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THE ENVIRONMENTAL PROTECTION AGENCY'S RESEARCH PROGRAM ON TOTAL HUMAN EXPOSURE

Wayne Ott, Lance Wallace, David Mage, Gerald Akland, Robert Lewis, Harold Sauls, Charles Rodes, David Kleffman, Donna Kuroda, and Karen Morehouse
U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C. 20460, and Research Triangle Park, North Carolina 27711

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The U.S. Environmental Protection Agency's (U.S. EPA) research program on total human exposure to environmental pollution seeks to develop a newly emerging concept in the environmental sciences. Instead of focusing purely on the sources of pollution or their transport and movement through the environment, this research focuses on human beings as the receptors of these pollutants. People and daily activities become the center of attention. The methodology measures and models the pollutant concentrations found at the physical boundaries of people, regardless of whether the pollutants arrive through the air, water, food, or skin. It seeks to characterize quantitatively the impact of pollution on people by determining if an environmental problem exists at the human interface and, if so, by determining the sources, nature, extent, and severity of this environmental problem. By exploiting an emerging new arsenal of miniaturized instruments and by developing statistically representative survey designs for sampling the population of cities, significant progress has been made in recent years in providing previously unavailable human exposure field data needed for making valid risk assessments. The U.S. EPA total human exposure research program includes: development of measurement methods and instruments, development of exposure models and statistical protocols, microenvironmental field studies, total human exposure studies, validation of human exposure models with empirical data, and dosage research investigations.

Introduction

Determining the risk of environmental pollution to public health requires a knowledge of five fundamental components: (1) the sources of pollutants, (2) the transport of these pollutants from sources to humans, (3) the exposures of humans to these pollutants, (4) the doses received by people who are thereby exposed, and (5) the adverse health effects resulting from these doses. These five components may be viewed as links in a chain—from source to effect—comprising the full risk model (Fig. 1).

Despite the importance of each of the five components for determining the public health risk associated with environmental pollution, our scientific knowledge about each component is not balanced. Usually, environmental pollution comes to the attention of public officials because pollutant sources, such as a smoke stack plumes or leaking toxic waste drums, provide obvious evidence of disturbing environmental conditions. The obviousness of the sources has focused attention on the source component of the five-component model, and much is known today about source abatement and control.

Once a source of environmental pollution is known and identified, interest often focuses on the manner in which the pollutant moves through the environment—its fate and transport—until it is ultimately assimilated by ecosystems or reaches humans. As with the source component of this conceptual risk model, the fate and transport component has received considerable research attention. The field of meteorology has developed a number of atmospheric dispersion models, and other fields have developed models for the movement of pollutants through streams, soil, and the food chain (Ott, 1976; Santolucito, 1982).

As with the first two components, the fifth component—the effects of pollutants on humans—also has received considerable research attention. Numerous studies have related various exposures and doses to identifiable effects on animals and humans, as can be seen in any of the air quality criteria documents published by the U.S. Environmental Protection Agency additional exposure of, say, 4 μL/L (ppm) may occur. If the person drives to lunch and eats in a smoke-filled restaurant, or one with a poorly vented gas stove, the lunchtime CO exposure may be 9 μL/L (ppm). Finally, the heavy traffic of the evening commute (5:00–6:00 p.m.) may account for an 18 μL/L (ppm) exposure, and additional exposures may occur if the person makes automobile shopping trips. The record of the exposure, expressed as the concentration that a person experiences as a function of time throughout the day, is called the "exposure profile."

For protection of public health, one might be interested in the highest 8-h running average CO exposure on this profile, because U.S. EPA has a CO National Ambient Air Quality Standard (NAAQS) of 9 μL/L (ppm) for 8 h.

Because each person's daily activities differ, his or her exposure profiles also differ. How are the exposure profiles for the population of an entire city to be characterized? From a public health standpoint, interest must focus on the frequency distribution of exposures of the entire population. To illustrate this concept, imagine a city of 200,000 residents. If the 24-h exposure profile on a given date were known for every person, it would be possible to calculate each person's maximum 8-h running average CO exposure. If we then plotted the resulting values on a histogram in which the vertical bars denote the number of persons falling into selected concentration intervals, it might resemble a bell-shaped curve (top of Fig. 2). The area under this curve to the right of the 9 μL/L (ppm) NAAQS represents all the people in the city whose 8-h maximum daily exposure exceeded 9 μL/L (ppm). The cumulative frequency distribution (bottom curve in Fig. 2) is derived from the histogram (top curve) by summing the proportions from left to right. For this example, 58% of the population of the city was below the NAAQS on this date. The result allows a precise statement to be made about the "level of protection" afforded by the standard: "On this date, the probability that any person's 8-h maximum exposure exceeded the 8-h standard was $Q = 1 - 0.58 = 0.42$". Obviously, a protection probability of $P = 1 - Q = 0.58$ does not seem very high, and a prudent public health goal might be to attain a probability of perhaps $P = 0.99$ or 0.999. A level of protection of $P = 0.999$ corresponds to a probability that a person's exposure exceeds the standard of $Q = 1 - P = 0.001$, or 1 in 1,000.

In the last 4 yr, the U.S. EPA has conducted expo-

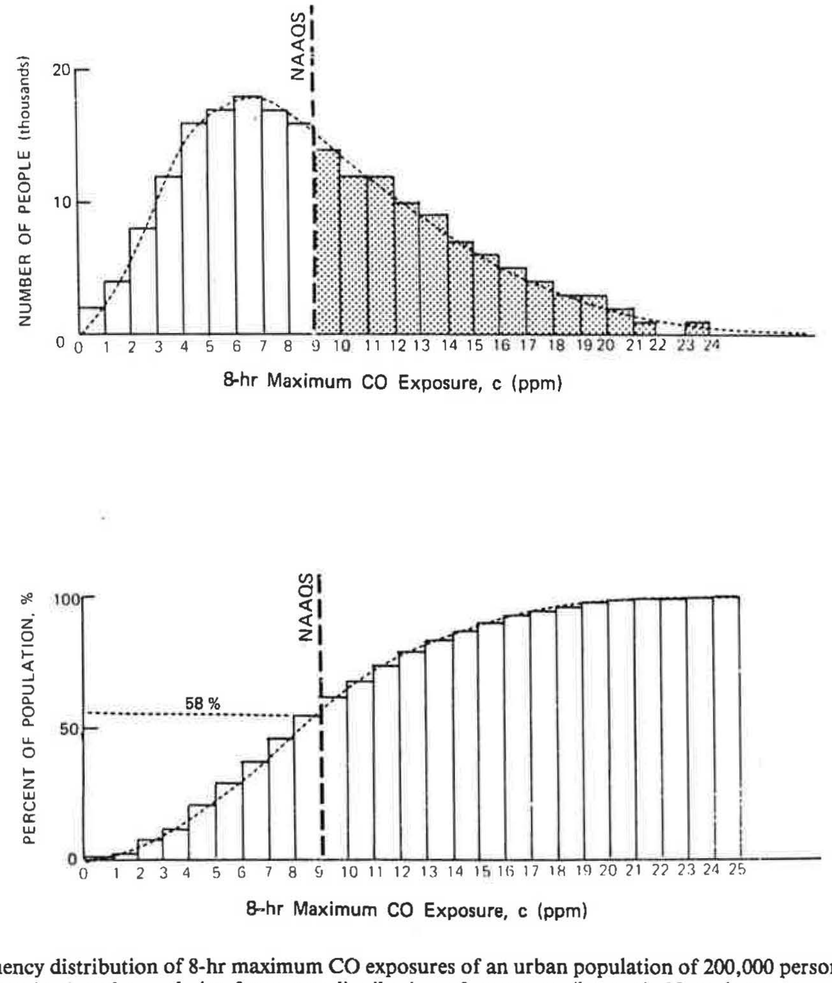

Fig. 2. Hypothetical frequency distribution of 8-hr maximum CO exposures of an urban population of 200,000 persons on a particular date showing: histogram of exposures (top) and cumulative frequency distribution of exposures (bottom). Note that ppm = μL/L

