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Exposure Assessment in the Occupational Setting

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Exposure assessment, the first step in risk assessment, has traditionally been performed for a variety of purposes. These include compliance determinations; management of specific programs that are implemented by comparison with an occupational exposure limit (such as medical surveillance, training, and respiratory protection programs); task/source investigations for determination of exposure control strategies; epidemiologic studies; worker compensation/toxic tort cases; health complaint or problem investigations; risk assessment and management; and evaluation of future changes in the workplace (e.g., introduction of a new chemical). Each purpose requires slightly different approaches, but there are also many similarities. The goal of this paper is to identify a general approach to assessing exposures that can be used for all purposes with only slight modifications. Five components of exposure assessments are identified: collection of data, identification of the hazard, selection of exposure metrics, definition of exposure groups and estimation of the exposures. The characteristics of these components for each type of assessment are discussed. From this review, it is clear that there is substantial overlap across the types of assessment. A single exposure assessment program is suggested that encompasses all the needs of these assessments and incorporates assessment of exposures for an entire workforce at a site at minimal cost by using prediction models and validation with measurements.

Keywords Exposure Assessment, Compliance Evaluation, Epidemiological Studies

Exposure assessment is a process that is used for a variety of purposes, but a review of the exposure assessment literature finds that the focus has been on determining compliance of current exposures with occupational exposure limits (OEL). Some exposure assessment literature is also available on assessing historical exposures in the context of epidemiological studies. It is interesting that the overlap between these two types of assessments has not been discussed. There is also little information on assessing exposures for purposes other than compliance determinations and epidemiological studies. A review of the basic components of the different types of exposure assessment finds that there is much common ground. Because of this commonality, development of a comprehensive system that incorporates all the needs of exposure assessment should be possible. Such a system would increase the coverage of the population being assessed, make more efficient use of available resources, and possibly improve the accuracy of the evaluations.

This article first presents a general overview of the components of exposure assessment: data collection, identification of the hazard, selection of appropriate metrics, formation of exposure groups, and estimation of the exposure levels. It then discusses how these components are used in the different types of exposure assessments. These include compliance determinations; management of specific programs that are implemented by comparison with an occupational exposure limit (such as medical surveillance, training, and respiratory protection programs); epidemiological studies; worker compensation/toxic tort cases; health complaint or problem investigations; risk assessment and management; and evaluation of future changes in the workplace (e.g., introduction of a new chemical). This article also addresses task/source investigations for determination of exposure control strategies when they are a part of the exposure evaluation, but not when they are done separately from exposures (e.g., area measurements). A comprehensive exposure assessment system is then described that meets the needs of all types of exposure assessments need with slight modifications to fit the particular requirements of a specific assessment.

COMPONENTS OF EXPOSURE ASSESSMENT

Three basic steps have been identified for assessing exposures for either current or historical workplaces: collection of data, formation of exposure groups, and the estimation of the exposures.(1) We believe there are two others: identification of the hazard to be evaluated and selection of appropriate exposure metrics. The order in which these five are presented in this article is not necessarily the sequence taken in any particular type of assessment. For example, in most types, data collection is likely to be continual throughout the assessment process.

Collection of Descriptive Data

Types of descriptive data used for exposure assessment have been described elsewhere,[1–3] and so are only listed here. These data include toxicological information on adverse health effects and levels, job titles, descriptions of tasks, information on the process, operating equipment, and engineering and administrative controls. Records on chemical inventories and production rates may be useful. Medical, safety, and industrial hygiene records, including descriptions of respiratory protection, personal protective equipment, hazard communication, and other industrial hygiene programs and worker compensation claims provide further information. These data may be process-specific, chemical-specific, job-specific, and/or person-specific. This information should be collected and retained because it contributes to the proper interpretation of exposure measurement data or estimates of exposure. An easily accessible system for entering, organizing, monitoring, and reviewing this information is crucial to its being used. Such a system has been described,[4] which, although developed for an epidemiological study, could be used as a model for a database for current workplace evaluations.

