develop a distribution or a probability function for soil loadings.

Past EPA guidance has recommended assuming that soil exposure occurs primarily to exposed body surfaces and used typical clothing scenarios to derive estimates of exposed skin area. The approach recommended above for estimating soil adherence addresses this issue in a different manner. This change was motivated by two developments. First, increased acceptance that soil and dust particles can get under clothing and be deposited on skin. Second, recent studies of soil adherence have measured soil on entire body parts (whether or not they were covered by clothing) and averaged the amount of soil adhering to skin over the area of entire body part. The soil adherence levels resulting from these new studies must be combined with the surface area of the entire body part (not merely unclothed surface area) to estimate the amount of contaminant on skin. An important caveat, however, is that this approach assumes that clothing in the exposure scenario of interest matches the clothing in the studies used to derive these adherence levels such that the same degree of protection provided by clothing can be assumed in both cases. If clothing differs significantly between the studies reported here and the exposure scenarios under investigation, considerable judgment is needed to adjust either the adherence level or surface area assumption.

The dermal adherence value represents the amount of soil on the skin at the time of measurement. Assuming that the amount measured on the skin represents its accumulation between washings and that people wash at least once per day, these adherence values can be interpreted as daily contact rates (U.S. EPA, 1992). However, this is not recommended because the residence time of soils on skin has not been studied. Instead, it is recommended that these adherence values be interpreted on an event basis (U.S. EPA, 1992).

6.5. REFERENCES FOR CHAPTER 6

American Industrial Health Council (AIHC). (1994) Exposure factors sourcebook. AIHC, Washington, DC.

Boyd, E. (1935) The growth of the surface area of the human body. Minneapolis, Minnesota: University of Minnesota Press.

Brainard, J.B.; Burmaster, D.E. (1992) Bivariate distributions for height and weight, men and women in the United States. Risk Analysis 12(2):267-275.

Brorby, G.; Finley B. (1993) Standard probability density functions for routine use in environmental health risk assessment. Presented at the Society of Risk Analysis Annual Meeting, December 1993, Savannah, GA.

Buhyoff, G.J.; Rauscher, H.M.; Hull, R.B.; Killeen, K.; Kirk, R.C. (1982) User's Manual for Statistical Processing System (version 3C.1). Southeast Technical Associats, Inc.

Costeff, H. (1966) A simple empirical formula for calculating approximate surface area in children. Arch. Dis. Childh. 41:681-683.

Driver, J.H.; Konz, J.J.; Whitmyre, G.K. (1989) Soil adherence to human skin. Bull. Environ. Contam. Toxicol. 43:814-820.

Dubois, D.; Dubois, E.F. (1916) A formula to estimate the approximate surface area if height and weight be known. Arch. of Intern. Med. 17:863-871.

Gehan, E.; George, G.L. (1970) Estimation of human body surface area from height and weight. Cancer Chemother. Rep. 54(4):225-235.

Geigy Scientific Tables (1981) Nomograms for determination of body surface area from height and mass. Lentner, C. (ed.). CIBA-Geigy Corporation, West Caldwell, NJ. pp. 226-227.

George, S.L.; Gehan, E.A.; Haycock, G.B.; Schwartz, G.J. (1979) Letters to the editor. The Journal of Pediactrics. 94(2):342.

Haycock, G.B.; Schwartz, G.J.; Wisotsky, D.H. (1978) Geometric method for measuring body surface area: A height-weight formula validated in infants, children, and adults. J. Ped. 93(1):62-66.

Kissel, J.; Richter, K.; Duff, R.; Fenske, R. (1996a) Factors Affecting Soil Adherence to Skin in Hand-Press Trials. In press: Bull. Environ. Contamin. Toxicol.

Kissel, J.; Richter, K.; Fenske, R. (1996b) Field measurements of dermal soil loading attributable to various activities: Implications for exposure assessment. Risk Anal. 16(1):116-125.

Lepow, M.L.; Bruckman, L.; Gillette, M.; Markowitz, S.; Rubino, R.; Kapish, J. (1975) Investigations into sources of lead in the environment of urban children. Environ. Res. 10:415-426.

Murray, D.M.; Burmaster, D.E. (1992) Estimated distributions for total surface area of men and women in the United States. J. Expos. Anal. Environ. Epidemiol. 3(4):451-462.

