Dust: A Metric for Use in Residential and Building Exposure Assessment and Source Characterization

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In this review, we examine house dust and residential soil and their use for identifying sources and the quantifying levels of toxicants for the estimation of exposure. We answer critical questions that focus on the selection of samples or sampling strategies for collection and discuss areas of uncertainty and gaps in knowledge. We discuss the evolution of dust sampling with a special emphasis on work conducted after the publication of the 1992 review by McArthur [Appl Occup Environ Hyg 7(9):599–606 (1992)]. The approaches to sampling dust examined include surface wipe sampling, vacuum sampling, and other sampling approaches, including attic sampling. The metrics of presentation of results for toxicants in dust surface loading (micrograms per square centimeter) or surface concentration (micrograms per gram) are discussed. We evaluate these metrics in terms of how the information can be used in source characterization and in exposure characterization. We discuss the types of companion information on source use and household or personal activity patterns required to assess the significance of the dust exposure. The status and needs for wipe samplers, surface samplers, and vacuum samplers are summarized with some discussion on the strengths and weaknesses of each type of sampler. We also discuss needs for research and development and the current status of standardization. Case studies are provided to illustrate the use of house dust and residential soil in source characterization, forensic analyses, or human exposure assessment. ***Key words:*** **chemical composition, exposure characterization, house dust, physical composition, residence wipe sampling, source identification, vacuum sampling.** ***Environ Health Perspect*** **110:969–983 (2002). [Online 15 August 2002]**
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The maturation of the field of exposure analysis and assessment has led to the development of many innovative methods and strategies to detect, reduce, and prevent human contact with environmental toxicants. These toxicants can be found in air, water, soil, or food. Some methods employed by investigators are new (e.g., biological markers and human videotaping), whereas others are adaptations of methods used for general or specific types of environmental or occupational investigations (microscopic analyses, modeling, and personal monitoring). Depending on the type of method chosen, each may be applicable for epidemiologic investigations, human exposure profiling for specific contaminants or events, and/or risk assessment. In addition, and as a result of the findings made in the Total Exposure Assessment Methodology (TEAM) studies and others conducted during the 1980s, the field of exposure analysis has turned its attention beyond primarily measuring toxicants in outdoor environmental situations (*1–9*). Now information is frequently obtained from one or more different microenvironments occupied or passed through by an individual or individuals over the course of a day.

The purpose of this article is to review the types of information available on dust in residential settings, the metrics used for exposure and source characterizations, and the composition of dust. We also review and evaluate the methods used to affect residential dust and soil. We explore the applications of dust for exposure and source-related analyses and ways to improve quantitative dust characterization in the future.

A number of studies have shown that for individuals and populations, especially children and other vulnerable subgroups, the home environment can be a potential source of passive or active exposure to toxicants (*10–23*). This presents a complex situation for the exposure specialist and for other environmental health scientists in their attempts to identify the potential or actual risk associated with common or specific environmental toxicants. There are many different types of toxicants that can be present for short or long periods in a building, and each could be in a form or location that is readily accessible for contact by inhabitants or visitors (*5,24–26*). Because toxicants can come from multiple sources (indoors or outdoors), media, and activities, exposures can occur at single or multiple routes of entry into the body. The question that arises is, how does one determine which toxicant and source, or multiples of each, are of greatest concern to the health of the residents?

Beyond obtaining measurements for the toxicant levels present at routes of entry into the body, variables needed to characterize exposure are the activities and the patterns of activity and uncommon events that may result in passive or active exposures. Thus, the number and complexity of the types of variables needed to understand exposure can become large. This leads directly to consideration of a triage to the application of sampling and analysis strategies for finding the best ways to identify, examine, and explain potential or actual exposures and to find and select the most appropriate mitigation or prevention strategies. Sampling and analysis strategies are becoming increasingly important as the field attempts to provide information on cumulative exposure to multiple toxicants in a single medium and the aggregate exposure associated with a single toxicant from multiple exposure pathways (*26–29*).

Because of the multiplicity of indoor and outdoor sources and routes of contact that can occur in the home, residential dust (house dust) and residential/community soil represent two categories within one medium—soil—that can benefit from a triage of measurement strategies. The approach will allow the investigation of the influence of multiple variables on the intensity and duration of contact with toxicants that can result in cumulative or aggregate exposures.

Soil and Dust: Perspective for Exposure Studies

For many years, soil samples have been collected as cores in various urban and industrial locations (*30*). There is a wealth of information

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on the chemistry, physics, and microbiology of soils (*31–33*). The analytic results obtained from many soil samples have been used to determine the levels of various materials and toxicants at a certain depth (0 to > 100 ft) from the surface, but most of this work does not deal directly with exposure characterization. Opportunities for using this type of data in exposure assessment include quantifying significant penetration of toxicants into the groundwater that is used for a drinking water supply or the diffusion of volatile material into a basement. Most of the measurements made in soil at a distance beyond 1 ft below the surface are of little value in assessing direct dermal exposure (*34,35*). Data or soil contamination, however, is still important for profiling the distribution of material to various depths, identifying sources, and assisting in defining the period of time when the deposition and/or accumulation of toxicants occurred in the soil. Core sampling is also used to detect the presence of a toxicant or tracer material in locations that include ice or snow packs and sediments below bodies of water (*26*). Numerous soil sampling and analysis programs have been conducted at hazardous waste sites (e.g., Superfund sites) and abandoned industrial sites (e.g., brown fields). These programs have been designed to establish the horizontal and vertical extent of contamination before remediation (*36*). In addition, research studies have been completed in arid regions around the world. These have focused on the reentrainment of desert sand and its redistribution to locations > 1,000 km away (*37–39*). However, the focus here is on the ability of sand to be used to assess higher exposure, with the primary purpose of accounting for the soil component of residential dust.

The results of soil characterizations at hazardous waste or urban sites have been used, and in many circumstances continue to be used, as the basis for exposure characterizations in the preliminary risk assessments required before site cleanup (*26,40–42*). However, in addition to questions about the appropriateness of these data for a specific exposure assessment, the analytic plan usually employs default factors when estimating intensity and duration of contact with individual or multiple toxicants. The results of such analyses usually provide very crude, and in some cases unreasonable, worst-case estimates of possible exposures and risks (*43*). Over the past half decade, however, efforts have been made to encourage the use of more site-specific data to determine plausible patterns of activity that lead to exposure to the toxicants that are present in soils (*44*).

By collecting samples from the surface of a yard, a park, open or abandoned spaces, or locations downwind of an explosion or fire, characterization of toxicant levels in the soils have improved human exposure assessments. One use of dust collection and analysis approaches has been to characterize the dust emitted in downtown Manhattan from the aftermath of the World Trade Center attack (*45*).

Initially, measurements in surface soil samples were used to detect the levels of a toxicant that were available for resuspension into the atmosphere and then used to estimate inhalation exposure (*46–48*). Now such measurements are also applied to estimate direct dermal contact and to determine the potential ingestion or skin absorption of a toxicant found in or on dust or soil as a chemical residue (*24*). In many circumstances, the levels of chemical, physical, or biological contaminants in or on surface soil will represent the material that has been recently deposited on the soil and the fractions of soil that can be most easily transferred indoors. Further, work by Wallace et al. (*2*) during the TEAM study; by Charney et al. (*49*) and Roberts et al. (*50*) on lead exposure; by Simcox et al. (*16*) for pesticide exposures on farms; by Freeman et al. (*19,51*) on chromium exposure; and by Pellizzari et al. (*52*) and Bonanno et al. (*53*) for multiple pollutant and multiple media exposures during the National Human Exposure Assessment Survey (NHEXAS), to name a few, have demonstrated that a complex series of interactions takes place between home characteristics and activities, which can alter toxicant exposure, or indoor and outdoor source strengths.

During the early part of the twentieth century, a convenient method for collecting total particulate matter (undifferentiated by particle size) in air that had deposited on surfaces was the dust bucket. It was a simple device, just an open water bucket placed on a roof or other secure location to collect material available in the air for deposition on a surface. The samples were usually analyzed by visual observations, color, and total content, and then subjected to simple chemical analyses. A bucket would remain out for at least a month to collect all the material (including bugs, etc.) that deposited from the atmosphere via wet and dry deposition (*54*). The results were semiquantitative at best and usually difficult to interpret. Fortunately, devices used to collect dry and wet deposition have improved over time, and some are designed to make quantitative determinations of outdoor atmospheric deposition. These modern devices are currently used in national and international monitoring networks sponsored by various agencies (*54*). Indoors, deposition plates and other passive collection devices have been used to quantify the contribution of outdoor and indoor sources of particulate matter onto indoor surfaces (*55*).

Once researchers began to consider human exposure in residential neighborhoods and on farms, field studies were designed that included potential or actual soil contamination, and they focused on quantifying the movement of resuspended, contaminated outdoor soil and road dust into indoor locations (*46–48,55–61*). These studies were designed to examine the exposure and risk posed by toxicants deposited in the lungs of people living in zones potentially affected by point and area sources. Eventually, hypotheses about the transport of dust and dirt indoors, and contact by residents, led to parallel efforts on developing and employing techniques to measure the levels of contaminants in house dust after it has been generated or transported indoors and settled on surfaces or has been tracked into the home (*15,16,23,52,53,62–71*). In urban areas, some field studies have characterized the movement and accumulation of lead and other metals indoors (*10,19,71–76*). Based on the results of these studies, important transport processes to consider include the resuspension and transport of toxicants indoors, including tracking toxicants present in the street or in yard dust or soil by residents or pets (*25,26*).

For farms and residential lawn applications, some investigations have focused on the drift of pesticides to homes after spraying and on the tracking and deposition of resuspended outdoor dust or surface soil indoors (*23,66*). Recent exposure assessments for lead, pesticides, and polycyclic aromatic hydrocarbons (PAHs) and other toxicants (e.g., asbestos) also include characterization of exposure that resulted from toxicants deposited in and on objects found in homes. As a result, house dust is being used as a tool to assess environmental health risks by providing answers to questions about the potential for personal contacts that may have led to a significant exposure for one or more routes of entry into the body. Further, such information is now being used to examine the liability issues related to residential toxicant exposure and will eventually lead to development of standardized protocols for use in quantified forensic exposure characterizations.

General Composition of House Dust

When residential dust is selected as a metric of exposure, questions include:

- What are the components of residential dust?
- What are the behaviors and activities of the individuals that live in a particular location that either led to exposure or resuspension of dust?

If there was a homogeneous distribution of material in a home, and a major fraction of the dust was similar in composition, it would be easier to conduct analyses of exposure. At this time, however, limited data are available that can accurately describe the distribution of basic major constituents of house dust in American residences or in residences in other countries.

However, we have acquired information on the distribution of particular toxicants that accumulate on surfaces and within rugs and carpets in residences, and a summary of typical results are found in Tables 1 and 2. From the standpoint of analysis of exposure, one would also like to have baseline information on other materials present within a large number of statistically representative houses, in the United States and elsewhere, and in locations that have a variety of indoor and outdoor sources.

Information available on the basic composition of house dust comes from very few studies, and results suggest that the composition varies throughout a home as well as between homes, across seasons, and among locations within a given country. It will be interesting to see which studies performed for the purpose of indoor and outdoor toxicant detection also have collected data to help determine the character of general residential house dust [see, e.g., Hunt et al. (*77*) and Molhave et al. (*78*)].

One investigation on household dust loading obtained samples from 10 homes in 7 diverse U.S. cities (*79*). The analyses indicated that the dust partitioned between fibrous and nonfibrous components. However, among and within the homes sampled, individual rooms could have very high fiber content or equivalent levels of fiber and nonfiber, or low fiber content (Table 3). Because the study was limited in the number of homes sampled, one cannot say which type of loading is most representative of U.S. residential stock. The study did, however, provide some insight as to what general types of materials can be found in households. The room with low nonfibrous dust loadings was frequently the kitchen, and the homes with high fiber dust appeared to have pets. All rooms sampled could have material that ranged from high to low fiber content. The basic composition of dust in a kitchen, however, would not necessarily be similar to the composition found in the bedroom or in the bathroom. This is primarily due to the presence of different sources and major activities associated with each type of room; however, many of the major components of dust are found in each type of room. Similarities in dust composition, for particles > 75 µm in diameter, would include the presence of crumbs, hair, synthetics, soil, starch, plant parts, skin, insect parts, and pollens. For individual residences and rooms, the presence or absence of these materials could also affect the adsorption and adhesion of more toxic particles on a surface or the deposition on larger particles because of coagulation, van der Waals' forces, or electrostatic charging. In a study of seven Danish offices, Molhave et al. (*78*) found materials similar in composition to the previously mentioned U.S. study (*79*), and they also determined that the types of toxicants present in dust can be numerous.

Depending on the situation and the types of indoor/outdoor or personal sources associated with a residence, the toxicants present in the dust can include semivolatile and nonvolatile pesticides, PAHs, heavy metals, persistent organic compounds, asbestos, and viable biological particles (*16,18,22,64,65,68,80*). The sources of these compounds include combustion, professional product applications, typical residential product uses, fugitive emissions, transport, and degradation of plants and animal and insect parts. In fact, the elemental nature or persistence of some of these materials allows an investigator to compile a historical record of material deposited in the carpet. Clearly, in some cases this could reveal significant loadings caused by indoor or outdoor sources, but a historical analysis could also provide fingerprints for specific toxicants, or general internal or external sources of toxicants. When investigating a home that has environmental problems or when attempting to characterize general patterns of exposure, baseline data will also improve forensic-based sampling for source identification or exposure characterization.