Identification of the Hazard to Be Evaluated

A hazard is defined here as a stressor or combination of stressors that is capable of causing an adverse health effect. The hazard may be known (e.g., when comparing a measurement to an OEL) or unknown (e.g., a contaminant in a process chemical that is causing an adverse health effect).[5] Even when the hazard is known, however, the assessment of the hazard may be less obvious. Although the primary route of exposure in many industries is inhalation, dermal or ingestion hazards can also contribute to the overall exposure, but quantitative assessment of these routes is rarely discussed in the published literature. Also, the presence of mixtures complicates evaluations because a hazard evaluation developed for a substance in isolation may be different than when that substance is in a mixture. A mixture of chemicals may change the physical characteristics of those chemicals. For example, the vapor pressure of solvents changes when solvents are in a mixture,[1] and some solvents, such as benzene and dimethyl formamide, can increase permeability through the skin of other substances dissolved in them.[6] A mixture can also change the effect of a chemical once the components of the mixture are absorbed into the body.[7] For example, industrial hygienists are familiar with the concept of additive effects for chemicals such as solvents. There may, however, also be more subtle interactions that the industrial hygienist is less familiar with. Examples are n-hexane's increased neurological toxicity with concurrent exposure to methyl ethyl ketone[8] and the change in the metabolism of toluene, trichloroethylene, and n-hexane when exposure to a mixture of these chemicals occurs at high levels compared to low levels.[9] Identification of hazards, then, requires careful study of the workplace and of physical and toxicological principles to ensure a comprehensive evaluation.

Selection of the Exposure Metric

Traditionally, the most commonly used metrics in exposure assessment have been the arithmetic and geometric mean and standard deviation of an eight-hour time-weighted average (TWA_8). Although useful for compliance determinations, they are not necessarily the best predictors of disease. It may be that a percentile of the exposure distribution, such as the 90th or 95th percentile, may be more appropriate. Selection of a metric may also be complex if the purpose of the assessment is to relate an adverse health effect to a hazard in the workplace when the health effect has not been associated with any of the hazards in that workplace. Furthermore, the appropriateness of the metric is dependent on the toxicological mechanism of the disease of interest,[5] yet there are few occupational diseases for which the toxicological mechanism is known. Selecting only one metric is risky, particularly when different exposure metrics group a population of workers differently.[10,11] Thus, it may be a better strategy to evaluate exposures for several different metrics to increase the likelihood that the appropriate one is evaluated.

Formation of Exposure Groups

Because assessing exposures for a large number of stressors for a large number of workers can be an extremely time-consuming task, generally, groups of workers who are thought to be similarly exposed are developed. Such grouping has been found to be difficult,[1] yet developing a group comprising workers with different exposures defeats the purpose of the assessment. The formation of exposure groups is, therefore, a crucial component of the exposure assessment process.

Prior to the 1990s, little attention was paid to grouping workers. In 1991, the term homogeneous exposure group (HEG) was used to describe "a group of employees who experienced agent exposures similar enough that monitoring agent exposures of any worker in the group provides data useful for predicting exposures of the remaining workers."[2] Although this definition is fairly general, its popular meaning evolved to mean a statistically homogeneous group from which the probability of exceeding an OEL could be calculated. Estimating the probability of compliance is an important reason for assessing exposures, but there are other reasons for assessing exposures that do not require sophisticated statistical techniques.

More recently, a new term, "similar exposure group," was defined as a group "of workers having the same general exposure profile because of the similarity and frequency of the tasks they perform, the materials and processes with which they work, and the similarity of the way they perform the tasks."[1] This definition, by not including a reference to statistical homogeneity, decreases the emphasis of this requirement. Because this definition does not include a reference to the duration of the exposure, however, it could be interpreted to mean the exposure profile is of a full work shift, that is, a job.

Here, the term, exposure group, is used to describe groups of workers having the same general exposure profile with a similar mean and distribution of exposure in a defined exposure situation. The profile reflects full-shift or shorter period exposures that may encompass similar tasks, exposures to similar materials, equipment, and processes and many other variables occurring with similar frequency in similar locations. The variables selected to describe the profile affect the level of preciseness with which the estimate is estimated and may be dependent on the needs and resources of the assessor.