Palisade. (1992) @Risk users guide. Palisade Corporation, Newfield, NY.

Phillips, L.J.; Fares, R.J.; Schweer, L.G. (1993) Distributions of total skin surface area to body weight ratios for use in dermal exposure assessments. J. Expos. Anal. Environ. Epidemiol. 3(3):331-338.

Popendorf, W.J.; Leffingwell, J.T. (1976) Regulating OP pesticide residues for farmworker protection. In: Residue Review 82. New York, NY: Springer-Verlag New York, Inc., 1982. pp. 125-201.

Que Hee, S.S.; Peace, B.; Clark, C.S.; Boyle, J.R.; Bornschein, R.L.; Hammond, P.B. (1985) Evolution of efficient methods to sample lead sources, such as house dust and hand dust, in the homes of children. Environ. Res. 38: 77-95.

Rochon, J.; Kalsbeck, W.D. (1983) Variance estimation from multi-stage sample survey data: the jackknife repeated replicate approach. Presented at 1983 SAS Users Group Conference, New Orleans, Louisiania, January 1983.

Roels, H.A.; Buchet, J.P.; Lauwenys, R.R.; Branx, P.; Claeys-Thoreau, F.; Lafontaine, A.; Verduyn, G. (1980) Exposure to lead by oral and pulmonary routes of children living in the vicinity of a primary lead smelter. Environ. Res. 22:81-94.

Sedman, R.M. (1989) The development of applied action levels for soil contact: a scenario for the exposure of humans to soil in a residential setting. Environ. Health Perspect. 79:291-313.

Sendroy, J.; Cecchini, L.P. (1954) Determination of human body surface area from height and weight. Journal of Applied Physiology. 7(1):3-12.

U.S. EPA. (1985) Development of statistical distributions or ranges of standard factors used in exposure assessments. Washington, DC: Office of Research and Development, Office of Health and Environmental Assessment. U.S. EPA No. 600/8-85-010. Available from: NTIS, Springfield, VA. PB85-242667.

U.S. EPA. (1989) Risk assessment guidance for superfund. Human health evaluation manual: Part A. Interim Final. Washington, DC: Office of

Solid Waste and Emergency Response. NTIS: PB-90-155581.

U.S. EPA. (1992) Dermal exposure assessment: principles and applications. Washington, DC: Office of Research and Development, Office of Health and Environmental Assessment/OHEA. U.S. EPA/600/8-9-91.

Van Graan, C.H. (1969) The determination of body surface area. Supplement to the South African J. of Lab. and Clin. Med. 8-2-69.

Versar, Inc. (1991) Analysis of the impact of exposure assumptions on risk assessment of chemicals in the environment, phase II: uncertainty analyses of existing exposure assessment methods. Draft Report. Prepared for Exposure Assessment Task Group, Chemical Manufacturers Association, Washington, DC.

Yang, J.J.; Roy, T.A.; Krueger, A.J.; Neil, W.; Mackerer, C.R. (1989) In vitro and in vivo percutaneous absorption of benzo[a]pyrene from petroleum crude-fortified soil in the rat. Bull. Environ. Contam. Toxicol. 43: 207-214.

Table 6-1. Summary of Equation Parameters for Calculating Adult Body Surface Area

Body Part	N	Equation for surface areas (m^2) a_o	W^{a1}	H^{a2}	P	R^2	S.E.
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] $SA = a_o W^{a1} H^{a2}$
W = Weight in kilograms; H = Height in centimeters; P = Level of significance; R^2 = Coefficient of determination; SA = Surface Area; S.E. = 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 6-2. Surface Area of Adult Males in Square Meters