sure analyses as an integral part of the standard setting process. For example, a tentative U.S. EPA analysis conducted to evaluate possible revision of the CO NAAQS estimated that a NAAQS consisting of 1 expected exceedance per year of 9 µL/L (ppm) for 8 h should provide sufficient protection to assure that 99.9% of the population should have blood carboxyhemoglobin levels below 2.5% (U.S. EPA, 1983). This analysis considered a single date in which the highest fixed air monitoring station read 9 µL/L (ppm) for 8 h and utilized a population exposure model to estimate human activity patterns, peak exposures, and blood carboxyhemoglobin levels of the population of a city.

Note that such an approach is less concerned with the exposures of a particular identifiable person and more concerned with the representative exposure distribution of the population as a whole. Despite the importance of such an exposure frequency distribution, until recently we have had virtually no information about the actual exposures of the population to important environmental pollutants. Indeed, much of the fragmentary exposure data available suggested that fixed air-monitoring stations did not reflect actual human exposures very accurately (Brice and Roesler, 1966; Ott, 1971; Ott and Eliassen, 1973; Ott and Mage, 1974; Cortese, 1976; Cortese and Spengler, 1976; Wallace, 1979; Peterson and Allen, 1982; Ott and Flachsbart, 1982; Flachsbart and Ott, 1984; Ziskind *et al.*, 1982; Godin *et al.*, 1972; Waldman *et al.*, 1977; Wright *et al.*, 1975; Repace and Lowrey, 1980). Over the last 5 yr, considerable progress has been made in developing methodology for determining exposures of the population; several exposure models have been developed and a new field survey methodology has been successfully tested for validating these models by actually measuring the population exposures of a city. These new efforts comprise the total human exposure methodology.

Two alternative approaches exist for developing a frequency distribution of exposures of a population: (1) measurement of the 24-h exposure profiles of a large number of persons in the population who are statistically chosen to allow extrapolation of the results to the entire population and (2) combining information on the times people spend in particular activities with the concentrations associated with those activities to calculate exposure profiles. In recent years, both complementary approaches have been tested in U.S. EPA's total human exposure research program.

Approach A

Called the "direct approach" by Duan (1982), this technique seeks directly to measure a person's exposures by measuring concentrations of the pollutant in the air breathed, the water drunk, and the food eaten. To characterize a population's exposures, it is necessary to monitor a relatively large number of people and to select them in a manner that is statistically representative of the larger population. This approach marries the survey design techniques of the social scientist to the latest measurement technology of the chemist and engineer, combining both statistical survey methodology and environmental monitoring in a single field survey. It uses the new miniaturized personal exposure monitors (PEMs) that have become available over the last decade (Mage and Wallace, 1979; Wallace, 1981; Wallace and Ott, 1982), and it adopts the same survey research methods that have been used for many years to measure public opinion and human behavior. In the last several years, U.S. EPA has conducted two major field studies using Approach A: the Total Exposure Assessment Methodology (TEAM) Study of volatile organic compounds (VOCs) and the CO field studies conducted in Denver and Washington, DC.

Approach B

Rather than measuring the exposure profile directly in the manner of Approach A, Approach B seeks to construct the exposure profile mathematically by combining information on the times people spend in particular locations (homes, automobiles, offices, etc.) with the concentrations expected to occur there. This approach requires a mathematical model, information on human activity patterns, and statistical information on the concentrations likely to occur in selected locations, or "microenvironments". U.S. EPA also has conducted studies using Approach B and has developed human activity pattern-exposure models and activity pattern data bases.

In its simplest form, Approach B seeks to compute the integrated exposure as the sum of the individual products of the concentrations encountered by a person in a microenvironment and the time the person spends there. The integrated exposure permits computing the average exposure for any averaging period by dividing by the time duration of the averaging period. If the concentration within microenvironment j is assumed to be constant during the period that person i occupies microenvironment j, then the integrated exposure E_i for person i will be the sum of the product of the concentration c_j in each microenvironment and the time spent by person i in that microenvironment

$$E_i = \sum_{j=1}^{J} c_j t_{ij},$$

where E_i = integrated exposure of person i over the time period of interest;
c_j = concentrations experienced in microenvironment j;

t_{ij} = time spent by person i in microenvironment j; and
J = total number of microenvironments occupied by person i over the time period of interest.

To compute the integrated exposure E_i for person i, it obviously is necessary to estimate both c_j and t_{ij}. If T is the averaging time, the average exposure $\bar{E}_i$ of person i is obtained by dividing by T; that is $\bar{E}_i = E_i/T$, where E_i is summed over time T.

U.S. EPA Research Program

U.S. EPA's current and ongoing research program on total human exposure consists of five distinct research program areas:

- development of exposure measurement methods and instrumentation;
- exposure modeling, data base development, and statistical protocols;
- microenvironmental field studies;
- total human exposure field studies;
- dosage research investigations.

The first program area—development of valid measuring techniques and systems—supports all field studies, including those involving either Approach A or B. The second program area, exposure modeling, supports Approach B, but Approach A field studies are essential to validate the models. Development of statistical protocols supports primarily the total exposure field studies (Approach A). The microenvironmental field studies are those seeking to characterize the concentrations found in selected microenvironments, and they represent more traditional forms of exposure research. The newly emerging fields are those of human exposure modeling, total human exposure field studies, and dosage research. The Approach A total human exposure field studies would not have been possible without the development of new personal monitoring techniques.

Development of Measurement Methods

As mentioned previously, the development of analytical measurement methods and instruments is necessary for all exposure field studies, whether under Approach A or Approach B, because human exposure to environmental pollution cannot be measured unless adequate measuring techniques are available. The measurement of exposures places new demands on the technology, because the size, weight, and power requirements of these instruments must be much less than for conventional monitoring instruments. In addition, the instruments must be quieter and more rugged than conventional systems. The ideal exposure monitor is quiet, lightweight, small, rugged, easily transported, capable of running 24 h or more without auxiliary power, replenishable, and able to provide continuous readings with the same precision and accuracy of conventional monitors.

Unfortunately, personal exposure monitors meeting such requirements are not available for most of the pollutants U.S. EPA regulates. Indeed, the field of exposure measurement methods is in its infancy, and virtually no available exposure measurement methods exist for many of the most critical environmental pollutants. Thus, U.S. EPA's human exposure research program is placing major emphasis on the evaluation of existing methods and the development of new measurement methods, including personal exposure monitors (PEMs), where they are most essential. Many of these projects are described below. Two general categories exist: (1) active monitors, which use an internal power source and (2) passive monitors, which require no internal or external power.

Carbon Monoxide

One of the most successful areas of research has been the development of a PEM for CO. The CO exposure monitor selected by U.S. EPA was made possible by advances in the technology in the occupational health and safety field, principally by the development of small lightweight monitors designed to measure the exposure of miners to CO. Most existing PEMs for CO employ a liquid or solid electrolyte in which CO is converted to CO_2, thereby generating an electrical signal. The signal is proportional to the quantity of CO present in the gas stream, and the continuous electrical signal either is recorded internally or is displayed on a digital readout system. A small pump operates continuously to send air into the sensing cell, and chemical filters in the intake stream remove interferents.

