Sampling and Analysis for Non-Occupational Pesticide Exposure Assessments

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SUMMARY

Direct measurements of pesticides in environmental media and diet continue to be an important tool for estimating human exposure and for determining the factors that have the greatest impact on people's exposures. The need to estimate aggregate and cumulative exposures to pesticides challenges researchers to develop and validate systematic sample collection protocols, as well as new sampling and analysis methods. Although sample collection methods are available for assessing exposure by all routes and pathways, there have been few recent advances in these methods. While many are adequate and have been described in a number of review articles, there is a need to advance and standardize sample collection methods. Significant advances have been made in the development and refinement of analytical methods, including multi-residue methods for many different matrices. There have also been significant advances in the analysis of pesticide degradation products (metabolites) in biological media, environmental media, and diet samples, which is important when interpreting biomonitoring results.

Sampling and analysis of pesticides and their degradation products will continue to provide critical information needed to protect public health and the environment. However, the lack of standardization of measurement protocols and sample collection methods creates a significant challenge when comparing results across measurement studies. The development of sampling and analysis methods for pesticides will also continue to be a challenge with the nearly continuous introduction of new pesticide active ingredients and formulations.

Keywords : Exposure, exposure assessment, pesticides, non-occupational exposure, pesticide sampling, pesticide analysis, environmental, diet, biomonitoring

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2.1 INTRODUCTION

Pesticides are used extensively in the United States to control a variety of pests. Commercial agriculture and non-agricultural industries account for about 80% of the total pesticide use in the U.S., while the remaining 20% is used for pest control associated with home, garden, yard, and pets. Pesticides frequently occur in the indoor environments that we occupy as a result of indoor applications, spray drift and infiltration, and track-in from outdoor applications. To fully assess human exposures to pesticides, it is necessary to understand the aggregate exposures in all of the microenvironments that people occupy.

As discussed in other chapters of the Handbook, it is critical to accurately assess and predict exposures in order to perform risk assessments for pesticides. The Food Quality Protection Act of 1996 requires that both aggregate exposure and cumulative risk be assessed. Aggregate exposure considers the exposure to a pesticide by all routes and pathways (inhalation, dietary and non-dietary ingestion, and dermal absorption). Cumulative risk considers the risk from aggregate exposures to all pesticides having a common mechanism of toxicity.

The measurement of pesticides or pesticide metabolites in biological specimens (e.g., urine), known as biomonitoring, is an important tool used to evaluate human exposure. Modeling is another important tool used to support exposure assessments. An extensive array of models has been developed and are described in other chapters in the Handbook. Despite the significant advances in biomonitoring and modeling tools, a continuing need exists to perform measurements of pesticides and pesticide metabolites in environmental media and to collect ancillary information to assess exposures. These measurement studies are critical for determining the factors that have the most significant impact on people's exposures and the

spatial and temporal variability of exposures as people go about their normal activities in their everyday environments. Measurement studies that incorporate the normal activities of people in their everyday environments fall under the category of studies described as observational exposure studies. It is important to note that when conducting observational studies, there should be no attempt to control the activities or actions of the participants that could impact their exposures. Any attempt to do so introduces significant ethical concerns and introduces bias that prevents obtaining the very data the studies are designed to collect, which is exposure information based on normal activities in everyday environments.

Various approaches are available for assessing human exposure to pesticides. Direct methods involve measurements of pesticides and/or their metabolites in environmental media, diet samples, and/or biological media. These data and selected ancillary information are used in simple algorithms, statistical methods, and models to estimate exposures. Indirect methods estimate individual's exposures through the use of questionnaires, diaries, exposure surrogates, or deterministic algorithms. Probabilistic methods are used to develop population-level exposure estimates.

This chapter focuses on the direct measurement methods used in observational human exposure studies and includes approaches employed in the design of observational studies and considerations that should be addressed during study design and implementation. State-of-the-science sample collection methods and considerations for the selection of methods used for estimating exposures associated with different routes and pathways of exposure are discussed. This discussion also includes the general principles and state-of-the-science analytical methods used to measure pesticides and metabolites in environmental media, diet samples, and biological samples. Measurements are centered around estimating exposures of people in their real-world

environments as they go about their normal day-to-day activities and apply to current use pesticides applied indoors (e.g., crack and crevice treatments, sprays, foggers, baits, gels) by occupants or professional applicators in buildings such as residences, child care centers, schools, and public access buildings. Occupational exposures are not addressed, although some of the methods may be applicable if differences in exposure routes, concentrations, and timing of exposures are considered.

2.2 DESIGN OF NON-OCCUPATIONAL OBSERVATIONAL EXPOSURE MEASURMENT STUDIES

This section describes guidance for designing observational measurement studies to assess exposure concentrations and exposure factors in non-occupational settings. Non-occupational settings refer to locations such as single and multi-residential housing units and also include child care centers, schools, public access buildings, and other non-occupational locations. The term "observational" is used to distinguish between measurements taken in everyday environments versus experiments conducted in a controlled laboratory system.

Observational exposure measurement studies are performed for many different reasons. Examples may include determining occurrence/co-occurrence and concentrations of pesticides in environmental media in a microenvironment (e.g., residence, school, public access building, yard, vehicle); identifying the important routes and pathways of exposure for different chemicals and chemical classes; determining which are the most important factors and activities affecting exposure; estimating exposure and dose for the exposed individual; evaluating exposure or dose models; and/or evaluating intervention and risk mitigation approaches and methods. A study

may be designed to meet one or more study objectives or it may be hypothesis driven (e.g., that diet is the primary route of exposure for the targeted pesticide). Regardless, the study objectives or hypothesis must be clearly defined in order to identify the data analyses and the data required to address the objectives. It is critical that the data analysis plan be developed during the study design phase because the data analysis plan should serve as the basis for the design of the study; it should not be developed in response to the data collected.

Unlike worker exposure, which is discussed in other chapters of the Handbook and for which there are several reviews and guidance documents on methodology for exposure measurements including those by Fenske and Day (2005), OECD (1997), and US EPA (1998), extensive guidance is lacking for approaches and methods for exposure assessments for pesticides in residential and other non-occupational environments. The *U.S. EPA Guidelines for Exposure Assessment* (US EPA, 1992) describe the general concepts of exposure assessment and provide guidance on the planning and conducting of an exposure assessment. The Guidelines focus on exposures of humans to chemical substances, but do not specifically address issues unique to particular classes of chemicals, such as pesticides. Various approaches and tools for exposure assessment and their appropriate use are discussed. It includes discussions for establishing the sampling strategy, including data quality objectives, a sampling plan, and quality assurance. The document also describes approaches for data collection, including examples of measurements to characterize various exposure-related media and parameters. The *U.S. EPA Guidelines for Exposure Assessment* document continues to be useful, but is out-of-date and does not reflect the substantial advances in exposure assessment made over the last 15 plus years; it is currently being revised.

The *U.S. EPA Residential Exposure Assessment Standard Operating Procedures (SOPs)* (US EPA, 1997) provide guidance for assessing exposure to pesticides in a residential setting when direct measurement data are not available. The SOPs provide standard default methods for developing residential exposure assessments for both handler and post-application exposures when chemical- and/or site-specific field data are limited. The methods in the SOPs may be used in the absence of, or as a supplement to, chemical data and/or site-specific data. Handler and post-application SOPs for developing assessments of dermal, inhalation, and/or incidental ingestion doses are provided for major residential exposure scenarios (e.g., residential lawns, fogging, crack and crevice treatments, broadcast treatments, pet treatments, inhalation of residues from indoor treatments).

A Framework for Assessing Health Risks of Environmental Exposures to Children (US EPA, 2006a) is a useful tool in the development of the technical study design for an observational human exposure measurement study. This document discusses lifestage-specific exposure characterization and presents concepts useful for estimating children's exposures.