Body part	Percentile 5	10	15	25	50	75	85	90	95	S.E.[a]
Total	1.66	1.72	1.76	1.82	1.94	2.07	2.14	2.20	2.28	0.00374
Head	0.119	0.121	0.123	0.124	0.130	0.135	0.138	0.140	0.143	0.0202
Trunk[b]	0.591	0.622	0.643	0.674	0.739	0.807	0.851	0.883	0.935[c]	0.0118
Upper extremities	0.321	0.332	0.340	0.350	0.372	0.395	0.408	0.418	0.432[c]	0.00101
Arms	0.241	0.252	0.259	0.270	0.291	0.314[c]	0.328[c]	0.339[c]	0.354[c]	0.00387
Forearms	0.106	0.111	0.115	0.121	0.131	0.144[c]	0.151[c]	0.157[c]	0.166[c]	0.0207
Hands	0.085	0.088	0.090	0.093	0.099	0.105	0.109	0.112	0.117	0.0187
Lower extremities	0.653	0.676	0.692	0.715	0.761	0.810	0.838	0.858	0.888[c]	0.00633
Legs	0.539	0.561	0.576	0.597	0.640	0.686[c]	0.714[c]	0.734[c]	0.762[c]	0.0130
Thighs	0.318	0.331	0.341	0.354	0.382	0.411[c]	0.429[c]	0.443[c]	0.463[c]	0.0149
Lower legs	0.218	0.226	0.232	0.240	0.256	0.272	0.282	0.288	0.299	0.0149
Feet	0.114	0.118	0.120	0.124	0.131	0.138	0.142	0.145	0.149	0.0147

[a] Standard error for the 5-95 percentile of each body part.
[b] Trunk includes neck.
[c] Percentile estimates exceed the maximum measured values upon which the equations are based.
Source: U.S. EPA, 1985.

Table 6-3. Surface Area of Adult Females in Square Meters

Body part	Percentile 5	10	15	25	50	75	85	90	95	S.E.[a]
Total	1.45	1.49	1.53	1.58	1.69[c]	1.82	1.91	1.98	2.09	0.00374
Head	0.106	0.107	0.108	0.109	0.111	0.113	0.114	0.115	0.117	0.00678
Trunk[b]	0.490	0.507	0.518	0.538	0.579	0.636	0.677	0.704	0.752	0.00567
Upper extremities	0.260	0.265	0.269	0.274	0.287	0.301	0.311	0.318	0.329	0.00833
Arms	0.210	0.214	0.217	0.221	0.230	0.238[c]	0.243[c]	0.247[c]	0.253[c]	0.00996
Hands	0.0730	0.0746	0.0757	0.0777	0.0817	0.0868[c]	0.0903[c]	0.0927[c]	0.0966[c]	0.0172
Lower extremities	0.564	0.582	0.595	0.615	0.657	0.704	0.736	0.757	0.796	0.00633
Legs	0.460	0.477	0.488	0.507	0.546	0.592	0.623	0.645	0.683[c]	0.0130
Thighs	0.271	0.281	0.289	0.300	0.326	0.357	0.379	0.394	0.421[c]	0.0149
Lower legs	0.186	0.192	0.197	0.204	0.218	0.233	0.243	0.249	0.261	0.0149
Feet	0.100	0.103	0.105	0.108	0.114	0.121	0.126	0.129	0.134	0.0147

[a] Standard error for the 5-95 percentile of each body part.
[b] Trunk includes neck.
[c] Percentile estimates exceed the maximum measured values upon which the equations are based.
Source: U.S. EPA, 1985.

Table 6-4. Surface Area by Body Part for Adults (m^2)

Body part	Men						Women					
	N[b]	Mean	(sd)[a]	Min.	-	Max.	N	Mean	(sd)	Min.	-	Max.
Head	32	0.118	(0.0160)	0.090	-	0.161	57	0.110	(0.00625)	0.0953	-	0.127
Trunk (Incl. Neck)	32	0.569	(0.104)	0.306	-	0.893	57	0.542	(0.0712)	0.437	-	0.867
Upper extremities	48	0.319	(0.0461)	0.169	-	0.429	57	0.276	(0.0241)	0.215	-	0.333
Arms	32	0.228	(0.0374)	0.109	-	0.292	13	0.210	(0.0129)	0.193	-	0.235
Upper arms	6	0.143	(0.0143)	0.122	-	0.156	-	-	-	-	-	-
Forearms	6	0.114	(0.0127)	0.0945	-	0.136	-	-	-	-		-
Hands	32	0.084	(0.0127)	0.0596	-	0.113	12	0.0746	(0.00510)	0.0639		0.0824
Lower extremities	48	0.636	(0.0994)	0.283	-	0.868	57	0.626	(0.0675)	0.492	-	0.809
Legs	32	0.505	(0.0885)	0.221	-	0.656	13	0.488	(0.0515)	0.423	-	0.585
Thighs	32	0.198	(0.1470)	0.128	-	0.403	13	0.258	(0.0333)	0.258	-	0.360
Lower legs	32	0.207	(0.0379)	0.093	-	0.296	13	0.194	(0.0240)	0.165	-	0.229
Feet	32	0.112	(0.0177)	0.0611	-	0.156	13	0.0975	(0.00903)	0.0834	-	0.115
TOTAL		1.94	(0.00374)[c]	1.66	-	2.28[d]		1.69	(0.00374)[c]	1.45	-	2.09[d]