Although traditionally the job title has been the basis for HEGs,[5] the large variability of exposures across job titles[12] suggests that in many cases, job title may not be an appropriate categorization of exposure. In the context of an epidemiological study, exposure groups have generally been identified based on plants, departments, locations, jobs, and tasks. These categories have been used for practical reasons (e.g., lack of more detailed information), rather than what was considered desirable, and may or may not have been homogeneous. For example, in a study of acrylonitrile (AN) workers, job title was the primary exposure unit assessed. It was recognized, however, that some of the jobs were likely to include people performing similar tasks in different locations of a plant (e.g., the locations were assigned to specific individuals based on their technical expertise or on an as-needed basis).[13] Such jobs (e.g., maintenance, engineering, quality control, and research positions) were evaluated as to how much time each person holding the job spent in AN and non-AN operating units. Forty percent of the individuals' jobs were not generally assigned to any AN operation; another 40 percent were assigned to AN operations between 5 and 90 percent of the time, and 20 percent were assigned to AN operations 100 percent of the time. Using job title as the exposure unit for these types of jobs would, therefore, have resulted in substantial misclassification of exposures. Rather than just job, the job (e.g., mechanic) and location (AN unit or non-AN unit) were used to define the exposure groups. The exposure of each group was estimated, and then a TWA_8 for each worker was calculated using the frequency of being in each group.

Historically, developing exposure groups has been done by observation. A more rigorous approach would be to develop groups by identifying determinants of exposure and then using the determinants to identify individuals with similar determinant exposure profiles (see following).

Another consideration when developing exposure groups is what exposure metrics will be evaluated. If only one exposure metric is to be considered, identification of exposure groups is easier than if several metrics are to be evaluated, because workers in an exposure group may not be similar for the second exposure metric. For example, investigators of a sodium borate study found that when workers were grouped by their TWA_8, a substantial percentage of each group had higher or lower peaks than the rest of their group.[15] Thus, if exposures or disease risks are to be evaluated for TWA_8s and peaks, either all people within an exposure group must have a similar TWA_8 exposure level and a similar peak level or two sets of exposure groups will be necessary. This concern is considerably reduced by the use of exposure groups as defined in this article, because by definition all workers in a group will have the same TWA_8, peak, and any other exposure metric.

The occurrence of other occupational exposures raises an additional concern when developing exposure groups. If exposures to other stressors are being estimated or health risks from other exposures will be examined, the exposures to these stressors of the individuals within each exposure group must be homogeneous also. Finally, the individuals within each exposure group must be affected similarly by changes occurring in the workplace so that the homogeneity of the group is maintained over time. Again, the definition of exposure groups as used here makes these concerns moot.

Inherent with any use of exposure groups is the issue of between and within group variability. The need to explore this issue depends on the type of assessment being performed (see following).

Estimation of Exposures: Measurement Means

There are several issues that must be considered when using measurement data to estimate exposures. First, several different metrics can be used to describe the exposure (i.e., TWA_8, peaks, etc). The estimate may be described in terms of a semi-quantitative scale (e.g., a scale of 1–10 or low, medium, or high), a measurement range (e.g., 1–10 ppm), or a point estimate (e.g., 5 ppm). The latter could represent an arithmetic or geometric mean and be accompanied by a standard deviation. Geometric means are usually used to describe exposures in a workplace, whereas the arithmetic mean is recommended in epidemiological studies when cumulative exposure is considered to be the toxicological mechanism.[16] Because knowledge of one mean and the geometric standard deviation allows calculation of the other mean, the type of mean calculated is not crucial. Other statistical values, such as the 90th percentile, may also be used. Regardless of the metric used, how well measurements represent the true exposure depends on the conditions of sampling, on whether the measurements were randomly collected, and on the similarity between the measured and unmeasured workers.