Historical Perspective on Dust Sampling

The original techniques used for indoor dust collection were developed before 1970, and the majority were wipe-sampling techniques. Until recently, however, none of the techniques had undergone much scrutiny or rigorous validations. A major review of dust contaminant sampling techniques, primarily wipe-sampling techniques, was published in 1992 by McArthur (*81*). His evaluation identified wipe sampling for detection of radionuclides in the laboratory and other nuclear facilities as one scenario in which dust sampling could be used to routinely monitor health and safety.

Table 1. Examples of typical nonexperimental studies or postremediation levels of dust and selected toxicants found indoors: loadings and concentrations.

Compound	Method	Concentration range	Loading
Dust			
Roberts et al. (*50*)	HVS3		0.32–14.4 g/m^2
Adgate et al. (*17*)	LWW wipe: floor		0.05–7.0 g/m^2
	LWW wipe: windowsill		0.12–13 g/m^2
	Vacuum		0.3–99 g/m^2
Roberts et al. (*74*)	HVS3: rug/typical home vacuum		< 1.0–26 g/m^2
	HVS3: rug/remodeled home vacuum		< 1.0–63 g/m^2
Lead			
Farfel et al. (*81*)	HVS3: floor		0.01–90 mg/m^2
	HUD-wipe: floor		0.09–60 mg/m^2
	HVS3: windowsill		0.05–600 mg/m^2
	HUD-wipe: windowsill		0.01–45,000 mg/m^2
Roberts et al. (*50*)	HVS3: floor	75–700 µg/g	38–3,871 µg/m^2
Adgate et al. (*17*)	Vacuum	23–12,000 µg/g	0.08–210 mg/m^2
	LWW wipe (windowsill)	24–91,000 µg/g	0.03–430 mg/m^2
	LWW wipe (floor)	19–33,000 µg/g	0.0004–116 mg/m^2
Pesticides			
Rudel et al. (*80*)			
Chlorpyrifos	Mini-vacuum	1.26–89 µg/g	
Carbaryl	Mini-vacuum	27.2–140 µg/g	
O-Phenyl-phenol	Mini-vacuum	0.1–0.81 µg/g	
Lioy et al. (*19*)			
Chlorpyrifos	LWW wipe: floor		0.06–4.18 µg/m^2
	EL sampler: carpet		0.02–44.5 µg/m^2
	EL sampler: floor		0.03–36.6 µg/m^2
PAHs			
Rudel et al. (*80*)			
Benzo[*a*]pyrene	Mini-vacuum	0.455–10.6 µg/g	
Chueng et al. (*18*)			
12 PAHs	HVS3	2–12 µg/g	
Dust mites			
Roberts et al. (*50*)	HVS3	< 0.2–0.94 µg/g	0.11–3.46 ug/m^2
Fungi and microorganisms			
Molhave et al. (*78*)			
Total microorganisms	Vacuum bags	130,000–160,000 CFU/g	
Fungi	Vacuum bags	71,000–90,000 CFU/g	
Phenols			
Rudel et al. (*80*)			
Bisphenol A	Mini-vacuum	0.25–0.48 µg/g	
4-Nitrophenol	Mini-vacuum	0.17–6.82 µg/g	
Phathalates			
Rudel et al. (*80*)			
Di-2-ethylhexyl phthalate	Mini-vacuum	69.4–524.0 µg/g	

Abbreviations: EL, Edwards and Lioy; HUD, Housing and Urban Development; HVS3, high-volume surface sampler; LWW, Lioy-Weisel-Wainman.

However, qualitative wipe samples were used as early as 1940 in hospitals to determine microbial levels in operating rooms and to evaluate cleanliness of pharmaceutical manufacturing facilities (*26,67,82*). The first technique used for wet wipe sampling of contaminants present on dust-laden surfaces was published by Vostal et al. in 1974 (*83*).

The conclusions made by McArthur (*81*) in his review were enlightening because he stated that surface sampling has limited reliability for use in exposure assessment. Further, there was an important final quote in his paper that was attributed to H. J. Dunster, who nearly 40 years earlier recommended that hygienists pause and consider finding a better way (*84*):

> Surface contamination monitoring has not become a tool of occupational hygiene in general, partly because of the difficulty of monitoring for non-radioactive materials on surfaces. If the techniques of measurement were easier it is likely that the occupational hygienist would find monitoring of surface contamination to be a technique as useful to him as it is to his radiological colleague.

Unfortunately, there was not enough interest during the 1960s to follow through on Dunster's observation. Based on MacArthur's analyses and review of the standard approaches used in the field during the mid-to-late twentieth century, it was clear that there was an inability to employ reliable surface samplers for quantitative measurements of occupational or community exposure. Fortunately, during the late 1980s and early 1990s, work was completed by a few investigators that improved the methods for surface sampling: new techniques for surface sampling and rug sampling [Roberts et al. (*15*), Lioy et al. (*85*)]; the size-selective rug vacuum sampler [Lewis et al. (*86*)], the EL press sampler [Edwards and Lioy (*87*)], and a number of chemical-specific samplers [e.g., for pesticides (*23,74*)].

House Dust as a Tool for Quantitative Exposure Analysis and Assessment

Regulatory and public health issues about residential soil and dust have identified two major questions that will usually drive the design of measurement and analysis programs for house dust:

- What can the dust tell us that will reduce concerns and uncertainties about the levels of toxicants and sources of toxicants present in the home?
- How can we measure levels of toxicants in a way that the results reduce concerns and uncertainties about the intensity of exposures individuals receive from soil or dust via one or more routes of entry into the body?

At first glance these appear to be straightforward questions, but the answer(s) to each are complicated for both research and forensic-type applications. The first step of a triage that examines exposure to toxicants found in house dust should be identifying the types, locations, and surfaces an individual contacts during the day. This makes sense because human exposure to toxicants can occur anywhere, and contact can be with virtually any type of surface. The second step involves developing a preliminary inventory of potential indoor and outdoor sources observed or suggested by the occupants or investigator that could contribute to the dust levels and any associated toxicant levels in the home. Once these two steps are completed, the researcher is left with the problem of selecting sampling and analytic measurement techniques that provide quantitative information on toxicants that may be of concern for particular health outcomes (*5*). Of course, the ubiquity of surfaces available in and around a residence for toxicant accumulation and human contact makes the selection of a sampling device that is appropriate for and representative of all surfaces difficult. In all cases, specific protocols and quality assurance and quality control procedures are required for each sampler to establish the precision and accuracy of the results. It is not sufficient to conduct a quantitative investigation in and around a residence that just employs wiping a rag, towel, or filter across a surface to collect dust. In some situations, however, a "swipe" across a surface may be an adequate screening tool that can be used to indicate the presence or absence of a toxicant in a room or residence. This approach is very common in crisis or emergency-response situations. However, in contrast to routine dust sampling, the field team must be fitted in the appropriate level of protective clothing and gear for hazardous material activities.

The type of surface to be sampled is an important decision that must be made before one begins selecting or designing a sampler or designing a study. As stated above, analyses for exposure characterization require knowledge about the sampling locations. This includes identifying rooms and other locations where people will spend a lot of time or where they participate in activities that can lead to contacts with various toxicants. Once this information is gathered, the investigator must then determine the types of surfaces that may come in contact with a person. Subsequently, each surface must be characterized as rough, textured, or smooth for the purposes of sampler selection.

The implementation of a house dust wipe-sampling program for use in an exposure

Table 2. Potential carcinogenic, neurotoxic, or endocrine-disrupting compounds in fine carpet dust.

	Dust concentration (ppm)				Carpet loading (µg/m²)	
Compound	No. of homes	Detected (%)	Median	Max	Median	Max
Metals						
Arsenic	25	100	5.15	16.70	5.11	91.90
Cadmium	24	100	6.75	20.40	9.10	113.00
Mercury	24	100	1.69	15.90	2.87	44.7
Lead	25	100	164	1,200	202	6,120
Copper	25	100	170	1,144	260	1,790
Sum of PCB congeners in house dust						
Three cities	32	100	0.42	3.60	0.26	17.00
Sum of seven probable (B-2) human carcinogens in house dust						
Phthalates (Ispra, Italy)	10	100	> 200	> 200	NA	NA

Abbreviations: Max, maximum; NA, not available; PCB, polychlorinated biphenyl. Adapted from summary table of data from various studies reviewed by Roberts (*74*).

Table 3. Summary data on composition of house dust in seven U.S. cities collected by high-efficiency vacuum cleaner.

Characteristic	Result
Range (% by gravimetric analysis) of fibrous particles	9–89
Range (% by gravimetric analysis) of non-fibrous particles	11–91
Size range (% nonfibrous of total particles collected)	
> 300 µm	4–83
75–300 µm	1–32
< 75 µm	0–20
Days since last cleaning (average)	14.2
Days since last cleaning (range)	1–150
No. of people living in home (average)	3.3
No. of people living in home (range)	1–10
Composition (qualitative) by polarized light microscopy	
Most frequently identified materials	Skin, soil, starch, hair, cotton, plant (> 85% of samples)
Second most frequently identified materials	Fungal material, synthetic fibers, polymers, paint, metals

Cities were San Diego, CA; Columbus, OH; Phoenix, AZ; Miami, FL; New York metropolitan area (including New Jersey); Denver, CO; Kansas City, KS. Included were 36 individual home samples and 12 sets of pooled samples. Samples were collected in the kitchen, living room, and/or bedroom, or another room other than the kitchen (*79*).

assessment and/or residential source identification can employ one or both of the following design options: *a*) a device that mimics the ability of the hand to pick up and retain contaminants on the particles that are found on many surfaces, and *b*) a device that will quantitatively collect all or a reproducible fraction of contaminants found on specific surfaces.

Currently, it is impossible to select one wipe sampler that functions properly under all conditions. For example, a sampler that can be used exclusively for smooth-surface sampling would not necessarily have the same design as a sampler used for textured surface sampling. It is straightforward to find a sampler that will retain the dust, dirt, and other particles present on a smooth surface. For textured surfaces, one has the added problem of ensuring that contact is made between the sampler and the entire surface, including the crevices. In both instances, a smooth or textured surface, an investigator must also try to mimic the levels of contaminants picked up by the hand. Thus, the sampler needs to be designed with surface characteristics that can collect the particle size distribution that best represents retention by the hand, after wet and/or dry contact with an object or floor.

Potential Exposure Variables or Metrics Measured for Residential Dust and Soil

Applications of household dust in exposure characterizations and assessments require a sampler that can measure one of two metrics (or variables) and preferably both. The first is the loading of materials on a surface in units of micrograms of material or toxicant per square centimeter of surface. To date, the metric "surface loading" has received the most attention during the development of techniques because it is the simplest quantity to measure. At a minimum, it tells the investigator whether a toxicant is present at a location, and it can provide values in micrograms per square centimeter for the distribution of a toxicant in a room on surfaces or throughout the entire residence. The second quantity is the "concentration of a material in the collected dust" collected by the sampler. It is reported as micrograms of a toxicant per gram of dust. This value is much more difficult to quantify because the collection medium must be pre- and postweighed under standard weighing conditions, and the medium must not change character during dust collection.

Both surface loading and dust concentration are valuable metrics in characterizing exposure. Measurements of surface loading can be used to estimate the amount of material available on a surface and the amount available for contact by a person. Dust concentration can be used to characterize potential sources and source types inside or outside a home. In each case, there are limitations and uncertainties based on the design and validation of each device for the intended purpose of sampling; the information available to characterize activities and activity patterns and actual source use; and the area on a surface in a room or in the residence that the samples actually represent. Some typical data collected on dust loading and the concentrations of common toxicants found in house dust are previously shown in Tables 1 and 2.

Sampling Methods

Surface wipe sampling. Almost any surface found in or around a residence can come into contact with some part of the human body, and each would be a candidate for surface wipe sampling. Thus, the investigator must clearly articulate the purpose of the sampling study. These will guide selection of the appropriate surfaces to sample, the toxicants to be measured, and the frequency of sampling. For example, if one were examining a child's contact with a toxicant, the focus would be on objects and surfaces that are frequently used, touched, or mouthed by the child during the day (*88*).

A number of devices have been used to examine the levels of toxicants on surfaces. Depending on cleaning frequency, the materials present on surfaces to be sampled can reflect deposits caused by many different activities that occurred over a range of time periods. Undisturbed surfaces (e.g., top of a refrigerator), can be indicative of materials deposited over a long period of time, whereas frequently cleaned surfaces (e.g., kitchen countertops) will be indicative of the most recent deposits. Toys and play surfaces or work surfaces can be indicator surfaces for objects most frequently contacted by children and adults, respectively. Windowsills and wells can provide information on materials that are carried from outdoors to indoors or may reflect the materials in paint flaking from the surfaces around the window. Thus, surface sampling can provide a wealth of material for estimating potential contact with any levels of toxicants of concern for acute or chronic health effects, aggregate or cumulative exposure assessments, or identification of sources. The ability to identify sources is sometimes difficult using wipe samples because of the relatively low levels of dust usually found on many surfaces.