EPA's *Draft Protocol for Measuring Children's Non-Occupational Exposure to Pesticides by all Relevant Pathways* (US EPA, 2001a) provides guidance for generating data for aggregate exposure assessments for children in residential environments. It provides a set of algorithms for estimating exposure by each route and pathway, describes the data needed for the estimates, and provides descriptions of approaches for data collection. It also includes examples and references for measurement methods for each exposure route (e.g., inhalation).

A more recent document prepared by the U.S. EPA, *Scientific and Ethical Approaches for Observational Exposure Studies* (SEAOES, US EPA, 2008) describes approaches for designing and implementing observational exposure measurement studies. Although the focus of the

document is on ethical issues associated with observational studies, it includes extensive discussion of the elements to be considered in study conceptualization and planning. The document stresses that the scientific and ethical approaches for these studies need to be fully integrated from the conception of the study through the final reporting and publication of results. It stresses that observational studies must be scientifically sound in order to be ethical. The document includes general information on approaches for designing and implementing observational exposure studies and citations for manuscripts and reports describing exposure measurement studies. Detailed information on alternative approaches for designing observational exposure measurement studies has not been systematically compiled and can only be obtained by a search of the scientific literature. Examples of EPA observational studies are described in the SEAOES document and also in an EPA report that summarizes results from 13 recent studies conducted or supported by EPA (US EPA, 2007a).

During planning for the National Children's Study (NCS), a study that will examine the impact of environmental factors on the health of a cohort of 100,000 children from birth to 21 years of age, workgroups discussed and recommended alternative approaches for exposure measurements to address a number of different hypotheses, including hypotheses related to pesticide exposures. The results of these discussions are published in a white paper on the "Measurement and Analysis of Exposures to Environmental Pollutants and Biological Agents during the National Children's Study (NCS, 2004), which is available on the NCS website (http://www.nationalchildrensstudy.gov). The work of the NCS Chemical Agents workgroup was also highlighted in a mini-monograph published in Environmental Health Perspectives in 2005 (Needham et al., 2005 and others). The manuscript by Bradman and Whyatt (2005) focused on pesticides.

Exposure measurement studies are complex in their design and implementation due to many factors, including differing study objectives, uniqueness of the study cohort, diversity of communities, involvement of human study participants, multiple media to be sampled for aggregate exposure estimates, and resource limitations. Figure 2-1 presents a conceptual model of residential exposures to pesticides, including elements such as mouthing activities that are important for children. The model can assist in framing the issues to be considered in design of measurement-based exposure studies. Conceptualization and planning of a study involve the following elements:

- Define the study problem – Measurement studies are performed for many different purposes. During study conceptualization, the exposure science questions and problem to be addressed must be clearly identified.
- Develop the study hypotheses and objectives – These are based on the science questions.
- Justify the study – There must be both scientific and ethical justification for the study. To be scientifically justified, there must be a need for the study, the scientific question must not have already been answered, and the study design must be scientifically sound. Involvement of human subjects in a study must also be justified. If the hypotheses can be tested or objectives addressed without human participants in the study, then human subjects research cannot be justified.
- Develop the data analysis plan - Although it may seem premature to develop a data analysis plan during the early phases of study design, the data analysis plan will determine what data should be collected. By determining how the study hypotheses will be tested or how the objectives will be addressed, the data analysis plan will identify the parameters that need to be measured (i.e., data needed) and define the required sample

size(s) needed. This will in turn help to define the sampling plan. This is also referred to as identifying the "critical data elements."

- Develop the study design – The SEAOES document (US EPA, 2008) describes the concepts, importance, features, and elements of a well-developed study design. Elements to be included are listed in the accompanying text box.
- Prepare the human subjects research protocol, if applicable – For guidance on ethical considerations in studies involving human subjects, the SEAOES document (US EPA, 2008) provides extensive references for information sources.
- Develop data quality objectives – Data quality objectives must be based on criteria that ensure that the data are adequate to perform the required analyses.

Elements That May Be Included in the Study Design

- Introduction and background, including the purpose and scope of the study
- The desired outputs and outcomes of the study, including the objectives and the hypotheses to be tested
- A brief description or overview of the study
- The technical approach and conceptual model that accounts for
  - sources of the chemicals being studied;
  - potential routes and pathways of exposure;
  - factors that may impact exposure and other relevant stressors;
  - selection and characteristics of the study participants; eligibility criteria; and recruitment, retention, and payment approaches;
  - justification for sample size, the methodology for selecting participants, and the sampling methods;
  - characteristics of the community in which the study will be performed;
  - environmental conditions, factors, or end points to be measured, including sampling and analysis approaches and methods (with description of expected performance);
  - survey design and questionnaires and other survey instruments, as applicable (with description of prior use and validation in similar studies);
  - pilot studies that may be undertaken;
  - quality assurance project plan and quality control;
  - timeframe for the study;
  - exposure scenarios to be considered;
  - burden of the study on the participants;
  - resources available; and
  - feasibility
- Discussion of alternative study designs and approaches considered and reasons for rejecting other approaches and selecting the one proposed
- An analysis plan that considers
  - Information and data needs, including data storage, security, access, and release;
  - nature of the measurement data (e.g., variability, quality assurance);
  - how the collected data will be used, and how the proposed analyses will address objectives of the study; and
  - hypotheses to be tested and statistical power and sample size required to test the hypotheses
- Resources required or available
- Project organization and management, including team members and roles and responsibilities
- Schedule

The study design document should address a number of very important issues essential to the design of a scientifically sound and valid study. These include the determination of the sample size for each data element. The sample size should be sufficient to support tests for statistical significance, confidence, and other statistically-based metrics. Estimates of the required sample size are important not only to ensure that the objectives of the study can be met, but also to reduce study costs by limiting the sample to only the required size (US EPA, 2008; Dattalo, 2008).

In addition to ensuring that the sample size is adequate to address the research objectives, the sample must be representative. Researchers must be concerned about the individuals that participate in a study and the group or population they represent. In some cases, the study hypothesis will require a very specific study population, for example children in child care centers with integrated pest management (IPM) practices. In other cases, the study may require that the sample be representative of the general population. Eligibility criteria for selection of study participants and the approaches and methods for recruitment must ensure that both the sample size is adequate and that the goals for representativeness are met.

When the study objectives or hypotheses have been defined, the study design has been developed, and the data needs have been determined, a detailed sampling scheme is developed. The sampling scheme should systematically detail the samples to be collected, the time, location, and related sample collection logistics, and the methods to be used for sample collection. The sampling scheme should include information for both field samples and quality control samples. Quality control samples normally collected in a measurement study will include field blanks, spiked field controls, and replicate samples. If possible, performance evaluation (PE) samples

prepared by an independent laboratory or standard reference materials (SRM) can also be included. Due to the nature of some of the matrices, it may not be possible to prepare spiked control samples for all sample types. A quality assurance project plan (QAPP) is required that describes the quality assurance plan for a study and describes the quality control samples and procedures to assess the accuracy and precision of the sample collection and laboratory analysis. General information on the preparation of QAPPs can be found on a number of websites, including EPA's website http://www.epa.gov/quality/.

As described above, the draft protocol developed by EPA (US EPA, 2001a) for measuring children's exposures provides guidance for identifying the parameters to be measured in order to estimate exposures by all routes and pathways. For some routes of exposure, for example inhalation, it is relatively straightforward to make estimates if the air concentrations are measured in each microenvironment, the time spent in the microenvironment is known, and there is a reasonable estimate of the individual's inhalation rate while in the microenvironment. For other routes of exposure, for example, dermal, the estimates are more difficult to make and there are alternative approaches for making the estimates. The protocol presents a "macroactivity" approach and a "microactivity" approach, each of which has different data requirements. The microactivity approach, for example, requires measurements of the surface loading of the chemical, an estimate of the transfer efficiency, the surface area contacted, and the frequency of contact events. The protocol provides alternative methods for measuring these parameters. The following section discusses available methods and their application for exposure assessment.

