Studying the Determinants of Exposure: A Review of Methods

AUTHORS
Igor Burstyn
Kay Teschke*

Occupational Hygiene Program, 3rd Floor, 2206 East Mall, University of British Columbia, Vancouver, B.C., Canada, V6T 1Z3

To better understand where, when, and how to control occupational exposures, it is vital that hygienists understand the factors that contribute to elevated or reduced exposure levels. Over the last two decades a burgeoning literature examining the determinants of exposure has developed, yet to date the methods used in this regard have rarely been summarized in texts or elsewhere. The purpose of this article is to provide an overview of the techniques used to study the predictors of workplace exposures. Both experimental and observational studies are examined, and the advantages and limitations of each are discussed. Fundamental study design features are reviewed. These include the selection and measurement of factors potentially related to exposure, as well as the measurement of exposure itself. Decisions reached by investigators in selecting the number of sites and workers, the number of repeated observations per worker, and the duration of sampling are discussed. Also examined are issues that commonly arise in the course of data analysis of exposure determinants. These include transformation of exposure variables, correlation of predictor variables, empirical model building, and interpretation of results. Finally, methods employed to evaluate the validity of findings are summarized.

Keywords: determinants of exposure, evaluation of control measures, occupational exposure, sampling strategy, statistical models, study design

APPLIED STUDIES

The identification of determinants of exposure is at the heart of a hygienist's practice, since it focuses on describing factors in the workplace that are associated with elevated or reduced exposure levels. Understanding these factors is essential to guide the rational design and location of control measures. For example, if a hygienist performing an exposure monitoring study records factors such as work tasks, equipment used, environmental conditions, existing controls, etc., subsequent data analysis should identify which are sources of exposure or effective controls. Studies lacking such documentation and analysis would indicate only the presence or absence of elevated exposures, and may promote anecdotal suggestions as to their causes.

While an extensive methodological literature has been devoted to exposure assessment for assessment of compliance and epidemiological studies, less attention so far has been paid to the wealth of experience being accumulated by hygienists studying determinants of exposure.

The objective of this article is to present an overview of current methodologies used to identify and quantify determinants of occupational exposure. For the purpose of this review, exposure determinants were defined as those factors that directly increase (e.g., processes producing airborne contaminants) or decrease (e.g., local exhaust) exposures, as well as factors more indirectly related to exposure (e.g., work location). Although the latter "determinants" may not be fundamental causes of reduced or elevated exposures, exploring reasons for their association with exposure levels may lead to the discovery of previously unidentified direct sources or controls.

This article describes the objectives of determinants of exposure studies, the diverse factors examined as potential exposure determinants, the sampling strategies used to measure both determinants and exposures, data analysis methods, and validation techniques. The authors do not attempt a review of the methods of every study, but seek to illustrate the breadth of approaches used.

* Author to whom correspondence should be addressed.

Copyright 1999, American Industrial Hygiene Association

METHODS

A number of methods were used to retrieve relevant literature for review. The following electronic databases were used: HISLINE CD-ROM 1987–1995 (Health and Safety Executive Library and Information Service, U.K.), CISDOC CD-ROM 1985–1995 (International Occupational Safety and Health Information Centre, International Labour Office, Geneva), NIOSHTIC CD-ROM 1987–1995 (National Institute for Occupational Safety and Health Technical Information Center, Cincinnati, Ohio) and Medline 1992–1996. Search words included determinants of exposure, design of control measures, and evaluation of control measures. The authors also searched every issue of the *Annals of Occupational Hygiene*, *American Industrial Hygiene Association Journal*, and *Applied Occupational and Environmental Hygiene* published from January 1993 to January 1997. Finally, Stewart and Dosemeci's [1] bibliography on exposure assessment for epidemiology, Boleij et al.'s [2] chapter on exposure modeling, as well as the other literature gathered, were examined for references related to determinants of exposure.

The selected articles were chosen to illustrate the breadth of methods that have been described in the literature. There were some specific exclusions. Many articles did not describe the methodology used to measure or ascertain potential determinants. Other articles, especially those conducted for epidemiological studies, examined job alone as an exposure determinant. Except where they illustrated issues not shown elsewhere, these articles were not included. Where the same study was described in several articles, the article with the best description of methods relevant to determinants of exposure was selected. It is probable that some relevant studies were missed, in part because there is no standardized vocabulary to describe this type of study for retrieval in literature searches. It is hoped that subsequent articles on this topic will expand this overview.

This review is divided into the following sections: overview of determinants of exposure studies, experimental studies, observational studies, and data analyses to ascertain determinants of exposure.

OVERVIEW OF DETERMINANTS OF EXPOSURE STUDIES

Study Designs

Determinants of exposure have been studied using both experimental and observational designs (Tables I and II).[3–46] In experimental designs, factors expected to influence exposure usually are selected using theoretical models or prior evidence from the hygiene literature,[5,7,9–14] though production personnel and work site surveys may also provide vital clues.[6] In many cases the main study question is not the identification of exposure determinants, but quantification of the magnitude of effect or development of controls for known high-exposure conditions. Study conditions are altered in a controlled way under the direction of the investigator, often in a laboratory setting. An example is the study of Garrison and Erig,[5] which aimed to optimize ventilation of a confined space. They designed three differently shaped spaces and tested the effect of high and low ventilation outlet positions and exhaust versus supplied air on contaminant clearance.

Quasi-experiments take place in real work settings.[3,4,6,8,9,10,14] The main effects under study are altered under investigator control, while other factors vary as usual in the occupational environment. This type of design is exemplified by Hornung et al.'s[8] study of formaldehyde exposures in embalming. Although solution concentration, air exchange rate, and cadaver condition were under experimental control, potential determinants such as spills, humidity, and temperature varied as in any workplace.

Observational studies are conducted in actual employment settings without investigator control.[15–46]. Although there may be some effect due to the presence of a study team, the intent is to examine the workplace under usual operating conditions. Walk-through surveys, process documentation, and discussions with plant personnel may provide the basis for selecting study factors, though theoretical models and existing literature also contribute. In any case, the potential determinants identified then must be observed and documented throughout the study. Investigator control of the variety of determinants studied exists only through the selection of varied work sites, times, workers, etc. The study of asphalt particulate by Hicks[25] is an example of an observational design. It included more than 30 sites in several different asphalt industries. Potential exposure determinants, including site characteristics, exposure controls, personal hygiene practices, weather conditions, and the asphalt temperature, were observed and recorded.

Study Objectives

While most studies of determinants of exposure are conducted with an explicit focus on identifying major sources of exposures or better means of control, many are performed as components of epidemiological research, to provide a basis for assigning exposure levels to employees for whom measurements are not available but determinants information exists (Tables I and II).

The purpose of the study may play a role in the choice of study design. Experimental designs have been used most frequently for studies developing new methods to control exposures.[3,5–7,9–14] However, the study by Hornung et al.,[8] described above, and that by Cherrie et al.[4] used experimental setups to develop an understanding of exposure determinants for epidemiological studies. In the latter, historical rock wool manufacturing processes were simulated to reconstruct exposures retrospectively.

Observational designs have been used widely in investigations aimed at either exposure control or epidemiological exposure assessment. Although many studies conducted for epidemiological purposes have collected new data in a way similar to studies for exposure control,[36,37,39–42,44,45] measurements of past exposures may be more valuable for retrospective epidemiology. A number of investigators have been able to retrieve data on historical exposures and determinants for modeling.[15,17,20,23,26,30] The study of crysotile textile workers by Dement et al.,[17] for example, used data collected between 1930 and 1975.

Studies conducted for exposure control may also differ from those for epidemiological purposes in the type of determinants studied. Jobs and departments may provide a sufficient predictive model of exposure for an epidemiological study using job histories to assign exposure,[17,20,39,44] but these "determinants" do not indicate how to control exposures. For example, in the study of exposures in animal feed production by Smid et al.,[39] job categories were effective at defining exposures, but the level of detail was insufficient to suggest control measures. Studies for exposure control, such as Scheeper et al.'s[38] investigation of inhalable wood dust, are likely to document factors that can more directly influence exposures, e.g., machine, task, raw materials, ventilation.

A number of investigations for epidemiological studies have provided detailed information on exposure determinants that could be used to direct controls.[23,26,30,34,36,41,42,45] For example, Hornung et al.[26] studied the impact of 17 different process, engineering, and administrative controls on ethylene oxide exposures in sterilization facilities as part of an exercise to model retrospective exposures. This is an especially useful combination of study purposes, since if adverse health effects are observed in the epidemiological study, the exposure assessment data can be used to identify where and how to control exposures.