In winter of 1982–1983, U.S. EPA demonstrated the use of these new CO PEMs in large-scale pilot studies of a statistically representative sample of the population in two cities, Denver and Washington, DC (see below). Over 1200 24-h human exposure profiles were collected in these field studies, and instrumentation problems were relatively minor, considering the newness and complexity of the technique. The EPA PEM for CO contained a sensing cell with a solid polymer electrolyte, and a microprocessor data logger was developed which records and stores readings from the PEM internally (Ott *et al.*, 1984). The PEM for CO, including both the monitor and data logger, weighs less than 2 pounds and includes a digital readout display (Fig. 3).

Volatile Organic Compounds

Under contracts from the Office of Toxic Substances and the Office of Research and Development,

Fig. 4. Personal exposures to volatile organic compounds in the general population were measured in the Total Exposure Assessment Methodology (TEAM) study using a Tenax™ cartridge, a miniaturized portable pump, and a specially designed vest. Air enters through the top of the 6-inch cartridge, which is strapped on the front of the vest. A battery-powered pump inside a lower pocket of the vest draws air through the cartridge, and the volatile organics are collected on the Tenax™ filter. After a 12-hr period, the cartridge is removed and is analyzed in the laboratory using gas chromatography-mass spectrometry (GC-MS) techniques. Personal, indoor, and outdoor exposures of 355 residents in Bayonne and Elizabeth, New Jersey, were measured using this approach.

less-steel badge is simply designed and inexpensive. It has a high equivalent sampling rate, is reusable and rechargable, and is designed for thermal desorption. Laboratory and field tests with Tenax® GC as the sorbent have shown that the device compares favorably with active (pump-based) samplers and has much better sensitivity than commercial passive monitors which utilize activated charcoal. Performance was examined under controlled test chamber atmospheres and in actual outdoor and indoor situations. Sampling rates have been determined for 17 VOCs and can readily be calculated for others. An extensive evaluation of the effects of air velocity, humidity, and temperature on the performance of the monitor has been undertaken.

The passive PEM for VOCs, which functions according to Fick's first law of diffusion, samples at rates up to 100 cm^3/min to provide sub-nL/L (ppb) detection limits for most volatile organics after only short exposure periods (e.g., 1 h). It is convenient to wear on the person (no heavy, noisy pump or sampling lines), and it can also be used for unattended indoor or outdoor area monitoring. Current research activities involve the use of supercritical fluid extraction to extend the PEM's capability to monitor semivolatile organics.

Table 1. Blank data for air and breath volatiles.

Compound	mg/cartridge ± SD	
	Field[a]	Laboratory[b]
Vinylidene chloride	1 ±2	<1
Chloroform	22 ±20	8 ±6
1,2-Dichloroethane	<1	<1
1,1,1-Trichloroethane	33 ±21	14 ±17
Benzene	97 ±64	41 ±26
Carbon tetrachloride	2 ±3	15 ±42
Trichloroethylene	3 ±5	1 ±2
Bromodichloromethane	ND	ND
Dibromochloromethane	ND	ND
Tetrachloroethylene	11 ±10	2 ±4
Chlorobenzene	1 ±3	2 ±3
Bromoform	ND	ND
Dibromochloropropane	<1	ND
Styrene	2 ±3	2 ±3
p-Dichlorobenzene	3 ±7	1 ±1
Ethylbenzene	12 ±13	5 ±10
o-Xylene	8 ±9	3 ±5
p-Xylene	22 ±21	7 ±11
o-Dichlorobenzene	1 ±2	1 ±1

[a]N = 76.
[b]N = 79.

Table 2. Control data for air and breath volatiles.

Compound	% Recovery ± S.D.	
	Field[a]	Laboratory[b]
Vinylidene chloride	85 ±23	110 ±33
Chloroform	89 ±22	90 ±39
1,2-Dichloroethane	100 ±15	106 ±31
1,1,1-Trichloroethane	87 ±19	94 ±28
Benzene	86 ±22	90 ±26
Carbon tetrachloride	80 ±20	93 ±24
Trichloroethylene	95 ±12	99 ±24
Bromodichloromethane	96 ±19	98 ±11
Dibromochloromethane	95 ±17	93 ±13
Tetrachloroethylene	108 ±18	109 ±29
Chlorobenzene	110 ±24	109 ±32
Bromoform	96 ±19	92 ±15
Dibromochloropropane	96 ±17	77 ±24
Styrene	104 ±14	92 ±15
p-Dichlorobenzene	101 ±11	87 ±13
Ethylbenzene	95 ±14	95 ±18
o-Xylene	100 ±13	88 ±19
p-Xylene	100 ±14	91 ±18
o-Dichlorobenzene	96 ±13	85 ±15

[a]N = 110.
[b]N = 91.

This passive PEM has been field tested at industrial and hazardous waste sites, where it compared favorably with the pumped Tenax® GC tube (Coutant, 1985; Wooten *et al.*, 1984; Coutant *et al.*, 1984; Lewis *et al.*, 1983; Lewis, 1984). In limited studies at a capacitor disposal site, the PEMs were used to monitor emissions of polychlorinated biphenyls (PCBs). Results compared quite well with those obtained with polyurethane foam (PUF). A comprehensive field comparison of the PEMs, pumped Tenax® GC tubes, and cryogenic sampling has been undertaken, and the results are being analyzed.

Supplemental diffusion barriers have been developed to permit long-term exposure measurements of the passive monitor, and a protective cage has been developed for the PEM to prevent contamination through careless handling when worn on the person.

Pesticides

A battery-powered, low-volume air sampling system utilizing PUF as a trapping medium has been developed and evaluated (Lewis and MacLeod, 1982; Lewis, 1983; Bristol and Lewis, 1981; Lewis *et al.*, 1980; MacLeod and Lewis, 1980, 1981; Lewis *et al.*, 1985a) The sampler provides air flows of up to 4 L/min, affording theoretical detection limits of less than 0.1 $\mu g/m^3$ for most chemicals tested. It is lightweight and portable and operates quietly, which makes it ideally suited for residential air sampling or as a personal air monitor. Sampling efficiencies were determined for 17 organochlorine pesticides and industrial compounds, three PCB mixtures, and 28 organophosphorus, organonitrogen, and pyrethroid pesticides. With few exceptions, these chemicals were trapped efficiently (>75%). Combination of PUF with Tenax® GC in a single, reusable sampling cartridge provided for quantitative collection of the more volatile compounds.

The sampler has been successfully employed in the agency's TEAM studies (Pellizzari *et al.*, 1982a, 1982b; Sparacino *et al.*, 1982; Sparacino *et al.*, 1982; Wallace *et al.*, 1984a; Pellizzari, *et al.*, 1984a, 1984b), in several termiticide and insecticide indoor air investigations, and at several hazardous waste landfills. The methodology has been selected to be utilized in the recently funded pesticides Total Exposure Assessment Methodology (TEAM) study (described below). In the latter application, it will be used to determine respiratory exposures of 500 urban-suburban residents to 34 pesticides and PCBs of interest to the Office of Pesticides Programs.

