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Project Summary

Application of the Microenvironment Monitoring Approach to Assess Human Exposure to Carbon Monoxide

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Exposure estimates based on monitoring carbon monoxide in microenvironments are compared to exposure estimates based on personal monitoring with individual, portable monitors. Methods of calculation are reviewed and discussed, and results of calculations are presented. These data indicate that population exposure estimates based on data from the Washington Microenvironment Study, combined with people's activity data from the Washington Urban Scale Study, are about 40 percent higher than estimates based on personal monitoring data from the Urban Scale Study. The former set of exposure estimates is found to be a good predictor of the latter. Nevertheless, generalizations of these findings to other data bases are not valid at this time.

This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Due to high costs, equipment requirements, and people-related difficulties associated with personal exposure monitoring, it is highly desirable to develop methodology with which to estimate population exposure to air pollution without directly monitoring individuals sampled from the population. Knowledge of pollutant concentrations in microenvironment types (METs) plus information about the activities and mobility of a population under study can be used to obtain all the elements, presumably, needed to produce a valid estimate of overall population exposure. Variability of pollutants, concentrations, and time within METs are the principal limiting factors of reliability, given that reported activities match up well with the defined METs.

This study applies the microenvironment monitoring (MEM) approach, called the *indirect* approach, to estimate human exposure to carbon monoxide (CO), using activity time data from the Washington Urban Scale Study and CO concentration data from the CO Microenvironment Study. The estimated exposures based on the MEM approach are then compared with estimated exposures based on the personal monitoring (PM) approach, called the *direct* approach.

For the specific data used in this study, the MEM exposures are about 40 percent higher than the PM exposures. However, despite this discrepancy, the MEM exposure is found to be a powerful predictor for the PM exposure. On the log scale, the MEM exposure has the correct span relative to the PM exposure; the relationship between the two sets of exposure estimates is found to be a constant drift.

Several factors offer some explanation of the observed difference between the MEM and the PM exposures. The two data collecting activities were not designed primarily for comparative analysis. Therefore, the microenvironments are imperfect matches with the reported activities. The commuting routes of the CO Microenvironment Study were selected as "heavily traveled" and sampled only during the rush hour periods. The PM study sampled travel in private cars at any time it occurred. Also, Wallace, Thomas, and Mage noted that COHb levels estimated from breath measurements were higher than those estimated from PM observations. It is believed that readings decline as the monitor battery discharges. Monitors were used for much shorter periods with more frequent calibrations during the CO Microenvironment Study than in the PM Study.

Exposure Assessment

Until recently, human exposure to air pollution could be assessed only with fixed-site ambient monitoring data. Typically, people residing in the same neighborhood near a monitoring station were treated as homogeneous receptors fixed at the location of the monitoring station. Recent field studies with personal exposure monitors (PEMs) have found this approach inadequate for such pollutants as carbon monoxide, which are spatially variable or have nonambient sources or sinks. During the Washington Microenvironment Study commuters were exposed to 9-12 ppm CO averaged over the entire commute route, while at the same time of day fixed-site monitors in DC logged an average of about 3 ppm CO. A study by Nagda and Koontz observed CO concentrations generally between the MEM and PM values reported here for comparable microenvironments. Obviously it is important to consider population activities and mobility when assessing exposure.

Incorporation of population mobility and activities into the CO exposure assessment process became a more practical reality with the development of reliable, continuous CO personal exposure monitors (PEMs). There are two general approaches to exposure assessment using PEMs. The first is the personal monitoring (PM) approach in which human subjects are sampled from the target population and are equipped with PEMs for a certain time to measure their exposures directly. This approach was taken in the Washington Urban Scale Study. Advantages are simplicity of design and freedom from modeling assumptions. The main disadvantage is cost, too high for large-scale investigations.

An alternative approach to assess exposure is the microenvironment type (MET) approach in which pollutant concentration data are combined with or enhanced by activity time data. The MET approach can be implemented either by the enhanced personal monitoring (EPM) method or by the microenvironment monitoring method. The latter approach was taken in the CO Microenvironment Study in Washington, DC, during the Winter of 1983.

The MET method combines MET-specific pollutant concentration data and activity time data to estimate exposures. This approach incorporates information about the mobility of the population under study. A relatively inexpensive way to implement the MET approach is through microenvironment (ME) monitoring. Instead of MET concentration data from personal monitoring, a number of MEs may be sampled in each MET, with research staff or trained technicians sent to the sampled microenvironments to monitor those microenvironments directly.