EXPERIMENTAL STUDIES

Overview

Table I summarizes the exposures of interest, numbers of samples, potential determinants tested under experimental conditions, sampling design, data analysis methods, and proportions of variance explained in the studies that used experimental methods to examine factors influencing exposure[3–14]

The experimental methods used tended to be simple. Most investigators appear to have used a factorial design, though only a few were explicit about this.[6,8] Full factorial designs include all combinations of each level of every factor being tested in the experiment and are usually balanced; i.e., they include the same number of observations for each treatment. The greenhouse study of Methner and Fenske[10] illustrates a simple experiment testing three ventilation configurations, two pesticide application pressures, and six applicators, for a total of 36 possible combinations. In a more elaborate design, Plinke et al.[11] tested three or four levels of each of five factors thought to affect powder handling (types of raw material, aerodynamic diameters, moisture contents, dropping heights, and mass flow rates) resulting in over 300 different experimental combinations.

Potential Determinants Tested

Experimental studies tended to focus on likely direct sources of exposure such as equipment,[12–14] raw material characteristics,[5,11] process characteristics,[4,6,8,10,11] or tasks.[3,7,11] In addition, many specifically aimed to test the effectiveness of particular control measures, such as protective clothing, ventilation, dust filters, and germicidal lamps.[3–10,12]

The main determinants being tested in experimental studies are defined by the research design, and documentation of the study setup is the basis for recording these factors. However, there may be opportunities for factors outside the investigators' control to vary. Several investigators reported that their experimental trials were randomly ordered, an important means to minimize the likelihood that unrecorded confounders affect results.[6–9,14] In some studies, particularly quasi-experiments, factors that were not part of the study design were recorded so that they could be checked for systematic differences between experimental treatments and adjusted for in statistical analyses.[8,9] Measurement of these factors can proceed in the same way as in observational studies, described below.

Sampling Design

Among experimental studies using laboratory settings to test effects of potential exposure modifiers,[5,7,11–14] most conducted area monitoring since workers tended not to be included in the experiment. Measurements were usually gathered over very short durations (i.e., seconds, minutes), often using direct-reading instruments.

As in laboratory experiments, investigators conducting quasi-experiments in real workplaces[3,6,8–10,14] most often used measurement periods considerably shorter than a full workday. However, most used workers to perform or simulate work activities, and measurements included personal and/or biological monitoring. All, except the study by Archibald et al.[3] in five greenhouses, used only one work site for their test environments, perhaps as a means of limiting the number of experimental factors requiring control or workplace factors requiring documentation.

The study of wood dust exposure control in hand sanding operations by Topmiller et al.[14] used both laboratory and work site settings, and illustrates the usefulness of progression from laboratory-based experiments in the initial design of control measures, to field validation using quasi-experiments in a real workplace. In the laboratory a sander, with and without a local exhaust plenum attached, was moved by motors across a flat wood surface, while 20-second air samples were taken at nine adjacent locations using a light-scattering photometer. In the field study chair factory workers used sanders in normal work operations with and without the plenum. The setting was controlled by placing the operation within an enclosed room that isolated it from air movements and dust from the rest of the plant. Short-term air samples were taken using photometers. In addition, personal and area half-shift filter samples were taken to help understand the overall impact of the exhaust system on dust levels throughout a work period.

Almost all of the experimental studies reported fewer than 100 exposure measurements,[3,6–10,12,14] illustrating both the simplicity and potential efficiency of experimental methods in which the number of predictor variables studied are limited to a manageable number.

Advantages and Disadvantages

Experimental studies may be the method of choice to study the efficacy of proposed control methods where a task or a piece of equipment has been identified as a principal source of exposure. They may also be the only way to reconstruct past exposures that no longer exist in industry.[4] An advantage of experimental studies is the control a researcher has over the conditions under which exposure is measured. This allows the investigator to vary conditions that ordinarily may be constant in existing work sites, and isolate other characteristics that might influence exposure.

On the other hand, experimental designs may miss many of the diverse variables affecting exposure present in real work sites under usual operating conditions. For example, where a worker was not included in an exposure scenario, the influence of human characteristics could not be determined.[5,6,11–13] The small number of working environments studied may also lead to a lack of generalizability. Observational studies can complement experimental designs by providing opportunities to overcome some of the latter limitations.

OBSERVATIONAL STUDIES

Overview

Table II summarizes the exposures of interest, number of samples, types of determinants documented during exposure measurements, sampling strategies, data analysis methods, and proportions of variance explained in the studies that used observational methods to examine factors influencing exposure.[15–46]

TABLE I. Summary of Experimental Studies of Determinants of Exposure

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Tested	Reported Sampling Design	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
Archibald et al. 1995 (3) exposure control	pirimicarb, deltamethrin	27	6 protective clothing configurations versus normal operating clothing; high versus low volume pesticide applications	5 greenhouses, 1 pesticide applicator from each, 6 applications each, short-term area air samples, dermal patch and urine samples, video imaging	log-transformed exposure; paired t-test, ANOVA	not reported
Cherrie et al. 1987 (4) epidemiology	inspirable and total rock wool	not reported	rock wool production and tasks each with and without oil; work on two shapes of fiber batt; monitoring of outdoor and indoor environmental conditions, general ventilation, and fiberization process parameters	1 rock wool plant, 1 production experiment and 1 labor intensive work experiment; 2 to 5 workers, short-term and direct-reading personal and area air samples taken over 2 days	geometric means by test condition	not estimated
Garrison and Erig 1991 (5) exposure control	nitrogen, carbon dioxide, halocarbon-22, sulfur hexafluoride	not reported	3 different confined spaces shapes; contaminant specific gravity; low versus high ventilation outlet position; exhaust versus supplied air ventilation	laboratery-simulated confined space models, 4 area sampling locations in each, direct-reading instrument	simple linear regression	80 to 99
Hawkins; et al. 1992 (6) exposure control	volatile organic chemicals, styrene, toluene, phenylcyclohexene	20	3 off-gassing times; 3 latex coating weights on carpet; 2 makeup air rates; 2 latex types	carpet samples from manufacturing line put in environmental chamber from which air samples drawn at 1 and 24 hours post enclosure, factorial design blocked on latex type, than randomized	multiple regression	52 to 98
Heinonen et al. 1996 (7) exposure control	flour additive powder	30	1 general ventilation and 5 local ventilation configurations	laboratory setting, 1 worker, short-term and direct-reading personal air samples, 5 replicates per ventilation configuration in mixed order	log-transformed exposure; one-way ANOVA	not reported
Hornung et al. 1996(8) epidemiology	formaldehyde	25	3 levels of ventilation; 2 concentrations of embalming fluid; autopsy or intact body; monitoring of spills, humidity, temperature, duration of procedure, injection points, solution volume, embalming product use	mortuary college embalming room, factorial design, random ordering of conditions with some modifications based on condition of body, 2 replicates per condition, 1 embalmer, personal and area task-specific short-term and direct-reading samples	log-transformed exposure; ANCOVA	73 to 75
Macher et al. 199 (9) exposure control	airborne bacteria and fungi	61	germicidal lamps on and off; temperature, humidity, carbon dioxide concentration, number of open windows, number of occupants, activity level, room fan operation	hospital outpatient waiting room, short-term area air samples at 1 location, alternating order of lamp use, 30 replicates per lamp condition over 2-month period	log-transformed exposure; multiple regression (general linear model)	44 to 64
Methner and Fenske 1996 (10) exposure control	fluorescent whitening agent	36	3 ventilation types; 2 application pressures	1 greenhouse, 6 pesticide applicators, 6 applications each, short-term personal air samples, dermal patches,	ANOVA	not reported