Nitrogen Dioxide

Two portable, real-time monitors for NO_2 in air have been fabricated and tested under a U.S. EPA contract. The units are based on the light-producing reaction between NO_2 and luminol (Wendel, *et al.*, 1983). Air entering the system is pulled through a unit and across the face of a filter wetted with a solution containing luminol. Light is detected on a photodiode, producing a voltage signal proportional to the NO_2 concentration. Detection sensitivity to the rate at which solution is passed through the filter material and to various physical dimensions, such as the filter width and diode-filter spacing, has been characterized. Evaluation tests at U.S. EPA are still underway.

The two monitors are intended for use in indoor air studies to characterize the real-time variability of concentrations of NO_2. They will be used in field studies along with special signal processing equipment to provide processed data on the excursion of NO_2 concentrations about chosen levels. The monitors are battery powered and operate for 26 h, weigh less than 4 kg, and are smaller than a 30-cm cube. The potential for miniaturization will be evaluated, with a possible follow-up effort to provide a personal exposure monitor.

A project with Washburn University (Topeka, KS) is underway to develop a more sensitive analytical technique for NO_2 in the Palmes passive sampling devices. The feasibility of using ion chromatography (IC) as the analytical finish for NO_2 in Palmes tubes has been demonstrated. The increased sensitivity attainable with ion chromatography and preconcentration will reduce the long sampling time for low concentrations of NO_2 from 168 h to approximately 4 h.

In-house research has shown that the U.S. EPA passive personal exposure monitor (PEM) designed for VOCs can be modified to collect NO_2 data. This involves replacing the Tenax® GC sorbent with triethanolamine-coated filter paper. The advantage of the U.S. EPA-modified PEM is that the sampling times are less than 2 h and that IC analysis can be done directly on a water extract of the filter without preconcentration.

Passive sampling devices are to be used in U.S. EPA's total human exposure research program whenever possible because of their simplicity and because they do not require noisy pumps. This is particularly important in personal monitoring and indoor monitoring as well.

Formaldehyde

Two commercial passive devices are under study for use as personal monitors for nonoccupational exposures to formaldehyde. One device consists of a diffusion tube containing sodium bisulfite. The diffusion badge is analyzed in the laboratory by the chromotropic acid method and is sensitive to 70 nL/L (ppb) of formaldehyde after 1 day of exposure. The other monitor, which is still under development, is a plastic badge containing a film of monodispersed hydroxybenzoic acid hydrazide. Upon exposure, crystalline nuclei are formed in 10 equally spaced bands of the film and read visually after development, which can be performed in the field. The current sensitivity of this badge is 166 nL/L (ppb) in 24 h. U.S. EPA has been working with the manufacturers in an attempt to reduce this to 10 nL/L (ppb).

The crystalline nuclei badges, when received, will be evaluated in chamber studies against a continuous monitor and a U.S. EPA-developed active dinitrophenylhdyrazine (DNPH) sampler. A matrix of concentration and exposure times will be employed in this evaluation, and the effects of humidity, temperature, and air velocity will be examined. The diffusion badges are currently undergoing this evaluation.

The diffusion badges have been extensively evaluated and used in occupational situations. Their application in U.S. EPA's future indoor air quality program may require long exposure times, however. Should efforts to improve substantially the sensitivity of the crystalline nuclei devices be fruitless and/or should greater sensitivity be deemed necessary, the U.S. EPA-developed DNPH active sampler can be used as a personal monitor. It is sufficiently sensitive for exposure periods as short as 1 h and may be used to determine a large number of aldehydes and keytones in addition to formaldehyde. This monitor currently is undergoing evaluation by the American Society for Testing and Materials.

Samplers for Particulate Matter

Several samplers for particulate matter, previously developed under a U.S. EPA interagency agreement, are currently being evaluated for use in personal, microenvironmental, and ambient air monitoring studies under the total human exposure research program.

The National Bureau of Standards (NBS) particulate matter monitor will be redesigned and repackaged to provide a more durable instrument that will provide more reliable operation in the field without altering the aerosol collection characteristics. Existing problems to be overcome include poor seals and short battery life.

A PEM for PM10 (particles of 10 μm or less diameter) is not currently available. U.S. EPA's approach for developing a gravimetric PM10 particulate matter monitor is to use the University of Minnesota-designed PM2.5 sampler (originally designed for Harvard field studies), and to modify the inlet to a PM10 to provide a 0–10 μm cutpoint. Two prototypes will be built and tested in an indoor microenvironment and compared with a PM10 dichotomous sampler.

Microenvironmental field studies require fixed location monitors rather than personal exposure monitors. The number of these fixed location monitors needed to characterize the microenvironment and the placement of samplers are dependent on the spatial and temporal concentration gradients that exist. There are several commercially available rapid response nongravimetric survey monitors that can be used to quantify these gradients rapidly. The accuracy, lower detection limit, and reliability of these survey monitors must be determined. The detection principle of these monitors is either by light scattering or by piezoelectric crystal frequency shift. In future research, the most responsive monitors will be compared to the dichotomous samplers in selected microenvironments.

Statistical Protocols, Data Base Development, and Exposure Models

Statistical sampling protocols are the blueprints for large-scale total human exposure field studies. They lay out the procedures to be used in identifying respondents, choosing the sample sizes, selecting the number of persons to be contacted within various subpopulations, and other factors. They are essential to the total human exposure research program to ensure that a field survey will provide the information necessary to meet its objectives. Because one's activities affects one's exposures, another unique component of the total human exposure research program is the development of human activity pattern data bases. Such data bases provide a record describing what people do in time and space. Finally, the total human exposure research program has produced a unique new class of mathematical models. These models are designed to combine data on human activity patterns with data on microenvironmental concentrations in order to generate estimated exposure profiles and population exposure frequency distributions.

Statistical Survey Design of Total Exposure Monitoring Field Study Protocols

Whenever the objectives of a study are to make valid inferences beyond the group surveyed, a statistical survey design is required. For exposure studies, the only statistically valid procedure that is widely accepted for making such inferences is to select a probability sample from the target population. The survey designs used in the total exposure field studies (described below) have been three-stage probability-based, which consist of areas defined by census tracts, households randomly selected within the census tracts, and stratified sampling of screened eligible individuals (Whitmore *et al.*, 1983, 1984; Akland *et al.*, 1982). The previous field studies utilizing this methodology are listed in below, and the same methodology has been incorporated into the following human exposure field studies conducted by U.S. EPA in 1985–1986:

- Pesticides Exposure Field Study;
- Indoor Air Quality Field Studies;
- Human Exposure Assessment Location (HEAL) Field Study for the World Health Organization (WHO).

Activity Pattern Data Bases

Since the classic international studies of "time budgets" by Szalai (1972), research on human activities by sociologists has emphasized the social and communicative activities of human beings (e.g., watching television, engaging in conversation, performing household chores). Some time budget studies have required respondents to fill out diaries covering their activities over a 24-hour period (Szalai, 1972), while others, such as Chapin (1974) and Robinson (1977), have used the recall methodology. These studies use a statistical protocol similar to the one adopted by U.S. EPA in its total human exposure research field studies (see below). A review of the literature on this topic by Ott (1982b) reveals that, unfortunately, few of these past time budget field studies have provided information that is useful for air pollution exposure estimation. Few investigators, for example, have provided knowledge on the times people spend indoors, outdoors, or in traffic, and few data are available on the use of indoor gas appliances, solvents, or other potential sources of pollution.

