Statistical Methods to Estimate Human Exposure to Environmental Pollutants

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1 INTRODUCTION

Using statistical methods to assess human exposure to environmental pollutants is a relatively new concept in environmental sciences. This paper contains discussion of (1) the importance of exposure studies to EPA's environment research and regulatory efforts; (2) new approaches to measuring total human exposure; (3) several recent human exposure field studies, looking at the specific contributions of survey research techniques to these studies: and (4) implications of the findings of total human exposure studies.

2 THE IMPORTANCE OF ACCURATE MEASURES OF HUMAN EXPOSURE

Finding ways to measure and predict pollution levels in the environment is essential to all of EPA's research and regulatory programmes. The Agency's ongoing research on air and water pollutants, toxics, pesticides, acid rain, and hazardous wastes involves evaluating, testing, improving, and standardising measurement systems to study pollutants and their potential health effects. The results of these multimillion dollar research programmes are used to determine trends, assess the state of the environment, and measure compliance with existing Federal regulations. Other Agency functions such as control technology, health assessment, and model development also depend upon good measurement methodology.

More specifically, in the area of air pollution, the goal of the national air pollution control programmes as mandated by Federal law and implemented by the States is to attain National Ambient Air Quality Standards (NAAQS) in all regulated urban areas. The NAAQS for carbon monoxide (CO), for example, specify two different concentrations and averaging times, neither of which is to be exceeded more than once per year, e.g., 35 parts per million (ppm) for 1 hour and 9 ppm for 8 hours. These standards are

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intended to protect against the accumulation of more than two percent carboxyhemoglobin in the blood.

To monitor compliance with the NAAQS for carbon monoxide, EPA has relied primarily on data collected from fixed air monitoring stations located in all major urban areas. EPA also uses these data to estimate and predict population exposure levels. In the past decade, a number of studies have revealed that air pollutant concentrations observed at fixed outdoor monitoring stations are not representative of concentrations sampled in normal urban settings (Wallace *et al.*, 1987). Furthermore, studies of human activities suggest that most people spend the greatest portion of any given 24-hour period indoors—in residences, stores, offices, and factories.

Such studies have raised questions about the usefulness of the data generated at outdoor monitoring stations for protecting the public health (Wallace and Ziegenfus, 1985). However, no previous studies examined the degree to which fixed monitoring stations either underestimate or overestimate the actual exposure of people as they go about their daily activities. In addition, little was known about individual variations in exposure to air pollutants in urban areas, or the frequency distribution of the exposure of urban subpopulations. Previous studies were generally concerned with developing the frequency distribution of representative exposures for the population as a whole (Ott, 1985).

3 NEW APPROACHES TO MEASURING TOTAL HUMAN EXPOSURE

Since the late 1970's, EPA scientists have been making significant progress in developing conceptual approaches and methodologies to assess actual human exposure to air pollutants. Before personal exposure monitors (PEMs) were developed, however, there was no low cost, accurate method for measuring the CO concentrations to which people are normally exposed. With the advent of microelectronics, considerable progress was made in developing reliable, compact air quality monitoring instruments that operate on batteries (Ott and Wallace, 1982). The most dramatic progress came in the new miniaturised personal exposure monitors.

The goal of total human exposure research has been to develop a method of measuring and accurately predicting exposures to various important air pollutants for the populations of major U.S. urban areas. This research has redefined the term "exposure." In the statisticians' terminology, an "exposure" is the event in which a person comes in contact with a "given pollutant at a higher than specified concentration." An exposure becomes the "intersection" or the joint occurrence of two events:

(1) the person is present; and
(2) the pollution is present at concentrations above a specified value.

Two complementary approaches were developed to calculate frequency distributions of a population's actual exposure to a pollutant:

(1) Measure the 24-hour exposure profiles of a large sample of people (who are selected probabilistically to allow extrapolation of the results to the entire population); and

(2) Combine information on the hours people spend in particular activities with the pollutant concentrations associated with particular locations and activities, and calculate exposure profiles.