2.3 SAMPLE COLLECTION METHODS

Environmental, personal, and biological samples should be selected that will account for exposure through the relevant routes and pathways based on study specific objectives/hypotheses/scientific questions. To address the requirements of the Food Quality Protection Act of 1996, for example, there is a need to conduct aggregate exposure estimates in support of cumulative risk assessments. As discussed above, aggregate exposures for pesticides may be estimated with simple algorithms or more sophisticated models that use measurements of pesticide concentrations in environmental media and diet samples. Alternatively, exposure may be estimated for some chemicals using biomonitoring data (also discussed in the chapter on biomonitoring in this Handbook). In both cases, ancillary information needs to be collected to interpret the data and to make exposure estimates.

Figure 2-1 depicts the potential routes of exposure (inhalation, ingestion, and dermal) and media that humans may contact. The following discussion addresses the measurements for these media, focusing primarily on the environmental media. This section describes the collection methods; the following section of the chapter describes analytical methods for identification and quantification of pesticides in the media.

There are many methods available for collection of samples of environmental media, as described in reviews by Bradman and Whyatt (2005) and Lewis (2005) and in numerous manuscripts that describe measurement studies (see the Tables and References for this chapter). It is important to note that there is little standardization of either the approaches for sample collection or the methods used to collect environment samples for exposure assessment. Methods are generally selected based on the researcher's familiarity with the method, available

instrumentation, and often, costs. The lack of standardization can be challenging, as it makes comparison of datasets from different studies difficult and, in many cases, may preclude conducting meta-analyses of datasets from different sources.

Criteria for Selection of Sample Collection Methods

Numerous factors must be considered when developing a sampling plan, including sampling locations, time of collection, frequency of collection, number of samples, sample collection order, containers, potential sample contamination, and proper handling and storage of the sample prior to preparation for analysis. In addition, safety concerns, technician labor, costs, and feasibility need to be considered. Method performance needs to be fully evaluated to identify the appropriate sample collection and analysis methods. The sampling plan and selection of the methods for sample collection should be based on well-defined criteria that are likely to include the following:

- Study objectives – As discussed above, the objectives determine what data are needed and what samples to collect.
- Study population size – The type of instrumentation and methods used in the study will vary depending on the size of the study population and the number of samples to be collected.
- Spatial variability – If concentrations of pesticide residues are expected to be highly variable across space (within a room, across rooms, for different surfaces in a room or building), it may be necessary to collect a large number of samples or to use methods that can integrate measurements across space.

- Temporal variability – If long-term average concentrations are required, methods will be needed that can integrate concentrations over extended time periods. If peak concentrations or short-term fluctuations need to be measured, methods with high temporal resolution and sensitivity will be needed.
- Sensitivity and detection limit – Particularly when attempting to estimate aggregate exposures and cumulative risks, method detection limits need to be sufficiently low so that the number of samples with non-detectable concentrations is minimized. This may require collection of large volumes (e.g., air samples), high mass amounts (e.g., dust), or large surface areas.
- Accuracy and precision – The required performance of the method needs to be defined in data quality objectives (DQOs) based on the data analyses to be performed to address the study objectives. Related to this factor is the need for a sufficient number of appropriate quality control samples that adequately document performance of the method.
- Instrument size and appropriateness for indoor monitoring – Methods used for personal monitoring (i.e., worn on the person) or for stationary sample collection in buildings can not be so large as to make it difficult to implement sample collection. Other factors, such as noise from pumps and sampler flow rates, must be considered for successful implementation in indoor environments. Security of instruments used indoors (with regard to children, pets, and curious adults) and outdoors (theft, tampering) are critical factors to consider in selection of methods.
- Sampler preparation and analysis requirements – Some methods require substantial preparation and labor costs. This may be related to pre-cleaning of sampling media and verification to ensure that background contamination is minimized. Some passive

sampling methods, although simple to deploy and retrieve, may require extensive preparations for use.

- Type of sample collection method – Both passive and active sampling methods are available, primarily for air sampling. Available methods are described by Lewis (2005).
- Costs – Costs are a function of many variables, including the cost of equipment, sampler preparation, the analytical method, the size of the study and number of samples, resources and labor needed to collect samples, etc. The reality is that, in most studies, cost is a major factor in the design of the study.
- Burden – In the design of the sampling plan and the selection of sample collection methods, the burden on the study participant and the field team needs to be carefully evaluated. Participant burden is quantified in terms of the demands that participation in a research study places on participants with respect to their privacy, time, and efforts involved in sample collection (Dattalo, 2008). Similar to participant burden, field technician burden is used to quantify the amount of work required by the field technician to complete the study and factors into the overall costs of the study. Participants in many measurement studies are compensated for their time and efforts. Burden on participants needs to be minimized to the fullest extent to maximize the likelihood of success for a study.

Methods for Estimating Inhalation Exposure

Methods for collection of air samples used for estimating inhalation exposures for pesticides are generally well-developed, validated, and reliable, particularly for the previous generation of semi-volatile pesticides (saturation vapor pressures between 10^{-2} kPa and 10^{-8} kPa at 25 °C). Air

samples are collected using either active pumping or passive diffusion systems in which the air sample is collected on a sorbent media. Air samples may be collected with stationary samplers indoors or outdoors, or as a personal sample (i.e., the participant wears or carries a personal air sampler) (US EPA, 2001a; Lewis, 2005). As highlighted in Table 2-1, a number of different sorbent materials can be used for sample collection. XAD has been used extensively for the current use indoor pesticides, such as the pyrethroids, which have lower vapor pressures. Sampling and analysis methods for selected pesticides have been published as a standard practice by ASTM (2008a) and have been reviewed by Lewis (2005) and others (Table 2-1).

Methods for Estimating Dermal Exposure

Dermal exposure monitoring techniques for assessing occupational exposure (e.g., for agricultural workers) are well-developed and used extensively (Fenske and Day, 2005; Lewis, 2005; and this Handbook). Similar approaches have been developed and applied for estimating dermal exposure in non-occupational environments. These include dermal patch samplers, garment samplers (covering either large portions of the body or the entire body), dermal wipes, and rinses and washes (US EPA, 2001a; Lewis, 2005; Ferguson et al., 2007; and Table 2-1). Patch samplers typically consist of several layers of surgical gauze and a cellulose paper backing, and represent 3-8% of the body surface area depending on the number of patches used (Ferguson et al., 2007). Researchers have used garments such as t-shirts, socks, and gloves when evaluating dermal exposure to regions of the body and whole body dosimeters have also been used. These garments can be made of many different materials, but the most usual are cotton, nylon, or blends (Ross et al., 1991; Lewis, 2005; Ferguson et al., 2007). Cohen Hubal et al.

(2006) reported use of whole body cotton garments to estimate young children's potential dermal exposure as they played in child care centers.

Dermal wipes, particularly hand wipes, have been used in a number of children's studies to estimate loading of pesticide residues on the skin (Fenske et al., 1986, 1998; Lewis et al., 1994; Aprea et al., 1998; Freeman et al., 2005; Morgan et al., 2005; Wilson et al., 2007). The wipes are typically wetted with aqueous surfactant solutions (e.g., 2-propanol) to remove the pesticide residues from the skin surface. Commercially-available wipes have also been used directly without additional treatment because they are the most "non-threatening" to very young children. The amount of residue collected by the surface wipe method will depend on the wipe used, the wetting solutions, the protocol for the method (e.g., number of wipes), and the technique of the technician doing the wiping. Therefore, it is very difficult to compare results across studies.