TABLE I. Continued

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Tested	Reported Sampling Design	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
Plinke et al. 1995 (11) exposure control	titanium dioxide, limestone, glass beads, lactose dusts	588	4 powder types; 3 ranges of aerodynamic diameter; 3 moisture contents; 3 dropping air heights; 3 mass flow rates	laboratory simulation of conveyor powder drop, 1 to 2 samples per condition, area air samples drawn from enclosure receiving air from powder drop area	multiple regression	59 to 65
Thorpe and Brown 1994 (12) exposure control	total wood dust	86	7 sander types; 6 sandpaper types; 3 levels of dust extraction; 3 types of filter bag; 2 wood shapes	laboratory setting; short-term and direct-reading area air samples drawn from filter bag enclosure	none	not estimated
Thorpe and Brown 1995 (13) exposure control	total and inhalable wood dust	not reported	23 wood types; 5 sandpaper grades; 6 sander types; 2 pressures; 2 wood shapes	laboratory setting; short-term and direct-reading area air samples drawn from filter bag enclosure	polynomial regression	not reported
Topmiller et al. 1996 (14) exposure control	wood dust	72	sander local exhaust on and off; 3 directions around sander; 3 distances around sander	laboratory setting, 4 replicate measurements at each experimental location and condition in random order, direct-reading area samples	log-transformed exposure; ANOVA	not reported
Topmiller et al. 1996 (14) exposure control	wood dust	80	sander local exhaust on and off; 8 positions around sander	1 chair-sanding process, several workers, direct-reading area and half-shift personal and area measurements taken over 3 days	log-transformed exposure; ANOVA	not reported

TABLE II. Summary of Observational Studies of Determinants of Exposure

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Documented During Exposure Measurements	Reported Sampling Strategy	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
Amandus et al. 1987 (15) epidemiology	asbestos	4,452	location, operation	1 mining and milling operation, historical area and personal full-shift and short-term samples from the company and regulatory agencies over the period 1964–1982	arithmetic means by location/operation	not estimated
Burstyn et al. 1997 (16) exposure control	inhalable flour dust	96	bakery, equipment, task, duration of task, amount and type of flour, ambient environmental conditions, seniority, right- vs. left-handedness	7 bakeries, every baker measured once on random days, personal full-shift air samples taken over 6-month period	log-transformed exposure, ANOVA, multiple linear regression	31 to 79
Dement et al. 1983 (17) epidemiology	asbestos	5,952	operation, job category, automation, ventilation, wet versus dry operations, calendar year	1 asbestos product manufacturing plant, historical area and personal samples from the company, its insurance carrier, and regulatory agencies over the period 1930–1975	log-transformed exposure, multiple linear regression	not reported
Demer et al. 1996 (18) exposure control	carbon monoxide	13	task duration, location, type of general ventilation, % fresh air circulation, maintenance practices	6 buildings at university, direct-reading data-logging monitor attached to cleaning equipment in worker's breathing zone, random times within a 2-week period	arithmetic means by location/operation	not estimated
Earnest 1996 (19) exposure control	perchloroethylene	49	job, location, task, ventilation	1 dry cleaning shop, 3 employees, personal and area full-shift and direct-reading air samples	geometric means by job and location	not estimated
Eisen et al. 1984 (20) epidemiology	respirable dust	1,153	shed, job, season, time period	69 granite sheds, historical personal full-shift samples taken over the periods 1970–71 and 1976–77	log-transformed exposure, ANOVA (general linear model)	12 to 46
Elias et al. 1993 (21) exposure control	ethylene oxide	16	type of sterilizing equipment, equipment isolation, gas pressure release and local exhaust ventilation, task, location, work procedures, worker training	1 hospital sterilizing area, short-term stationary and task-specific area samples before and after implementing controls	none	not estimated
Greenspan et al. 1995 (22) exposure control	noise, dust, asphalt fumes	11 to 14	stage of construction, operations, tasks, ambient environmental conditions	1 construction site, volunteers among 25 workers, full-shift personal and short-term area measurements, monitored on one randomly chosen day within a week for 8 consecutive weeks	none	not estimated
Hallock et al. 1994 (23) epidemiology	machining fluids	394	plant, department, task, type of machining fluid, presence of engineering controls, reason for survey, time period	3 automobile parts plants, historical area and personal full-shift samples from the companies over the period 1958–1987	log-transformed exposure, ANOVA	20 to 41

TABLE II. Continued

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Documented During Exposure Measurements	Reported Sampling Strategy	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
Hansen and Whitehead 1988 (24) sampling strategy development	solvents	21	task, location, ventilation, volume of solvent used, number of plate changes	1 printing plant, all 7 press operators, each monitored for 3 consecutive days, direct-reading measurements of breathing zone concentration every 5 minutes throughout shift	Simple linear regression	57
Hicks 1995 (25) exposure control	respirable and total asphalt particulate	219 air, 131 dermal	asphalt industry category, job, hand washing, use of personal protective equipment, enclosure, local exhaust ventilation, weather conditions, temperature of asphalt	31 asphalt work sites representing 5 industry categories, 230 workers sampled once each, full-shift personal air samples and dermal wipes of hand or forehead	Kruskal-Wallis	not estimated
Hornung et al. 1994 (26) epidemiology	ethylene oxide	2,700	facility, department, job, type of product, product age, automation of loading, characteristics of ethylene oxide used, vessel volume, airwashers, local & general ventilation, isolation, gas recirculation, year	18 sterilization facilities, historical full-shift personal samples taken over the period 1976–1985	log-transformed exposure, multiple regression (general linear model)	85 to 90
Kalliokoski 1990 (27) epidemiology	toluene	39	plant, solvent consumption, enclosure, number of presses in operation, location, task	2 rotogravure plants, personal, and direct-reading area samples taken over 2 consecutive weeks	simple linear regression	3 to 72
Kromhout et al. 1994 (28) exposure control	particulate, curing fumes, solvents	137 to 669	production process, process pressure and temperature, task, duration of task, outdoor versus indoor work, ventilation, enclosure, personal protective equipment	10 rubber product manufacturing plants, randomly selected workers within process/job groups, 2 to 3 repeat measures per worker on randomly selected days, personal full-shift air and dermal exposure measurements taken over a 5-month period	log-transformed exposure, multiple regression (general linear model)	22 to 57
Kumagai et al. 1996 (29) exposure control	cobalt	935	job, task, machinery	1 hard metal tool manufacturing plant, 356 randomly selected workers in 9 job groups, 2 to 10 repeat measures each, full-shift personal samples taken on randomly selected days over a period of 5 years	arithmetic and geometric means by job, task, and machinery	not estimated
Lemasters et al. 1985 (30) epidemiology	styrene	1,512	process, plant construction, resin and styrene usage, department, job, ventilation pattern, number of employees, type and number of products produced, contact with wet resins	28 fiberglass reinforced-plastic plants, historical samples from the company and regulatory agencies over the period 1969–1981	log-transformed exposure, variance components (general linear model)	not reported
Materna 1985 (31) exposure control	perchloroethylene	20	process, equipment, ventilation, solvent transport method, gasket condition, machine isolation, personal protective equipment use, task	20 dry-cleaning shops, 1 operator per shop, cleaning-duration personal and short-term area air samples taken over a 4-month period	arithmetic means by process and local exhaust	not estimated

TABLE II. Continued

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Documented During Exposure Measurements	Reported Sampling Strategy	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
McDevitt 1990 (32) exposure control	cyclophosphamide	73 air, 76 wipe	location, work practices	2 areas in a hospital, 1- to 2-day stationary air samples and surface wipes taken over a 19-day period	none	not estimated
Nieuwenhuijsen et al. 1995 (33) exposure control	rat urinary aeroallergen	205	site, exposure group, task, duration of task	2 research sites, 1 sample per worker, full-shift personal air sampling	log-transformed exposure, gamma distribution, multiple regression (general linear model)	3 to 73
Nieuwenhuijsen et al. 1995 (34) epidemiology	flour dust, flour aeroallergen	209	exposure zone, task	3 bakeries, 1 flour mill, and 1 flour, packing station, task-specific short-term personal air samples, ~ 5 repeats per task	arithmetic and geometric means by task group	not estimated
Nieuwenhuijsen et al. 1996 (35) exposure control	dust, noise, pesticides (self-reported)	1,947	farm commodity, farm size, region, use of farm workers, other jobs held, duration of tasks, use of protective equipment, tractor enclosure	1,933 farms, usually 1 farmer each, questionnaire-reported duration of exposure	dichotomized exposure, logistic regression	not reported
Preller et al. 1995 (36) epidemiology	endotoxin	350	location, task, duration of task, outdoor temperature, feeding methods, flooring	198 pig farms, 1 farmer each measured twice, full-shift personal samples, in 1-month summer and winter periods	log-transformed exposure, multiple linear regression	33
Rocskay et al. 1993 (37) epidemiology	naptha	587	department, job, location, wet versus dry work, ambient temperature	1 fuel injector manufacturing plant, personal and area short-term and full-shift air samples collected over a 1-year period	multiple linear regression, ANOVA	19 to 42
Scheeper 1995 (38) exposure control	inhalable wood dust	363	factory, machine, task, duration of task, raw materials, local exhaust ventilation	3 wood manufacturing plants, most workers measured 1 to 5 times each, full-shift and direct-reading personal and area air samples collected on consecutive days over a 1- or 2-week period	log-transformed exposure, ANOVA, multiple linear regression	47
Smid et al. 1992 (39) epidemiology	dust, endotoxin, fungi	609	facility, type and age of facility, products, number of employees, job category, automation, dust control	8 animal feed production and storage facilities, all 131 workers sampled on 1 or more days, personal and area full-shift exposure measurements taken over 1 to 24 days	log-transformed exposure, ANOVA	not reported
Smith et al. 1984 (40) epidemiology	respirable dust, quartz, inorganic matter, extractable organic matter, nicotine	182	location, job, shift, day of week	1 silicon carbide production plant, 75 workers measured 1 to 4 times each, full-shift personal and direct-reading area air samples, stratified by job category and work area	log-transformed exposure, geometric means by location and job, ANOVA	not reported