Rug and carpet sampling. When the analysis of exposure moves beyond surface sampling of floors, tables, and so on, an investigation can focus on toxicant levels in rugs and carpets and other plush objects such as pillows. These residential furnishings pose another set of challenges for the researcher to address, both conceptually and analytically. For example, carpets and rugs have major structural features that require the investigator to first establish what the material deposited in a carpet actually represents (*74*). The first feature of a rug or carpet associated with dust retention is its surface and the easily accessible layers of carpet fibers. The second is the base that binds the carpet or rug fibers together. From the standpoint of variables used for research or forensic application of exposure analysis and assessment, each provides variables and results that can be interpreted in different ways.

When the material sampled from the surface layers of the rug is analyzed for dust mass and composition, it is usually done to determine the levels and types of material that are accessible or available for contact with a human hand or other parts of the body. The results can also be used to represent the layers of a rug that can contact edible materials (e.g., food) that are rubbed or dropped on the rug by a potentially exposed person and removed by friction (*89*). In some instances, materials present on a rug are called dislodgeable dust, but the definition does not truly describe all contact issues.

Resuspendable dust can also be deposited onto clothing or skin or scavenged by food and other mouthable objects that contact the rug surface (*90*). Therefore, any material or toxicant attached to the surface of a rug or carpet can be collected and quantified. Subsequently, it may be appropriate to use the results as an indicator of a potential dermal contact and nondietary intake by adults or children. The latter requires the collection of information on activity patterns and the intensity and frequency of contact with a toxicant to adequately assess a person or population's exposure.

The major challenge for exposure analyses is ensuring that the sampler retrieves material that is indicative of the types and levels that a person comes into contact with on the rug. For example, the type of rug (e.g., level loop or shag) will have different retention characteristics for particles on the rug surface. The surface can also significantly affect the efficiency of removal of particles from the surface by a vacuum cleaner (*74*). The problems posed by such situations include ensuring that a true indication of the levels and distribution of material deposited on the surface of rug fibers is obtained during sampling and that the sample of dust is representative of material available for removal. Finally, work by Wang et al. (*91*) has shown that the collection efficiency of a vacuum cleaner is affected by the relative humidity in the home.

In contrast to the surface of a rug or carpet, the material embedded at the base of a rug or carpet can provide information needed to complete exposure analyses. The embedded material can be considered to be equivalent to the weathered loading of soil and air pollution deposited outdoors on surfaces over time via atmospheric deposition at the base of a forest canopy or within the sediments of a lake. In this case, the loading of particles at the base of a rug would be affected by particle deposition, dynamic removal and redeposition of material, and spills.

An individual rug does not provide a complete historical record of the loading that could theoretically accumulate over time. However, a rug/carpet can provide a record of indoor and outdoor sources that have contributed to the overall levels of dust and components of dust that were tracked into a residence, were spilled or applied to the surface, or were removed from the air over time. Rugs and carpets also are major reservoirs of material because their large total surface area increases the total amount of material deposited on or stored in the fibers. Potentially rugs and carpets have levels of specific materials that are available for resuspension or reemission (semivolatile compounds). Thus, rugs or carpets can be used as a research or a forensic tool *a*) to determine the levels of materials that have accumulated from daily living in the home, *b*) to discriminate among persistent sources (indoors or outdoors), or *c*) to specify or document one-time or infrequent events that could lead to acute health outcomes.

The most important variables to consider before attempting to sample a rug or carpet are type (e.g., level loop or shag), age, condition, location in the residence, cleaning frequency, and family history. An individual rug could provide a variety of long-term or short-term data and information on the types of activities and sources that affect toxicant levels in an individual home.

Similar to outdoor situations, materials present in the rug or carpet can be resuspended from the rug or carpet. However, the mechanisms of resuspension are different from those associated with outdoor air. For example, the reentrainment of carpet dust, both surface and embedded, occurs using the typical household vacuum cleaner. Vacuum cleaners that do not use a HEPA filter system and do not have a sealed capture system will not efficiently pick up and retain the fine particles in carpet dirt and dust (*92*). These include most devices generally used by the public. Some fine particles will be resuspended and then redeposited on the floor and other surfaces. Thus, over time any residuals from major spills or applications that remain after clean up or degradation will eventually be reduced in magnitude but will also contribute some amount of mass to the general long-term material burden in the rug. The last point also brings up the consideration that if one is attempting to look at outdoor influences on the rug burden, it is important to include sampling locations near high-traffic doorways. This was recently done by Bonanno (*93*) and by Farfel et al. (*94*) for lead, cadmium, and arsenic.

Work done at the Environmental and Occupational Health Sciences Institute (EOHSI) and the U.S. Environmental Protection Agency (EPA) has also shown that semivolatile materials initially deposited on a floor or in a crack or crevice will evaporate and condensate from the point of application onto other surfaces (*64,66,95*). This is of particular concern for pesticides sprayed in the home. Over time a lower concentration of the semivolatile compound will be spread to a variety of surfaces in a room or residence that were not initially sprayed with pesticides, thus increasing the possibility of exposure to residents and visitors.

In a recent study by researchers at the Harvard School of Public Health (*80*), a large number of chemicals were measured and the viable biological particles in vacuum cleaner samples obtained in residences were tested. The investigators also measured the levels of specific toxicants in the air. The objective of the study was to quantify the levels of hormonally active agents and mammary carcinogens in homes. A similar, but more focused, hypothesis-driven investigation was conducted for microbiologicals and fungi obtained from rugs in offices located in Denmark (*78*).

Other sampling approaches. A number of techniques in addition to wipe samplers and vacuum samplers can provide data for research, regulatory, risk reduction, and forensic analyses of population and individual exposures. Each can be used to collect dust from undisturbed locations within a residence or associated structures (e.g., garages, utility sheds). One of the best examples, but one that has been rarely used in exposure analyses, is attic dust. When one considers that the normal life of a residential roof is 20–30 years or longer, if you add multiple layers of roofing materials, the attic can contain a record of undisturbed archived deposited particles. Particles would have infiltrated the residence by diffusion and advection through the eves or other passive ventilation portals (indoor or outdoor), and then settled on surfaces. Attic dust has been used periodically to examine the deposition of radionuclides from nuclear fallout and nuclear power plant emissions. Recently, studies have examined attic dust for the levels of toxicants that may have been emitted to the ambient air, transported, and then deposited in the attic (*96,97*). Other studies examined deposition in attics located in Nevada (*98*) or downwind of the Chernobyl nuclear accident (*59,99–101*). Each included measurements of radionuclides emitted by nuclear arms tests and/or nuclear power plants, metals emitted from point or area sources, and specific tracers emitted by from industrial facilities.

Status and Issues for House and Building Dust Samplers and Their Use

There are a variety of samplers available to collect indoor-generated or outdoor-generated house dust, yard, or street dust. However, no one sampler has been invented that will collect material from all surfaces. Further, many samplers are not designed to take the same type of sample. In fact, although a number of samplers have been developed, most have never been tested for performance in terms of what the collected material is supposed to represent. Some devices have been compared during field studies to test sampler collection performance characteristics, but usually this is done only with respect to the levels of a compound or mass that other samplers generally collect. In general, the devices used in health physics, industrial hygiene, environmental hygiene, and exposure assessment measure surface loading as the amount of a toxicant per square centimeter. However, in evaluating sampler performance, it is important to evaulate and identify the method used for operating the sampler. Clearly, without performance testing for specific physical/chemical properties, it is not possible to obtain the information necessary to determine what the measured values in a sample actually represent for a surface or exposure. One also requires information about the character of the surface sampled and the atmospheric (environmental) condition at the time of sampling. Over time, a level of consistency between samplers used in a study and sampling location can be established through intercomparison studies and side-by-side sampling (*102–105*).

For example, a baby wipe has been used as a wet surface sampler (*102*). It will scour any material from the surface, and possibly the subsurface, but the results obtained will be independent of many variables that affect accumulation on the hand. This is just one example of an issue associated with all surface samplers. Such a problem, however, does not preclude using the results for forensic analyses or research in exposure analysis; it just requires definition of the applicability of the measurements or what aspects of the results increase or decrease the uncertainty of an assessment.

Wipe samplers. McArthur (*81*) summarized wipe sampling methods available in 1992, and a modified list is provided in Table 4 (*106–119*). The variety of sampler types and solvents used to collect the material for a surface is large, and some are more applicable with one toxicant, whereas others can be tailored to collect and provide measurements for a number of toxicants. Fenske et al. (*14*) commented that the precision of wipe sampling would be improved by defining the area and standardizing the materials and methods used for sampling.

We have developed two devices for surface dust sampling. The first was the Lioy-Weisel-Wainman (LWW) dust wipe sampler (*85*). It was designed and tested to quantitatively collect all materials deposited on flat surfaces, and the design eliminated the confounding influence of operator pressure on the amount of dust pickup by the sampler. The LWW was also the first wipe sampler that could quantitatively establish both the concentration (in micrograms per gram) in dust and the surface loading (in micrograms per square centimeter) of dust from the same sample. Its applications are confined to sampling horizontal or vertical flat surfaces, although the basic substrate used for the collection from the surface, a nucleopore 50 mm × 55 mm Perkin-Elmer drain disc (Perkin-Elmer, Norwalk, CT), has been tested and found to be durable enough to collect material present in a window well. The sampling substrate used by the LWW can be changed to efficiently collect specific toxicants (e.g., empore carbon-18 discs; 3M, Minneapolis, MN) for the collection of pesticides (*120*).

The LWW also operates as a wet or dry collection substrate for sampling specific surfaces. Caution must be exercised, however, when selecting a wetted substrate because water and/or solvents can ruin finished surfaces frequently found on furniture and floors. In addition, if a surface is painted and the paint is in poor condition, a wipe can take off small chips of paint. This may give anomalously high levels of lead in dust, but the data cannot be ignored because lead paint chips present a hazard. Yiin et al. (*75*) found that lead loading varies with time of the year. Finally, Paustenbach (*26*) stated that the development of the LWW provided "fairly sophisticated work to standardize (wipe sampling) procedures." Applications of the LWW within various studies have found the loading of dust on flat surfaces to be associated with biomarkers of exposure (*20*) and with cleaning practices within the house (*121,122*).

Another issue is the protocol used for sampling dust. This was intensively examined and incorporated as a major feature in the design of the LWW sampler patent (*123*). The features of the sampler (no operator pressure and a defined template) were rigorously tested in the design phase of the LWW and achieved reproducibility for a standard dust of a coefficient of variation between 6 and 25% for replicate samples (*86*). Freeman et al. (*121*) demonstrated that for side-by-side field samples, the mean difference was 35%. This was in an uncontrolled situation; thus there is large potential for variability of dust loadings in adjacent locations. The initial versions of the LWW were a bit cumbersome to use, but eventually a modified design was employed to the collection of samples in approximately 300 homes during the six Midwestern State NHEXAS pilot study, and the samples were analyzed for elements and pesticides (*52*). In contrast, most other devices used for wipe sampling, including cloth wipes, gauze pads, and gloves, have not received the same level of performance testing.

After the success of the LWW sampler, it was important to go beyond collecting all the dust deposited on a surface to make inferences about the dermal uptake of a toxicant (*88*). Thus, we developed the Edwards and Lioy (EL) sampler, which had a sampling surface designed specifically to mimic the collection efficiency for the size distributions of particles on the surface of the human hand. It had an application pressure coincident with the pressure placed on a surface by a human. The first model of the device focused on the "nonsticky hand" (i.e., dry), and it was designed to collect a sample composed of repeated presses on a surface. It has been successfully used to determine the amount of dust and pesticides picked up from various types of textured and smooth surfaces (e.g., floors and carpets) (*120*).

Edwards and Lioy (*87*) made extensive comparisons with other wipe samplers (adhesive tapes, cotton gloves, etc.) to determine their utility as a metric of hand exposure to dust present on surfaces. The metric for calibration was the final particle size distribution retained on a human hand for a series of controlled experiments. This was the first attempt to determine what types of loadings could be transferred from the floor to a hand by a sampler to eventually provide a device that could eliminate use of the human hand as the dermal sampling device. Up until now the only effective way of completing dermal sampling was to sample the actual hands of adults and children after contact with various surfaces. The hand rinse method can have large uncertainties. For example, if one does not know the history of activities, including hand washing, and surfaces contacted prior to washing the hand, it is difficult, if not impossible, to accurately assess exposure. Further, in some cases the hand is washed with a liquid other than water, which requires added scrutiny by institutional review boards.

Edwards and Lioy (*87*) showed that methods typically used for wipe and surface sampling did not have the same particle size distribution as that retained by the human hand. The results in Figure 1 indicate that only synthetic skin and the C18 filter used in the EL sampler closely mimicked the uptake and retention characterization of the dry hand for particles < 250 µm in diameter. This was anticipated because none of the samplers was designed specifically to mimic exposure to house dust. The final version of the EL sampler collected a size distribution of the particles equivalent to that attached to the human hand for a "non-saliva–laden" condition of the hand. The studies to date have shown that if one wants to mimic hand retention with a surface sampler, the total burden on the floor or other surfaces is not representative of what will be found on a human hand.