Many different hand rinse and wash methods have also been used to estimate dermal exposure (reviewed by Lewis, 2005). The different approaches for hand rinses include "bag washes," spray rinses with a laboratory wash bottle, open vessel rinses, prescribed washing routines, etc. Like the hand wipe methods, the recovery of residues with these methods is highly variable. Researchers use hand wipe, rinse, or wash data to estimate the amount of pesticide residue that a child may ingest when putting his/her hands into his/her mouth. These data may also be used to estimate the amount of pesticide residue on other parts of the body, but a number of assumptions are required for extrapolation from residues on the hand to other parts of the body.

Fluorescent tracers are a non-invasive and direct means to assess dermal exposure by quantifying deposition of fluorescent materials on the skin (Cohen Hubal et al., 2005; Lewis, 2005; Ferguson et al., 2007). Fluorescent tracers are usually used in a laboratory setting where

the activities of the participants can be controlled to understand how activities and surface interactions influence dermal exposure. In these laboratory studies, experiments can be designed to develop transfer coefficients (e.g., TCs) for a variety of microenvironmental/macroactivity combinations. A transfer coefficient provides a measure of dermal exposure resulting from contact with a contaminated microenvironmental surface while engaged in a specific macroactivity (US EPA, 2001a).

Indirect Methods for Estimating Dermal Exposure

Estimating dermal exposure is a challenge. The direct methods of measuring residues on skin described above are often not practical to perform in large measurement studies, particularly studies involving young children. Alternative methods that might be considered "indirect" methods are more easily implemented. Researchers have used different approaches for estimating dermal exposure in non-occupational environments, including macroactivity (US EPA, 2001a) and microactivity (Zartarian et al., 1995, 1997; US EPA, 2001a) approaches. These assessment approaches provide different ways of integrating exposure over time and space. In the macroactivity approach, exposure is estimated individually for each of the microenvironments where a child spends time and each macroactivity that the child conducts within that microenvironment. To do this, exposure is modeled using empirically-derived transfer coefficients to aggregate the mass transfer associated with a series of contacts with a contaminated medium. In the microactivity approach, exposure is explicitly modeled as a series of discrete transfers resulting from each contact with a contaminated medium. Both approaches require a measure of the loading of the pesticides on the surfaces being contacted. The same data

on surface loadings can be used to make estimates of indirect ingestion of pesticide residues, as described below.

There is no standard method or approach for the measurement of surface residues. This is likely the result of the lack of satisfaction with existing methods and the failure to determine suitable methods that significantly reduce the uncertainty of the measurement and the resulting estimates of exposure. Due to the lack of standardization, comparing results across studies is difficult. Methods reported in the literature for collecting surface residues from hard surfaces (e.g., vinyl, tile, or wood), carpeted surfaces, and other surfaces (e.g., toys and objects children mouth) include surface wipes, press samplers, the PUF roller, the California roller, a modified California roller, and drag sleds. These methods are highlighted in Table 2-1. When selecting the sample collection method, a number of factors need to be considered:

- If the surface residue measurements will be used to estimate dermal exposure by the macroactivity approach, the sample collection method should be the same as the method used to determine the empirically-derived transfer coefficient (US EPA, 2001a). That is, if a press sampler was used to derive the transfer coefficient, a press sampler should be used to measure the surface residues.
- Methods of collection need to be appropriate for the types of surfaces being monitored. Wipe methods generally are not adequate for fabric surfaces.
- The recovery of pesticide residues from surfaces differs for each method and may represent different measurement parameters. The terms "total" residues and "transferrable (or dislodgeable)" residues have been used to describe the measurements (US EPA, 2001a; Lewis, 2005). Surface wipes, for example may recover nearly 100% of the residues on a surface, not all of which may be available for transfer to the skin. On

the other hand, methods such as the PUF roller and the press sampler were designed specifically to represent a child's contact with a surface and the potential transfer to the skin.

- The method needs to collect a representative sample, accounting for spatial variability of residues and the microenvironments where contact is most likely to occur (e.g., areas of a room where children play).
- To reduce analytical costs, it may be possible, and necessary, to collect aggregate samples (e.g., with surface presses), or combine samples (e.g., surface wipes) prior to analysis to obtain "average" concentrations.

Detailed descriptions of methods and sampling devices for measuring surface residues can be found in Lewis (2005). The performance of surface residue sampling methods has been compared by a number of researchers, including, but not limited to Klonne et al. (2001), Lu and Fenske (1999), and Fortune et al. (1997) and reviewed by Lewis (2005).

Methods for Estimating Indirect Ingestion

Indirect ingestion (also referred to as non-dietary ingestion) occurs when an individual places into their mouth a hand or an object that has on its surface pesticide residues that are available for transfer to the mouth. Indirect ingestion can be estimated by determining the amount of the residue on the surface, the transfer efficiency of the residue from the object to the mouth, the area contacted, and the frequency of contacts (US EPA, 2001a). The wipe and rinse methods described above can be used to determine the residue on the surface. The area contacted and the number of contacts have been determined in some studies by observation or with the use of video. The transfer efficiency must be determine experimentally or estimated using default

"exposure factor" assumptions. Estimates of indirect ingestion may also be made using surface loadings of residues measured in dust on household surfaces and floors. Lioy et al. (2002) reviewed the importance of house dust in estimating exposures.

Household dust samples have been collected by a variety of vacuum methods. The sophistication of the vacuum sampling methods ranges from use of bags from a study participant's vacuum cleaner to collection of a dust sample from floors or furniture using the specially-designed HVS3 (High Volume Surface Sampler) or other vacuum cleaners modified specifically to collect samples under more controlled conditions (Lewis et al., 1994; Lewis, 2005; Roberts and Ott, 2007). The HVS3 is a special-purpose vacuum cleaner designed to collect house dust from surfaces in a standardized manner (ASTM, 2008c) for subsequent chemical analysis (Roberts and Ott, 2007). Lewis (2005) described a number of other hand-held vacuum samplers for which the collection efficiency has been evaluated and that have been used in field measurement studies. Results of dust measurements are reported as surface loading of compound "A" (ng of A/m^2) or dust concentration (ng of A/g of dust). The loading measurement is useful for estimating potential dermal exposure or indirect ingestion. The concentration measurement, although an indication of the magnitude of contamination, is not useful alone for estimating potential exposure. Table 2-1 highlights selected vacuum sample collection methods.

Direct Methods for Estimating Dietary Exposure - Duplicate Diet Samples

A duplicate diet sample is an exact copy of the foods and beverages that the participant eats and drinks during an observational period. The portions are identical to those consumed by the participant with respect to all aspects of preparation, type, and amount of food and drink. For

sample collection purposes, it is conventional for the solid and liquid foods to be collected and stored in separate containers and for non-edible food parts to be removed before being placed in the container (e.g., bones, wrappers, etc.) as described by Thomas et al. (1997), US EPA (2001a), and MacIntosh et al. (2001). Berry (1997) presented an overview of the EPA's dietary exposure program which is still currently the accepted approach for collecting duplicate diet information.

Water Collection Methods

A water sample is typically collected from each unique water source in the geographical location where the observational study is being conducted. If some homes are on individual wells and others are connected to a municipal water system, then a water sample should be collected from each home with well water and one sample would be collected to represent all homes on the municipal water system. A large volume (e.g., 1 L) of water is typically collected when analyzing for pesticide residues. Water collection usually involves running the water through the system to ensure that fresh water is collected in the sample container (e.g., not water that has been standing in the pipes), collecting the water sample, preserving, if necessary, and storing at low temperature until analysis (Troiano et al., 2001). Additional guidance for collection and analysis of pesticides in drinking water (Table 2-1) is provided in ASTM (2008b) and the EPA Method 500 Series (US EPA, 2009).