Instead of mounting separate activity pattern field investigations, it was more cost-effective for U.S. EPA to include an activity pattern survey as an integral part of its past total human exposure field studies. Thus, both the TEAM study and the Denver–Washington, DC, field study on CO requested that respondents fill out activity diaries during the same 24-h period in which their exposures were monitored. The result is a rich data base on the activity patterns of the population of several cities. Certain activities are relevant for exposures to VOCs (e.g., dry cleaning, use of solvents), while different activities are relevant to CO (e.g., driving a car, entering a parking garage), so the two activity pattern data bases differ. These data bases are extremely important for interpreting the data collected in the total human exposure field studies and also can be used in the development of human exposure activity pattern models.

Total Human Exposure Models

The new total exposure models combine data on human activity patterns with data from microenvironmental field studies in accordance with Approach B, the indirect approach for estimating exposure (described above). An example is the Simulation of Human Air Pollution Exposure (SHAPE) model (Ott, 1983–84) developed by U.S. EPA for modeling CO exposures on the computer. The SHAPE model simulates the movements of each person on a minute-by-minute basis through 14 microenvironments. Whenever a person is known to be within a particular microenvironment, stochastic submodels are called which expose the person to the appropriate CO concentration for that microenvironment. For example, if the person is known to be inside a parking garage, a submodel is called that is designed to simulate CO concentrations inside a parking garage. As long as the person is in the garage, the person's CO exposures are modeled stochastically to reflect CO concentrations similar to those found in real parking garages, as revealed by data from microenvironmental field studies (see below).

A dose submodel has been included in SHAPE to compute the blood carboxyhemoglobin associated with the simulated CO exposure profile (Thomas *et al.*, 1984). One advantage of an exposure model is that it allows different control options to be compared. It also allows exposures to be "predicted" in future years and in cities where limited exposure field data may be available. However, it is important to stress that human exposure models must be validated with actual field data, and only limited field validation has been conducted for any of the existing models. In addition, similar exposure models are needed for most of the other pollutants of concern, such as NO_2, particulates, VOCs, and others.

Models of Exposure Microenvironments

Utilizing data collected in the Washington, DC, microenvironment study (Mack *et al.*, 1984), the Washington, DC, urban-scale CO study, and the Washington, DC, traffic mix study, two modeling and evaluation analyses have been developed. The first, conducted by Duan (1984) under contract, is for the purpose of evaluating the use of microenvironmental and activity pattern data in estimating a defined population's exposure to CO. The second, conducted by Flachsbart of the University of Hawaii, is to model the microenvironmental situation of commuter rush-hour traffic (considering type and age of vehicle, speed, and meteorology) and observed CO concentrations. With the assistance of a contractor, U.S. EPA has collected data on traffic variables, traffic volume, types of vehicles, and model year (see below). An earlier study by Holland and Mage (1983) measured CO in a variety of microenvironments and under a variety of conditions.

The indirect (Approach B) method for estimating population exposure to CO—i.e., use of population activity data along with microenvironment CO concentration data—was compared to exposures to the CO concentrations observed while people carried PEMs during their daily activities (Approach A). The indirect (Approach B) estimate was lower than the estimate derived from personal monitoring at the low concentration levels, say 1 μL/L (ppm) but higher at levels above that. For example, at the 5 μL/L (ppm) level, Approach A estimates were about half the Approach B estimates within the regression model utilizing these data. Many analyses remain to be done, but it appears that when monitoring experts design microenvironmental field surveys, there is a tendency to sample more heavily in those settings where the concentration is expected to be higher, thereby causing exaggerated levels by the indirect method. The possibility of using microenvironmental measurements and/or activity patterns from one city to extrapolate to those of another city is doubtful but not yet fully evaluated.

Development of a microenvironmental model—primarily testing and iterating by computer—formulating commuter exposure as a dependent variable to several predictor variables (traffic characteristics, meteorology, highway configurations, and ambient air quality) currently is in progress.

Preliminary traffic count data indicate that in 1982–1983, cars constituted 96% of vehicular traffic during rush hours, light trucks about 2%, heavy duty trucks slightly less, and motorcycles less than 1%. About 20% to 25% of the autos were 1974 models or older; 35% to 40% are 1981 or later.

Microenvironmental Field Studies

A microenvironmental field study seeks to characterize exposure and sources in a physical microenvironment of relatively small size (usually under 500 m). Because a smaller physical setting is studied, the pollutant exposures and the factors responsible for the exposure can be evaluated in considerable detail. Because of the great number of microenvironments in which people ordinarily conduct their activities, the microenvironments selected for study must be important from an exposure standpoint and must be amenable to analysis. Examples for CO are parking garages and highways; examples for VOCs are showers, dry cleaners, and buildings.

Exposure to Volatile Organic Compounds From Drinking Water Through a Model Shower

A study is underway with the University of Pittsburgh to measure the off-gasing of various VOCs found in drinking water. Drinking water will be spiked with various VOCs, chlorinated ethanes and chlorinated ethylenes, and sent to a model shower to measure the potential exposures to VOCs in drinking water via inhalation. Certain variables (water temperature and pressure) affecting inhalation exposure in the shower will be varied to determine their effect on the volatilization of the compounds. Air samples will be collected and analyzed using gas chromatography/mass spectrometry (GC/MS) methodology. Protocols for determining dermal absorption of various VOCs through bathing are under development.

CO Commuter Route Exposure Field Study

A CO commuter route exposure field study was undertaken in Washington, DC, to build the necessary data base to facilitate: (1) an evaluation of the microenvironmental concept as related to emissions from automobiles; (2) development of a model describing relationships between emissions from motor vehicles in Washington commute traffic and exposures to commuters in the same traffic environment (as discussed above, the model includes variables such as traffic density and vehicle mix, vehicle type, age, and speed); (3) input to the larger data base with activity patterns and exposures to CO in multiple microenvironments; and (4) input to total exposure prediction models such as SHAPE and the NAAQS Exposure Model (NEM).

There are nearly 2,000,000 vehicles in the Washington, DC, metropolitan area, almost 10,000 mi of streets, including 579 mi of major arterials, and about 1,200,000 commuter work trips daily. Intensive study of travel patterns resulted in selection of eight major routes daily funneling a large proportion of the commuter traffic, and these were extended into suburban areas creating "typical" commuter routes. Five autos were driven over these routes for 17 days with CO concentrations averaged (10-sec readings) within the car for every link of every route. CO concentration data also were collected for other commute modes (bus, rail, walking) as well as for shopping centers and office buildings with attached parking garages.

CO exposure levels averaged over links rarely exceeded 25 μL/L (ppm) during auto commuting and averaged 8–13 μL/L (ppm) over entire routes (Mack *et al.*, 1984; Mack, 1984). Concentrations reached 100 ppm in parking garages during the morning and afternoon rushes, but commuters spend only about 5 minutes in such elevated levels. Concentrations in offices usually ranged from 1–5 μL/L (ppm), averaging 2 μL/L (ppm) and retail stores in downtown Washington, DC, averaged about 5 μL/L (ppm).

The PEM employed was the GE-COED instrument attached to a HP-41CV programmed calculator. The data acquisition system worked well and was the subject of one of the published reports (Fitz-Simmons and Sauls, 1984).

Indoor Air Pollution Field Studies

People spend over 90% of their time indoors (Ott, 1982b), so indoor locations are important with respect to possible pollutant exposure. Indoor locations, in general, constitute an extremely large class of microenvironments (restaurants, bowling alleys, ice rinks, schools, office buildings, stores, churches, houses, auditoriums, factories, etc.). Some of these locations have been studied in considerable detail; others have not been studied at all.