When sampling a surface with the EL sampler, there was no continual and uniform buildup of mass. In fact, after about four to five presses, little new mass was added to the surface loading. The results of Rodes et al. (*124*) indicate that at some point new contacts with a surface just replace some of the

Table 4. Summary of information on a number of available wipe sampling methods.

Reference	Compound	Sampler type	Sample area (cm^2)	Solvent
Alexander et al. (*106*)	TCDD	Glass fiber	625	Dry
Bently et al. (*107*)	Chlorophenol	Whatman 1	14.2	Dry
Chalk et al. (*108*)	MDA	NA	—	—
Chavalitnitkul et al. (*109*)	Lead	Whatman 42	100	Water
U.S. EPA (*110*)	Misc	Cotton swab	5 × 19.6	Acetone
	Misc	Cotton swab	2,500	Acetone/hexane
Fenske et al. (*111*)	Chlorophenol	Surgical gauze	231	Dry
Fenske et al. (*14*)	Chlorpyrifos	Surgical gauze	100	Water
	Chlorpyrifos	Surgical gauze	100	Isopropanol
Hryhorczuk et al. (*112*)	PCBs	Whatman	900	Hexane
	PCBs	Glass fiber	900	Hexane
Lees et al. (*113*)	PCBs	Whatman smear tab	100	Methanol
Lichtenwalner (*114*)	Misc	Whatman smear tab	100	Water
O'Malley et al. (*115*)	DTBP	Cotton swab	—	Ethanol
OSHA (*116*)	Misc	Glass fiber filters	100	Wet/dry
	Misc	Whatman smear tabs	100	Wet/dry
Rappe et al. (*117*)	PCBs	Kleenex	200	Dry
	PCBs	Kleenex	200	Water
Stephens (*118*)	PCBs	Cloth wipe	—	Octane
Vostal et al. (*83*)	Lead	Commercial wet wipes	900	Ethanol
Lioy et al. (*85*)	Multiple	Template wipe	100	Dry/wet
HUD (*119*)	Lead	Commercial wet	100	Wet

Abbreviations: DTBP, 2,4-di-*tert*-butylphenol; HUD, Housing and Urban Development; MDA, 4,4'-methylenedianiline; Misc, miscellaneous; NA, not available; OSHA, Occupational Safety and Health Administration; PCBs, polychlorinated biphenyls; TCDD, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin; Adapted from McArthur (*81*).

material already on the hand, and the transfer of particles to the hand is a complex process. Loading was dependent on many variables, including dampness of the skin and surface roughness. However, they did show that the maximum uptake for coarse Arizona road dust, 20–40 µm in diameter, was greatest within the first 5–10 repeated presses. Our studies showed that the human hand collected the particles < 250 µm with the greatest efficiency. Calibration studies for the EL sampler and the Rodes et al. laboratory studies (*124*) indicated that a number of issues still need to be resolved for future versions of surface samplers that mimic pick-up by hands. Included is how to collect information necessary to describe the activities and frequency of activities that led to contact with toxicant laden surfaces.

The Department of Housing and Urban Development (HUD) has used the baby wipe sampler as the method of choice for comparisons of lead values to a household clearance standard after remediation or control of lead sources in a home (*125*). It is simpler to use than the LWW sampler and is designed specifically to determine the surface loading of lead and other heavy metals in micrograms per square centimeter or micrograms per square foot (*119*). The simplicity of the HUD device allows it to be used to compare the levels of lead detected with a clearance value for lead to define when a home is "clean." It is based on the amount of lead picked up by the sampler in the defined space. This is accomplished by using a wetted material (Little Ones, Baby Wipes Lightly Scented; Kmart Corporation, Troy, MI) and moving it around a defined template area-sampling surface. However, there is no control for operator pressure, and the wetting agent can remove materials from deep below the surface being sampled.

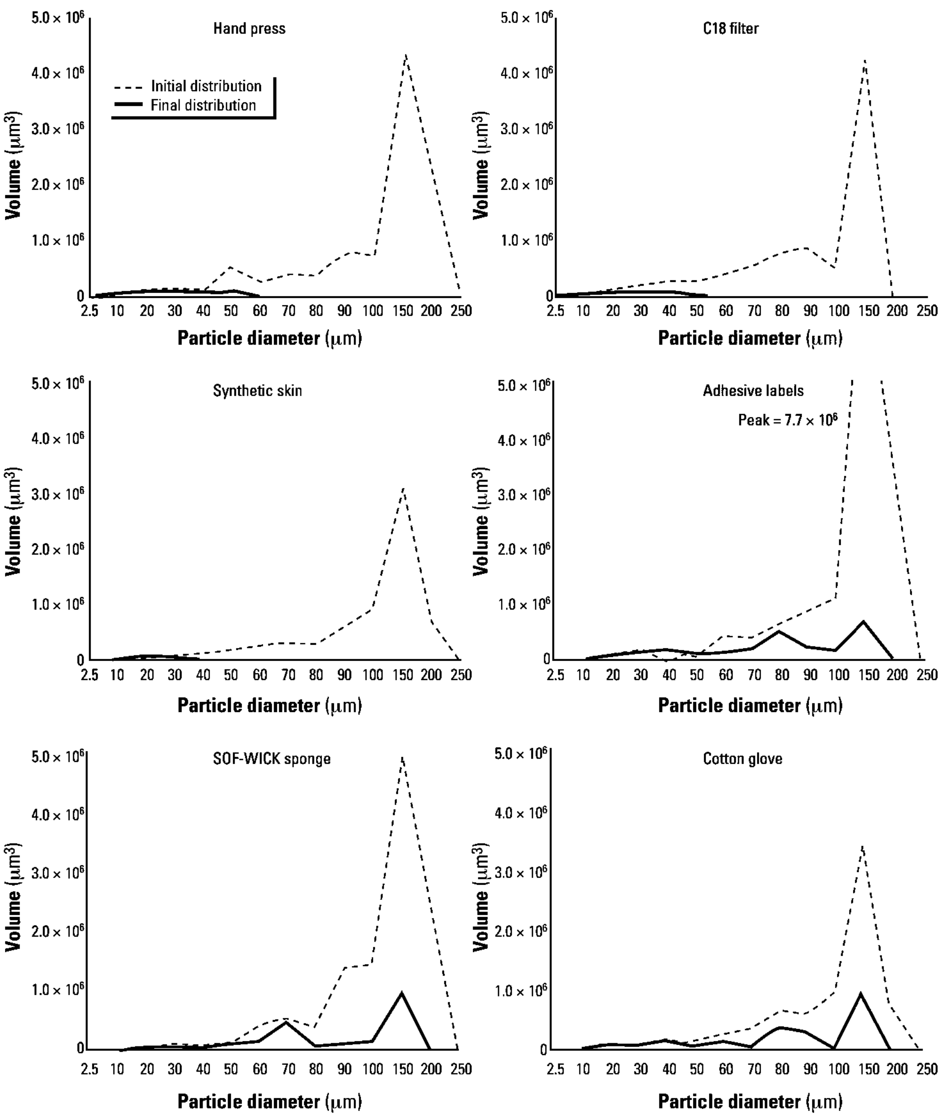

Figure 1. Particle size collection characteristics for six types of methods for examining particle adhesion. Particles used were typical house dust ≤ 250 µm in diameter.

Farfel et al. (*102*) compared the HUD wipe sampler with an HVS3 vacuum sampler, and Rich et al. (*105*) compared the HUD wipe sampler with the LWW sampler. However, each was a performance test and did not test what the collected sample represents. However, Rich et al. (*105*) used a calibrated LWW method for comparison with the HUD sampler.

The comparison completed by Rich et al. (*105*) using the LWW and the HUD sampler showed that the HUD sampler would consistently pick up more lead than the LWW sampler. Analysis of the data suggested that the HUD sampler scours the surface more deeply, but it also had much more variability and a much higher detection limit than the LWW. Paustenbach (*26*) noted in his evaluation of surface samplers that operator pressure is a major concern when attempting to assess the reproducibility and utility of surface samplers for characterization of exposure.

Vacuum samplers. The vacuum cleaner samplers pose their own series of problems for dust collection. First, not all vacuum cleaners are alike. In fact, they can have very different designs and particle collection characteristics and particle retention characteristics. However, vacuum cleaner bag samples have been used for many years to collect dust samples.

One vacuum sampler designed specifically to collect house dust was the HVS3. It collects the dust from a floor using various cyclone collectors for particles > 5 µm and a final HEPA filter for collection of smaller particles. It has been used successfully in a number of programs to collect house dust from rugs and bare floors (*86,103*). There are also a number of rug samplers that use different types of mini-vacuum cleaners.

Farfel et al. (*103*) compared the efficiency of two vacuum systems, the HVS3 and the CAPS (Comprehensive Abatement Performance Study) cyclone. They used three types of dust: a large-diameter dust sample (25–2,000 µm) from the U.S. EPA, an intermediate-size Buffalo River sediment (39–149 µm; NIST-SRM-2704; National Institute of Standards and Technology, Gaithersburg, MD), and a small size (0.5–44 µm) sample of USP talc (United States Pharmacopia, Rockville, MD). This study was a first and important step toward standardization of soils for vacuum cleaner calibration comparisons.

The vacuum cleaner, as a tool for forensic analysis of house dust, has advantages over the wipe sampler. It can provide the investigator with a large quantity of mass, which can subsequently be used to detect the range of toxicants and toxicant levels in the dust. Further, the concentration or loading can be compared to the values used for residential cleanup of soil or for determining potential exposures that may cause a specific health effect. Each device will capture different mass fractions, depending on its design. The results obtained by various samplers indicate that for detailed exposure assessments a very well-characterized vacuum sampler should account for particle size and/or determine the particle size fractionated mass distributions. Vacuum sample results can be useful, at a minimum, in determining the presence or absence of a toxicant, and the suite of material or tracer compounds can be used to identify sources. For example, Colt et al. (*126*) compared the collection of pesticides and other compounds collected by a standard vacuum cleaner bag with a particle size selection high-volume sampler. The compounds were detected in each, but a more accurate record of potential exposure was derived from the HVS3 and not the typical vacuum bag.

The simplest sampling method is to collect dust from residential vacuum cleaner bags (*126,127*). Although lacking the precision of systematic designed vacuum sampling methods, this is an effective tool for gross identification of contaminant levels in homes. Thus, it is an important screening tool for identifying high-end exposures. To improve the applicability of the results from standard vacuum bags, information needs to be gathered on the characteristics and activities in the homes. Included would be the age of house, age of carpet, when the vacuum cleaner bag was replaced, residential construction activities, ventilation patterns, and cleaning patterns.

Obviously, more precision can be obtained using a standardized vacuum cleaner that collects a documented size fraction of dust and that vacuums a standard section of carpet (*17,89,128*). Finally, the vacuum cleaner method of dust collection has also been used in conjunction with polyurethane foam (PUF) rollers to characterize the distribution of pesticides on surfaces and at various levels in a carpet (*129*) or with the LWW sampler to examine surfaces in a home (*89,92*).

Other samplers. The attic dust sampler, the surface deposition plate, mats, microscope slide plates, or sticky tapes and rollers are devices that can provide quantitative information on the particle size and composition of material that have been generated indoors or outdoors. The sampling device is deposited on a surface and left undisturbed for a specific amount of time. In the case of all but the attic dust sample, the location, timing, and the duration of the sample are selected by the investigator. Analytically this is helpful because some types of events and sources influencing the deposited material can be qualitatively or quantitatively identified using survey tools before or during sample collection. During the use of a deposition collector, the accuracy of source identification can be improved if videotape is running throughout the sampling period, but this is difficult to achieve because of logistics. A prospective sampling strategy can be tailored to the toxicant or the source of concern.

An attic sample can represent the long-term dynamic accumulation of material that has been influenced for many years by the natural movement of air, penetration of the dust indoors, and the eventual deposition of dust on many surfaces. Most samples are collected and placed in a bag using plastic scoops or a wisk broom (*96,97*). The major concern is that important household activities and home maintenance may disturb the attic dust (e.g., roof replacement, renovations).

Farfel et al. (*94*) placed floor mats in residential entryways to examine the movement of material into and out of a residence. Floor mats can be used to quantify the dust or toxicant levels that are tracked into the residence from outdoors and accumulate on the mat over a specified period of time. This study focused on comparing the collecting efficiency of two vacuum cleaners for removal of deposited dust, and they concluded that older homes appeared to yield high lead loading and this was due to higher lead concentrations in the deposited dust. They also did comparative testing of the devices for standard reference material that contained lead. Included were two NIST samples and a bag house sample. Farfel et al. (*94*) indicated that the mat collection technique needs further evaluation if it is to be used to estimate dust deposition rates. They stated that it is essential to determine which type of mat should be used, and eventually what the collected data can represent to assess exposure and eventually risk for toxicants deposited on the mat left in an entry way. Finally, they made the important point that we need to find better methodologies for determining incremental dust deposition in the home.