The limitation of selecting a single exposure metric was discussed previously from the toxicological standpoint. Ideally, an exposure profile would provide summary statistics (e.g., a mean and standard deviation) that describe the typical exposure and the frequency of that exposure. Frequency information is important because it can be used with half-life information to evaluate the potential for adverse health effects. The variability indicates the potential for peak exposures. The profile would also include statistical descriptions for scheduled atypical (e.g., shutdowns) and unscheduled atypical conditions (e.g., spills), because these could also be useful when evaluating disease risk.[17] Practically, such documentation could be very burdensome. At the very least, however, the means of typical and routine scheduled and unscheduled conditions should be identified with their frequency of occurrence.

Estimation of Exposures: Other Methods

Other methods have been used more often in estimating historical exposures in epidemiological methods because of the usual lack of sufficient historical measurements. These methods include statistical modeling, using measurements for an agent that was used in parallel with the exposure of interest, deterministic modelling, or professional judgment.[5] In a statistical model, determinants of exposure are identified as independent variables and measurements are used as the dependent variable. The coefficients derived from the model are then used to predict unmeasured exposures.[18,19] A limitation of statistical models is that statistically significant determinants do not automatically mean that the determinants are, in fact, the true determinants. It may be that the observed determinant is simply highly correlated with the true determinant. In addition, models can only be used for the conditions under which the measurements were made (e.g., if measurements were made with effective ventilation controls on a sander the model cannot estimate the exposures from an unventilated sander). Furthermore, the model coefficients may be applicable only to the situation in which the measurements were made and not to another situation with the same conditions (e.g., another plant with a ventilated sander).[20]

A few epidemiological studies evaluating historical exposures have used exposure information from an agent used in parallel to the one being estimated.[21,22] Application of this estimation method requires confirmation that the agents were used in parallel in all circumstances where this method is used and that any process, control, or work practice changes that occurred did not differentially affect the exposures to the two agents of interest within the population being evaluated.

The exposure zone approach to estimating exposures involves developing exposure estimates in different zones, weighing the exposure estimates by the percent of time worked in the zone, and summing across all zones for an individual worker or job.[23] The estimates for the zone can be developed from any estimation method.[13] Error in the estimates generated from the zone method comes from two sources: the estimates of time and of the estimation method. Little information is available on how estimates vary within an exposure group. In an epidemiological study of electrical lineworkers investigators found that the standard deviation of the mean observed work time varied from 13–31 percent for five job groups,[24] suggesting that the error in time estimates may vary by exposure group. Estimates may also vary over time. A different study of electrical utility workers found that the time spent working from a pole decreased from 35 hr/wk in 1940–1949 to 0.5 hr/wk in 1990, whereas working from a bucket was not done until 1970 and by 1990 the time spent in a bucket was up to 13.5 hr/wk.[25] The uncertainty of the time estimates can be reduced by collecting this information at regular intervals (e.g., monthly).

A deterministic model uses physical and chemical laws to estimate exposures. The limitations of this method are that a true determinant may be missed, a false determinant may be identified, or an incorrect weight may be assigned to the determinant. In most epidemiological studies, the procedure for using deterministic models has been to identify determinants of exposure, such as engineering controls and respirator use, from the published literature (e.g., Table I), observation, records, interviews, or measurements. Measurements and/or professional judgment are then used to assign weights to the determinants.[13]

Finally, the term professional judgment has been used to describe the estimation process in many epidemiological studies. This term has been defined by the American Industrial Hygiene Association (AIHA) as the ability "to draw correct inferences from incomplete quantitative data . . .,"[1] that is, professional judgment develops an approximation of the true exposure, in contrast to professional opinion that may or may not approximate the true exposure. Evaluation of the estimates (i.e., validation) allows one to determine how correct the inferences were, and thus distinguishes professional judgment from professional opinion. In most studies professional judgment has been used to encompass the entire assessment process without indicating what criteria were considered in the estimation process or how those criteria were weighted. Lack of a detailed description of the assessment process makes interpretation of the results difficult and raises the question of the accuracy and the credibility of the estimates.[5]

Types of Exposure Assessments and Their Characteristics

The various components already discussed vary by the purpose of the exposure assessment being performed.