The first approach has been field tested by EPA over the past ten years in several studies described in detail in the next section. The second approach has not been fully validated in the field, although some small-scale studies have been carried out (Flachsbart *et al.*, 1987).

4 TOTAL HUMAN EXPOSURE STUDIES

In 1982 and 1983, EPA conducted two pilot studies in Washington, DC, and Denver, Colorado, to test for carbon monoxide exposures (Akland *et al.*, 1985; Wallace *et al.*, 1984a). The specific objectives of the studies were to:

(1) develop a methodology for measuring the distribution of CO exposures of a representative urban population using the newly developed portable personal exposure monitors (PEMs);

(2) test, evaluate, and validate this methodology in pilot studies in two cities; and

(3) develop an activity pattern database relating to CO exposures.

EPA developed several models to test CO exposure levels in a variety of microenvironments—stores, office buildings, automobiles, restaurants, and private homes. These models differed from the traditional diffusion models based on fixed station monitoring data, in that they simulated human activity patterns—the movement of people through time and space in daily living and work settings (Ott, 1985).

CO was given primary emphasis in these studies for several reasons:

(1) Accurate and portable field-tested instruments (PEMs) were available for measuring CO;

(2) CO appeared to be a good "indicator" (or surrogate) pollutant for estimating exposure to several other air pollutants of interest;

(3) CO is a nonreactive air pollutant, thus it is simple to treat analytically;

(4) The health effects of CO were reasonably well documented, and EPA had promulgated NAAQS based on these effects;

(5) Considerable data existed showing that CO varies spatially and that most urban locations have concentrations that differ from those reported at fixed air monitoring stations.

To further test the effectiveness of the first approach for obtaining statistically valid frequency distributions of population exposure, EPA conducted a Total Exposure Assessment Methodology (TEAM) survey in eight U.S. cities from March 1979 to the Fall of 1984. The TEAM study was designed to measure concentrations of volatile organic compounds (VOCs) (Wallace *et al.*, 1984b). VOCs comprise a large class of chemicals which includes many carcinogens and mutagens.

Because VOCs are dispersed in media other than air; the study also measured levels of these compounds in the drinking water of the study participants and on their breath (Wallace *et al.*, 1985, 1987). The participants were required to wear personal exposure monitors (PEMs) during their normal everyday activities. Researchers then constructed a complete exposure profile of each participant based on exposure data recorded by the PEM and the participants' diaries.

The new field of total human exposure monitoring has prompted EPA statisticians and environmental scientists to find innovative ways of measuring pollution concentrations in a variety of environments where people spend most of their time.

In both the CO and TEAM studies, traditional social science survey techniques were employed to select the study samples; develop data collection methodologies; and design field protocols for the new CO and VOC measurement devices. Each of these contributions of statistical methods is reviewed below.

4.1 SAMPLE SELECTION TECHNIQUES

Sampling is one of the most important concepts in survey research. Statistical sampling involves selecting a portion of the population representative of the entire population. For both the CO and the TEAM studies, exposure data were collected from a stratified probability sample.

In a probability sample, the members of the population are selected at random. "Random" is not equivalent to "haphazard." A true random selection must be independent of human judgment. With probability sampling, every unit in the population has a known, non-zero probability of being included in the sample. This method of selecting the study participants makes it possible for researchers to draw statistically valid inferences about the entire population that the sample is designed to represent (Kollander *et al.,* 1985; Kalton and Moser, 1972).

In stratified sampling, the population from which the sample is drawn is divided into two or more strata, and the selection of the sample is carried out separately (and randomly) for each subgroup or stratum. Stratification does not imply any departure from probability selection; it does, however, result in better precision, because it ensures that subgroups of the population (such as very high or very low exposure groups) will be included in the sample.