TABLE II. Continued

Author, Reference No., and Purpose	Exposure	N	Potential Determinants Documented During Exposure Measurements	Reported Sampling Strategy	Data Analysis for Determinants of Exposure	Proportion of Variance Explained (%)
Teschke et al. 1994 (41) epidemiology	respirable and total wood dust	237	mill, department, job, wood-cutting machines, distance from sources of exposure, enclosure, local exhaust ventilation, weather conditions, season, personal protective equipment, indoor versus outdoor work	2 lumber mills, randomly selected workers within each job, 2 samples per job, full-shift personal air samples taken over two seasons	log-transformed exposure, ANCOVA (general linear model)	not reported
Teschke et al. 1995 (42) epidemiology	cobalt, chromium	278	mill, job, month, day of week, task, task duration, equipment, distance from sources of exposure, local exhaust ventilation, metal composition, coolant use	8 lumber mills, all 112 workers measured 1 to 4 times, full-shift personal air samples taken over a 6-month period	ANOVA, multiple linear regression	12 to 24
Williams et al. 1984 (43) exposure control	formaldehyde	23	work practices, ventilation, type of body, constituents of embalming products, embalming technique	7 funeral homes, 12 workers sampled 1 to 4 times each, short-term personal and area air samples	arithmetic average by body	not estimated
Woskie et al. 1988 (44) epidemiology	diesel exhaust respirable particulate	534	railroad, job, ambient temperature	4 railroad companies, personal and area full-shift air samples taken in two seasons	log-transformed exposure, ANOVA	10 to 83
Woskie et al. 1994 (45) epidemiology	machining fluid aerosols	309	facility, type of machining fluid, machine enclosure, machine type, machine age, distance from machines, local exhaust ventilation, humidity, temperature	3 automotive component manufacturing plants, 309 workers sampled once each, personal full-shift air samples	log-transformed exposure, ANCOVA	34 to 57
Zock et al.1995 (46) exposure control	inhalable and respirable dust, endotoxin, microorganisms	38 to 211	plant, job category, ambient temperature and humidity	4 potato processing plants, each worker monitored on 2 consecutive days, full-shift area and personal measurements taken in one fall season	log-transformed exposure, ANOVA	72

The design of observational studies usually presents more difficulties to the investigator, because of the multiplicity of factors in the workplace that may affect exposure. Since these factors are not under experimental control, nor likely to occur randomly with respect to each other, the ideal study design would document all potential determinants of interest so that associations with exposure are not mistakenly attributed. The problem then becomes identifying a priori the majority of likely exposure modifiers so they can be documented, then mounting a study of sufficient size to permit data analysis accounting for all documented factors related to exposure. Where possible, random selection of sites, days, and workers is an important strategy to increase the representativeness of the sample and to reduce the potential for systematic biases in the resulting data, but observational designs cannot achieve either the randomization of exposure determinants or the factorial structure possible in experimental studies. In most cases the organization of the work site means that certain determinants are nested within others, rather than varying across all levels. A related problem is that observational designs are less likely to be balanced.

The resulting designs can still be simple if the study aims to identify the determinants of exposure in one facility where the number of processes, types of equipment, and tasks are limited. For example, Hansen and Whitehead[24] studied solvent exposures in a single print shop. They monitored all seven press operators on 3 consecutive days and looked for the relationship between personal solvent exposures and ventilation, location, and the number of printing plate changes made in a day. However, such studies cannot account for the effects of factors that do not vary within a single job or plant. The larger study of Kromhout et al.,[28] conducted in 10 rubber-manufacturing plants, was able to examine the impact of differing production process characteristics, as well as tasks, work location, ventilation, enclosure, and protective equipment.

Potential Determinants Documented

Observational studies must document in detail those worker and work site characteristics with a potential to influence exposure during the measurement period. Table II indicates the breadth of variables that have been documented in such studies: plant; age of facility; work site construction materials; process; automation; number of processes in operation; process conditions; raw materials; machinery; location; seniority of employees; number of employees; jobs; tasks; work practices; skin contact; training; indoor versus outdoor work; ambient environmental conditions; day of week; season; calendar year; ventilation; enclosure; and personal protective equipment.

Some of these characteristics, e.g., long-term features of the work site, are stable and can be documented at any time during walk-throughs or by interviews with company personnel. This kind of information may be all that is available in historical studies, yet still may include very useful details on job, location, season, calendar year, raw materials, product type, process conditions, engineering and administrative controls, etc.[17,20,23,26,30] Other characteristics, such as process and ambient temperatures, require physical measurements during each exposure monitoring period.

Characteristics associated with the workers' daily operations, such as tasks, locations, and equipment used, may change frequently within work shifts and thus present their own special measurement challenges. To collect information on these variables, several approaches have been used, each associated with a different type of exposure monitoring.

Documenting Determinants during Full-Shift Personal Sampling

When full-shift personal exposure is measured, the most obvious method to describe frequently changing conditions of work is to observe workers during exposure measurement. Information can be recorded on tasks performed, machinery operated, raw materials used, and existing exposure control measures.[16,25,27,42,43] For example, in the flour dust study of Burstyn et al.,[16] all monitored bakers were observed for the entire duration of exposure measurement, and information on tasks, machinery used, raw materials, personal protective equipment, and engineering controls was recorded in 15-minute intervals.

The above approach is very labor-intensive; consequently task profile diaries,[18,33,36] worker interviews,[27,28] or questionnaires at the end of sampling[38,46] have been used as alternatives. Demer et al.[18] studied carbon monoxide exposures of custodians operating propane-powered floor burnishers. The investigators attached log sheets to the burnishers and instructed the custodians to complete questions about schedule of use and locations where burnishers were operated. In a study of the rubber-manufacturing industry, Kromhout et al.[28] interviewed subjects about tasks performed, time spent on each task, the use of personal protective equipment, ventilation, and process characteristics. While investigating the causes of wood dust exposure in woodworking processes, Scheeper et al.[38] assessed potential determinants of exposure by having monitored workers fill out a questionnaire designed to ascertain the type of machine operated, type of wood used, use of local exhaust ventilation, use of personal protective equipment, general ventilation, cleaning methods, and use of compressed air.

Studies using questionnaires or interviews to collect information on task duration may need to validate the methods of collecting these surrogate measures. Kalliokoski[27] found no significant differences in time estimates between direct observations and postsampling interviews for 32 of the 34 tasks examined. However, in similar comparisons, others have found that workers tend to overestimate tool operation times[47] and duration of chemical exposure,[48] often assigning half- or full-shift durations to dominant tasks, even when their actual duration was considerably shorter.

Source-Oriented Sampling

Another approach to identifying factors contributing to exposure is to measure contaminant concentrations close to and far away from machinery, tasks, or processes considered to be potential sources, using stationary samplers.[32,38,43] Area sampling, however, usually underestimates personal exposures and ignores worker-machine interactions.[38] Thus, McDevitt et al.[32] were unable to identify specific tasks associated with exposure to antineoplastic agents among nurses, because they took source-oriented samples but did not collect information on worker behavior.

A combination of area monitoring and estimates of task duration at various locations may overcome this problem.[19,27,38,43] Kalliokoski[27] collected stationary exposure measurements at task locations where workers spent most of their work time. The investigator found a linear correlation between measured personal full-shift toluene exposure and toluene exposure predicted on the basis of area samples and self-reported time spent in each area. Thus, using area sampling to identify locations at which high exposures occur can be an important clue to understanding the determinants of full-shift exposures.