Soil Measurement Methods

For the purpose of estimating exposures to pesticides in soil by the dermal, indirect ingestion, or ingestion (pica) routes of exposure, soil surface scrapings are typically collected. Core soil samples are not representative of the soil that comes into contact with the skin because of the

depth at which core samples are collected. There are no standard protocols for collection of surface scrapings, although various collection protocols have been reported (Lewis et al., 1994; Simcox et al., 1995; Mukerjee et al., 1997; Bradman and Whyatt, 2005). Samples need to be collected from multiple locations to be representative of potential exposure to pesticides on outdoor soil and turf surfaces.

Collection of Biomonitoring Samples

Biomonitoring has been used extensively to determine if individuals have been exposed to chemicals, including pesticides (CDC, 2005). Biomarkers of exposure include measurements of pesticides, pesticide metabolites, or modified molecules or cells (e.g., protein and DNA adducts) in biological samples such as urine, blood, breathe, hair, or nail clippings (Barr et al., 2005; CDC, 2005). Criteria for selection of the biomarkers and matrix to be collected are discussed by Sobus et al. in the companion chapter in this Handbook. Barr et al. (2005) discuss the various types of biomarkers that may be collected at different lifestages. For the current-use pesticides, which are generally non-persistent and have short half-lives in the human body, pesticide metabolites are typically analyzed in urine. Methods for collection of adult urine samples are well-established and readily available. They are generally collected as spot samples or as a 24-hour daily composite sample (Kissel et al., 2005), the results of which are easier to interpret. Collection of urine samples from children is more challenging. In clinical settings, urine samples can be collected with an infant urine collection bag. However, the method would be difficult to implement in a large field study with measurements collected in participant's homes. For children who are toilet-trained, a bonnet can be inserted into the toilet for sample collection if the child is not comfortable with a direct void into a container. For younger children, cloth diapers

and diapers with cotton inserts have been used (Hu et al., 2000; summarized by Barr et al., 2005). Recently, there have been advances in development of methods to extract urine samples from the acrylate gel in disposable diapers (Hu et al., 2004).

Collection of Ancillary Information Such as Activity Data and Questionnaires

The type of ancillary information to be collected in a measurement study is a function of the objectives of the study and the data analyses to be performed. At a minimum, to estimate exposure, it is necessary to know the concentration of the substance in the media that is contacted, the duration of contact, and the frequency of contact. The information needed to estimate the exposure depends on the route of exposure and the models that are being used to make the estimates. Using simple algorithms, inhalation exposure can be estimated using the air concentration in all occupied microenvironments, the duration of time spent in each microenvironment, and the breathing rate of the individual. Estimates of other routes of exposure, e.g., indirect ingestion, are more difficult and require more ancillary information on activities.

Ancillary information may be collected for a various purposes. Typically, questionnaires are used to collect information on sources of exposure. This information may be used in the interpretation of the study results, assessment of routes and pathways of exposure, or development or assessment of mitigation strategies or methods. Data may be collected in surveys and questionnaires to serve as surrogate metrics for parameters that cannot be measured in a study due to the complexity or the cost. For example, dietary intake may be recorded in a diary or log because costs for duplicate diet samples are high. Questionnaires are also used to collect household demographic information as well as personal information such as occupation.

Although it is beyond the scope of this chapter to discuss the design and use of questionnaires and surveys, there are several good references on the topic such as the White Paper on Measurement and Analysis of Exposures to Environmental Pollutants and Biological Agents during the National Children's Study (NCS, 2004).

2.4 ANALYTICAL METHODS FOR PESTICIDE MEASUREMENTS

The analytical methods to be applied to the samples described above face several technical challenges because of the need to conduct (1) aggregate exposure assessments, addressing all routes and pathways of exposure and (2) cumulative risk assessments that involve multiple chemicals having the same mode of toxic action. These challenges include the development of robust methods for a large suite of pesticides at or near their limits of detection, the complexity of the media/matrices, cost limitations, wide concentration ranges, and the ever-changing suite of compounds being studied.

In developing methods for ultra-trace analysis of multiple pesticide residues, the primary consideration must always be data quality. The data quality objectives for the study determine the detection limits, precision, accuracy and resolution required from the measurement. This influences everything from the selection of laboratory equipment (e.g., pipettes and balances) to the post-analysis handling of data. For these reasons, it is vital that analytical capabilities and limitations be recognized and accounted for in the study design process. The challenge arises in meeting data quality objectives for each component measured in a multi-residue suite. Though different classes of pesticides can be separated and independently processed through sample preparation procedures, there is usually enough physiochemical variation within a class to reduce

the specificity of the procedure. In a clean matrix, such as solvent, this is not a concern; however, field samples may contain large quantities of other chemicals or interfering contaminants. These other chemicals may come from the environment being sampled or from the sampling media itself. The expense of collecting and analyzing samples justifies the analysis of large chemical suites, so the continuing development of improved techniques and technologies is vital. The discussion in this chapter focuses on general principles and considerations for the analyses of pesticides at trace or ultra-trace levels in the many different media collected in pesticide exposure studies. There is a wealth of information in the scientific literature describing development and application of analytical methods for pesticides. It is beyond the scope of this chapter to review and critique the many existing methods for the many different pesticide classes in environmental, food, and biological media. Existing methods are highlighted below and in Tables 2-2 and 2-3. Selected references are included to assist the reader in identifying sources of information that may be useful in evaluating and selecting methods for their specific applications.

General Principles

Sample analysis methods typically follow the following scheme:

The first step in the analysis process is the extraction of analytes from the medium collected (e.g., air, residue, dust, food, soil). This is accomplished through solvation or by bringing in contact with a sorbent that selectively attracts the analytes of interest. Traditional methods of

sample extraction, such as liquid/liquid and Soxhlet extraction, have proven to be very robust and simple to employ, though they tend to use relatively large volumes of organic solvent and throughput is usually limited by space and glassware requirements. Current trends in sample extraction show preference to methods such as pressurized fluid extraction (PFE), solid-phase micro-extraction (SPME) and supercritical fluid extraction (SFE) that use substantially less solvent and are capable of much higher throughput than traditional methods (Lambropoulou and Albanis, 2007).

Extract complexity is one of the most significant analytical challenges with field samples collected in observational measurement studies. In many cases, the extract from a sampling device or medium contains chemicals that change the way a target compound may perform on analytical instruments versus the way that same chemical would perform in a clean solvent. This is problematic because instruments are typically calibrated using standard solutions prepared in high purity solvent, so any change in behavior could likely lead to erroneous quantitative results (Poole, 2007). To reduce the complexity of the sample extracts, they are purified or "cleaned-up". Sample clean-up involves the removal of unwanted chemicals from the sample extract, thus reducing the complexity and improving the likelihood of consistent data quality. Some proven methods of clean-up include liquid partitioning, column chromatography and gel permeation chromatography (GPC). Like the traditional extraction methods, they are very effective, but are very materials and labor intensive. Improved sorbent technologies and the need for higher throughput have led to the wide acceptance of solid phase extraction (SPE) as a primary clean-up technique. Most SPE methods use tubes or disks that contain a hydrophobic or hydrophilic sorbent that the analytes bind to when an extract is passed through the sorbent bed. The analytes are then eluted from the sorbent with solvent. The selection of the sorbent and solvents used to

load, wash, and elute are very important and are dependent on the pesticides being analyzed and the medium from which they were extracted (Pico et al., 2007).

Since the concentration of pesticides in many samples is typically very low, it is generally necessary to reduce (i.e., concentrate) the volume of sample extracts. Useful methods for sample concentration include: rotary evaporation, Kuderna-Danish (K-D), nitrogen evaporation, centrifugal vacuum evaporation, and SPE. The evaporation system and conditions are an important consideration when performing pesticide analysis. Heat applied and the speed of the evaporation can have a tremendous effect on recovery of some pesticides. One very important concentration step is fine volume adjustment which is critical in achieving accurate volumes for clean-up or final volumes for analysis. Volumes used in SPE are very important for selectivity and the final volume of the extract must be accurate to quantify the pesticide constituents.