In the TEAM study using a stratified probability sample, EPA was able to calculate highly accurate frequency distributions of the exposures of the adult residents of two major U.S. metropolitan areas having a combined population of 1.5 million. The data collection protocol was designed to be virtually free of bias, and the resulting statistics had a high level of precision. (The level of precision is another common term in survey methodology. The level of precision of the statistics obtained from a probability sample is a measure of how much the statistics differ from the results that would have been obtained had the entire populations been surveyed.)

Let us examine how the EPA statisticians "reduced" the populations of interest in the human exposure field studies to a manageable number of sampling units.

Most large-scale surveys require researchers to select the study sample in several stages. Both the CO and the TEAM study used a multi-stage design, selecting smaller and smaller units at each stage of the study until the population was reduced to a practical number of sampling units.

Multi-stage samples typically use cluster sampling in one or more of the stages. In cluster sampling, groups or "clusters" of adjacent units—apartment buildings, for instance—are formed and a random sample of the clusters is selected. By concentrating sampling units in a small geographic area, cluster sampling can produce enormous cost savings, especially in surveys where face-to-face interviews are required; however, there is also an associated loss of precision, because clustered units tend to be homogeneous.

As an example of clustering, to select a sample of adults living in New York State, researchers might

(1) Select a sample of 20 counties;
(2) Within each of these counties, select three cities;
(3) Within each of these cities, select 5 square blocks;
(4) Within each square block, select 10 households; and
(5) Within each of the households, select one adult for interview purposes.

In this way, a population of several million can be reduced to a sample of 3,000 adults—20 counties × 3 cities × 5 square blocks × 10 households × 1 adult.

In the CO field studies in Washington, DC, and Denver, Colorado, a total of 1,166 nonsmoking adults between the ages of 18 and 70 ultimately were selected to participate. A stratified probability sample was selected in three stages.

In the TEAM study in the neighbouring New Jersey cities of Bayonne and Elizabeth, a three-stage stratified probability sample also was used. The combined population of these two cities, 128,000, was reduced to 852 individuals in the final stage of selection. Ultimately, 355 of these individuals meeting the eligibility requirements were interviewed for the study.

4.2 DATA COLLECTION TECHNIQUES

Some data collection methods are more appropriate for certain research situations; which method is chosen may be dictated both by resource restrictions and specific data requirements (Kollander *et al.*, 1985). The three methods most frequently used to collect quantitative survey data are:

(1) Face-to-face, or personal interview, where the respondents supply data in a face-to-face encounter with a professional interviewer;

(2) Telephone interviews, where the data are collected over the phone directly by an interviewer; and

(3) Self-administered questionnaires, which may be completed at home or in the presence of an interviewer.

It is beyond the scope of this paper to compare the advantages and disadvantages of these three types of interviews, but for much research and development work, face-to-face interviews are the only viable way of collecting detailed technical information. Face-to-face interviews have many advantages: They generally produce a higher response rate, greater cooperation from respondents, and more complete and consistent data, especially when in-depth exploration of issues is desirable. Face-to-face interviews are uniquely suited to probing—a technique used to study the respondent's knowledge of key issues and frames of reference, or, more typically, to clarify and learn the reasons for respondents' answers. The disadvantages of face-to-face interviewing are higher costs and personnel requirements, and the need for extensive training of field staff and close supervision of interviewers throughout the data collection period.

In both CO studies and in the TEAM study, researchers used face-to-face interviews to survey members of the sample selected at the final stage. The field protocols were complex, and required the cooperation of the participants both in activating the measurement device and in maintaining an activity log of their activities.

Short telephone interviews or mail questionnaires were used at the second stage of the exposure field studies to hold down costs and save time. These screening questionnaires were used to identify a group of potential participants with certain characteristics (non-smokers, for instance). The questionnaire used for the second-stage selection of the TEAM study sample contained 61 questions designed to capture comprehensive information relating to respondent's potential exposure to hazardous chemicals, physical condition, dietary habits, and residential characteristics.