Task-Specific Sampling

If exposure is suspected to occur in a series of peaks associated with certain activities, a task-specific sampling strategy can be applied,[22,24,34,49] provided that the duration of the task is sufficiently long to collect a detectable contaminant mass.[36,42]

Hansen and Whitehead[24] estimated the proportion of time spent by printing plant workers on different tasks by observing them over short, sequential time intervals. To ensure a representative sample of worker activities, they first observed production cycles and found that the duration of tasks in the plant varied from 6 to 60 minutes. Therefore, to capture all tasks performed by an individual, instantaneous solvent exposure was measured in the breathing zone every 5 minutes, giving a surrogate of the real-time exposure profile for every worker in the plant, task-specific exposure levels, and an estimate of the workers'' time-weighted average exposure.

Thus, either short-term or long-term sampling can be used in studies of tasks determining exposure, depending on measurement techniques and the nature of exposure. It is worth noting that short-duration tasks, even if highly exposed, might not be associated with a full-shift average exposure. Where a relationship exists, it may not be detected in statistical modeling unless the task's duration is estimated and included in the model.[28]

Videotaping Worker Activities Combined with Real-Time Exposure Measurements

Establishing a relationship between exposure and tasks of very short duration poses a considerable challenge. Since 1985, advances in technology have allowed researchers to combine real-time exposure measurements for some agents with videotaping of workers.[50,51] Such techniques can be useful for studying tasks or emissions of very short duration, yielding new insights into determinants of exposure. They also allow investigators to analyze an individual's interaction with machines and equipment and observe the influence of individual differences in working practices.

There are a number limitations to such an approach. The most important is that it assumes that the influence on exposure of tasks being videotaped will be instantaneous and therefore easily identifiable. Bennett et al.[52] used deterministic modeling of formaldehyde generation rates in combination with real-time measurements to isolate tasks with the greatest impact on embalming exposures. They illustrated that prior emissions or inefficient control processes may obscure relationships between specific tasks and continuously measured concentrations. A related problem is that measurements taken over short intervals within a sampling day are likely to be autocorrelated, requiring special procedures in data analysis.[50,51] In addition, direct-reading instruments suitable for real-time exposure measurement may not be chemical-specific, problematic where multiple exposures exist.

Finally, since these techniques are newly emerging and are equipment- and labor-intensive, studies using them may include only small samples of time and workers, likely underestimating the variance of exposures and the number of potential determinants. The videotaping technique may work best as a follow-up to a more traditional observational study of exposure determinants, as a means of understanding within-shift sources of exposure among specific workers, jobs, or locations previously identified as exposed.

Sampling Strategy

The strategies used to collect data in observational studies were not always reported in detail, but it is clear that distinctly different choices were made about the number of sites, the period of sampling, and the number of workers and repeated measurements per individual.

Sites Studied

Many studies investigated determinants in a single plant or facility.[15,17,19,21,22,24,29,37,40] For example, Amandus et al.[15] studied morbidity and mortality in vermiculite miners and millers from one company, and Elias et al.[21] studied the impact of design changes on ethylene oxide exposures in one hospital sterilizing area. While these data may serve as models for potential exposures and their determinants in similar workplaces, studies of multiple sites have the advantage that their results are more likely to be generalizable.[16,18,20,25,26,28,30,31,35,36,39,42,43] For example, Preller et al.[36] examined endotoxin exposure in almost 200 pig farms, and Eisen et al.[20] investigated respirable dust exposures in 69 granite sheds. Assuming the sites were selected in an unbiased manner, the potential determinants observed in such studies should be representative of those found in the industry. Hicks's study[25] of 31 asphalt industry sites stratified site selection to ensure representation from five sectors of the industry.

Time Period Studied

Most investigators measured exposures and determinants on consecutive or randomly selected days over periods of weeks or months within a single year.[16,18,22,27,28,31,32,36–39,41,42,44,46] A few, where outdoor ambient conditions were suspected to influence exposure levels, stratified measurements by season.[36,41,44] Some studies included historical measurements collected over periods ranging from 2 to 29 years.[15,17,20,23,26,30] Since the purpose of these studies was to estimate historical exposures of workers for epidemiological analyses, understanding exposure determinants over a long period was particularly relevant. Unique to studies for exposure control, Kumagai et al.[29] collected cobalt samples in the Japanese hard metal industry prospectively over a 5-year period.

In studies examining autocorrelation of exposure measurements, relatively little correlation has been found between measurements taken on consecutive days;[53–55] however, estimates of exposure variability have been shown to increase with the interval between measurements.[54,56] Measurements taken over periods longer than a year appear to exhibit systematic changes (lack of stationarity).[57] Therefore, except for exposure studies used in assessing chronic disease risks, an approach using several sampling campaigns covering conditions representative of an industry within a year would appear to be a reasonable one. Selecting measurement periods at random should maximize the likelihood that the data are representative, ensure that they meet the assumptions of data analysis methods, and facilitate interpretation of results.[54,58]

Workers Studied

Almost all the observational studies used personal exposure monitoring.[15–17,19,20,22,23,25–29,31,33,34,36–46] Among those reporting the method of selecting study subjects, some included all willing participants on site,[16,22,24,38,39,42] and others took random samples of the work force within job categories.[28,29,41]

Although a few investigators reported sampling each study subject once,[16,22,25,31,33,45] most monitored each participant on several occasions, usually with 2 to 5 repeat measurements per worker,[24,28,36,38–40,42,43,45] though Kumagai et al.[29] had up to 10 replicates per subject.

Repeated measurements of workers allows researchers to distinguish the within- and between-worker components of variance[29,36,38,40,46] and allows modeling of the separate determinants of each.[58] Several recent studies have provided limited data suggesting that certain types of exposure determinants are more likely to affect variability within-day (e.g., short-term changes in tasks or processes), day-to-day (e.g., daily changes in tasks, processes, production, ventilation, and ambient conditions), and person-to-person (e.g., work station and equipment assignment, work practices).[29,58,59] An understanding of such variance components (within workers, between workers, and between groups) has also been shown to be valuable for optimizing exposure groups in epidemiological research.[60]

Given limited resources, a researcher must decide how best to ensure that the most important exposure determinants are included in a study by considering the balance of multiple work sites, number of workers, and number of replicates per worker. As few as two replicates per subject for a random subset of subjects may be sufficient for distinguishing within-worker exposure variability.[28,58] Some investigators have chosen sampling strategies with a single measurement per individual in favor of maximizing the number of workers and sites sampled and thus the number of hypothesized determinants captured in their studies.[16,33,45] Existing measurement data and observations of the work process before monitoring may suggest to investigators how potential determinants vary, and aid decision making in this element of sampling strategy.

Most observational studies included more than 100 samples of each agent,[23,25,28,29,33–42,44–46] including five historical studies each of which retrieved more than 1000 measurements.[15,17,20,26,30] Several studies had fewer than 50 measurements; these usually did not use empirical modeling or inferential analyses to interpret results.[18,19,21,22,31,43]

Advantages and Disadvantages

Although observational studies can vary greatly in the sophistication of their aims and resulting designs, they offer the potential for industrial hygienists to identify a multitude of exposure determinants that arise in the complex circumstances of occupational environments. However, as a direct consequence, the investigator must deal with much greater complexities in determinant documentation, decision making about sampling strategies, and subsequent data analyses.

DATA ANALYSES TO ASCERTAIN DETERMINANTS OF EXPOSURE

Analysis of data gathered in experimental and observational studies of determinants of exposure does not differ fundamentally from the drawing of inferences from any other data set. To illustrate common issues faced in modeling exposure determinants, the authors address certain features of the analyses performed in the studies reviewed: transformation of the exposure variable, correlation of predictor variables, empirical model building, interpretation of results, and validation of results.

Transformation of the Exposure Variable

In almost all of the studies included in this review, the exposure variable was log-transformed (Tables I and II). Several reasons were given, including evidence from statistical tests that the exposure distribution was log-normal,[16,25,33,38,45] skewness of the untransformed data,[9,26,42] and stabilization of the variance.[30] Hornung et al.[26] noted that the assumption of normality of the dependent variable is not critical in model building, but preferred to transform the exposure data to provide assurance that no negative exposure estimates would be produced since the ensuing model is multiplicative. Although this is an advantage of log transformation, the multiplicative nature of the model also means that interpretation of the coefficients derived for each factor is not as straightforward as with an additive model (i.e., with exposure untransformed).