Compliance with an OEL

This category is used to define the most common reason for assessing exposures, that is, comparing the exposure of a group of workers to a legally mandated OEL as a permissible exposure limit. The term OEL is also used here to represent employers' internal OELs. This type of assessment tends to focus on both typical and expected unusual exposures based on the exposures of the highest exposed group(s) of workers. Collection of descriptive data is usually limited to that which is necessary to ensure that the highest exposed group(s) of workers and the highest exposure scenarios have been identified. Identification of the hazard is generally straightforward (i.e., used as a raw or process material or is a by-product or final product). Selection of an exposure metric may not be straightforward when occupational standards (e.g., lead) have multiple levels triggering actions, such as training, respiratory protection, and so on. Formation of exposure groups is generally straightforward. Although within group variability is important, between group variability is not crucial for this type of evaluation, because the purpose of the evaluation is not to contrast the groups but to compare

TABLE I
Examples of determinants of exposure

Determinant	Exposure	Population	Reference
	Characteristics of the substance		
Fluid type	Machining fluid	Auto machinists	29
	Individual determinants		
Distance to other operations	Chromium	Saw filers	18
Overtime	Trichloroethylene	NP[A]	30
Frequency of task	Ethanol	Hairdressers	20
	Toluene	Printers	31
	Captan	Pesticide applicators	32
Task duration	Captan	Pesticide applicators	32
	Urine tetrachlorophenol	Timber mill workers	33
Personal protective	Captan	Pesticide applicators	32
equipment	Cyclohexane-soluble matter	Rubber workers	34
	Job determinants		
Job	Chromium	Saw filers	18
	Silica	Granite workers	35
Job function (e.g., maintenance)	Ethylene oxide	Ethylene oxide workers	19
Type of task	Particulates	Rubber workers	34
	Dust	Farmers	36
	Facility determinants		
Operation/product type	Ethylene oxide	Ethylene oxide workers	19
	Styrene	Lay-up workers	37
Age of product	Ethylene oxide	Ethylene oxide workers	19
Ventilation	Ethylene oxide	Ethylene oxide workers	19
	Machining fluid	Auto machinists	29
Size of equipment	Ethylene oxide	Ethylene oxide workers	19
Type of equipment	Machining fluid	Auto machinists	29
	Dust, endotoxin	Pig farmers	38
Enclosure type	Machining fluid	Auto machinists	29
Production rates	Urine mercury	Chloralkaline workers	39
	Formaldehyde	Embalmers	40
Energy/raw material consumption	Toluene	Printers	31
	Captan	Pesticide applicators	32
	Urine mercury	Chloralkaline workers	39
Process upsets	Formaldehyde	Embalmers	40
Pressure/temperature of operation	Rubber fumes	Rubber workers	34
Background concentration	Chromium	Saw filers	18
Year	Ethylene oxide	Ethylene oxide workers	19
	Environmental determinants		
Indoor humidity	Machining fluid	Auto machinists	29
Wind speed	Dust	Farmers	28
Outdoor temperature	Machining fluid	Auto machinists	29
	Dust, endotoxin	Pig farmers	38

[A]NP = not provided.

each group to the OEL. Determination of the exposure level has traditionally been a substantial effort because it has required the collection of a large number of measurements per group to assure statistically stable estimates.[2]

Implementation of an Industrial Hygiene Program

This type of assessment is defined as the effort to comply with occupational standards that require implementation of different industrial hygiene programs when exposures exceed different levels. For example, Occupational Safety and Health Administration (OSHA) standards often specify hazard communication training, respiratory or other protective equipment, and implementation of medical surveillance, engineering controls, or other such programs at different exposure levels. This type of assessment also includes the situation when employers have their own internal OELs that implement such programs. Because each program for a specific stressor may have a different limit, multiple evaluations for a stressor may be required. For example, respirators may be triggered at the OEL, medical surveillance at half the OEL, and monitoring at 10 percent the OEL. The characteristics of the exposure assessment process (data collection, identification of the hazard, selection of the exposure metrics, etc.) are similar to those of compliance determination.