A field study of CO concentrations of commercial settings (stores, office buildings, and other areas of commerce) was undertaken (Ott and Flachsbart, 1982; Flachsbart and Ott, 1984) using personal exposure monitors. Studies of exposures to respirable particles in a wood burning community were conducted by Sexton (1984) and Sexton *et al.* (1984). The latter study used 48 volunteers in 24 homes in Waterbury, VT, and it showed that: (1) indoor particle levels were consistently higher than outdoor levels regardless of heating fuel types and (2) outdoor (ambient) particles were not an important determinant of personal exposure to respirable particles. Other indoor air quality studies have yielded similar results.

In 1984, U.S. EPA launched an indoor air quality research program. One of its goals was to better characterize the nature of indoor air quality problems in the United States. In general, the indoor air quality research program focuses on exposures in selected indoor microenvironments, while the research program on total human exposure includes in-transit and outdoor exposures as well, since human exposure profiles ordinarily cover a full 24-h period.

Exposure Methods Test Site (EMTS)

U.S. EPA's Exposure Methods Test Site (EMTS) is a single locale at which research on exposure monitoring methodologies can be conducted in a cost-effective, expeditious, and scientifically credible manner.

The primary objective of the EMTS is to provide a site at which multimedia exposure monitoring methodologies, equipment, and systems can be developed, tested, and compared. Appropriate quality assurance methodologies can be developed in conjunction with the exposure systems development and testing. Methodologies and results developed under this program will be published and made available to the scientific community through the scientific literature.

By using a location in an urban area which has a variety of emission sources, true field trials can be conducted. The geographic size and populations of the EMTS is designed to be sufficiently small to be manageable. General guidelines for the ranges of area and population are: Area, 200–400 mi^2 square miles, about 20% urban and 80% rural/suburban; population, 500,000 to 1,000,000, about 90% urban/suburban and 10% rural.

A survey of the nation was conducted to select candidate sites for EMTS. Fifteen candidate sites were reported to have met at least some of the desirable criteria. These 15 sites were ranked using Census and Standard Metropolitan Statistical Area (SMSA) data and the top five areas were selected for more detailed study.

Total Human Exposure Field Studies

The total human exposure field studies form the centerpiece of U.S. EPA's research program on total human exposure. These studies (Wallace *et al.*, 1982; Zweidinger *et al.*, 1983; Pellizzari *et al.*, 1984a; Hartwell *et al.*, 1984a, 1984b, 1984c; Wallace *et al.*, 1984a; Whitmore *et al.*, 1984; Johnson, 1984a, 1984b; Akland *et al.*, 1985) have demonstrated the feasibility of using statistical procedures to choose a small representative sample of the population from which it is possible to make inferences about the whole population. Certain subpopulations of importance from the standpoint of their unique exposure to the pollutant under study are "weighted" or sampled more heavily than others. In the subsequent data analysis phases, sampling weights are used to adjust for the overrepresentation of these groups. As a result, it is possible to draw conclusions about the exposures of the entire population of a city or a region with a study that is within acceptable costs. Given the richness and usefulness of the data base thus obtained, we believe the approach is especially cost-effective.

Once the carefully drawn sample of people has been selected, their exposures to the pollutant through all environmental media (air, water, food, skin) are measured. Some pollutants have negligible exposure routes through certain media, thus simplifying the study. For example, CO exposure occurs primarily through the air medium, so other routes of exposure can be eliminated from consideration. Two large-scale total human exposure field studies have been undertaken by U.S. EPA to demonstrate this methodology: the TEAM study VOCs and the Denver–Washington, DC, field study of CO.

Total Exposure Assessment Methodology (TEAM) Study

The TEAM Study (1980–1984) was the first and largest study yet undertaken of personal exposures to multiple pollutants and corresponding body burdens. As of December 1984, more than 700 persons in 10 U.S. cities (Wallace *et al.*, 1982; Pellizzari *et al.*, 1984a, 1984b, 1984c; Zweidinger *et al.*, 1983; Hartwell *et al.*, 1984c; Wallace *et al.*, 1984b, 1984c) have had their personal exposures to 20 toxic compounds in air and drinking water measured, together with levels in exhaled breath as an indicator of blood concentrations. Because of the statistical survey design employed, inferences can be made about the entire population of certain areas: 128,000 persons in Elizabeth/Bayonne, NJ; 100,000 persons in the South Bay section of Los Angeles, CA; and 50,000 persons in Antioch/Pittsburg, CA.

The major findings of the TEAM Study may be summarized as follows:

1. Great variability (2–3 orders of magnitude) of exposures occurs even in small geographical areas (such as a college campus) monitored on the same day. This implies that epidemiological studies assuming fairly uniform exposures in a given location cannot succeed.

2. Personal and overnight indoor exposures consis-

tently outweigh outdoor concentrations. At the higher exposure levels, indoor concentrations may be 10–100 times the outdoor concentrations, even in New Jersey.

3. Drinking water and beverages in some cases are the main pathways of exposure to chloroform and bromodichloromethane—air is the main route of exposure to 10 other prevalent toxic organic compounds.

4. Breath levels are significantly correlated with previous personal air exposures for all 10 compounds. On the other hand, breath levels are usually not significantly correlated with outdoor levels, even when the outdoor level is measured in the person's own backyard.

5. Activities and sources of exposure were significantly correlated with higher breath levels for the following chemicals:

benzene: visits to service stations, smoking, work in chemical and paint plants;
tetrachloroethylene: visits to dry cleaners.

6. Although questionnaires adequate for identifying household sources were not part of the study, the following sources were hypothesized:

p-dichlorobenzene: moth crystals, deodorizers, pesticides;
chloroform: hot showers, boiling water for meals;
styrene: plastics, insulation, carpets;
xylenes; ethylbenzene: paints, gasoline.

Future directions using this methodology might include:

1. Inventories and associated chamber studies of building materials and consumer projects contained in high-exposure homes to determine sources and emission rates.

2. Breath measurements of persons living near major point, area, or line sources, such as factories, hazardous waste sites, and expressways.

3. Comparative investigations of exposures and body burden in different countries (WHO HEALS Program).

4. Expansion of the methodology to other compounds: pesticides, PCBs, metals, respirable particulates.

Denver, Colorado-Washington, DC, Human CO Exposure Field Study

A methodology for measuring the frequency distribution of CO exposures in a representative sample of an urban population was developed and applied in two urban areas: Washington, DC, and Denver, CO, during the winter of 1982–1983 (Akland *et al.*, 1985; Johnson, 1984a, 1984b; Hartwell *et al.*, 1984a, 1984b; Ziskind *et al.*, 1982; Jungers, 1983a, 1983b). Household data were collected from 4408 households in Washington, DC, and 2133 households in the Denver metropolitan areas. Exposure data using PEMs were collected from 814 individuals in Washington, DC, and 450 individuals in Denver, together with activity data from a stratified probability sample of the residents living in each of the two urban areas. Well-established survey sampling procedures were used. The resulting exposure data permit statistical comparisons between population subgroups (e.g., commuters vs. noncommuters, and residents with and without gas stoves). The data also provide evidence for judging the accuracy of exposure estimates calculated from fixed site monitoring data.

Additional efforts are underway to use these data to recognize indoor sources and factors which contribute to elevated CO exposure levels and to validate existing exposure models (see above).