[a] standard deviation.
[b] number of observations.
[c] median (standard error).
[d] percentiles (5th - 95th).
Source: Adapted from U.S. EPA, 1985.

Table 6-5. Percentage of Total Body Surface Area by Part for Adults

Body part	Men						Women					
	N[a]	Mean	(s.d.)[b]	Min.	-	Max.	N	Mean	(s.d.)	Min.	-	Max.
Head	32	7.8	(1.0)	6.1	-	10.6	57	7.1	(0.6)	5.6	-	8.1
Trunk	32	35.9	(2.1)	30.5	-	41.4	57	34.8	(1.9)	32.8	-	41.7
Upper extremities	48	18.8	(1.1)	16.4	-	21.0	57	17.9	(0.9)	15.6	-	19.9
Arms	32	14.1	(0.9)	12.5	-	15.5	13	14.0	(0.6)	12.4	-	14.8
Upper arms	6	7.4	(0.5)	6.7	-	8.1	-	-	-	-	-	-
Forearms	6	5.9	(0.3)	5.4	-	6.3	-	-	-	-		-
Hands	32	5.2	(0.5)	4.6	-	7.0	12	5.1	(0.3)	4.4		5.4
Lower extremities	48	37.5	(1.9)	33.3	-	41.2	57	40.3	(1.6)	36.0	-	43.2
Legs	32	31.2	(1.6)	26.1	-	33.4	13	32.4	(1.6)	29.8	-	35.3
Thighs	32	18.4	(1.2)	15.2	-	20.2	13	19.5	(1.1)	18.0	-	21.7
Lower legs	32	12.8	(1.0)	11.0	-	15.8	13	12.8	(1.0)	11.4	-	14.9
Feet	32	7.0	(0.5)	6.0	-	7.9	13	6.5	(0.3)	6.0	-	7.0

[a] Number of observations.
[b] Standard deviation.
Source: Adapted from U.S. EPA, 1985.

Table 6-6. Total Body Surface Area of Male Children in Square Meters[a]

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

[a] Lack of height measurements for children < 2 years in NHANES II precluded calculation of surface areas for this age group.
[b] Estimated values calculated using NHANES II data.
Source: U.S. EPA, 1985.

Table 6-7. Total Body Surface Area of Female Children in Square Meters[a]

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

[a] Lack of height measurements for children < 2 years in NHANES II precluded calculation of surface areas for this age group.
[b] Estimated values calculated using NHANES II data.
Source: U.S. EPA, 1985.

Table 6-8. Percentage of Total Body Surface Area by Body Part for Children

Age (yr)	N M:F	Percent of Total											
		Head		Trunk		Arms		Hands		Legs		Feet	
		Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max
< 1	2:0	18.2	18.2-18.3	35.7	34.8-36.6	13.7	12.4-15.1	5.3	5.21-5.39	20.6	18.2-22.9	6.54	6.49-6.59
1 < 2	1:1	16.5	16.5-16.5	35.5	34.5-36.6	13.0	12.8-13.1	5.68	5.57-5.78	23.1	22.1-24.0	6.27	5.84-6.70
2 < 3	1:0	14.2		38.5		11.8		5.30		23.2		7.07	
3 < 4	0:5	13.6	13.3-14.0	31.9	29.9-32.8	14.4	14.2-14.7	6.07	5.83-6.32	26.8	26.0-28.6	7.21	6.80-7.88
4 < 5	1:3	13.8	12.1-15.3	31.5	30.5-32.4	14.0	13.0-15.5	5.70	5.15-6.62	27.8	26.0-29.3	7.29	6.91-8.10
5 < 6													
6 < 7	1:0	13.1		35.1		13.1		4.71		27.1		6.90	
7 < 8													
8 < 9													
9 < 10	0:2	12.0	11.6-12.5	34.2	33.4-34.9	12.3	11.7-12.8	5.30	5.15-5.44	28.7	28.5-28.8	7.58	7.38-7.77
10 < 11													
11 < 12													
12 < 13	1:0	8.74		34.7		13.7		5.39		30.5		7.03	
13 < 14	1:0	9.97		32.7		12.1		5.11		32.0		8.02	
14 < 15													
15 < 16													
16 < 17	1:0	7.96		32.7		13.1		5.68		33.6		6.93	
17 < 18	1:0	7.58		31.7		17.5		5.13		30.8		7.28	

N: Number of subjects, male to female ratios.