Retrospective Epidemiological Studies

The term retrospective epidemiological studies is used in this article to define studies that evaluate the mortality, morbidity, or subclinical health effects of workers from past exposures. In mortality and morbidity studies, large populations of workers may be assessed (e.g., all employees at a work site). Oftentimes, the identification of the exposure is straightforward: there is a single or major agent in the workplace that is known to have adverse health effects. The goal of the assessment is to determine whether these adverse effects are occurring or have occurred in the population of interest. In other cases, identification is less straightforward. The process of refining oil, for example, has been associated with brain cancer,[26] but the etiologic agent in the refining process has never been identified. Nor is the selection of the exposure metric always straightforward. It is generally assumed that the TWA_8 cumulative exposure is the important metric for chronic effects but this assumption may not be correct.[17] Peak exposures or the number of peaks exceeding an exposure level may be the critical exposure metric. Data collection, which generally occurs throughout the entire study, can be extensive in epidemiological studies, depending on the number of exposures, the number of exposure groups, and the length of the study period. Formation of exposure groups can be complex if the study population is large and it works in a large and diverse environment carrying out a wide spectrum of tasks. For practical reasons development of exposure groups has typically been based on job title, although, as indicated previously, job title may not result in homogenous exposure groups.[12]

Development of exposure groups is further complicated as to how the exposure level is described. For example, if a small number of exposure categories (e.g., high, medium, low, and none) is used for exposure categorization, small within group variability and large between group variability is desirable. If a continuous scale (e.g., ppm) is used to categorize exposure, small within group variability is desirable, however, between group variability is irrelevant, because contrast is not being made across groups, but rather across a continuous scale.[27] Quantitative determination of exposure can be complex if there are few measurements available and changes in exposure levels occurred over the study period. Moreover, it is common that in studies of large populations many workers, and even many exposure groups, have never been measured for the exposure of interest.[13] These problems usually necessitate the use of prediction models.

Cross-Sectional or Prospective Epidemiological Studies

In contrast to retrospective studies, cross-sectional or prospective studies are defined here as studies that evaluate current or future disease risks and exposures. The size of the population of interest in prospective studies may be similar to that of retrospective studies, but the population in a cross-sectional study is often much smaller. Identification of the hazard, selection of an exposure metric, and formation of the exposure groups require considerations similar to those in retrospective studies. Data collection for either type of study can be extensive and continuous throughout the assessment process but may be substantially less than retrospective studies if the study period is short (e.g., a year), such as in a cross-sectional study. Evaluation of exposure levels may be done entirely with measurements (albeit at possibly a high cost) or with a smaller number of measurements, supplemented by prediction models.

Health Complaint or Problem Investigation

Investigation of health complaints or problems differs from epidemiological studies in this article because the evaluation is not statistically based but is observational, such as in a case study. These types of investigations usually involve a smaller group of workers than epidemiological studies and comprise a more limited assessment effort. Identification of the hazard and selection of an exposure metric may be complicated if the health effects of concern have not been associated with any of the stressors present in the workplace or they have been associated with the stressors present, but at much higher levels. Data collection may be extensive, although more limited than in epidemiological studies. Between and within group variability is not an issue in the formation of exposure groups for this type of investigation because statistical evaluations are not conducted (as defined here). Evaluation of exposure levels is similar to that of retrospective epidemiological studies, although it is likely to be more limited in scope.

Worker Compensation/Toxic Tort Cases

These types of investigations are similar in approach to health complaints and problems. They may, however, involve even a smaller number of workers. The interpretation of the plaintiff's health effects may be clearer if the exposures and health experience of the plaintiff can be compared to those workers who are in the same exposure group. The exposure group therefore should be homogeneously exposed, but between group variability is irrelevant. Morbidity or mortality epidemiological studies may also provide valuable insight into the possible causes of the plaintiff's condition.