Methods for Estimating Exposure

The MET concentration data and the MET time data can be combined in several ways to estimate exposure. If one is interested only in average exposure, one can use the average time-weighted summation formula and estimate average exposure by

$$\overline{E} = \sum_k \overline{C}_k \times \overline{T}_k \qquad (1)$$

where $\overline{E}$ is the average exposure, $\overline{C}_k$ is the average MET concentration for the k^{th} MET, and T_k is the average MET time for the k^{th} MET. This method implicitly assumes that the MET concentrations and MET times are uncorrelated. The assumption basically rules out responses to air pollution episodes which might cause people to stay away from high concentration METs during such days.

For most purposes the mere estimation of average exposure is inadequate, and it is necessary to estimate exposure distribution or individual exposures. One way of doing this is to use a simulation model in which the concentration and activity data are summarized by probabilistic distributions, human activity and concentration data are simulated from those probabilistic distributions, and the simulated data are used to estimate exposures. This type of approach generally assumes that the concentration and time are independent. Another approach is the convolution method. Units (e.g., persons) from the activity data base are paired with units (e.g., days) from the concentration data base to form convoluted units (e.g., person-days), and the exposure for each convoluted unit is estimated using a time-weighted summation formula similar to Equation (1).

$$E_{im} = \sum_k C_{mk} \times T_{ik} \qquad (2)$$

where E_{im} is the exposure combining the i^{th} unit in the activity data base and the m^{th} unit in the concentration data base, C_{mk} is the MET concentration for the m^{th} unit in the concentration data base in the k^{th} MET, and T_{ik} is the MET time for the i^{th} unit in the activity data base in the k^{th} MET.

To illustrate the application of Equation 2, consider a study that has 43 days of MEM data, combined with a sample of 705 persons, each providing one day of activity diary. If the i^{th} person in the activity sample spent the day according to T_i and was exposed to concentrations C_m in the METs encountered during that day, he would receive exposure E_{im}. As independence is assumed between the MET concentrations and times, each of the 43 concentration vectors C_m is equally likely for each of the 705 participants. With the convolution method, the exposures E_{im} are derived for each of the 43 x 705 = 30,315 pairings of persons and days in the two data bases. Each such pairing forms one convoluted person-day.

Another method can be viewed as a hybridization between the average time-weighted summation formula Eq. (1) and the convolution method Eq. (2). With this hybrid method, the average MET concentration in each MET is used to estimate the exposure for each unit (day or person-day) from the activity data base by

$$E_i = \sum_k \overline{C}_k \times T_{ik} \qquad (3)$$

This method ignores the variability in exposures between microenvironments of the same MET. If all microenvironments belonging to the same MET have the same concentration, this method is preferable to the convolution method because of its simplicity. If the microenvironments belonging to the same MET vary substantially, this approach is likely to underestimate the variability of the exposure distribution.

Activity Time Data

A population-based study of CO exposure was conducted during the winter of 1982-83 in the Washington, DC metropolitan area. An area probability sample of human subjects was enrolled for one day for each in this study. The participants filled out activity diaries giving the activities they were engaged in during each time period. The activities were entered in the diaries as activity segments, where each activity segment was defined to be the time period between two reported changes in activities in the activity diary. The participants' exposures to CO were measured using PEMs, which recorded the average concentration over each activity segment.

The participants in the Washington Urban Scale Study were selected from a probability sample. To extrapolate from the sample to the target population, it is necessary to weight the individual observations by the sampling weights based on sampling probabilities. In preliminary analysis, the summary statistics based on the weighted and the unweighted procedures were compared. The weighting did not have a major effect on the results. For example, the average time spent in car commuting differs by about 2 percent between the weighted and the unweighted estimates. Because the primary goal of the comparative study is to compare the estimated exposures based on the MEM and PM approaches for the observed sample, the extrapolation to the target population is not crucial. Therefore, to simplify the analysis, it was decided not to weight the individual observations.

In the Washington Urban Scale Study each participant filled out activity diaries for one day. During this sampling day, whenever there was a new activity—e.g., the participant stopped reading a newspaper in the living room (end of an old activity) and went outside for a walk (beginning of a new activity)—the participant was required to record the start time of the new activity and describe it. The period between two entries in the activity diary is referred to as an activity segment. Each activity segment is regarded as one microenvironment.

Based on information available, activity segments are grouped into seven METs: parking, public transportation, private car, pedestrian, shops, offices, and other. The rest of this section gives the heuristic definitions of these METs.

The MET *parking* is restricted to indoor parking because only indoor parking concentration data are available from the CO Microenvironment Study. The MET *public transportation* includes both bus and metrorail. Because both buses and metrorails are monitored in the Microenvironment Study, it is possible to consider them as distinct METs. However, in the evaluation of MET classification schemes, it was found unproductive to distinguish between these two METs; therefore, *public transportation* is considered as one MET without further refinement.