4.3 FIELD PROTOCOLS

The field protocols involved personal exposure monitoring (PEM), which required study participants to wear a small measuring device as they went about their normal activities and to keep a record of their activities for a certain period of time—usually 24 hours.

In the CO studies, the study participants pressed an "activity button" on top of the PEM each time they completed an activity or changed their location. The PEM automatically recorded an average concentration over the length of the activity. The participants also were required to fill out certain information in diary form about each of their activities as soon as they were completed. Researchers used participants' diaries to develop exposure profiles, which plot observed concentrations as they varied at different times of the day. This protocol allowed researchers to relate exposures to specific daily activities of the participants.

In the TEAM study, participants completed a questionnaire and activity log. Each participant was given a specially designed miniature pump connected to a "tenax" cartridge. These monitors were to be worn during the day, and placed on a bedside table when the participant went to sleep. The six-inch cartridge and pump operated for up to 14 hours and was capable of collecting a variety of organic compounds. (The TEAM study measured approximately 20 compounds, but several hundred compounds can be measured with this device.) The participants carried these monitors for two consecutive 12-hour periods; at the end of 24 hours, monitors were collected and analysed by gas chromatography-mass spectrometry.

Also at the end of 24 hours, interviewers had participants breathe into a specially designed spirometer to measure levels of VOCs on their breath. Scientists analysed the contents of the spirometer, and were able to compare VOCs in breath levels (i.e., the air that participants breathed out) to exposures recorded on the monitors (i.e., the air that they breathed in).

In some homes, outdoor monitors were set up and operated over the 24-hour period. When readings were completed following the field work, researchers found that levels of 11 important organic compounds, many of which are regarded as potential carcinogens, were significantly higher indoors than outdoors.

5 IMPLICATIONS OF THE HUMAN EXPOSURE FIELD STUDIES

The major findings and conclusions of the human exposure field studies to date are the following:

(1) Exposures are generally greater than indicated by fixed outdoor monitors;

(2) The sources of these higher exposures are often indoors, at home or at work, and in vehicles;

(3) Breath analysis is more sensitive and less complicated than blood analysis for determining body burdens of volatile organics and carboxyhemoglobin; and

(4) Existing source transportation models of human exposure may be inadequate for carbon monoxide and VOCs such as benzene and tetrachloroethylene.

These findings are helping EPA fill basic gaps in our knowledge of environmental risks, and have prompted many hypotheses about new unsuspected sources of human exposure to toxic air pollutants.

Moreover, the wealth of new data is helping EPA assess more accurately than was previously possible the margins of safety incorporated into the NAAQS. Also, by comparing exposure data with measurements from conventional monitoring stations, EPA is now in a position to evaluate the adequacy of existing monitoring networks in terms of actual population exposures. These comparisons may help EPA develop improved criteria for siting air monitoring stations.

Total human exposure studies also have important implications for the emerging field of indoor air quality research. Because in a single field study it is possible to characterise indoor, outdoor, and in-transit contributions to the total exposure of an individual or an entire community, EPA scientists are beginning to discover previously unknown indoor pollution sources. One study already has revealed surprisingly high indoor exposures to a number of organic compounds, apparently due to furnishings and other common items found in the home (Wallace *et al.*, 1985).

From these studies, EPA may discover new ways to mitigate human exposures. Some mitigation strategies, such as removing solvents from the home, may be relatively inexpensive and easy to implement. EPA is now coordinating the results of the TEAM study with (a) studies evaluating the dynamics of building design on indoor air quality; and (b) epidemiological studies of the relative exposure/risk of specific pollutants or families of pollutants.

Survey research techniques will continue to play an important role in human exposure research. Statisticians are now exploring ways to apply the total human exposure methodologies to other pollutants such as nitrogen dioxide, inhalable particulates, trace materials, pesticides, and semivolatile organic compounds.

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