Edwards et al. (*55*) used a deposition plate to determine the amount of particulate matter that settled on a deposition plate over the course of 30 days. The plates were located on a flat surface at 0.3 and 1.5 m off the ground. The deposited particles were measured by image analyzer to determine the particle size distributions by height and time of the year. The results revealed significant differences in deposition based on particle size alone, with large numbers of deposited particles in the winter and greater deposited mass in the summer. The latter was due to the influence of large particle deposition. The lower height samples had more particles in the summertime, but the size of the deposited particles was smaller during the winter.

Pellizzari et al. (*52*) and Bonanno et al. (*53*) used entrance mats to examine the tracking of metals indoors during the NHEXAS. Farfel et al. (*94*) used mats to collect and analyze samples for lead. In each case, the sampler was left in the doorway for a specific period of time, approximately 3–4 weeks, to collect an incremental amount of mass with or without contamination. Nishioka et al. (*23*) used SOF-WICK pads to collect pesticides deposited on lawns. They also used PUF rollers and cotton gauze (*23,130*).

Finally, surface soil samples, which would be taken from the top 1–3 cm of soil, are another source of information on potential residential exposures. The purpose is to obtain the scientific data for estimates of dermal contact and incidental ingestion by collecting soil in the yard that has a high potential for sustained human contact either currently or in the future. Thus, surface soil can be analyzed to determine if the soil is the source of toxicants of concern. The technique usually involves selecting a Teflon or other non-background laden pan and using an appropriate brush to sweep the surface soil into the pan. After a prescribed area is sampled, the material is placed in a sealed bag and sent out for analysis. This technique has been used by numerous investigators for a variety of toxicants. As an example, archived soil samples collected over 36 years in the United Kingdom at two experimental stations were recently analyzed for organochlorine pesticides. The results showed decreases in levels over time, and the results indicated the peak soil concentrations coincided with peak usage in the 1960s (*131*).

In addition to examining a rug or other surfaces for individual particles, elements, and other physical or chemical constituents, one can obtain quantitative and qualitative information on bacteria, molds, spores, and other viable particles. For the material present on individual surfaces, it is possible to transfer material to slides for analysis or to petri dishes filled with an agar for colony growth and identification. In addition, the investigator can place a sampler such as a petri dish to collect biologicals that can deposit on surfaces (*132*).

Other issues. The materials that can be subjected to analysis are far ranging in types and characteristics. From the standpoint of forensic or exposure research analyses this is exceptionally good because one can address a number of different types of exposure issues and source receptor relationships. The major concern is 2-fold: how to triage the analytic opportunities and how to collect enough of the appropriate sample type to detect the toxicant of concern. Collection issues affect our ability to measure heavy metals, organic compounds, asbestos, other inorganic species, radionuclides, and viable and nonviable biological materials. Particle size and morphology are also helpful for identifying and addressing many residential exposure issues. The work of Rudel et al. (*80*) piloted a methodology to examine hormonally active agents and animal mammary carcinogens in house dust. This advanced the use of dust to measure phenolic compounds, phthalates, in addition to the more common toxicants PAHs and pesticides. The samples were collected using a "Mighty-Mite" vacuum cleaner. Unfortunately, the samples were not differentiated by surface, so the results can only be considered "whole" residence samples. One observation was that house dust provides a record of past exposure and can increase understanding of potential exposures due to the use of commercial products. It should be examined for pre- and postevent issues.

The work of Molhave et al. (*78*) focused on microorganisms and allergens, as well as aldehydes and the basic components of dust. Their goal was to demonstrate that dust is a source of airborne particles found in a workplace. However, an important aspect of the experiment was the use of the contents of a typical vacuum cleaner bag as the source of material for an analyses. Thus, for forensic and screening experiments, it appears logical to examine the content of the basic vacuum cleaner bag as a first step in a triage for conducting exposure and assessments in a home for research and/or forensic purposes to select the major contaminants of concern.

Dust not only is present on surfaces and carpets, but it can transfer to people's hands. This is of particular concern for children who exhibit mouthing behaviors. Methods for collecting dust from hands can be as simple as wiping the hands with a moist towelette or paper or rinsing the hand with water, weak acid, or solvent, or placing the hand on the surface of a culture medium. The type of method used depends on the aspect of the dust that is of interest. Several investigators have used hand wipes for collection of dust. Vostal et al. (*83*) used commercial hand wipes, Wash'n Dri Towelettes, to collect dust from the hands of children and from windowsill or floor surfaces. Duggan et al. (*133*) used another commercial hand wipe, Wet Ones, to collect hand wipe samples and also evaluated a range of commercially available wipe media. The hand wipe method was found to be simple and reproducible when the contaminant of concern was lead. The efficacy of the method in collection of lead has been demonstrated for both house dust and playground dust, with the first wipe collecting between 50 and 70% of the lead on hands. The use of the same method for collection of hand wipes and environmental samples makes it easy to compare the measures obtained from the two sources.

The challenge in using hand wipes to measure total dust on children's hands is that the sampling medium is not easily preweighed and therefore a mass cannot be directly calculated. A way to get around this problem is to back-calculate mass using the measurements of metals or pesticides on the hand and use another database that provides the amount of metals or pesticide found in size fractions of dust that will strongly adhere to hands and other locations on the skin. This method was recently used with metals (*90*).

Hand rinses with water or rubbing alcohol have been used to collect dust when the materials of concern are pesticides (*87,120, 130,134,135*). The disadvantage of hand rinses are their messiness in collection and the labor-intensive reduction methods necessary before analysis. It is possible, however, through careful evaporation of the rinsate, to obtain a measure of dust mass on the hand (*133,135*).

Assessment of Data Obtained from Residential Dust

Information on activities and lifestyles needed to assess residential exposure to dust and other media requires the application of survey instruments to record home and occupant histories before determining the exact location of dust sampling. For instance, an exposure-based investigation first requires information on the who, what, where, when, and why associated with a particular problem. This information can be gathered in a variety of ways, including questionnaires, videotaping, diaries, and interviews (*88*). Each of these tools can be modified to address problems in specific situations. For example, questionnaires exist that can be used to identify sources, characterize the physical structure of the house and the activities in the house, identify external and internal source types, health status of occupants, and product uses. Daily diaries and videotaping are survey instruments that can be used to get prospective information on the likelihood and frequency of potential contact with chemical, physical, and biological agents.

Fairly simple questionnaires can be used to evaluate the "dustiness" of homes. Rough estimates of the amount of visible dust on a 3-point scale have been found to associate well with blood lead levels in children (*136*) and with dust levels on windowsills (*121*). These scaled indicators of dust have also been associated with chromium loadings on windowsills and urine chromium of residents near chromate waste sites.

Questions posed to householders that address cleaning habits, ventilation and heating practices, residential construction, and presence of pets and children in the home can also provide valuable information related to the dust levels and composition found in homes.

Videotaping is a new and useful tool in exposure assessment. It provides an unobstructed and noncumbersome approach to examining passive or active contact with an environmental toxicant (*137,138*). With new video technology, miniaturized cameras can now be deployed that do not require the shadowing of an individual subject by a technician carrying a video camera pack. Such data can be an extremely valuable addition to forensic analyses of exposure because digitalized results from the videotaping can help focus attention on specific locations, sources, and times that require sampling. The videotape also helps reduce the amount of speculation about what sources or conditions or activities lead to contact. Videotaping is an evolving tool and is extremely valuable for characterizing exposure to materials and contaminants that have multimedia sources and multiple exposure pathways.

In the area of inhalation exposure, for example, certain volatile organic solvents can be emitted and accumulate in the ambient air, by drinking and showering water, and by specific products used in or around a home or workplace (*2,139*). Videotaping provides an objective measure of the types and locations of duration of potential or actual contact with volatile toxicants.

Each home or building environment has general dynamic conditions associated with the structure's inherent characteristics and the lifestyle of the occupants. The variables that can influence the accumulation, movement, and removal of materials present in a rug include type of housing, the season, age and condition of housing, furnishings, insulation, behavior and activities of occupants, construction, and location with respect to outdoor sources. Gathering information on the large number of variables that can affect a home environment is a daunting task; however, many variables will have a long-term and consistent influence on the levels of materials present in the carpet. Thus, specific variables may provide information on levels for materials present, which can range in composition from starch through heavy metals. Other variables will reflect deposits caused by specific events, accidents, planned activities, discrete changes in lifestyle, and changes in the number of occupants.

Freeman et al. (*89*) have shown that food that is frequently dropped on the floor accumulates toxicants, and children who play in and on contaminated surfaces will transfer toxicants to the foods they eat when they do not wash their hands before handling food. A recent analysis by Bonanno et al. (*53*) of the NHEXAS data obtained in a statistically representative population within six Midwestern states has demonstrated that the home characteristics and activities are good indicators of the potential for toxicant contamination in house dust and indoor air. This is an important observation that can be used in the design and implementation of field studies because such information can help with defining the triage for a dust analysis and sampling strategy.

Hunt et al. (*77*) and Adgate and colleagues (*140,141*) were among the first groups to attempt multiple source signature identification and differentiation (*142*). In the case of Hunt et al. (*77*) and Adgate et al. (*140*), the analyses were done for lead present in residential carpets and other surfaces, respectively. Because lead can be emitted by many types of sources, just identifying the presence and levels of lead in a carpet will only provide information on the potential level of contamination. The lead levels alone, however, will not provide quantitative source signatures even if only one source is supported. Fortunately, individual sources or source types may yield different emission profiles that include other elements and materials beyond lead.

Adgate et al. (*140*) used the statistical technique of chemical mass balance and a suite of elements detected in the rug along with the measured lead to match with patterns or fingerprints of major source types that contributed to the lead levels in the rug. The results were then used to apportion the percentage of the lead mass that would be contributed by each source. This approach had been used successfully for detailed analysis of air pollutant sources and the origins of crushed rock using a series of home samples from Jersey City, New Jersey. Adgate et al. (*140*) identified interior house paint, street dust, and yard dust as the major ultimate or proximate sources of the lead. This information can be used to identify interim and final remediation strategies for children affected by high lead in blood (> 10 µg/dL). Hunt et al. (*77*) performed studies using the scanning electron microscope energy dispersive X-ray analysis technique to identify sources and characterize samples for lead and then applied cluster analysis on the dust from six households in London. The authors concluded that road dust was the highest contributor to lead, with paints and soils being the next largest contributors. For other multiple source toxicants, similar techniques can be used (e.g., isotope ratios), while in other cases just the measurement of an individual compound of concern or unique tracer that easily identifies a source would be adequate. For the latter, a good example would be pesticides and herbicides that are sprayed inside or outside of the home. Normally, each has one unique or distinctive active ingredient, which provides a distinct marker or tracer for the source (e.g., backyard and farm applications or residential applications). In the case of viable particles, environmental conditions of the home or a particular room, rug, or carpet may offer an opportunity for breeding more material (e.g., bacteria and mold). Thus, visible material may not just be an indication of moisture problems, but also the source of viable biological particles that can cause specific health outcomes.

Brown et al. (*72*) were able to discern the source of lead infiltrating a home by microscopic analysis. In this case, the morphology of the particles found in residences, neighborhood soils, and industries were compared to the morphology of the particles found in uncovered piles of electric furnace flue dust that had been dumped under and around the house. The analyses showed that the lead-laden particles had been transported from the piles into the surrounding area, which resulted in lead and cadmium contamination. The difference between the above techniques was that the studies of Hunt et al. (*77*) and Brown et al. (*72*) were qualitative, while the study of Adgate et al. (*140*) was quantitative. However, each was able to differentiate sources in residences and other structures.

House dust sampling has also been found to be useful in analyzing the success of interim or long-term mitigation or remediation strategies used for indoor or outdoor sources that affect a residence. Examples include the study of Roberts et al. (*50*) that showed the reduction in lead loading on rugs after repeated vacuuming. A similar study conducted by Farfel and Chisolm (*143*) in Baltimore tried to link the reductions in lead loading after cleaning with changes in blood lead. This approach was also used in Jersey City, New Jersey, by Rhoads et al. (*21*), who showed an average drop in blood lead in children of 17% after a year-long cleaning intervention. The reductions in lead loading over the course of the year for both the cases and controls were measured using surface wipe sampling and rug or carpet sampling. The approach used by Rhoads et al. (*21*) involved collecting initial and final samples with the LLW and a vacuum sampler that were used to define the reduction in potential exposure (*89,122*).

Application of Household Dust to Exposure/Source Characterization

Chromium exposure characterization. A series of studies was conducted to determine the influence of chromate production waste sites and waste site remediation of residential chromium concentrations and the exposure of individuals who lived near the waste sites (*20,51,144–146*). These studies were conducted in Jersey City over a 10-year period. During the first study (*144*), several environmental measures of exposure were used: soil samples close to residences, indoor and outdoor air samples, indoor vacuum samples, and indoor surface wipe samples. Vacuum samples were collected from 200-cm^2 floor sections by the front and back entryways onto cellulose fiber filters using a Gast diaphragm pump. Dust wipe samples were collected with a 50-cm^2 template using the LWW sampler.