Several investigators used their exposure data in other forms. Methner and Fenske's data[10] describing air and dermal exposure to a fluorescent marker approximated a normal distribution, so was left untransformed. Lemasters et al.[30,61] dealt with residual skewness in styrene data after an initial log-transformation by adding 1 to the exposure measurements prior to log-transformation. This method can also be used to handle zero values (which cannot be log-transformed), but interpretation is somewhat complicated because the resulting models are no longer simply multiplicative. Nieuwenhuijsen et al.[33] used a gamma distribution to model determinants of exposure to rat urinary aeroallergen. Hicks[25] and Nieuwenhuijsen et al.[33] found that some of their data were not normally distributed with or without transformation, so used nonparametric statistics.

Exposures Below Detection Limits

The exposure variable may also be fully or partially transformed to handle observations where there is no exposure or where exposures are less than the detection limit. Some investigators have dichotomized the exposure variable and used logistic regression as the analysis method. In a study using farmers' self-reported duration of exposure to dust, noise, and pesticides, Nieuwenhuijsen et al.[35] used this method to manage large numbers of subjects reporting no exposure. Teschke et al.[42] used this treatment as one method to deal with a large proportion of cobalt and chromium measurements below detection limits. Other authors reported more traditional methods for handling data below detection limits, including division of the detection limit by 2 or the square root of 2,[8,16,41] and random selection of a value between 0 and the detection limit from the underlying data distribution.[46] Some investigators have recommended that analytical laboratories provide whatever quantitative data is available for observations below the detection limit for use in modeling, since it is likely to be of better quality than fill-in values for left-censored data.[42]

Correlation of Predictor Variables

Independence between predictor variables is an important issue in modeling exposure, since there are many opportunities for potential determinants to be related. Examples include relationships between times devoted by a worker to different tasks, between location and job, and between season and ambient environmental conditions. The assumptions of regression analysis require that predictor variables be independent, and a regression model can be difficult to interpret in the presence of multicollinearity. A number of authors reported checking for correlation between variables prior to modeling.[16,26,36]

To prevent problems from modeling with correlated variables, several approaches have been used. Burstyn et al.[16] chose to offer in the model single variables among those correlated, selecting variables whose effects were most likely to be easily interpreted. Nieuwenhuijsen et al.[33] developed three separate models after dividing tasks into distinct groups. Lemasters et al.[30,61] used a hierarchical structure for analysis of independent variables that were correlated because they were nested. Teschke et al.[42] restricted analysis to tasks that directly increased exposure, since tasks that passively reduced exposures (e.g., attending meetings) were considered less important to model, but were strong negative correlates of exposed tasks. Hornung et al.[26] chose to create a new variable from the combination of job and location, which were highly correlated.

This last strategy can also be performed objectively using principal component analysis in which correlated variables are combined to create "factors" that are independent of all other factors and represent components shared by several of the original predictor variables. There can be problems if the factors created are difficult to interpret, e.g., if variables with no known theoretical relationship are combined. This method was not reported in any of the studies reviewed.

Empirical Model Building

Some investigators tested the association with exposure of only a single independent variable using simple regression for continuous predictor variables[5,13,24,27] or one-way analysis of variance (one-way ANOVA), Kruskal-Wallis, or t-tests for categorical variables.[3,7,25] Such analyses indicate whether a variable is associated with exposure, but usually do not provide useful predictions because they oversimplify the description of the work environment. Since more than one potential predictor of exposure was experimentally altered or observed to vary in virtually all the studies, most investigators developed models using techniques that accommodate more than one predictor variable: ANOVA, analysis of covariance (ANCOVA), multiple linear regression, or logistic regression.[6,8,9,11,16,17,20,23,26,28,30,33,35,39,41,42,44–46]

Because of the control inherent in experiments, these designs were likely to be balanced, allowing analysis using classical statistical methods.[6,8,10,14] In quasi-experiments, work ite characteristics other than the main effects being tested may vary during the study period and require inclusion in the analysis. Hornung et al.[8] included uncontrolled covariates in their model of embalming exposures using ANCOVA. Unbalanced data, with different numbers of exposure measurements for each combination of independent variables, was much more common in observational studies. Several investigators performed ANOVA, ANCOVA, or regression using more general algebraic formulae (general linear modeling) that handle data in this form.[9,20,26,28,30,33,41]

Many of the observational studies included repeated exposure measurements on individual workers, requiring analytical methods that account for potential within-subject correlation beyond that explained by the independent variables. Several methods can be used in this situation. Kumagai et al.,[29] Scheeper et al.,[38] and Zock et al.[46] used an ANOVA model with random effects nested within a worker. Teschke et al.[42] used generalized estimating equations with robust variance estimates. Preller et al.[36] tested the correlation between the repeated measures, found it to be low, then treated each measurement as independent. It is interesting to note that none of the studies using historical measurements reported the number of replicates per subject, possibly because data identifying individuals was missing or withheld to maintain confidentiality.[15,17,20,23,26,30] Such studies would be unable to account for possible correlation between replicates. Given Preller et al.'s result,[36] and those of investigations that have found little autocorrelation in exposure time-series,[53–55] this may not be a problem.

Decisions about the designation of variables as fixed or random effects and nesting variables within a hierarchical structure have importance beyond the issue of replicate measurements of subjects. As an example, Lemasters et al.[30,61] used hierarchical mixed-effect ANOVA to estimate sources of variability in styrene levels. In the analysis process/route-of-exposure categories were treated as fixed effects, since they were defined by the study protocol rather than selected from a pool. The remaining variables, company, date, and person, were considered random effects nested within a hierarchical structure. The authors noted that ignoring the hierarchical nature of data can result in underestimation of variance. The same would be true of wrongly designating a variable as a fixed effect, since it does not then contribute to the total variance estimate.

Interpretation of Results

Among both experimental and observational studies reporting proportions of variance explained by the determinants measured, many included models accounting for more than 50% of the exposure variability, indicating that for many scenarios, occupational hygienists would be able to understand factors associated with exposure very well.[5,6,8,9,11,16,24,26–28,33,44–46]

Whether the determinants identified will direct the researchers to methods of exposure control depends on the character of and relationship between factors included in the model. Such factors as facility, job, and day may simply identify high exposure conditions that then require further study. Difficulties in interpretation may also occur with task or control variables. Some examples of interpreting regression coefficients and data with missing combinations of variables follow.

Regression Coefficients

In many cases, regression coefficients simply reflect the direct effects of exposure sources or control measures. Scheeper et al.[38] and Kromhout et al.[28] found negative associations between the presence of local exhaust and wood dust exposure in a joinery, and fume exposure in curing rubber, respectively, indicating that ventilation was effective in reducing the exposures. However, a negative coefficient can also represent tasks, conditions or equipment for which exposures are lower than the reference level represented by the intercept in the model, but which are passively, not actively, reducing exposure. For example, in the study by Scheeper et al.,[38] time spent finishing wood was negatively associated with dust exposure due to the fact that "no activities with exposure to wood dust took place" in finishing. A negative regression coefficient can also represent exposed tasks, conditions or equipment that are correlated with more highly exposed activities in such a way that they take time away from greater exposure opportunities. The latter situation was encountered in a study of bakeries by Burstyn et al..[16] A mixing task was performed in combination with pouring (which entailed higher exposures); consequently, time spent mixing had a negative regression coefficient when time spent pouring was included in the model, but a positive coefficient in univariate analysis.

Missing Combinations of Variables

In experimental studies with full factorial designs, all possible combinations of variables are used, so interactions between determinants can easily be tested in the ensuing models.[6,8] In observational studies it is likely that certain combinations of determinants of exposure may not be observed. In such circumstances it is not possible to examine interactions for the missing combination of predictor variables. For example, in their study of flour dust exposure in bakeries, Burstyn et al.[16] were not able to establish whether substitution of dough-brakers with reversible sheeters in puff-pastry making would reduce exposure, because this combination of factors was not observed in the study. In this case the combination was missed by chance, therefore, additional sampling might be scheduled. If the combination of determinants simply never occurs in industry, it may be necessary to subdivide the data set in analysis. For example, Kromhout et al.[28] constructed separate exposure models for different production functions in the rubber manufacturing industry, prior to constructing a model for the entire industry.

A related difficulty with observational studies is that only those determinants that vary in the studied population can be examined. Thus, in the study of the rubber manufacturing industry by Kromhout et al.[28] it was not possible to examine the effect of some tasks on exposure, since they were performed for the same duration by all workers. Similarly, Hansen and Whitehead[24] were not able to comment on the effect of ventilation on solvent exposure, since there was no variation in measured air velocities in workers' breathing zones.