Radon Feasibility Study

An epidemiological feasibility study is being conducted in New England with the Maine Medical Center. The purpose of the study is to determine if there is sufficient exposure of a large enough population to justify an epidemiological study to determine if radon from drinking water sources is associated with lung cancer. The study is establishing a reporting system to identify individuals with lung cancer at hospitals throughout Maine and New Hampshire. Once the individuals are identified, they will be asked to answer a questionnaire to determine the type of water supply they use, the style and construction of their house, their smoking and other personal history, and their lifestyle. In addition, the actual radon in their drinking water supply and air in their homes will be measured (using Track Etch detectors). If possible, a case control study will follow the feasibility study to determine the dose-response relationship between radon in drinking water and lung cancer. The results of this study would also include analysis of the distribution of radon in the indoor air from drinking water, construction materials, and natural background sources.

Development of Epidemiologic Protocols

Prior to the development of testable hypotheses on the relationships between indoor air pollutant exposure and human health response, knowledge of pollutant concentrations is needed. It also is critical to determine what the expected health response may be from a knowledge provided by toxicological studies and/or descriptive survey studies. Human survey studies are needed which determine the associations between human symptoms and, if possible, concentrations of particular indoor air pollutants. In the case of several pollutants (e.g., NO_2, CO, and sidestream cigarette smoke) and for certain health effects (e.g., respiratory effects), it has been possible for investigators to develop exposure-response hypotheses which are now being tested in ongoing epidemiology studies.

A plan is being developed for an NO_2 epidemiology

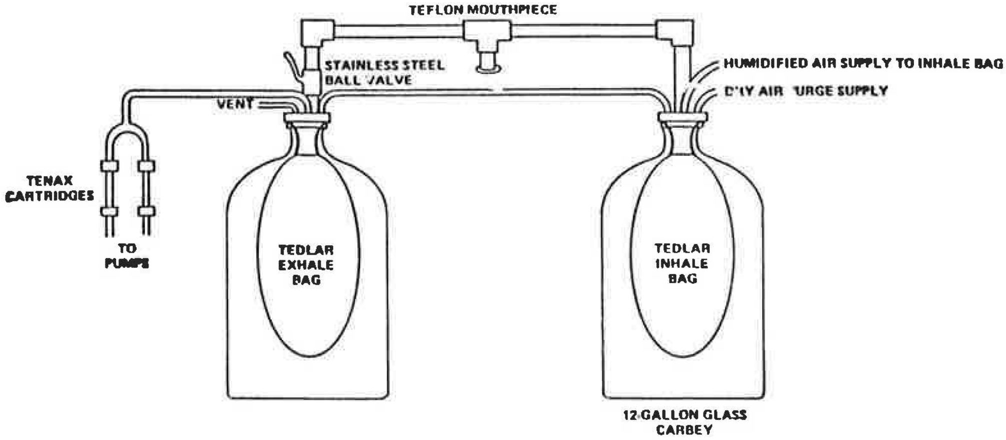

Fig. 5. New spirometer design for collection of breath samples.

cals give further proof that the source of the high exposure is in personal activities or indoors, at home as well as at work.

The basic advantage of monitoring breath rather than blood or tissues are:

1. *Greater acceptability by volunteers*. Persons give breath samples more readily than blood samples. The procedure is rapid and convenient, taking only 5–10 min in all.

2. *Greater sensitivity*. Since volatile organic compounds often have a high air-to-blood partition coefficient, they will have higher concentrations in breath than in blood under equilibrium conditions. Thus, more than 100 compounds have been detected in the breath of subjects where simultaneously collected blood samples showed only one or two above detectable limits.

3. *Fewer analytical problems*. Several "clean-up" steps must be completed with blood samples, including centrifuging, extraction, etc., with each step carrying possibility for loss or contamination of the sample.

The procedure has been successful in detecting brief exposures (to gasoline vapors or dry cleaning shop

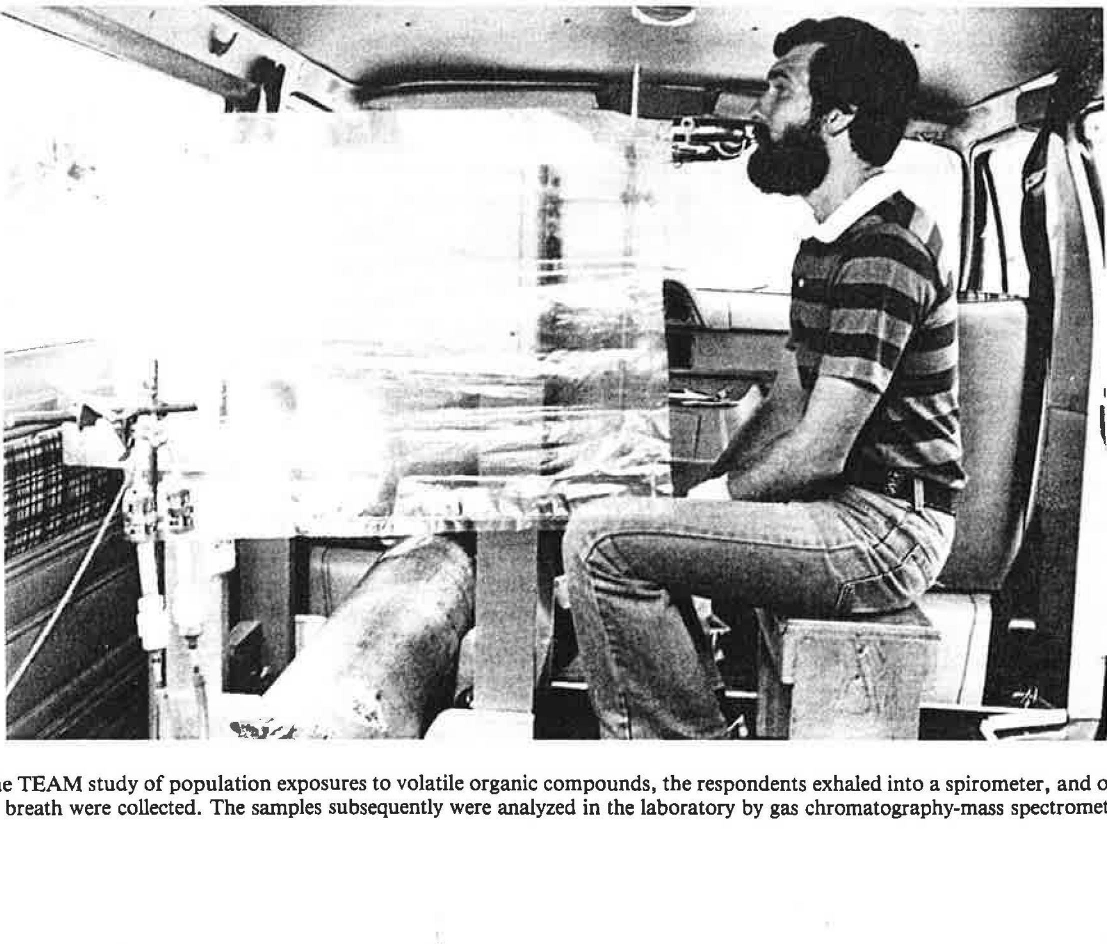

Fig. 6. In the TEAM study of population exposures to volatile organic compounds, the respondents exhaled into a spirometer, and organics present on their breath were collected. The samples subsequently were analyzed in the laboratory by gas chromatography-mass spectrometry (GC-MS).

interiors) occurring several hours before the sample was collected. Thus, the possibility of employing breath sampling to detect recent exposures to chemical spills or releases, or elevated exposure of persons living near a source (hazardous waste site, stationary point sources, heavily trafficked areas) appears to have great potential advantages. The U.S. Navy has recently adopted the technique to investigate the exposures of submarine crewmen breathing completely recycled air during 90-day cruises.