Sample extracts are quantitatively analyzed using techniques such as gas chromatography/mass spectrometry (GC/MS) or high performance liquid chromatography/mass spectrometry (LC/MS). The chromatographic system separates components in an extract and the detection system provides a measurement of each component. The high degree of selectivity along with the ability to confirm chemical identity make mass spectrometers the detection system of choice since concentrations that occur in non-occupational exposure samples are usually very low. The separation process is very important since many pesticides within a class can exhibit similar characteristics that would make them indistinguishable, even when using mass spectrometers.

GC/MS is the preferred means of analysis because of unmatched separation efficiency, high reliability and minimal maintenance, mass spectrometric simplicity from analytes since they are already in the gas phase, and higher degree of automation because the mobile phase (a

compressed gas) does not have to be prepared and can last for months from a single cylinder. GC/MS is a very powerful analytical technique, but also has some key limitations. In order to be analyzed by GC, a compound must be volatile, thermally stable, and relatively non-polar. For many years, these limitations were not a great concern in pesticide analysis, since most pesticides were amenable to analysis by GC methods. The current trend toward LC/MS analysis arose from the need to measure metabolites of non-persistent pesticides in biological media (Hernandez et al., 2005). Most pesticide metabolites are non-volatile and polar (Soler et al., 2008), so without derivatization, they cannot be analyzed by GC. Other factors that have led to the increasing popularity of LC/MS are improvements in interfaces, chromatographic columns, and mass analyzer technologies. These improvements have made LC/MS as robust as it is versatile, so applications that would have typically been performed by GC/MS are being consolidated into LC/MS methods. A practical application of this is the combination of parent and metabolite analysis from the same sample in a single analytical run (Jansson et al., 2004). The analysis of both in the environmental and biological sample can help to better correlate the two measurements.

Table 2-2 highlights selected analytical methods for measurements of pesticides in food and environmental media. Table 2-3 presents methods published for biological media.

Method Performance Requirements

As noted previously, the measurement methods, which include both the sample collection and the analytical methods, must meet well-defined data quality requirements in order to address study objectives. Data quality objectives need to be defined for accuracy, precision, and completeness. Additionally, limits of quantitation and detection limits need to be determined.

To meet data analysis objectives, the limitations of both the sample collection and sample analysis methods need to be identified. In many cases, the sample collection method may be the limiting factor in meeting data quality objectives, particularly with regard to detection limits (e.g., collection of adequate mass of floor dust for analysis).

Aside from the technical considerations regarding analyte detection, there has been a copious amount of discussion regarding the definition of detection limit and data reporting at or below the detection limit. The U.S. EPA method detection limit (MDL) procedure can be found in Title 40 Code of Federal Regulations (40 CFR 136, Appendix B, revision 1.11). Despite some criticism of this procedure, it remains a simple, well-documented way to determine method detection limits. Another significant issue for consideration is data censoring resulting from non-detects (Helsel, 1990). Although this does not affect the handling of data in the analytical laboratory, it significantly impacts analyses of data from aggregate and cumulative exposure studies employing multi-residue analyses in multiple media where there can be a potentially large number of samples with concentrations below the method detection limit. This issue indicates the continuing need for development of methods with lower detection limits.

Analytical methods are needed that have the capability to measure multiple pesticide residues in a single sample. Requirements for performing cumulative risk assessments and measuring exposures to multiple pesticides with the same toxicological endpoint, in addition to the high level of effort and the high costs associated with sample collection and analysis make this a necessity. The analytical performance for a suite of pesticides needs to be evaluated early in the design of a measurement program. Performance may vary for different pesticides in the suite, necessitating decisions on what measurements to perform, the selection of sample collection

methods, and determination of whether the data analysis objectives can be met for all pesticides proposed for the measurement study.

In addition to achieving acceptable detection limits, these analytical methods must be developed for a variety of media. Though some methods can be used for a variety of matrices, specialized methods are typically developed for each type of medium. This is done because of the wide variation in the physical qualities of media (solid/liquid/gas) as well as the materials that are co-extracted or co-soluble with targeted pesticides in each.

A key consideration in selection of sampling and analysis methods is the ability to obtain sampling media that are of consistent quality and have minimal background contamination and/or interferences with the analytical method. Inter-media variations in purchased media such as surface wipes and polyurethane foam (PUF) need be accounted for. Standardization is highly recommended due to batch to batch variation in sampling media as well as background contamination. Standardization includes cleaning and storage of media in the same way prior to field deployment. Media may be purchased that is pre-cleaned or batches may be prepared in the analytical lab. It is critical that samples from all batches of media be analyzed for the target analytes prior to use to confirm that there is no, or at least minimal, background contamination.

State of the Science

Current analytical trends reflect the need to measure non-persistent pesticides and their degradation products. This is evidenced by the increasing number of methods being developed for application to biological matrices and development of methods for analyses of both the parent compounds and metabolites/degradation products in biological and environmental samples. Table 2-3 highlights methods for biological media and provides selected literature references,

including review articles. Advances in biological monitoring methods have been significant in recent years due to improvements in LC/MS interfaces and the commercial availability of reference standards.

Advances in analytical technology have made it easier to deal with the ever-changing suite of analytes being studied. New extraction, sample preparation, and analytical systems are capable of automating tedious tasks and improving throughput. This can translate into more efficient methods development and can eliminate human bias in many processes. There are certain limitations to these new systems, primarily due to the size of the sampling media, which are usually large, and the content of co-extractable chemicals. This is an important consideration since the acquisition cost of many of these new instruments is significant.

In addition to better availability of analytical reference standards for pesticides, stable isotopes increasingly are becoming commercially available. Although they can be very expensive, isotopically labeled analogs of pesticides can be invaluable when used as internal standards or surrogate recovery standards. Because they are not naturally-occurring, the labeled standards can be used to normalize responses or quantify recoveries without the concern for interference. Because they behave in the same way as the unlabelled pesticide, anything that happens to the pesticide during the analytical method will also happen to the standard. This allows for the identification, and in many cases, correction of errors in sample preparation or instrumental analysis. The availability of these labeled analogs is another factor that has made mass spectrometry the primary detection method used. Two-dimensional detection systems cannot distinguish between a pesticide and its labeled analog if they co-elute, which is considered the ideal situation to compensate for instrument effects.

Much research into immunochemical methods has occurred in the last few years. Enzyme-linked immunosorbant assay (ELISA), in particular, has advanced to a point where many commercially available kits can be purchased for pesticide analysis. The advantages of ELISA are very low detection limits and high selectivity. The selectivity is a disadvantage when applied to multi-residue methods since a suite of chemicals cannot be measured in a single test. Other disadvantages are the limited analytical range and quantitative limitations due to matrix effects. Immunochemical methods and technologies are improving and may become more viable alternatives in the future (Van Emon, 2006).

Summary

Direct measurements of pesticides in environmental media and diet continue to be an important tool for estimating human exposure and for determining the factors that have the greatest impact on people's exposures. Unlike worker exposure, for which there are several reviews and guidance documents on methodology for exposure measurements, extensive guidance is lacking for approaches and methods for exposure assessments for pesticides in residential and other non-occupational environments. The need to estimate aggregate and cumulative exposures to pesticides challenges researchers to develop and validate systematic sample collection protocols, as well as new sampling and analysis methods. Some guidance on sampling protocols has been published, but in general, neither the sample collection protocols, nor the collection methods have been standardized. As a result comparison of results collected by different researchers is a challenge.