Validation of Results

A number of studies examined the validity of their results. Heinonen et al.[7] and Plinke et al.[10] compared their laboratory-based empirical models to deterministic models based on physical principles. Topmiller et al.[14] first tested a new local exhaust system for a handheld sanding machine in a laboratory setting, then reevaluated its performance in field conditions in a chair factory. Evaluation of exposure before and after interventions can verify whether sources of exposure have been correctly identified in prior observational studies. To investigate the importance of sources of hospital sterilizer ethylene oxide exposures identified in the literature, Elias et al.[21] conducted source-oriented sampling for the duration of specific tasks before and after the implementation of control measures designed to reduce emissions from these sources.

Repeated analyses using subsets of the data, analyses using different methods, or sensitivity analyses can also be used to test validity.[62] Plinke et al.[11] constructed a model of exposure determinants on a random subset of 75% of their dust exposure data and compared this with a second model built using the remaining 25% of the data. Hornung et al.[26] used a similar approach in their observational study of ethylene oxide exposures. The validation exercise was conducted using data withheld from six randomly selected plants (20% of the data). This was a more severe test, more clearly examining the generalizability of the original model.[62]

Validity testing with data subsets demands large data sets, so other methods may be used where this is not available. Teschke et al.[42] evaluated their model of cobalt and chromium exposure determinants in several ways: sensitivity analyses for different fill-in values for concentrations below detection limits; comparison of a logistic regression model to the multiple regression model; and comparison with the results of the exposure-response analysis. In Hallock et al.'s study of printers' exposures to solvents,[23] sensitivity analyses were conducted with and without outliers.

An empirical model of exposure can also be evaluated by soliciting expert opinion or examining published data. Preller et al.[36] interviewed specialists in pig farming to ascertain whether the identified causes of exposures in Dutch pig-farming were reasonable. In the quasi-experimental study of formaldehyde exposure in embalming, Hornung et al.[8] tested their results by examining agreement with exposures assessed subjectively by industrial hygienists and with results in the published literature. Hallock et al.,[23] in their study of machining fluids, also used comparisons with the published literature.

CONCLUSIONS

This review illustrates the wide variety of approaches that have been developed to elucidate determinants of exposure, reflecting the diversity of the industrial settings under which exposures occur, the different goals of the investigations, and the available study designs. There appears to be an interplay between exposure determinants studies, creating a continuum of study types. Observational studies are usually used to identify sources of exposure requiring attenuation. Control measures may then be developed and tested in experimental studies, and reevaluated in the workplace. Determinants of exposure studies may also form components of epidemiological investigations. These studies can identify subsets of the work force in whom health effects are occurring and suggest means to minimize etiologic exposures.

The complexity of factors with the potential to influence exposures demands careful choices for optimal study design. The often sophisticated measurement strategies, in turn, give rise to complex data sets, making modern statistical packages an essential tool in the practice of industrial hygiene. Many occupational hygienists may feel more comfortable seeking statistical consultation for the sampling design and data analysis aspects of these studies, but this should not dissuade them from investigating determinants of exposure. The documentation of potential exposure sources and controls is a relatively simple addition to exposure measurement studies, one that promises to enrich our understanding of work sites and provide vital information for controlling occupational exposures.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Steve Marion for his helpful comments during the drafting of this manuscript, and Pamela Cruise for her proofreading and editing.

REFERENCES

1. **Stewart, P.A., and M. Dosemeci:** A bibliography for occupational exposure assessment for epidemiologic studies. *Am. Ind. Hyg. Assoc. J. 55*:1178–1187 (1994).
2. **Boleij, J.S.M., E. Buringh, D. Heederik, and H. Kromhout:** Exposure modeling. In *Occupational Hygiene for Chemical and Biological Agents.* Amsterdam: Elsevier, 1995. pp. 132–136.
3. **Archibald, B.A., K.R. Solomon, and G.R. Stephenson:** Estimation of pesticide exposure to greenhouse applicators using video imaging and other assessment techniques. *Am. Ind. Hyg. Assoc. J. 56*:226–235 (1995).
4. **Cherrie, J., S. Krantz, T. Schneider, et al.:** An experimental simulation of an early rock wool/slag wool production process. *Ann. Occup. Hyg. 31*:583–593 (1987).
5. **Garrison, R.P., and M. Erig:** Ventilation to eliminate oxygen deficiency in a confined space—Part III: Heavier-than-air characteristics. *Appl. Occup. Environ. Hyg. 6*:131–140 (1991).
6. **Hawkins, N.C., A.E. Luedtke, C.R. Mitchell, et al.:** Effects of selected process parameters on emission rates of volatile organic chemicals from carpet. *Am. Ind. Hyg. Assoc. J. 53*:275–282 (1992).
7. **Heinonen, K., I. Kulmala, and A. Säämänen:** Local ventilation for powder handling—combination of local supply and exhaust air. *Am. Ind. Hyg. Assoc. J. 57*:356–364 (1996).
8. **Hornung, R.W., R.F. Herrick, P.A. Stewart et al.:** An experimental design approach to retrospective exposure assessment. *Am. Ind. Hyg. Assoc. J. 57*:251–256(1996).
9. **Macher, J.M., L.E. Alevantis, Y-L. Chang, and K-S. Liu:** Effect of ultraviolet germicidal lamps on airborne microorganisms in an outpatient waiting room. *Appl. Occup. Environ. Hyg. 7*:505–513 (1992).
10. **Methner, M.M., and R.A. Fenske:** Pesticide exposure during greenhouse applications. III. Variable exposure due to ventilation conditions and spray pressure. *Appl. Occup. Environ. Hyg. 11*:174–180 (1996).
11. **Plinke, M.A.E., D. Leith, M.G. Boundy, et al.:** Dust generation from handling powders in industry. *Am. Ind. Hyg. Assoc. J. 56*:251–257 (1995).