Task/Source Investigation

Task/source investigations are defined in this article as evaluating personal exposures for the purpose of identifying or quantifying sources of exposure with the intent of controlling them. Generally, these investigations evaluate the highest sources of exposure rather than all sources. This type of investigation is used here to describe the effort taken once the hazard is identified; therefore, identification of the hazard has already been made, by definition. Because this type of investigation evaluates personal exposures, rather than emissions, as defined in this article, it does not include area measurements, although area measurements may provide supplemental information in the investigation. Selection of an exposure metric varies, depending on the duration of the interaction between the worker(s) and the source(s), and is generally straightforward. The extent of the data collection is generally dependent on the number of sources, but is likely to be limited. This type of investigation is usually concerned with current exposures. The formation of exposure groups is likely to be limited to highly exposed jobs or tasks and therefore only a small number of workers. Between and within group variability is not an important issue. Determination of the exposure level can be done with measurements or with prediction models, and is generally limited in scope. (This approach can be used for reconstructing historical conditions, in which case the sources evaluated may not only be the highest sources).

Risk Assessment and Risk Management

Exposure assessment is a necessary component of risk assessment and risk management because it provides the exposure information that indicates the level of risk to which the population is exposed. The exposure assessment process may be similar to that of epidemiological studies or health investigations, depending on the rigor desired in the risk assessment/management goal.

Evaluation of Future Changes in the Workplace

Oftentimes, industrial hygienists play a role in the determination of whether a new chemical or process will be introduced into the workplace or when an existing process is modified. The industrial hygienist may identify toxicity information and OELs, but may also estimate what exposure levels are likely and identify what controls are necessary. If a new chemical is introduced the identification of the hazard and selection of an exposure metric may or may not be straightforward (unintended by-products could occur). Data collection and formation of exposure groups should be relatively simple but will generally require new efforts to characterize exposure determinants. Between worker variability is not important but within variability is important. Estimation of exposure levels may be difficult, depending on the complexity of the process (e.g., multiple chemicals and varying operating conditions) and the ability to evaluate the exposure scenarios. Measuring exposures of a new chemical on a trial basis may be possible; measuring exposures from a new process before it has been permanently installed is generally economically infeasible. In addition, measurement techniques for a new substance may not be available. Thus, a distinct advantage of exposure assessment models is that the effect of possible changes on exposure levels can be evaluated before the changes are implemented, rather than after implementation as may be necessary for monitoring.

DISCUSSION AND RECOMMENDATIONS

This article describes the exposure assessment process as it has been performed for a variety of purposes. It is evident from this review that there are many more similarities in the process than what would have been expected from the literature on this subject. It appears that the biggest difference is the development of exposure groups, but even this difference is slight. The other components of the exposure assessment process—data collection, identification of the hazard, selection of the appropriate measure, and estimation of the exposure levels—are very similar.

This review also suggests that it may be possible to develop a single system that meets the needs of the different types of assessment. Such a system has been developed in a major U.S. chemical corporation.[28] That system has the following characteristics:

1. All possible hazards in the workplace are identified.
2. Every employee in the workplace is identified with one or more exposure groups. Careful formation of the groups is necessary because, as indicated previously, for most efficient assessments, each group needs to be qualitatively and quantitatively homogeneous. In some cases, job title may be sufficient to group workers. In other cases, more complex groupings may be required based, for example, on the determinants identified in the section on exposure groups.

   It must be emphasized that an exposure group, as defined in this system, need not be representative of a workers' full-shift exposure. Rather, it can represent any component of a worker's exposure experience. In the exposure assessment program being described a number of determinants are considered when developing exposure groups. These include: job classification (e.g., operator), job assignment (e.g., board operator), area or location, department, task assignment, equipment, craft, product, process container, batch or lot (e.g., formulation), project (e.g., in a research and development department), production unit, and ambient air (e.g., exposures due to cross contamination). Although this list is quite extensive, the industrial hygienists of this company have found that for most exposure groups only three or four variables are needed to describe an exposure group's uniqueness. To assess exposures individual workers are initially ignored. Using the 13 above-identified variables, exposure groups are developed that both qualitatively and quantitatively meet the definition of exposure group as used here.