Source: U.S. EPA 1985.

Table 6-9. Descriptive Statistics for Surface Area/Body Weight (SA/BW) Ratios (m^2/kg)

Age (yrs.)	Mean	Range Min-Max	SD[a]	SE[b]	Percentiles 5	10	25	50	75	90	95
0-2	0.0641	0.0421-0.1142	0.0114	7.84e-4	0.0470	0.0507	0.0563	0.0617	0.0719	0.0784	0.0846
2.1 - 17.9	0.0423	0.0268-0.0670	0.0076	1.05e-3	0.0291	0.0328	0.0376	0.0422	0.0454	0.0501	0.0594
≥ 18	0.0284	0.0200-0.0351	0.0028	7.68e-6	0.0238	0.0244	0.0270	0.0286	0.0302	0.0316	0.0329
All ages	0.0489	0.0200-0.1142	0.0187	9.33e-4	0.0253	0.0272	0.0299	0.0495	0.0631	0.0740	0.0788

[a] Standard deviation.
[b] Standard error of the mean.
Source: Phillips et al., 1993.

Table 6-10. Statistical Results for Total Body Surface Area Distributions (m^2)

	Men			
	U.S. EPA	Boyd	DuBois and DuBois	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
	Women			
	U.S. EPA	Boyd	DuBois and DuBois	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 6-11. Skin Coverage with Soil by Body Part and Activity

Exposure Trial	Percent Skin Coverage by Body Part: N[a]	Hands	N[a]	Lower legs	N[a]	Forearms	N[a]	Face
Children playing in wet soil	24	80	18	20	18	10	13	0
Adults transplanting plants in wet soil	28	70	24	10	26	0	15	0
Pipe laying trials	3	36-52 (M)[b]	3	6-12 (M)	--	--	--	0
dry soil, 15-30 min. duration	3	54-62 (W)[b]	3	15-33 (W)	--	--	--	0
Pipe laying trials	4	75-82 (M)	4	12-25 (M)	--	--	--	0
wet soil, 15-30 min. duration	3	56-86 (W)	3	4-14 (W)	--	--	--	0

[a] N = number of subjects
[b] M = men; W = women
Source: Kissel et al., 1995.

Figure 6-1. SA/BW Distributions for Infants, Adults, and All Ages Combined
Source: Phillips et al., 1993.

Figure 6-2. Frequency Distributions for the Surface Area of Men and Women
Source: Murray and Burmaster, 1992.