The sample collection methods highlighted in this chapter are not new to the field of exposure assessment (e.g., these methods have been reported in the literature dating back to the

early 1990's) and all have been described at great length in various review articles (including Bradman and Whyatt, 2005; Lewis, 2005). While many of the methods appear adequate, there is a need to advance and standardize sample collection methods. For example, surface wipes are routinely used for pesticide residue sample collection, but there are multiple methods in use and the collection protocols are not standardized. There have been few reports of systematic evaluation of the wipes, documenting method performance in terms of accuracy and precision. Similarly, methods and protocols for hand wipes and rinses are highly variable. There have been a number of reports documenting the performance of vacuum dust collection methods, but many of these were for previous generation pesticides (e.g., the organophosphates). The data for collection efficiency of these methods for current residential-use pesticides, such as the pyrethroids, is limited. In spite of the large number of measurement studies in which pesticides have been measured in various media during the past decade, it appears that advances in sample collection methods have been limited. Many of the methods still require substantial investment in equipment, materials, and labor to implement. Advances are needed for lower cost and lower burden methods that can be used in larger measurement studies, such as the National Children's Study.

Significant advances have been made in development and refinement of analytical methods. Multi-residue methods have been published by a number of researchers. These methods have been adapted for many matrices. Improved sensitivity of the methods has been reported. There have also been significant advances in the analysis of pesticide degradation products (metabolites) in biological media, environmental media, and diet samples. With the expansion of biomonitoring programs and the desire to use biomarkers to estimate exposures, it is increasingly

important that the metabolite concentrations also be quantified in environmental media and diet in order to interpret biomonitoring results.

Sampling and analysis of pesticides and their degradation products will continue to provide the critical information needed to protect public health and the environment. However, development of sampling and analysis methods for pesticides will continue to be a challenge with the nearly continuous introduction of new pesticide active ingredients and formulations.

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Table 2-1. Multimedia sample collection methods.

Matrix	Method	Key Features	References
Air	Pump with: polyurethane foam (PUF) plug	Collection period up to 24-hr, air volume up to 10 m^3, convenient to use, less resistance to air flow	Lewis, 2005
	Pump with: granular sorbents: XAD, Chromosorb 102, Tenax, Porapak-R, Florisil	Collection period up to 24-hr, air volume up to 10 m^3, useful for collection of volatile pesticides	Lewis, 2005
	Pump with: PUF/granular sorbent combination	Collection period up to 24-hr, air volume up to 10 m^3, extends range of compounds that can be collected.	Lewis, 2005
	Passive PUF sampler	PUF disk sampler deployed for integrated measurements over extended periods (weeks); have been used primarily for persistent pesticides.	Jaward et al., 2004
House Dust	HVS3 (High Volume Surface Sampler)	24-lb specialized vacuum cleaner used to collect a representative sample of house dust. Controlled airflow and pressure drop across the nozzle maintain uniform sampling conditions. High airflow volume ranges from 17-20 cfm. ASTM D5438.	US EPA, 2001a; Lewis, 2005; Roberts and Ott, 2007; ASTM 2008d
	Vacuums	A number of different commercial vacuum cleaners have been adapted for controlled sample collection. Many makes and models exist in use today.	Roberts and Ott, 2007; Lewis 2005
	Vacuum Bag	For convenience and low cost, researchers collect vacuum bags from study participants. Dust concentrations can be measured, but not loading. Limited information can be collected with this method.	Lewis, 2005
	LWW Sampler (Lioy-Weisel-Wainman Wipe Sampler)	Flat surface wipe sampler developed to measure dust on flat surfaces. Uses a template to map a specific area for the quantitative collection of dust and to control the movement of the collection plate. Sampler is constructed of Delrin with a sampling area of 109.2 cm^2.	Lioy et al., 1993, 2000
	EL Press Sampler (Edwards and Lioy Press Sampler)	Delrin block fitted with octadecyl (C18) extraction sheets for sample collection. Standardized 5-s press, contact pressure 0.026 lb/cm^2. Small surface area of	Edwards and Lioy, 1999

		sampler limits the amount of residue collected.	
Surface Residues	Surface Wipes	Used to measure residues from hard flooring and other hard residential surfaces. Many different types of wipes have been used with a variety of collection protocols. Cotton gauze wetted with isopropanol has been used in a number of studies.	US EPA, 2001a; Lewis, 2005; Tulve et al., 2006
	C18 Surface Press Sampler	Modified from the EL press sampler. Block shaped device using C18 impregnated Teflon extraction disks as sample collection media. Surface area sampled is 114 cm^2, contact pressure approximately 1200 Pa. Small surface area of sampler limits the amount of residue collected.	Bernard et al., 2008
	PUF Roller	Apparatus constructed of aluminum, with two permanent rear wheels and the detachable axle cylinder on the front where the PUF roller is attached. Total weight of 3.9 Kg for a sampling pressure of 8000 Pa. Sampling speed of 10 cm/s, used with dry sampling media, total surface area sampled is 800 cm^2. (ASTM D6333).	Camann et al., 1996; ASTM, 2008c; Lewis, 2005
	California Roller (regular); modified and mega samplers available also	Roller is weighted with 11.4 Kg for a total weight of 14.5 Kg and applied pressure of 2300 Pa. Sampling medium is a bed sheet laid on the surface. Twenty passes are made over the sampling area.	Ross et al., 1991; Fuller et al., 2001; Lewis, 2005; Williams et al., 2008
	Drag Sled	A block of wood or other material which is used to hold down a 10 cm X 10 cm piece of denim cloth as it is dragged across the surface. A 3.6 Kg weight rests on top of the block, providing a downward pressure of 4500 Pa. Sampling speed of 8 to 12 cm/s, along a 1.2 m path.	Vaccaro and Cranston, 1990; Lewis, 2005
Food	Duplicate Diet	Exact copy of food and liquids consumed. Solid and liquid food collected and stored in separate containers of sufficient size. Type of container dependent on contaminants of interest.	Berry, 1997; Thomas et al., 1997; Bradman and Whyatt, 2005
Drinking Water	Grab sample	Approximately a 1-L sample is collected from each unique drinking water source in a study area.	Troiano et al., 2001; Bradman and Whyatt, 2005; US EPA, 2009

Soil	Surface Scrapings	Typically, a sample collected from the top 1-cm depth in multiple locations.	Simcox et al., 1995
Dermal	Patch Samplers	Considered spot or grab samples. Consists of several layers of surgical gauze and an impermeable backing (e.g., paper, cellulose, aluminum foil, etc.). Attached at specific locations on the body.	Ferguson et al., 2007
	Garment Samplers	Range from whole body to specific regions of the body (e.g., t-shirts, gloves, socks, etc.). Materials may be cotton, nylon, leather, blends, etc.). Advantage over patch samplers is that contaminant loading over anatomical regions of the body can be conveniently collected.	Lewis, 2005; Cohen Hubal et al., 2006; Ferguson et al., 2007
	Wipes	Wetted wipes are moved across the body part of interest to collect contaminant from specific regions (e.g., hands, feet, knees, etc.). Little standardization of collection protocols.	Ferguson et al., 2007
	Rinses	One or both hands are rinsed with aqueous surfactant solutions by a variety of methods (open rinse, bag methods, wash bottles). Protocols are not standardized.	Ferguson et al., 2007 ; Lewis, 2005
	Washes	Participant washes hands according to a defined protocol and all liquid is collected and analyzed.	Ferguson et al., 2007
	Fluorescent Tracers	Directly and non-invasively assess dermal exposure by quantifying the deposition of fluorescent materials on the skin.	Lewis, 2005; Cohen Hubal et al., 2005; Ferguson et al., 2007

Table 2-2. Methods and method reviews for measuring pesticides in exposure studies[a].