Breath Measurements of Carbon Monoxide

Measurements of CO in expired air often are used as indicators of carboxyhemoglobin (COHb) concentrations in blood, although the precise relationship between alveolar CO and blood COHb has not been agreed upon.

Following the advice of U.S. EPA's Science Advisory Board, the U.S. EPA exposure monitoring program therefore included a breath monitoring component in its large-scale study of CO exposures in Denver and Washington, DC. The purpose was twofold: (1) to estimate the distribution of alveolar CO (and therefore blood COHb) concentrations in the nonsmoking adult residents of the two cities; and (2) to compare the alveolar CO measurements to preceding personal CO exposures.

The major findings of the breath monitoring program (Wallace *et al.*, 1984b) included:

1. The percent of nonsmoking adults with alveolar CO exceeding 10 μL/L (ppm) (i.e., blood COHb 2%) was 11% in Denver and 6% in Washington, DC.
2. The Spearman correlations between breath CO and previous 8-h CO exposure were 0.5 for Denver and 0.66 for Washington, DC, significant at the $p <$ 0.0001 level.
3. The correlations between personal CO exposures at home or at work and ambient CO at the nearest stations averaged 0.25 at Denver and 0.19 at Washington, DC. Thus, the ambient data explained little of the variability of CO exposure.

A major advantage of the breath measurements was in providing an independent estimate of recent exposure, which could be compared with the personal monitor measurements. This comparison helped lead to the discovery that battery drain near the end of the 24-h period caused slightly reduced readings by the personal monitor. Thus, a more accurate estimate of actual CO exposures of the target populations was made possible.

Effects of Ingestion vs. Inhalation Exposure on the Pharmacokinetics and Toxicity of VOCs

U.S. EPA also is conducting a study to compare the pharmacokinetics and toxicity of VOCs found in drinking water, following either ingestion or inhalation exposures. This study will develop and experimentally confirm the application of a pharmacokinetic model to determine the levels of dosage of VOCs from drinking water. Rats will be exposed to VOCs through ingestion and inhalation to determine the extent to which these chemicals are absorbed and distributed to key target organs and the results will be compared using pathological and histological techniques. Pharmacokinetic scale-up procedures will be applied to these results in order to extrapolate them to humans. The most likely compounds to be tested in this system are chloroalkanes and chloroalkenes, such as trichloroethane and/or trichloroethylene.

Radon Pharmacokinetics

A study is underway at Massachusetts General Hospital and Harvard University to determine the distribution of radon in animals (dogs) and humans from both inhalation and ingestion exposures. Krypton and xenon are being used as surrogate gases for radon in this study. A noninvasive radio-tracing technique is being used to trace the distribution of these compounds through the lung, gastrointestinal tract, kidney, and brain. The relative absorption, tissue distribution, and rate of elimination will be determined for these model compounds. The effect of these pharmacokinetic parameters on tissue dose will be compared to toxicity of radon. These data will be useful for determining the levels of radon in various tissues resulting either from inhalation or ingestion.

Health Effects of Heterotrophic Bacteria Found on Point-of-Use Granular Activated Carbon Water Filters

Many individuals and communities are encouraging the use of in-house water treatment devices, such as granular activated carbon filters on water taps, to remove drinking water contaminants. Various unidentified heterotrophic bacteria colonize these devices and may be able to cause disease in humans. U.S. EPA is sponsoring a study at Yale University: (1) to isolate and identify the bacteria which grow in these devices and (2) epidemiologically to compare rates of wound infections and gastrointestinal disease in houses. Initially, the study will determine only rates of disease either by direct contact or by ingestion, because the type of device used is not on shower heads where aerosols could be formed. However, in the future the study will expand to include point-of-entry devices covering disease caused by inhalation of microbial pathogens.

Indoor Air Mutagenic Bioassays

Research to determine the impact of indoor pollutants on human health presents special difficulties due to the number and variety of sources and individual pollutants as well as the variation in indoor environments (e.g., ventilation rate). Although there have been numerous case reports of serious adverse health effects due to indoor exposures to CO and other unvented combustion products and organic chemicals from consumer products, the health effects from indoor exposures to air pollutants have not been extensively investigated.

The approach to be taken to evaluate the health effects of indoor air pollutants (as with outdoor air pollutants) depends on the nature of the pollutant and the type of health effect being investigated. In the case of indoor air pollutants, there is a wide range in the current knowledge of health effects and human exposure relationships. On one extreme are pollutants such as CO and radon, where the health effects are well documented and even the exposure-response relationships are known. However, information is lacking for these pollutants on the extent of population exposed and the total personal exposure levels. The Denver–Washington, DC, field studies (described earlier) have done much to fill this gap. The other extreme is a variety of organic pollutants (e.g., combustion products), where few studies have been conducted to determine the nature or extent of the potential adverse health effects.

Short-term mutagenesis bioassays (e.g., Ames *Salmonella* testor strains) will be used to identify and quantify the contribution of various combustion sources to the mutagenicity of indoor air. The sources being examined will include kerosene heaters, gas stoves, woodstoves, cooking, and cigarettes. Micromutagenesis methods have been developed to allow determination of the mutagenicity of indoor air samples of either particulate associated organic matter or semi-volatile organic compounds.

Conclusions

The U.S. EPA research program on total human exposure seeks to provide a balanced structure for developing methodology and knowledge of the exposures of actual populations to environmental pollution. Because human exposure data fill an important gap in the public health risk model (Fig. 1), the resulting data can greatly improve our estimates of the risk to human health from environmental pollution. By better quantifying human risk, it is possible to formulate better environmental standards, ones that include a more precisely defined margin of safety than previously was possible. Also, by comparing exposure data with measurements from conventional monitoring networks, it should be possible to evaluate the adequacy of existing monitoring networks in terms of actual human exposures. Such comparisons also may help us to develop improved criteria designing such networks.

The total human exposure methodology has important implications for the newly emerging field of indoor air quality. In a single field study, it is now possible to characterize indoor, outdoor, and in-transit contributions to total exposures, which in turn can lead to discovery of previously unknown indoor sources. For example, the TEAM study of VOCs revealed surprisingly high indoor exposures to a number of important organic compounds, apparently due to the materials found commonly in homes. From these studies, we may discover a variety of new procedures for reducing exposures and thereby protecting public health. For example, sealing solvents at home more tightly is one approach that is relatively easy and inexpensive to implement. Total human exposure studies also can help us better understand the influence of human activities, lifestyles, and occupations on pollutant exposures. Finally, the data from these field studies can be used to develop and validate new exposure models such as SHAPE and NEM. Using such models, it may be possible to predict the effect on exposures of different regulatory strategies, and possibly even to predict future exposure frequency distributions in new urban areas or in existing cities where limited field data are available.

Studies of total human exposure and the techniques evolving from them provide a powerful new methodology for filling basic gaps in the environmental risk model. The findings from these studies should help us characterize the sources, nature, and extent of environmental problems with an accuracy never before attainable, and such information is essential for formulating intelligent and effective regulatory programs. In 1985–1986, U.S. EPA adapted the total human exposure methodology to the pesticides problem to conduct a TEAM study of human exposure to pesticides.

As measurement techniques improve, the total human exposure methodology can be applied to other pollutants, such as NO_2, particulates, respirable suspended particles, trace metals, pesticides, and semivolatile organic compounds. In addition, the methodology for CO and VOCs can be applied easily to other locations to compare the results obtained elsewhere with the data already collected. It is extremely important that the initial successes attained in this newly emerging scientific field be followed by continued development of these important new concepts, methodologies, and techniques.

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