Table 6-12. Summary of Field Studies

Activity	Month	Duration (hr)	*n*	Male	Female	Ages	Conditions	Clothing
Outdoor								
Soccer No. 1	November	0.67	8	8	0	13-15	Half grass-half bare earth	6 of 8 long sleeve shirts 4 of 8 long pants 3 of 4 short pants & shin guards
Soccer No. 2	March	1.5	8	0	8	24-34	Allweather field (sand-ground tires)	All in short sleeve shirts, shorts, kneee socks, shin guards
Soccer No. 3	November	1.5	7	0	7	24-34	Allweather field (sand-ground tires)	All in short sleeve shirts, shorts, kneee socks, shin guards
Grounds Keeper No. 1	March	1.5	2	1	1	29-52	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Grounds Keeper No. 2	March	4.25	5	3	2	22-37	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Grounds Keeper No. 3	March	8	7	5	2	30-62	Campus grounds, urban horticulture center, arboretum	All in long pants, intermittent use of gloves
Grounds Keeper No. 4	August	4.25	7	4	3	22-38	Campus grounds, urban horticulture center, arboretum	10 of 15 short sleeve shirts, intermittent use of gloves
Grounds Keeper No. 5	August	8	8	6	2	19-64	Campus grounds, urban horticulture center, arboretum	10 of 15 short sleeve shirts, intermittent use of gloves
Irrigation Installers	October	3	6	6	0	23-41	Landscaping, surface restoration	All in long pants, 3 of 6 short sleeve or no sleeve shirts
Rugby Players	March	1.75	8	8	0	20-22	Mixed grass-bare wet field	All in short sleeve shirts, shorts, sock lenghts variable
Farmers No. 1	May	2	4	2	2	39-44	Manual weeding, mechanical cultivation	All in long pants, heavy shoes, short sleeve shirts, no gloves
Farmers No. 2	July	2	6	4	2	18-43	Manual weeding, mechanical cultivation	2 of 6 shorts, 4 of 6 long pants, 1 of 6 long sleeve shirt, no gloves
Reed Gatherers	August	2	4	0	4	42-67	Tidal flats	2 of 4 short sleeve shirts/knee length pants, all wore shoes
Kids-in-mud No. 1	September	0.17	6	5	1	9-14	Lake shoreline	All in short sleeve T shirts, shorts, barefoot
Kids-in-mud No. 2	September	0.33	6	5	1	9-14	Lake shoreline	All in short sleeve T shirts, shorts, barefoot
Totals			92	57	35			
Indoor								
Tae Kwon Do	February	1.5	7		1	8-42	Carpeted floor	All in long sleeve-long pants martial arts uniform, sleeves rolled back, barefoot
Greenhouse Workers	March	5.25	2		1	37-39	Plant watering, spraying, soil blending, sterilization	Not given
Totals			9	7	2			

[a] N = number of subjects
Source: Kissel et al., 1996

Table 6-13. Mean Soil Adherence by Activity and Body Region

Activity	Body Part (mg/cm^2)					
	N[a]	Hands	Arms	Legs	Face	Feet
Outdoor						
Soccer No. 1	8	0.11 0.066-0.18	0.011 0.0058-0.019	0.031 0.010-0.093	0.012 0.0083-0.016	--
Soccer No. 2	8	0.035 0.011-0.11	0.0043 0.0022-0.0083	0.014 0.0034-0.055	0.016 0.011-0.022	--
Soccer No. 3	7	0.019 0.013-0.028	0.0029 0.0014-0.0060	0.0081 0.0052-0.013	0.012 0.0078-0.018	--
Grounds Keeper No. 1	2	0.15	0.0050	--	0.0021	0.018
Grounds Keeper No. 2	5	0.098 0.040-0.24	0.0021 0.00065-0.0067	0.0012 0.00063-0.0021	0.010 0.0045-0.023	--
Grounds Keeper No. 3	7	0.030 0.014-0.065	0.0023 0.0012-0.0043	0.0009 0.00044-0.0019	0.0047 0.0021-0.010	0.0041 --
Grounds Keeper No. 4	7	0.046 0.025-0.082	0.014 0.0079-0.023	0.0008 0.00035-0.0018	0.0029 0.0018-0.0044	0.018 --
Grounds Keeper No. 5	8	0.032 0.021-0.049	0.023 0.0098-0.052	0.0010 0.0008-0.0014	0.0037 0.0019-0.0073	--
Irrigation Installers	6	0.19 0.12-0.31	0.018 0.0053-0.062	0.0054 0.0029-0.010	0.0063 0.0047-0.0086	--
Rugby Players	8	0.40 0.26-0.62	0.27 0.18-0.40	0.36 0.23-0.55	0.059 0.026-0.13	--
Farmers No. 1	4	0.41 0.20-0.84	0.059 0.0094-0.37	0.0059 0.0012-0.028	0.018 0.011-0.030	--
Farmers No. 2	6	0.47 0.33-0.69	0.13 0.056-0.29	0.037 0.0088-0.16	0.041 0.013-0.13	--
Reed Gatherers	4	0.66 0.25-1.7	0.036 0.011-0.12	0.16 0.0047-5.4	--	0.63 0.028-14
Kids-in-mud No. 1	6	35 15-84	11 1.7-73	36 18-75	--	24 6.2-9.3
Kids-in-mud No. 2	6	58 24-140	11 2.6-44	9.5 4.0-23	--	6.7 0.47-94
Indoor						
Tae Kwon Do	7	0.0062 0.0036-0.011	0.0019 0.0006-0.0062	0.0020 0.0011-0.0034	--	0.0024 0.0012-0.0049
Greenhouse Workers	2	0.043 --	0.0064 --	0.0015 --	0.0051 --	--