Matrix	Analytes	Method Description	Analysis Method	Reference
Food	Organophosphates (OPs) DDT	PFE, ASE	GC/MS ELISA	Chuang et al., 2001
	OPs, pyrethroids, triazoles, triazines	QueChERS	GC/MS	Hercegova et al., 2006
	Multi-Class Pesticides, PCBs	LLE, Soxhlet, PFE, SFE, GPC (Review)	Not Specified	Beyer and Biziuk, 2008
	Multi-Class Pesticides	SPE (Review)	GC/MS, GC/ECD, LC/MS, CE	Pico et al., 2007
	Multi-Class Pesticides	Detailed LC/MS (Review)	LC/MS	Soler et al., 2008
	Multi-Class Pesticides	Soxhlet, QuEChERS, SFE, Ultrasonication, GPC, SPE (Review)	GC/MS, LC/MS	Lambropoulou and Albanis, 2007
Multi-Media (Review)	Multi-Class Pesticides	ELISA Specific – Ranges and MDLs (Review)	ELISA	Morozova et al., 2005
	Multi-Class Pesticide Residues	SPE, Column switching, On-line SPE (Review)	LC/MS/MS	Pico et al., 2004
	Multi-Class Pesticides	CE Specific (Review)	CE	Malik and Faubel, 2001
	Organophosphates, PCBs	Extraction, clean-up, QA considerations (Review)	GC/MS, GC/ECD, ELISA,	Muir and Sverko, 2006
	Multi-Class Pesticides	Sample description and collection considerations (Review)	Not Specified	Bradman and Whyatt, 2005
	Organophosphates, Pyrethroids	Sampling and Extraction, PFE	GC/ECD	Bernard et al., 2008
	Chlorpyrifos	Soxhlet, Shake-flask extraction	GC/ECD	Stout and Mason, 2003
Water	Carbamates and Carbamate Metabolites	SPE Extraction (Review)	LC/MS – Interfaces discussed	Soriano et al., 2001
Dust	Pyrethroids and	Extraction, clean-up,	GC/MS	Starr et al., 2008

	Pyrethroid Metabolites	derivitization		
Non-Specific	Multi-Class Pesticides	LC/MS and GC/MS Comparison by pesticide. (Review)	GC/MS,LC/MS LODs and LOQs for many pesticides	Alder et al., 2006

[a] Definitions for acronyms used in Tables 2-2 and 2-3

Term	Definition
ASE	Accelerated Solvent Extraction
CE	Capillary Electrophoresis
ELISA	Enzyme-Linked Immunosorbant Assay
GC/ECD	Gas Chromatography/ Electron Capture Detector
GC/FPD	Gas Chromatography/ Flame Photometric Detector
GC/MS	Gas Chromatography/ Mass Spectrometry
GC/MS/MS	Gas Chromatography/ Tandem Mass Spectrometry
GC/MS-NCI	Gas Chromatography/ Mass Spectrometry – Negative Chemical Ionization
GC/NPD	Gas Chromatography/ Nitrogen Phosphorous Detector
GPC	Gel Permeation Chromatography
HPLC/EC	High Performance Liquid Chromatography/ Electrochemical Detector
HPLC/UV	High Performance Liquid Chromatography/ Ultraviolet Detector
LC/MS	Liquid Chromatography/ Mass Spectrometry
LC/MS/MS	Liquid Chromatography/ Tandem Mass Spectrometry
LLE	Liquid- Liquid Extraction
MDLs	Method Detection Limits
PFE	Pressurized Fluid Extraction
SFE	Supercitial Fluid Extraction
SPE	Solid Phase Extraction

Table 2-3. Methods and method reviews for analysis in biological media.

Matrix	Analytes	Method Description	Analysis Method	Reference
Multiple Biological	Multi-Class Pesticides and Metabolites	Extraction, Clean-up and Analysis	GC/ECD, GC/MS, HPLC/UV, LC/MS	Aprea et al., 2002
	Multi-Class Pesticides and Metabolites	Emphasis on LC/MS	LC/MS	Hernandez et al., 2005
	Multi-Class Pesticides and Metabolites	Sample Extraction, Preparation and Analysis Considerations by Class	GC/MS,GC/FPD, GC/NPD, GC/ECD, LC/MS	Barr and Needham, 2002
	Multi-Class Pesticides and Metabolites	Discussion by Class	GC/MS, LC/MS, HPLC/UV, HPLC/EC	Barr, 2008
Urine	Organophosphates	SPE, Derivitization	GC/MS/MS	Hemakanthi De Alwis et al., 2006
	Multi-Class Metabolites	Preparation and Analysis, Labeled Analogues	GC/MS/MS	Shealy et al., 1996
	Cis- CDCA, *trans*-CDCA	Ultrasonic Extraction, SPE, Derivitization	GC/MS – NCI	Elflein et al., 2003
Adipose, Heart, Kidney, Liver	Organochlorine Pesticides and Other Halogenated Pollutants	PFE, GPC, SPE	GC/MS	Saito et al., 2004

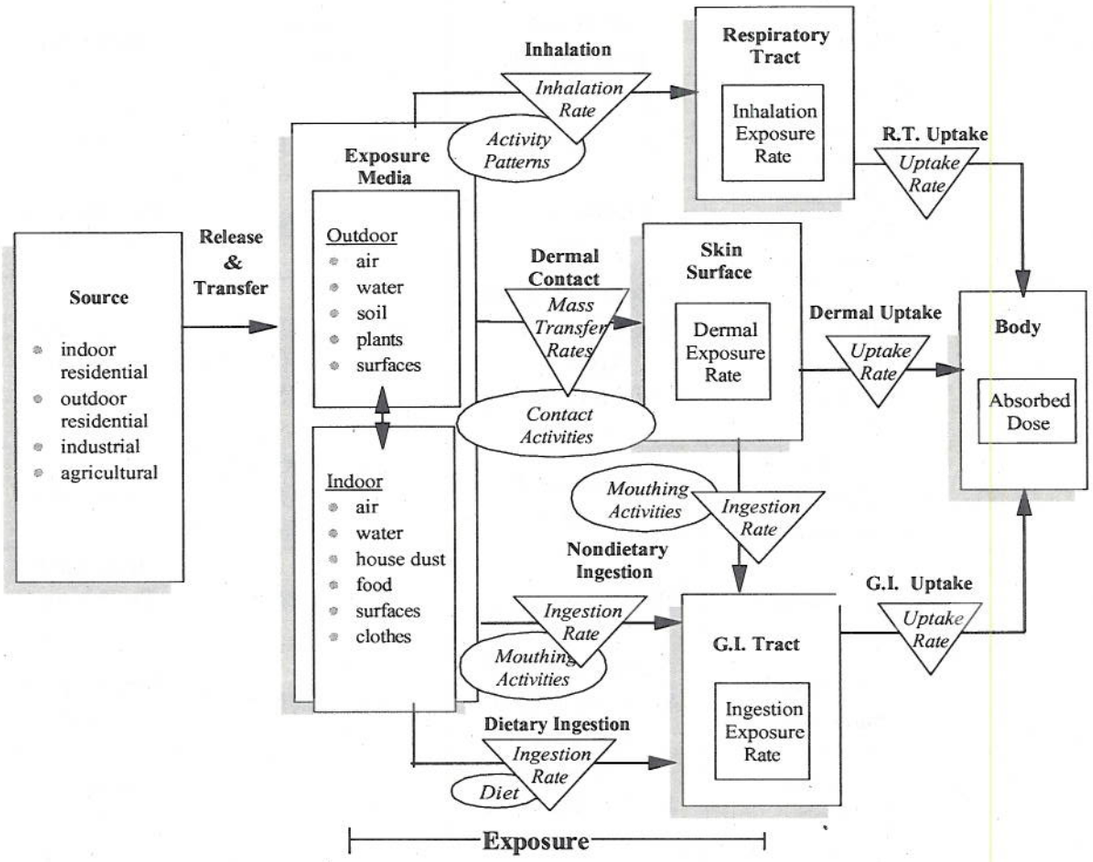

Figure 2-1 Conceptual framework for children's pesticide exposure.