Among the indoor measures in the first study (*144*), air levels of chromium were fairly low, typically between 0.5 and 1 ng/cm^3. The air samples were correlated with the smoking patterns of the residents and were not indicative of exposure from outdoor sources. In contrast, wipe samples ranged from nondetectable to 320 ng/cm^2, with a median household level of 24 ng/cm^2. The wipe sample surface loadings were significantly higher in homes near chromium waste sites than in control homes. Vacuum dust chromium loadings were much lower than what was found in wipe samples (1.9 ng/cm^2). Although the loadings obtained by the two house dust collection methods were different, the concentration of chromium in dust samples was similar.

Impact of human activities on chromium in house dust could be observed in this first study (*144*). The concentration of chromium in wipe dust samples (micrograms per gram) on windowsills tended to be higher than levels detected on interior surfaces such as refrigerator tops and bookshelves. Concentrations in house dust were also associated with residential cleaning habits such as when dusting or sweeping was performed last. House cleaning was seen to have several effects: it could episodically increase airborne chromium after vacuuming and reduce surface chromium levels after dusting.

In follow-up studies performed in conjunction with the New Jersey Department of Health Chromium Medical Surveillance project, the LWW wipe sampler was used to collect house dust specifically from windowsills (*51,146*). Again it was demonstrated that chromium dust loadings were associated with house-cleaning practices as reported by homeowners. Chromium loadings were lowest in homes that had been cleaned recently and greatest in homes that had been cleaned more than one week before to the dust sampling visit.

Dust loadings and chromium loadings in the home were effected by the absence of doormats, an important means of reducing dust tracked in from outdoors. In addition, chromium dust levels in homes were also associated with urine chromium of the residents,

Table 5. Chromium concentrations in house dust before and after remediation for median homes that initially had high, medium, and low concentrations using the LWW sampler.

Category of home	Chromium (µg/g) Initial visit	Final visit
Low Cr		
Mean ± SD	58 ± 33	54 ± 106
Median	48	51
n	7	5
Medium Cr		
Mean ± SD	248 ± 76	66 ± 77
Median	245	34
n	8	6
High Cr		
Mean ± SD	782 ± 331	55 ± 60
Median	239	50
n	8	7

Adapted from Freeman et al. (*51*).

suggesting either inhalation of resuspended or ingestion of the chromium in dust (*51,146*).

Evaluation of homes after remediation of the waste sites found the LWW wipe sampler to be an effective tool for evaluating reduction in chromium concentrations following the removal of the chromate waste site source (*51,146*). Concentrations of chromium showed significant reductions from levels preceding site remediation (Table 5).

Forensic analysis and evaluation of exposure to biologics and other particles using microscopic techniques. Environmental forensic microscopy can play a useful role in the investigation of indoor exposure concerns. Like criminal forensic analysis of trace evidence, microscopical analyses of environmental samples can provide information about the identity and possible source of contaminants. As described earlier, fungal spores, pollens, skin cells, synthetic fibers, natural fibers, and animal hairs are prominent in the dust of many buildings. Air pollution particles deposited in the building (e.g., metallic fragments), soots, and building material debris may also be present. Thus, as discussed in the previous section, identification of these particles by microscopical analysis is useful in determining whether the source of the possible irritants is in the building or comes from outside. Polarized light microscopy using dispersion staining and microchemical tests is used to identify a range of particles found in airborne and settled dust samples, from fungi to pollens to combustion products to fibers (synthetic and natural) (*147*). The scanning electron microscope with X-ray elemental analysis capability (SEM/EDS) augments the light microscopic examination with information about the elemental composition of materials. In the automated mode, the SEM/EDS can examine thousands of particles in a sample of dust. The information about size and elemental composition of the particles can be organized to give a comprehensive inventory of a dust sample that is useful in determining the source. The transmission electron microscope with electron diffraction and X-ray analysis capabilities is used to identify very small particles (including soots), < 1 µm in diameter. Infrared microscopy is used to identify particles made of organic molecules such as polymers and pharmaceuticals. The following case studies illustrate the use of environmental forensic microscopy in the investigation of indoor contaminants.

Sample collection. In the following, samples of airborne particulate were collected with polycarbonate filter cassettes attached to area pumps. Samples of surface dust were collected by dry wiping, adhesive lift, or vacuuming techniques depending on the amount of dust present and/or the question that needed to be answered (*148*). If the dust layer was substantial, a sample may have been collected with a clean spatula and placed in a clean plastic container. Lesser amounts were collected with a microvacuum constructed with an air sampling cassette and nozzle or by wiping with a plastic glove or with a plastic bag. Adhesive lifts were used in special circumstances where surfaces might have been damaged easily.

Microscopy equipment. Millette and Few (*148*) used several types of microscopy for particle identification:

- Stereomicroscopy using a Zeiss Stemi 2000 stereomicroscope having a magnification range from 6.5× to 47×
- Polarized light microscopy including microchemical tests using an Olympus BH-2 polarized light microscope with a magnification of 40–1,000×
- SEM using a JEOL 6400 coupled with an X-ray EDS Noran Voyager system
- Transmission electron microscopy (TEM) using a JEOL 1200, 100 kV scanning transmission electron microscope (STEM), equipped with a Noran EDS X-ray analysis system or a JEOL 2010, 200 kV TEM with an X-ray analysis system
- Infrared microscopy or, as it is more properly known, Fourier transform infrared microspectrophotometry (micro-FTIR) utilizing a Perkin-Elmer Auto Image System coupled to a Series 2000 FTIR.

All samples were first examined by stereomicroscopy and in most cases the particles were analyzed by polarized light microscopy. Depending on what was found, portions of the sample were analyzed by SEM, TEM, or infrared microscopy. Methods for the microscopy of particles can be found in the *Particle Atlas* (*149*).

Case studies. Applications of microscopic techniques as an approach to understanding issues of exposure intensity and source identification are provided in the following three case studies. One is an example of outdoor contamination causing indoor problems. The other two are related to microbiological issues related to moisture and dust mites, respectively.

Case 1. Black ghosting areas were found throughout a new house in Michigan. The black areas formed readily on plastic surfaces such as kitchenware, drapery rods, and medicine containers in medicine cabinets. Microscopic examination of the black material on a piece of drapery rod by TEM and X-ray elemental analysis showed that the black material was soot particles (Figure 2). The particles were consistent with carbon soot from paraffin burning, but candles were not used in the residence. Information gathered by surveying the residents showed that paraffin logs had been used during one period of time, but not concurrently with the black ghosting problem. Further investigation showed that there was a backdraft from the fireplace drawing air down the chimney into the residence. Once the chimney flue was closed, the problem went away. Apparently, the soot forming on the residence plastic materials was coming from the carbon soot deposited on the chimney.

Case 2. In a Georgia governmental office building, black and white particles were found several days in a row on a desk located under an air system duct grate in the late fall. Samples were collected by an adhesive lift. Light and scanning electron microscopy showed that the particles were black clusters of fungal spores and white fragments of galvanized metal. Apparently moisture accumulated in the ductwork during the summer season

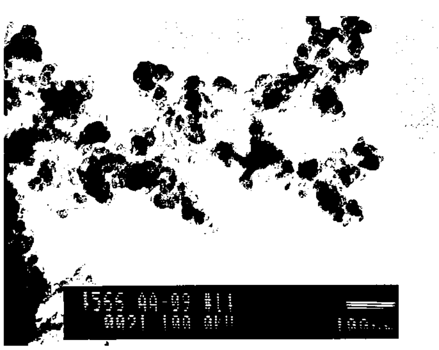

Figure 2. Soot particles as seen by TEM.

Figure 3. Mite found in dust as seen by polarized light microscopy.

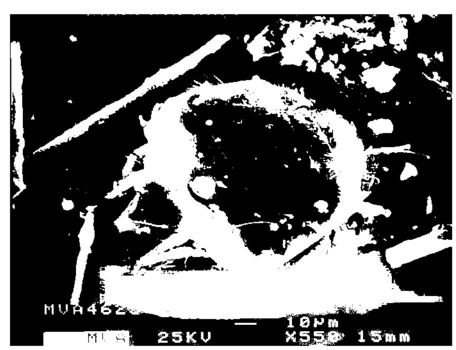

Figure 4. Mite found in reference insulation dust as seen by SEM.

and caused a growth of fungal material as well as a corrosion of the galvanized metal in the air supply system. When the atmosphere in the building turned cooler and drier, the particles were released from the duct system.

Case 3. In a convent in Oklahoma, residents complained of eye irritation and general itchiness. Glass fibers from the duct insulation were suspected of causing the problem. Air samples collected on polycarbonate filters and examined by light microscopy did not show the presence of glass fibers or other particles that are considered irritants. Analysis of particles associated with the duct insulation sent as a reference showed a high concentration of mites (Figures 3 and 4). Additional testing for mite antigens was recommended.

Finally, the microscopical analysis of particles has been a fundamental activity of the law enforcement forensic community for many years. The French detective Locard published several classic articles in the 1930s about the microscopical study of dusts to determine their origin (*67*). As these case studies have shown, microscopy using light, electron, and infrared microscopes can provide helpful information in characterizing a suspected exposure to environmental contaminants.

Conclusions

Dust in the home has traditionally been considered as a nuisance and material that must be removed by a vacuum cleaner or broom. Thus, historically little time was spent sampling or analyzing the material for contaminants. Lead exposure changed that philosophy. This review indicates that we have come a long way in determining the uses of house dust and residential samples to identify sources of indoor contaminants and to provide improved estimates of residential total human exposure. Research and applications of dust analyses in recent years demonstrated that we can take meaningful samples for the detection of a variety of chemical, physical, and biological toxicants. The challenge for the future is to continue the evolution of reliable techniques for wipe, surface, and vacuum samples. These are necessary to improve qualitative determinations of surface loading and dust concentrations. Finally, the efforts to establish performance evaluations and determine what a dust sample represents must become part of the process for development and selection of samples for use in research, regulating, and forensic investigations.