12. **Thorpe, A., and R.C. Brown:** Measurement of the effectiveness of dust extraction systems of hand sanders used on wood. *Ann. Occup. Hyg. 38*:279–302 (1994).
13. **Thorpe, A., and R.C. Brown:** Factors influencing the production of dust during the hand sanding of wood. *Am. Ind. Hyg. Assoc. J. 56*: 236–242 (1995).
14. **Topmiller, J.C., D.S. Watkins, S.A. Shudlman, et al.:** Controlling wood dust from orbital hand sanders. *Appl. Occup. Env. Hyg. 11*: 1131–1138 (1996).
15. **Amandus, H.E., R. Wheeler, J. Jankovic, et al.:** The morbidity and mortality of vermiculite miners and millers exposed to tremolte-actinolite: Part I. Exposure estimates. *Am. J. Ind. Med. 11*:1–14 (1987).
16. **Burstyn, I., K. Teschke, and S. M. Kennedy:** Exposure levels and determinants of inhalable dust exposure in bakeries. *Ann. Occup. Hyg. 41*:609–624 (1997).
17. **Dement, J.M., R.L. Harris, M.J. Symons, and C.M. Shy:** Exposures and mortality among chrysotile asbestos workers. Part 1: Exposure estimates. *Am. J. Ind. Med. 4*:399–419 (1983).
18. **Demer, F.R., J.C. Rosen, and T.J. Finman:** Carbon monoxide exposures during the use of propane-powered floor burnishers. *Appl. Occup. Env. Hyg. 11*:1087–1091 (1996).
19. **Earnest, G.S.:** Evaluation and control of perchloroethylene exposure during dry cleaning. *Appl. Occup. Env. Hyg. 11*:125–132 (1996).
20. **Eisen, E.A., T.J. Smith, D.H. Wegman, et al.:** Estimation of long-term dust exposures in the Vermont granite sheds. *Am. Ind. Hyg. Assoc. J. 45*:89–94 (1984).
21. **Elias, J.D., D.N. Wylie, A. Yassi, et al.:** Eliminating worker exposure to ethylene oxide from hospital sterilizer: an evaluation of cost and effectiveness of an isolation system. *Appl. Occup. Environ. Hyg. 8*:687–692 (1993).
22. **Greenspan, C.A., R. Moure-Erason, D.H. Wegman, et al.:** Occupational hygiene characterization of a highway construction project: a pilot study. *Appl. Occup. Env. Hyg. 10*:50–58 (1995).
23. **Hallock, M.F., T.J. Smith, S.R. Woskie, and S.K. Hammond:** Estimation of historical exposures to machining fluids in the automotive industry. *Am. J. Ind. Med. 26*:621–634 (1994).
24. **Hansen, D.J., and L.W. Whitehead:** The influence of task and location on solvent exposures in a printing plant. *Am. Ind. Hyg. Assoc. J. 49*:259–265 (1988).
25. **Hicks, J.B.:** Asphalt industry cross-sectional exposure assessment study. *Appl. Occup. Env. Hyg. 10*:840–848 (1995).
26. **Hornung, R.W., A.L. Greife, L.T. Stayner, et al.:** Statistical model for prediction of retrospective exposure to ethylene oxide in an occupational mortality study. *Am. J. Ind. Med. 25*:825–36 (1994).
27. **Kalliokoski, P.:** Estimating long-term exposure levels in process-type industries using production rates. *Am. Ind. Hyg. Assoc. J. 51*:310–312 (1990).
28. **Kromhout, H., P. Swuste, and J.S.M. Boleij:** Empirical modeling of chemical exposure in the rubber manufacturing industry. *Ann. Occup. Hyg. 38*:3–22 (1994).
29. **Kumagai, S., Y. Kusaka, and S. Goto:** Cobalt exposure level and variability in hard metal industry of Japan. *Am. Ind. Hyg. Assoc. J. 57*: 365–369 (1996).
30. **Lemasters, G.K., A. Carson,and S.J. Samuels:** Occupational styrene exposure for twelve product categories in the reinforced-plastics industry. *Am. Ind. Hyg. Assoc. J. 46*:434–441 (1985).
31. **Materna, B.L.:** Occupational exposure to perchloroethylene in the dry cleaning industry. *Am. Ind. Hyg. Assoc. J. 46*:268–273 (1985).
32. **McDevitt, J.J., P.S.J. Lees, and M.A. McDiarmid:** Exposure of hospital pharmacists and nurses to antineoplastic agents. *J. Occup. Med. 35*:57–60 (1990).
33. **Nieuwenhuijsen, M.J., S. Gordon, J.M. Harris, et al.:** Variation in rat urinary aeroallergen levels explained by differences in site, task and exposure group. *Ann. Occup. Hyg. 39*:819–825 (1995).
34. **Nieuwenhuijsen, M.J., C. Sandiford, D. Lowson, et al.:** Peak exposure concentrations of dust and flour aeroallergen in flour mills and bakeries. *Ann. Occup. Hyg. 39*:193–201 (1995).
35. **Nieuwenhuijsen, M.J., M.B. Schenker, S.J. Samuels, et al.:** The exposure to dust, noise, and pesticides, their determinants, and use of the protective equipment among California farm operators. *Appl. Occup. Env. Hyg. 11*:1217–1225 (1996).
36. **Preller, L., D. Heederik, H. Kromhout, et al.:** Determinants of dust and endotoxin exposure of pig farmers: development of a control strategy using empirical modeling. *Ann. Occup. Hyg. 39*:545–557 (1995).
37. **Rocskay, A.Z., T.G. Robins, D. Echeverria, et al.:** Estimation of cumulative exposures to naptha at an automobile fuel-injector manufacturing plant. *Am. Ind. Hyg. Assoc. J. 54*:480–7 (1993).
38. **Scheeper, B., H. Kromhout, and J.S. M. Boleij:** wood-dust exposure during wood-working processes. *Ann. Occup. Hyg. 39*:141–154 (1995).
39. **Smid, T., D. Heederik, G. Mensink, et al.:** Exposure to dust, endotoxin and fungi in the animal feed industry. *Am. Ind. Hyg. Assoc. J. 53*:362–368 (1992).
40. **Smith, T.J., S.K. Hammond, F. Laidlaw, et al.:** Respiratory exposures associated with silicon carbide production: estimation of cumulative exposures for an epidemiological study. *Br. J. Ind. Med. 41*: 10–108 (1984).
41. **Teschke, K., C. Hertzman, and B. Morrison:** Level and distribution of employee exposures to total and respirable wood dust in two Canadian sawmills. *Am. Ind. Hyg. Assoc. J. 55*:245–250 (1994).
42. **Teschke, K., S.A. Marion, M.J. van Zuylen, et al.:** Maintenance of stellite and tungsten carbide saw tips: determinants of exposure to cobalt and chromium. *Am. Ind. Hyg. Assoc. J. 53*:661–669 (1995).
43. **Williams, T.M., R.J. Levine, and P.B. Blunden:** Exposure of embalmers to formaldehyde and other chemicals. *Am. Ind. Hyg. Assoc. J. 45*:172–176 (1984).
44. **Woskie, S.R., T.J. Smith, K. Hammond, et al.:** Estimation of the diesel exhaust exposures of railroad workers: I. Current exposures. *Am. J. Ind. Med. 13*:381–394 (1988).
45. **Woskie, S.R., T.J. Smith, K. Hammond, et al.:** Factors affecting worker exposures to metal working fluids during automotive component manufacturing. *Appl. Occup. Environ. Hyg. 9*:612–621 (1994).
46. **Zock, J-P., D. Heederik, and H. Kromhout:** Exposure to dust, endotoxin and microorganisms in the potato processing industry. *Ann. Occup. Hyg. 39*:841–854 (1995).
47. **Tominaga, Y.:** Dose-response relation for the vibration syndrome. In *Vibration Effects on the Hand and Arm in Industry*, A.J. Brammer and W. Taylor (eds.). New York: John Wiley & Sons, 1982. pp. 277–281.
48. **Teschke, K., S.M. Kennedy, and A.F. Olshan**: Effect of different questionnaire formats on reporting of occupational exposures. *Am. J. Ind. Med. 26*:327–337 (1994).
49. **Nicas, M., and R.C. Spear:** A task-based statistical model of a workers's exposure distribution. Part 1, description of the model. *Am. Ind. Hyg. Assoc. J. 54*:211–220 (1993).
50. **Heitbrink, W.A., M.G. Gressel, T.C. Cooper, et al.:** Video exposure monitoring—a means of studying sources of occupational air contaminants exposure, Part 2—Data interpretation. *Appl. Occup. Environ. Hyg. 8*:339–343 (1993).
51. **O'Brien, D.M., T.J. Fischbach, T.C. Cooper, et al.:** Acquisition and spreadsheet analysis of real time dust exposure data: a case study. *Appl. Ind Hyg. 4*:238–243 (1989).
52. **Bennett, J.S., C.E. Feigley, D.W. Underhill, et al.:** Estimating the contribution of individual work tasks to room concentration: Method applied to embalming. *Am. Ind. Hyg. Assoc. J. 57*:599–609 (1996).
53. **Francis, M., S. Selvin, R. Spear, and S.M. Rappaport:** The effect of autocorrelation on the estimation of worker's daily exposures. *Am. Ind. Hyg. Assoc. J. 50*:37–43 (1989).
54. **Symanski, E., and S.M. Rappaport:** An investigation of the dependence of exposure variability on the interval between measurements. *Ann. Occup. Hyg. 38*:361–372 (1994).
55. **Kumagai, S., I. Matsunaga, and Y. Kusaka:** Autocorrelation of short-term and daily average exposure levels in workplaces. *Am. Ind. Hyg. Assoc. J. 54*:341–350 (1993).
56. **Buring, E., and R. Lanting:** Exposure variability in the workplace: its implications for the assessment of compliance. *Am. Ind. Hyg. Assoc. J. 52*:6–13 (1991).

57. **Symanski, E., L.L. Kupper, H. Kromhout, and S.M. Rappaport:** An investigation of systematic changes in occupational exposure. *Am. Ind. Hyg. Assoc. J. 57*:724–735 (1994).
58. **Kromhout, H., E. Symanski, and S.M. Rappaport:** A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Ann. Occup. Hyg. 37*:253–270 (1993).
59. **Woskie, S.R., P. Shen, E.A. Eisen, et al.:** The real-time dust exposures of sodium borate workers: examination of exposure variability. *Am. Ind. Hyg. Assoc. J. 55*:207–217 (1994).
60. **Kromhout, H., and D. Heederik:** Occupational epidemiology in the rubber industry: implications of exposure variability. *Am. J. Ind. Med. 27*:171–185 (1995).
61. **Samuels, S.J., G.K. Lemasters, and A. Carson:** Statistical methods for describing occupational exposure measurements. *Am. Ind. Hyg. Assoc. J. 46*:427–433 (1985).
62. **Hornung, R.W.:** Statistical evaluation of exposure assessment strategies. *Appl. Occup. Environ. Hyg. 6*:516–520 (1991).