3. Prediction models rather than measurements are used to estimate the exposures to each stressor of each exposure group to control cost and effort. Such models need not be complex. A simple model using a scoring system incorporating vapor pressure or particle size of the stressor, frequency and duration of exposure, and the extent of engineering controls is used. In this model, to ensure that both typical and expected atypical exposures are estimated, the model predicts the 90th percentile value, which determines the exposure category assigned (<.1 OEL, .1–.25 OEL, .25–.5 OEL, .5–1 OEL and >OEL) to the exposure group. Thus, each worker may be a member of several exposure groups.
4. Once exposure categories have been assigned for each stressor in each exposure group, the individual workers are assigned to all appropriate exposure groups. Their overall TWA_8 is derived by weighing the exposure level in each exposure group by the time spent in the exposure group and summing these weighted values to derive the TWA_8.
5. The models are validated using measurement data. The model described previously was evaluated by conducting full-shift monitoring for a variety of exposures. Of over 250 estimates, 50–60 percent of the estimates were assigned to the correct exposure category and 85–95 percent were assigned to within one exposure category, most to the more conservative (protective) category.[28]
6. Once the exposure groups are developed for the population's exposure experiences, exposure groups may be combined based on the particular purpose of an assessment. For example, an industrial hygiene program could require implementation at exposure levels <0.5 OEL and another at 0.5–1.0 OEL. Two separate groups, however, are unnecessary for a cross-sectional epidemiological study that contrasts the health experience of a group of workers exposed above the OEL with one exposed below the OEL. For that assessment, the two groups exposed below the OEL can be combined into a single exposure group for the temporary purpose of the cross-sectional study. The original exposure groups are, however, always retained.

The attractiveness of using a single exposure assessment system based on prediction models is that it allows development of a comprehensive evaluation of an entire workplace without the prohibitive costs associated with comprehensive measurement of the workplace. For example, the authors estimated that if only monitoring were used to assess exposures for the 35 work sites in their company of 10,000 workers using 50,000 chemicals, it would cost $37.5 million in analytical costs and 1820 person years to collect the 1,250,000 measurements necessary to assess all exposure groups (assuming 5 samples/group). This is obviously impractical. Using the assessment model described here, the exposure levels of about 750 exposure groups were estimated for all 50,000 substances in the 35 plants in the company in just two person-years.

Another advantage of taking such an approach is that from the information collected, all workers exceeding OELs for all stressors are identified. Expected extreme case scenarios can be identified by using a statistical parameter, such as the 90th percentile, which can be estimated from the geometric mean and standard deviation. Developing a single approach also serves as an effective management tool, because it facilitates a comprehensive, long-term strategy to control all exposures in a workplace. It provides a credible and rigorous evaluation for who should be the subject of the various industrial hygiene programs and identifies which exposure groups should be evaluated for more effective exposure controls. It also increases the credibility of the industrial hygienist with management, in that management is provided a comprehensive picture of the problems in the workplace, rather than receiving reports of problems one at a time. It develops information for retrospective epidemiological studies, health investigations, and toxic tort-worker compensation cases at the time of exposure, not retrospectively. The exposure estimates therefore have greater credibility, having been developed at the time of the exposure rather than at the time of the adverse health report.

The assessment can also be used to assess exposures for cross-sectional and prospective studies. It allows a clear identification of the number of people at risk, what their level of risk is, and which exposure groups need further control. Using models to estimate exposures, rather than relying on measurements, reduces analytic development costs and time for substances without analytic methods. Finally, the approach described can be used to estimate exposures from new or modified products and processes before the changes are implemented.

Once the workplace has been evaluated, ongoing effort requires a periodic review of workers' jobs and of the workplace. This effort is fairly minimal as long as the workplace situation remains static. Even when it changes, however, such as introduction to the plant of a new chemical or a new or modified process, the amount of effort required is likely to be limited.

RECOMMENDATIONS

The various types of exposure assessments have been evaluated in terms of assessment components and were found to be quite similar. A general approach to assessing exposures for all types of assessments was therefore described. This approach develops exposure groups based on multiple criteria and allows a worker to be assigned to multiple exposure groups based on his or her exposure experience. The results can be used for a variety of exposure assessment purposes.

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