References and Notes

1. Akland GG, Hartwell TD, Johnson TR, Whitmore RW. Measuring human exposure to carbon monoxide in Washington, D.C. and Denver, Colorado, during the winters of 1982–1983. Environ Sci Technol 19:911–918 (1985).
2. Wallace LA, Pellizzari ED, Hartwell TD, Sparacino C, Whitmore R, Sheldon L, Zelon H, Perritt R. The TEAM (Total Exposure Assessment Methodology) study: personal exposures to toxic substances in air, drinking water, and breath of 400 residents in New Jersey, North Carolina and North Dakota. Environ Res 43:290–307 (1987).
3. Sexton K, Ryan PB. Assessment of Human Exposure to Air Pollution Measurements and Models, Air Pollution: The Automobile and Public Health. Washington, DC:National Academy Press, 1988.
4. Ott, WR. Total human exposure: basic concepts, EPA field studies and future research needs. J Air Waste Manag Assoc 40:966–976 (1990).
5. Lioy PJ. The analysis of total human exposure for exposure assessment: a multi-discipline science for examining human contact with containments. Environ Sci Technol 24:938–945 (1990).
6. Lioy PJ, Waldman JM, Buckley T, Butler J, Pietarinen C. The personal, indoor and outdoor concentrations of PM-10 measured in an industrial community during the winter. Atmos Environ 24B:57–66 (1990).
7. Ott WR. Human exposure assessment: the birth of a new science. J Expo Anal Environ Epidemiol 5:449–472 (1995).
8. National Research Council. Human Exposure Assessment for Air Pollutants: Advances and Opportunities. Washington, DC:National Academy Press, 1991.
9. Clayton CA, Perritt RL, Pellizzari ED, Thomas KW, Whitmore RW, Wallace LA, Ozkaynak H, Spengler JD. Particle total exposure assessment methodology (PTEAM) study: distributions of aerosol and elemental concentrations in personal, indoor, and outdoor air samples in a Southern California community. J Expo Anal Environ Epidemiol 3:227–250 (1993).
10. Duggan MJ, Inskip MJ. Childhood exposure to lead in surface dust and soil: a community health problem. Public Health Rev 13:1–54 (1985).
11. Que Hee S, Peace B, Clark CS, Boyle JR, Bornschein RL, Hammond PB. 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 (1985).
12. Lowengart RA, Peters JM, Cicioni C, Buckley J, Bernstein L, Preston-Martin S, Rappaport E. Childhood leukemia and parents occupational and home exposures. J Natl Cancer Inst 79:39–46 (1987).
13. Fenske RA, Black KG, Elkner KP, Lee C, Methner MM, Soto R. Potential exposure and health risks of infants following indoor residential pesticide applications. Am J Public Health 80(6):689–693 (1990).
14. Fenske RA, Curry PB, Wandelmaier F, Ritter L. Development of dermal and respiratory sampling procedures for human exposure to pesticides in indoor environments. J Expo Anal Environ Epidemiol 1:11–30 (1991).
15. Roberts JW, Budd WT, Ruby MG, Camann DE, Fortmann RC, Lewis RG, Wallace LA, Spittler TM. Human exposure to pollutants in the floor dust of homes and offices. J Expo Anal Environ Epidemiol (suppl) 1:127–146 (1992).
16. Simcox NJ, Fenske RA, Wolz SA, Lee I-C, Kalman DA. Pesticides in household dust and soil: exposure pathways for children of agricultural families. Environ Health Perspect 103:1126–1134 (1995).
17. Adgate JL, Weisel C, Wang Y, Rhoads GG, Lioy PJ. Lead in house dust in relationship between exposure metrics. Environ Res 70:134–147 (1995).
18. Chuang JC, Callahan PJ, Menton RG, Gordon SM, Lewis RG, Wilson N. Monitoring methods for polycyclic aromatic hydrocarbons and their distribution in household track-in-soil. Environ Sci Technol 29:494–500 (1995).
19. Freeman NCG, Wainman T, Stern AH, Shupack SI, Lioy PJ. The effect of remediation of chromium waste sites on chromium levels in urine of children living in the surrounding neighborhood. J Air Waste Manag Assoc 45:604–614 (1995).
20. Stern AH, Fagliano JA, Savrin JE, Freeman NCG, Lioy PJ. The association of chromium in household dust with urinary chromium in residences adjacent to chromate production waste sites. Environ Health Perspect 106:833–839 (1998).
21. Rhoads GG, Ettinger AS, Weisel CP, Buckley TJ, Goldman KD, Adgate JL, Lioy PJ. The effect of dust lead control and blood lead in toddlers: a randomized trial. Pediatrics 103:551–555 (1999).
22. Lewis RG, Fortune CR, Willis RD, Camann DE, Antley JT. Distribution of pesticides and polycyclic aromatic hydrocarbons in housedust as a function of particle size. Environ Health Perspect 107:721–726 (1999).
23. Nishioka MG, Lewis RG, Brinkman MC, Burkholder HM, Hines CE, Menkedick JR. Distribution of 2,4-D in air and on surfaces inside residences after lawn applications: comparing exposure estimates from various media for young children. Environ Health Perspect 109:1185–1191 (2001).
24. Lioy PJ. Measurement methods for human exposure analysis. Environ Health Perspect 103(suppl 3):35–43 (1995).
25. Lioy PJ. The 1998 ISEA Wesolowski Award Lecture. Exposure analysis: reflections on its growth and aspirations for its future. International Society of Exposure Analysis. J Expo Anal Environ Epidemiol 9:273–281 (1999).
26. Paustenbach DJ. The practice of exposure assessment: a state of the art review. J Toxicology Environ Health, Part B 3:179–291 (2000).
27. U.S. EPA. An SAB Report: The Cumulative Exposure Project. EPA-SAB-IHEC-ADV-96-004. Washington, DC:U.S. Environmental Protection Agency, 1996.
28. ILSI. Aggregate Exposure Assessment: Model Evaluation and Refinement. Washington, DC:International Life Science Institute, 2000.
29. Lioy PJ. Exposure analysis and research needs to support environmental health sciences in the 21st century. Eur J Oncol 5 (suppl) 2:13–16 (2000).
30. U.S. EPA. Guidance on Remedial Investigations under CERCLA. EPA 540/G85-002. Washington, DC:U.S. Environmental Protection Agency, 1985.
31. Tate RL III. Soil Microbiology. 2nd ed. New York:John Wiley & Sons, 2000.
32. Hillel D. Environmental Soil Physics. San Diego, CA:Academic Press, 1998.
33. Cresser MS, Killham K, Edwards T. Soil Chemistry and Its Applications. Cambridge Environmental Chemistry Series. Cambridge/New York:Cambridge University Press, 1993.
34. Little JC, Daisey JM, Nazaroff WW. Transport of subsurface contaminants into buildings: an exposure pathway for volatile organics. Environ Sci Technol 26:2058–2066 (1992).
35. Kerger B, Schmidt C, Paustenbach D. Assessment of airborne exposure to trihalomethanes from tap water in residential showers and baths. Risk Anal 20:637–652 (2000).
36. Georgopoulos PG, Lioy PJ. Exposure measurement needs for hazardous waste sites: two case studies. J Toxicol Environ Health 12:651–665 (1996).
37. Prospero JM, Ness RT, Uematsu M. Deposition rate of particulate and dissolved aluminum derived from Saharans dust in precipitation at Miami, Florida. J Geophys Res 92(14):723–731 (1987).
38 Nicholson KW. A review of particle resuspension. Atmos Environ 22:2639–2652 (1998).
39 Perry KD, Cahill TA, Eldred RA, Dutcher DD, Gill TE. Long range transport of north American dust to the eastern United States. J Geophys Res 102(11):225–238 (1997).
40. Hawley JK. Assessment of health risk from exposure to contaminated soil. Risk Anal 5(4):289–302 (1985).
41. Alexander M. How toxic are chemicals in soil? Environ Sci Technol 29:2713–2717 (1995).
42. Calabrese EJ, Stanek EJ III, Pekow P, Barnes RM. Soil ingestion estimates for children residing on a Superfund site. Ecotoxicol Environ Saf 36:258–268 (1997).
43. Davis A, Sherwin D, Ditmars R, Hoenke KA. An analysis of soil arsenic records of decision. Environ Sci Technol 35(12):2401–2406 (2001).
44. de Silva PE. How much soil do children ingest—a new approach. Appl Occup Environ Hyg 9:40–43 (1994).
45. Lioy PJ, Weisel CP, Millette J, Eisenreich S, Vallero D, Offenberg J, Buckley B, Turpin B, Zhong M, Cohen MD, et al. Characterization of the dust/smoke aerosol that settled east of the World Trade Center (WTC) in lower Manhattan after the collapse of the WTC September 11, 2001. Environ Health Perspect 110:703–714 (2002).
46. Thatcher TL, Layton DW. Deposition, resuspension, and penetration of particles within a residence. Atmos Environ 29:1487–1497 (1995).
47. Roberts JW, Dickey P. Exposure of children to pollutants in house dust and indoor air. Rev Environ Contam Toxicol 143:59–78 (1995).
48. Georgopoulos PG, Roy A, Yonone-Lioy MJ, Opiekun RE, Lioy PJ. Environmental copper: its dynamics and human exposure issues. J Toxicol Environ Health Part B 4:341–394 (2001).
49. Charney E, Sayre J, Coulter M. Increased lead absorption in inner city children: where does the lead come from?. Pediatrics 65:226–231 (1980).
50. Roberts JW, Clifford WS, Glass G, Hummer PG. Reducing dust, lead, dust mites, bacteria, and fungi in carpets by vacuuming. Arch Environ Contam Toxicol 36:477–484 (1999).

51. Freeman NCG, Lioy PJ, Stern AH. Reduction in residential chromium following site remediation. J Air Waste Manag Assoc 50:948–953 (2000).
52. Pellizzari E, Lioy PJ, Quackenboss J, Whitmore R, Clayton A, Freeman N, Waldman J, Thomas K, Rodes C, Wilcosky T. The design and implementation of phase I national human exposure assessment study in EPA Region V. J Expo Anal Environ Epidemiol 5:327–358 (1995).
53. Bonanno LJ, Freeman NCG, Greenberg M, Lioy PJ. Multivariate analysis on levels of selected metals, particulate matter, VOC, and household characteristics and activities from the Midwestern states and NHEXAS. Appl Occup Environ Hyg 16:859–874 (2001).
54. Lioy PJ. Community air sampling strategies. In: Air Sampling Instruments (Cohen BS, McCammon CS, eds). 9th ed. Cincinnati, OH:American Conference of Governmental Industrial Hygienists, 2001;51–74.
55. Edwards RD, Yurkow E, Lioy PJ. Seasonal deposition of housedusts onto household surfaces. Sci Total Environ 224:69–80 (1998).
56. Franklin CA, Grover R, Markham JW, Smith AE, Yoshida K. Effect of various factors on exposure of workers involved in the aerial application of herbicides. Trans Am Conf Gov Ind Hyg 43:97–117 (1981).
57. Chester G, Ward RJ. Occupational exposure and drift hazard during aerial application of paraquat to cotton. Arch Environ Contam Toxicol 13:551–563 (1984).
58. Raunemma T, Kumala M, Saari H, Olin M, Kumala MH. Indoor air aerosol model: transport indoors and deposition of fine and coarse particles. Aerosol Sci Technol 11:11–25 (1989).
59. Pires do Rio MA, Amaral ECS, Paretzke HG. Resuspension and redeposition of ^{137}Cs in an urban area: the experience after the Goiania accident. Aerosol Sci Technol 25(5):821–831 (1994).
60. Scott PK, Sung H, Finley BL, Schulze RH, Turner DB. Identification of an accurate soil suspension/dispersion modeling method for use in estimating health-based soil cleanup levels of hexavalent chromium in chromite ore processing residues. J Air Waste Manag Assoc 47(7):753–765 (1997).
61. Long CM, Suh HH, Catalano PJ, Koutrakis P. Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior. Environ Sci Technol 35:2089–2099 (2001).
62. Fergusson JE, Kim ND. Trace elements in street and house dusts: sources and speciation. Sci Total Environ 100:125–150 (1991).
63. Nishioka MG, Burkholder HM, Brinkman MC, Gordon SM, Lewis RG. Measuring transport of lawn-applied herbicide acids from turf to home: correlation of dislodgeable 2,4-D turf residues with carpet dust and carpet surface residues. Environ Sci Technol 30:3313–3320 (1996).
64. Gurunathan S, Robson M, Freeman N, Buckley B, Roy A, Meyer R, Bukowski J, Lioy PJ. Accumulation of chlorpyrifos on residential surfaces and toys accessible to children. Environ Health Perspect 106:9–16 (1998).
65. Nishioka MG, Burkholder HM, Brinkman MC, Lewis RG. Distribution of 2,4-dichlorophenoxyacetic acid in floor dust throughout homes following homeowner and commercial lawn applications: quantitative effects of children, pets, and shoes. Environ Sci Technol 33:1359–1365 (1999).
66. Lewis RG, Fortune CR, Blanchard FT, Camann DE. Movement and deposition of two organophosphorus pesticides within a residence after interior and exterior applications. J Air Waste Manag Assoc 51:339–351 (2001).
67. Locard E. The analysis of dust traces. Am J Police Sci 1(3):276 (1930).
68. Davies JE, Edmundson WF, Raffonelli A. The role of house dust in human DDT pollution. Am J Public Health 65:53–57 (1975).
69. Wright CG, Jackson MD. Insecticide residues in non-target areas of rooms after two methods of crack and crevice application. Bull Environ Contam Toxicol 13:123–128 (1975).
70. Wright CG, Leidy RB, Dupree HE Jr. Chlorpyrifos and diazinon detection on surfaces in dormitory rooms. Bull Environ Contam Toxicol 32:259–264 (1984).
71. Kitsa V, Lioy PJ, Chow JC, Watson JG, Shupack S, Howell T, Sanders P. Particle size distribution of chromium—total and hexavalent chromium in inspirable thoracic and respirable soil particles from contaminated sites in New Jersey. Aerosol Sci Technol 17:213–229 (1992).
72. Brown RS, Millette JR, Mount MD. Application of scanning electron microscopy for pollution particle source determination in residential dust and soil. Scanning 17:302–305 (1995).
73. Gulson BK, Davis JJ, Mizon KJ, Korsch MJ, Bawden-Smith J. Sources of lead in soil and dust and the use of dust fallout as a sampling medium. Sci Total Environ 166:245–262 (1995).
74. Roberts JW. Reducing health risks from dust in the home. In: Master Home Environmentalist Training Manual (Dickey P, ed). Seattle,WA:American Lung Association of Washington, 1998;72–86.
75. Yiin LM, Rhoads, Lioy PJ. Seasonal influences on childhood lead exposure. Environ Health Perspect 108:177–182 (2000).
76. Clark S, Bornshein R, Succop P, Roday S, Peace B. Urban lead exposures in Cincinnati, OH. Chem Spec Bioavail 3:163–171 (1991).
77. Hunt A, Johnson DL, Watt JM, Thornton I. Characterizing the sources of particulate lead in house dust by automated scanning electron microscopy. Environ Sci Technol 26(8):1513–1526 (1992).
78. Molhave L, Schneider T, Kjaergaard SK, Larsen L, Norn S, Jorgensen O. House dust in seven Danish offices. Atmos Environ 34:4767–4779 (2000).
79. Lepow J (SC Johnson Co.). Personal communication.
80. Rudel RA, Brody JG, Spengler JD, Vallarino J, Geno PW, Sun G, Yau A. Identification of selected hormonally active agents and animal mammary carcinogens in commercial and residential air and dust samples. J Air Waste Manag Assoc 51:499–513 (2001).
81. McArthur B. Dermal measurement and wipe sampling methods: a review. Appl Occup Environ Hyg 7(9):599–606 (1992).
82. Caplan K. The significance of wipe samples. Am Ind Hyg Assoc J 53:70–75 (1993).
83. Vostal JJ, Taves F, Sayre JW, Charney E. Lead analysis of house dust: a method for the detection of another source of lead exposure in inner city children. Environ Health Perspect 7:91–97 (1974).
84. Dunster HJ. Surface contamination measurements as an index of control of radioactive materials. Health Phys 8:353–356 (1962).
85. Lioy PJ, Wainman T, Weisel CP. A wipe sampler of the quantitative measurement of dust on smooth surfaces: laboratory performance studies. J Expo Anal Environ Epidemiol 3:315–330 (1993).
86. Lewis RG, Fortmann RC, Camann DE. Evaluation of methods for monitoring the potential exposure of small children to pesticides in the residential environment. Arch Environ Contam Toxicol 26:37–46 (1994).
87. Edwards RD, Lioy PJ. The EL sampler: a press sampler for the quantitative estimation of dermal exposure to pesticides in household dust. J Expo Anal Environ Epidemiol 9:521–529 (1999).
88. Cohen Hubal EA, Sheldon LS, Burke JM, McCurdy TR, Berry MR, Rigas ML, Zartarian VG, Freeman NCG. Children's exposure assessment: a review of factors influencing children's exposure, and the data available to characterize and assess that exposure. Environ Health Perspect 108:475–486 (2000).
89. Freeman NCG, Sheldon L, Jimenez M, Melnyk L, Pellizzari E, Berry M. Contributions of children's activities to lead contaminated food. J Expo Anal Environ Epidemiol 11:1–8 (2001).
90. Freeman NCG, Adgate J, Pellizzari ED, Melnyk LJ, Barry M. Unpublished data.
91. Wang EY, Rhoads GG, Wainman T, Lioy PJ. The effects of environmental and carpet variables on vacuum cleaner sampling efficiency. Appl Occup Environ Hyg 10:111–119 (1995).
92. Lioy PJ, Wainman T, Zhang JJ, Goldsmith S. Typical household vacuum cleaners: the collection efficiency and emissions characteristics for fine particles. J Air Waste Manag Assoc 49:200–206 (1999).
93. Bonanno LJ. Household Characteristics, Activities, and Contamination: Exposure Assessment of Children in the NHEXAS Population [PhD dissertation]. Piscataway, NJ:The State University of New Jersey and UMDNJ-Robert Wood Johnson Medical School, 2000.
94. Farfel MR, Orlova AO, Lees PSJ, Bowen C, Elias R, Ashley PJ, Chisolm JJ Jr. Comparison of two floor mat lead dust collection methods and their application in pre-1950 and new urban houses. Environ Sci Technol 35:2078–2083 (2001).
95. Bukowski JA, Robson MG, Buckley BT, Russell DW, Meyer LW. Air levels of volatile organic compounds following indoor application of an emulsifiable concentrate insecticide. Environ Sci Technol 30:2543–2546 (1996).
96. Cizdziel JV, Hodge VF. Attics as archives for house infiltrating pollutants: trace elements and pesticides in attic dust and soil from southern Nevada and Utah. Microchem J 64:85–92 (2000).
97. Ilaqua V. Using Attic Dust to Reconstruct Historical Air Pollution [PhD dissertation]. Piscataway, NJ:The State University of New Jersey and UMDNJ-Robert Wood Johnson Medical School, 2001.
98. Cizdziel JV, Hodge VF, Faller SH. Plutonium anomalies in attic dust and soils at locations surrounding the Nevada test site. Chemosphere 37(6):1157–1168 (1998).
99. Allott RW, Hewitt CN, Kelly MR. The environmental half-lives and mean residence times of contaminants in dust for an urban environment: Barrow-in-Furness. Sci Total Environ 93:403–410 (1990).
100. Kashparov VA, Protsak VP, Yoschenko VI, Watterson JD. Inhalation of radionuclides during agricultural work in areas contaminated as a result of the Chernobyl reactor accident. Aerosol Sci Technol 25(5):761–766 (1994).
101. de Meijer RJ, Aldenkamp FJ, Brummelhuis MJAM, Jansen JFW, Put LW. Radionuclide concentrations in the northern part of The Netherlands after the Chernobyl reactor accident. Health Phys 58(4):441–452 (1990).
102. Farfel MR, Lees PSJ, Rohde CA, Lim BS, Bannon D. Comparison of wipe and cyclone methods for the determination of lead in residential dusts. Appl Occup Environ Hyg 9(12):1006–1012 (1994).
103. Farfel MR, Lees PSJ, Bannon D, Lim BS, Rohde CA. Comparison of two cyclone-based collection devices for the evaluation of lead-containing residential dusts. Appl Occup Environ Hyg 9(3):212–217 (1994).
104. Lamphear AP, Emond M, Jacobs DE, Weitzman M, Tanner M, Winter NL, Yakin B, Eberly S. A side-by-side comparison of dust collection methods for sampling lead contaminated house dust. Environ Res 68:114–123 (1995).
105. Rich DQ, Yinn LM, Rhoads GG, Glueck DH, Weisel C, Lioy PJ. A field comparison of two methods for sampling lead in household dust. J Expo Anal Environ Epidemiol 9:106–112 (1999).
106. Alexander LR, Patterson DG, Myers GL, Holler JS. Safe handling of chemical toxicants and control of interferences in human tissue analysis for dioxins and furans. Environ Sci Technol 20:725–730 (1986).
107. Bently RK, Horstman SW, Morgan MS. Reduction of sawmill worker exposure to chlorophenols. Appl Ind Hyg 4:69–74 (1989).
108. Chalk JL. 4,4-Methylenedianiline—industrial hygiene experiences. Appl Ind Hyg Special Issue 12:60–63 (1989).
109. Chavalitnitikul C, Levin L, Chen L. Study and models of total lead exposure of battery workers. Am Ind Hyg Assoc J 45:802–808 (1984).
110. U.S. EPA. EPA Guide for Decontaminating Buildings, Structures, and Equipment at Superfund Sites. EPA/600/2-85/028. Cincinnati, OH:U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, Office of Research and Development, 1985.
111. Fenske RA, Horstman SW, Bentley RK. Assessment of dermal exposure to chlorophenols in timber mills. Appl Ind Hyg 2:143–147 (1987).
112. Hryhorczuk DO, Orris P, Kominsky JR. PCB, PCDF, and PCDD exposure following a transformer fire: Chicago. Chemosphere 15:1297–1303 (1986).
113. Lees PSJ, Corn M, Breysse PN. Evidence for dermal absorption as the major route of body entry during exposure of transformer maintenance and repairmen to PCBs. Am Ind Hyg Assoc J 48:257–264 (1987).
114. Lichtenwalner CP. Evaluation of wipe sampling procedures and elemental surface contamination [Abstract]. Presented at the American Industrial Hygiene Conference, May 1990. Orlando, FL.
115. O'Malley MA, Mathias CG, Priddy M. Occupational vitiligo due to unsuspected presence of phenolic antioxidant byproducts in commercial bulk rubber. J Occup Med 30:512–516 (1988).
116. OSHA. Sampling for surface contamination. In: Industrial Hygiene Technical Manual. Washington, DC:Occupational Safety and Health Administration, 1990;40–56.
117. Rappe C, Marklund S, Kjeller L, Hansson M. Strategies and techniques for sample collection and analysis: experience from the Swedish PCB accidents. Environ Health Perspect 60:279–292 (1985).
118. Stephens RD. Transformer fire Spear Street Tower One Market Plaza San Francisco, California. Chemosphere 15:1281–1289 (1986).