[a] N = number of subjects
Source: Kissel et al., 1996

Table 6-14. Surface Area Studies

Study	Surface Area				
	No. of Individuals	Type of Surface Area Measurement	Recommended Formulae Used	Population Surveyed	Comments
KEY STUDIES					
Boyd (1935)	231	Direct measurements using data for coating, surface integration, and triangulation methods only	$SA=0.0178*W^{0.500}*H^{0.4838}$	Children Adults	Reviewed all methods and data used to measure or estimate SA
Dubois & Dubois (1916)	9	Linear	$SA=0.0178*W^{0.425}*H^{0.725}$	Children Adults	Direct measurement
Gehan & George (1970)	401	Based on Boyd, 1935	$SA=0.0235*W^{0.51456}*H^{0.42246}$	Children Adults	Used 401 observations from Boyd's data where direct measurement for SA, height, and weight were compiled. Used least squares method to develop constants for equation. > 50 percent of data were for children < 5 years old.
Phillips et al. (1993)	Based on data from USEPA (1985): 401 individuals	NA	calculated surface area to body weight ratios	Children Adults	Developed distributions of SA/BW and calculated summary and statistics for 3 age groups and the combined data set
U.S. EPA (1985)		Based on Gehan & George (1970)	$SA=0.0239*W^{0.517}*H^{0.417}$	Children Adults	Provides statistical distribution data for total SA and SA of body parts
RELEVANT STUDY					
Murray & Burmaster (1992)	Based on data from USEPA: 401 DuBois & Dubois: 9 Boyd: 231 Costaff: 220	Calculated based on regression equation using the data of USEPA, 1985	Various	Children Adults	Analysis of and comparision of four models developed by Dubois & Dubois (1916), Boyd (1935), U.S. EPA (1985), and Costeff (1966). Presents frequency distribtions

[a] Based on height weight data presented in report.

Table 6-15. Summary of Recommended Values for Skin Surface Area

Surface Area	Central Tendency	Upper Percentile	Multiple Percentiles
Adults			
Whole body and body parts	see Table 6-4	see Tables 6-2 and 6-3	see Tables 6-2 and 6-3
Bathing/swimming	20,000 cm^2	23,000 cm^2	---
Outdoor soil contact	5,000 cm^2	5,800 cm^2	---
Children			
Whole body	---	see Tables 6-6 and 6-7	see Tables 6-6 and 6-7
Body parts	---	see Table 6-8	see Table 6-8

Table 6-16. Confidence in Body Surface Area Measurement Recommendations

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

Table 6-17. Confidence in Dermal Adherence Recommendations

Considerations	Rationale	Rating
Study Elements		
• Level of Peer Review	Peer reviewed journal articles	High
• Accessibility	Articles published in widely circulated journals	High
• Reproducibility	Reports clearly describe experimental method	High
• Focus on factor of interest	Studies have goal to determine soil adherence to skin	High
• Data pertinent to U.S.	Experiments conducted in the U.S.	High
• Primary data	Experiments directly measure soil adherence to skin; exposure and dose of chemicals in soil measured indirectly or estimated from soil contact	High
• Currency	New studies in rapidly changing area	High
• Adequacy of data collection period	Seasonal factors may be important but have not been studied adequately	Medium
• Validity of approach	Skin rinsing technique is a widely employed procedure	High
• Representativeness of the population	Studies, limited to Seattle, WA, may not be representative of other locales	Low
• Characterization of variability	Variability in soil adherence is affected by many factors including soil properties, activity and individual behavior patterns	Low
• Lack of bias in study design	Studies attempt to measure soil adherence in selected activities and conditions to identify important activities and groups	High
• Measurement error	Experimental error is low and well controlled but application of results to other similar activities may be subject to variation	Low/High
Other Elements		
• Number of studies	Controlled experiments being conducted by a few laboratories; activity patterns being studied by only one laboratory	Medium
• Agreement among researchers	Results from key study consistent with earlier estimates from relevant studies and assumptions, but limited to hand data	Medium
Overall Rating	Limited data is difficult to extrapolate from experiments and field observations to general conditions	Low