119. HUD. Lead-based Paint: Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing: Appendix A. Washington, DC:U.S. Department of Housing and Urban Development, 1990.
120. Lioy PJ, Edwards RD, Freeman NCG, Gurunathan S, Pellizzari E, Adgate JL, Quackenboss J, Sexton K. Housedust levels of selected insecticides and a herbicide measured by the EL and LWW samplers and comparisons to hand rinses and urine metabolites. J Expo Anal Environ Epidemiol 10:327–340 (2000).
121. Freeman NCG, Wainman T, Lioy PJ. Field testing of the LWW sampler and association of observed household factors with dust loading. Appl Occup Environ Hyg 11(5):476–483 (1996).
122. Lioy PJ, Yiin LM, Adgate J, Weisel C, Rhoads GG. The effectiveness of home cleaning intervention strategy in reducing potential dust and lead exposures. J Expo Anal Environ Epidemiol 8:17–35 (1998).
123. Lioy PJ, Weise CP. Wipe Template Sampler. U.S. Patent 5,373,748. Washington, DC:U.S. Patent and Trademark Office, 1994. Available: http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=5373748 [cited 27 June 2002].
124. Rodes CE, Lawless PA, Evans GF, Sheldon LS, Williams RW, Vette AF, Creason JP, Walsh D. The relationships between personal PM exposures for elderly populations and indoor and outdoor concentrations for three retirement center scenarios. J Expo Anal Environ Epidemiol 11:103–115 (2001).
125. HUD. Guidelines for Evaluation and Control of Lead-based Paint Hazards in Housing. HUD-1539-LBP. Washington, DC:U.S. Department of Housing and Urban Development , 1995.
126. Colt JS, Zihm, SH, Camann DE, Hart JA. Comparison of pesticides and other components in carpet dust samples collected from used vacuum cleaner bags and from a high volume surface sampler. Environ Health Perspect 106:721–724 (1998).
127. Colt JS, Hartge P, Camann DE. Pesticides, PAH, and PCB congeners in house dust from four sites [Abstract]. Presented at the annual meeting of the International Society of Exposure Analysis, 27–29 October 2000, Monterey, CA.
128. Hysong TA, Burgess JL, O'Rourke MK. Floor dust and urinary arsenic levels in two Arizona Mining Towns. J Expo Anal Environ Epidemiol (In Press).
129. Fortune CR, Ellinson WD, Blanchard FT, Camann DE. Distribution of pesticide and PAH residues in aged residential carpeting [Abstract]. Presented at the Annual meeting of the International Society of Exposure Analysis, 27–29 October 2000, Monterey, CA.
130. Lu C, Fenske R. Dermal transfer of chlorpyrifos residues from residential surfaces, comparison of hand press, hand drag, wipe and polyurethane foam roller measurements after broadcast and aerosol pesticide applications. Environ Health Perspect 107:463–467 (1999).
131. Meijer SN, Halsall CJ, Harner T, Peters AJ, Ockenden WA, Johnston AE, Jones KC. Organochlorine pesticide residues in archived UK soil. Environ Sci Technol 35:1989–1995 (2001).
132. Macher J, Burger HA. Sampling biological aerosols. In: Air Sampling Instruments (Cohen BS, McGammon CS, eds). 9th ed. Cincinnati, OH:American Conference of Governmental Industrial Hygienists, 2001;661–701.
133. Duggan MJ, Inskip MJ, Rundle SA, Moorcroft JS. Lead in playground dust and on the hands of school children. Sci Total Environ 44:65–79 (1985).
134. Fenske RA, Lu C. Determination of handwash removal efficiency, incomplete removal of the pesticide chlorpyrifos from skin by standard handwash techniques. Am Ind Hyg Assoc J 55:425–432 (1994).
135. Kissel JC, Richter KY, Fenske RA. Field measurement of dermal soil loading attributable to various activities: implications for exposure assessment. Risk Anal 16:115–125 (1996).
136. Yankel AJ, von Lindern IH, Walter SD. The Silver Valley lead study: the relationship between childhood blood lead levels and environmental exposure. J Air Pollut Control Assoc 27(8):763–767 (1977).
137. Zartarian V, Ferguson AC, Leckie JO. Quantified seasonal activity data from a four child pilot field study. J Expo Anal Environ Epidemiol 7: 543–553 (1997).
138. Reed KJ, Jimenez M, Lioy PJ, Freeman NCG. Quantification of children's hand and mouthing activities. J Expo Anal Environ Epidemiol 9:513–520 (1999).
139. Jo WK, Weisel CP, Lioy PJ. Routes of chloroform exposure and body burden from showering with chlorinated tap water. Risk Anal 10:575–580 (1990).
140. Adgate JL, Willis RD, Buckley TJ, Chow JC, Watson JG, Rhoads GG, Lioy PJ. Chemical mass balance source apportionment of lead in house dust. Environ Sci Technol 32:108–114 (1998).
141. Adgate JL, Rhoads GG, Lioy PJ. The use of isotope ratios to apportion sources of lead in Jersey City, NJ. Sci Total Environ 106:833–839 (1998).
142. Angle CR, Manton WI, Stanek KL. Stable isotope identification of lead sources in preschool children—the Omaha study. Clin Toxicol 33:657–662 (1995).
143. Farfel MR, Chisolm JJ. An evaluation of experimental practices for abatement of residential lead. Environ Res 55:199–212 (1991).
144. Lioy PJ, Freeman NCG, Wainman T, Stern AH, Boesch R, Howell T, Shupack SI. Microenvironmental analysis of residential exposure to chromium laden wastes in and around New Jersey homes. Risk Anal 12:287–299 (1992).
145. Stern AH, Freeman NCG, Pleban P, Boesch R, Wainman T, Howell T, Shupack SI, Johnson BB, Lioy PJ. Residential exposure to chromium waste—urine biological monitoring in conjunction with environmental exposure monitoring. Environ Res 58:147–162 (1992).
146. Freeman NCG, Stern AH, Lioy PJ. Exposure to chromium in dust from homes in a chromium surveillance project. Arch Environ Health 52:213–219 (1997).
147. Millette JR, Hopen TJ. Characterizing household dirt: 1928–2001. In: Second NSF International Conference on Indoor Air Health Proceedings. 28–31 January, 2001, Miami Beach, FL. Ann Arbor, MI:NSF International, 2001;174–183.
148. Millette JR, Few P. Sample collection procedures for microscopical examination of particulate surface contaminants. Microscope 49(1):21–27 (2001).
149. McCrone WC, Delly JG. The Particle Atlas. 2nd ed. Ann Arbor, MI:Ann Arbor Science Publishers, 1973.