Table 6-18. Summary of Soil Adherence Studies

Study	Size Fraction (μm)	Soil Adherence (mg/cm^2)	Population Surveyed	Comments
KEY STUDIES				
Kissel et al., 1995	--	Various	28 adults 24 children	Data presented for soil loadings by body part. See Table 6-13.
RELEVANT STUDIES				
Driver et al., 1989	< 150 < 250 unsieved	1.40 0.95 0.58	Adults Adults Adults	Used 5 soil types and 2-3 soil horizons (top soils and subsoils); placed soil over entire hand of test subject, excess removed by shaking the hands.
Lepow et al., 1975	--	0.5	10 children	Dirt from hands collected during play. Represents only fraction of total present, some dirt may be trapped in skin folds.
Que Hee et al., 1985	--	1.5	1 adult	Assumed exposed area = 20 cm^2. Test subject was 14 years old.
Roels et al., 1980	--	0.9-1.5	661 children	Subjects lived near smelter in Brussels, Belgium. Mean amount adhering to soil was 0.159 g.
Sedman, 1989	--	0.9; 0.5	Children	Used estimate of Roels (1980) and average surface of hand of an 11 year old; used estimates of Lepow, Roels, and Que Hee to develop mean of 0.5 mg/cm^2.
Yang et al., 1989	< 150	9	Rats	Rat skin "monolayer" (i.e., minimal amount of soil covering the skin); in vitro and in vivo experiments.

APPENDIX 6A

Formulae for Total Body Surface Area

APPENDIX 6A

FORMULAE FOR TOTAL BODY SURFACE AREA

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

$$SA = KW^{2/3} \qquad \text{(Eqn. 6A-1)}$$

where:

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

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

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

$$SA = a_0 \, H^{a_1} \, W^{a_2} \qquad \text{(Eqn. 6A-2)}$$

where:

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

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

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

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

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

$$SA = 0.02350\ H^{0.42246}\ W^{0.51456} \qquad \text{(Eqn. 6A-3)}$$

or in logarithmic form:

$$\ln SA = -3.75080 + 0.42246 \ln H + 0.51456 \ln W \qquad \text{(Eqn. 6A-4)}$$

where:

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

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

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

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

$$SA_i = a_0\ H_i^{a1}\ W_i^{a2}\ e_i \qquad \text{(Eqn. 6A-5)}$$

or in logarithmic form:

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

where:

Sai = surface area of the i-th individual (m^2);
Hi = height of the i-th individual (cm);
Wi = 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:

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

The model is then:

$$SA = 0.0239\ H^{0.417}\ W^{0.517} \qquad \text{(Eqn. 6A-7)}$$

or in logarithmic form:

$$\ln SA = -3.73 + 0.417 \ln H + 0.517 \ln W \qquad \text{(Eqn. 6A-8)}$$

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

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

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

Table 6A-1. Estimated Parameter Values for Different Age Intervals

Age group	Number of persons	a_0	a_1	a_2
All ages	401	0.02350	0.42246	0.51456
< 5 years old	229	0.02667	0.38217	0.53937
≥ 5 - < 20 years old	42	0.03050	0.35129	0.54375
≥ 20 years old1	30	0.01545	0.54468	0.46336

The surface areas estimated using the parameter values for all ages were compared to surface areas estimated by the values for each age group for subjects at the 3rd, 50th, and 97th percentiles of weight and height. Nearly all differences in surface area estimates were less than 0.01 square meter, and the largest difference was 0.03

m^2 for an 18-year-old at the 97th percentile. The authors concluded that there is no advantage in using separate values of a_0, a_1, and a_2 by age interval.

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

$$SA = 0.024265\ H^{0.3964}\ W^{0.5378} \qquad \text{(Eqn. 6A-9)}$$

expressed logarithmically as:

$$\ln SA = \ln 0.024265 + 0.3964 \ln H + 0.5378 \ln W \qquad \text{(Eqn. 6A-10)}$$

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

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

$$\ln SA = \ln a_0 + a_1 \ln H + a_2 \ln W \qquad \text{(Eqn. 6A-11)}$$

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

Table 6A-2. Summary of Surface Area Parameter Values for the DuBois and DuBois Model

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

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

Nomograms

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