The MET *private car* includes private cars, trucks, motorcycles, and vans. It is debatable whether this MET should be restricted to the narrow definition including private cars only. (Only private cars were monitored in the Microenvironment Study). The four modes of travel were grouped into one MET for two reasons. (1) The amount of time spent in trucks, motorcycles, and vans is very small compared with the amount of time spent in private cars. The total amount of time spent in the four modes of travel is 1.623 hours per person per day, out of which only 0.106 hours belong to the three modes other than private car, less than 7 percent of the total. (2) The MET concentrations based on PEM for those four modes of travel are roughly similar. The difference between car and truck is small (about 1 ppm) and statistically insignificant. The difference between car and van is not small (about 3 ppm) and is statistically significant, but only seven people reported using a van in their travel.

The MET *pedestrian* includes walking, biking, and jogging. It is again debatable whether jogging and biking should be grouped with walking into one MET. The amount of time spent jogging and biking is very small (less than 6 percent) compared with time spent walking. The difference in concentrations between walking and jogging is very small (less than 0.1 ppm) and statistically insignificant ($t = 0.09$). The difference between walking and biking is about 2 ppm and is statistically significant ($t = 2.09$). However, only five people reported biking during the sampling period. Therefore, they are combined into one MET.

The MET *shops* consists of the activity segments reported as stores, shopping malls, and theaters in malls. The amount of time spent in the malls is small relative to the time spent in stores (less than 5 percent). The difference in concentration is very small (less than 0.5 ppm) and statistically insignificant ($t = 0.65$). Therefore, they are combined into one MET.

The MET *offices* consists of activity segments reported as offices. The MET *other* is a residual category for activity segments not considered above. The main component of activity segments in this MET is home. Because there are no microenvironment monitoring data corresponding to these activity segments in the Microenvironment Study, this MET cannot be refined any further.

CO Concentration Data

The Washington CO Microenvironment Study was conducted in the metropolitan area during the winter of 1983. Primarily the study focused on the measurement of commuting microenvironments including parking garages, driving an automobile, riding a bus, riding a train, and walking. For automobile commutes, the study identified eight routes that "collectively extend 160 miles, about 8.6% of the total length (1,853 miles) of Washington's arterials and freeways." (In 1980, the Washington metropolitan area had 9,432 miles of streets and roads, including arterials, freeways, and locals). The routes selected were ones considered to be heavily traveled and predicted to have high CO exposures during rush hour periods.

Although the routes were chosen to be representative of the arterials and freeways, they might not be representative of all routes traveled by the general population. The empirical analysis found that for the commuting METs, the MET concentrations from the CO Microenvironment Study are substantially higher than corresponding MET concentrations based on personal monitoring from the Urban Scale Study.

A Commuter Study Links Data Base was constructed from the commuting part of the Microenvironment Study. Each commuting route was divided into links ranging from one-half to three miles, each link being a physically distinct segment of the route and regarded as an individual microenvironment. For quality assurance, several commuting trips used collocated monitors or inside/-outside pairs. In the paired situation, this study restricts attention to the primary monitor.

The ME study included monitoring on some indoor microenvironments—shopping centers and offices. Additional monitoring was conducted on *walking* microenvironments. The *pedestrian* data are combined with those from the commuting part of the study and analyzed as belonging to the same MET.

One major exclusion in ME coverage was the *home* microenvironment. A residual MET, referred to as the MET *other* consists of all microenvironments not covered in the Microenvironment Study. For the exposure estimation, the microenvironment monitoring data are supplemented with personal monitoring data from the Urban Scale Study for those microenvironments not covered in the Microenvironment Study.

Observed MET Concentrations

Concentrations Based on MEM

For each MET except the MET *other*, the measurements from the Microenvironment Study are aggregated into daily averages, which are used as the MET concentrations in further analysis. A total of 43 days were measured during the period from January 1 through March 18, 1983.

As expected, the concentrations in parking garages are very high. The average concentration exceeds the one-hour federal standard level of 35 ppm. The concentration in private cars is also fairly high. The average concentration exceeds the eight-hour federal standard level of 9 ppm. *Public transportation, walking,* and *shops* have moderate levels averaging about 5 ppm. *Offices* have low levels, averaging about 2 ppm.

Concentrations Based on PM

An alternative set of estimates of MET concentrations can be derived from the personal monitoring data in the Urban Scale Study. For each activity segment reported, the exposure for that activity segment is computed as the product of the duration of the activity segment and its average CO concentration. For each participant and for each MET, the exposures from the activity segments belonging to that MET are summed as the total exposure for that MET. The total exposure in the MET is divided by the total amount of time (hours) in the MET to get the average MET concentration.

For certain activity segments, the CO concentrations are not available, possibly because of monitor failure. Those activity segments are not included in the calculation of the MET concentrations. To assess the effect of those missing data, the amount of time belonging to such activity segments is calculated for each participant and for each MET. For three METs—namely, *shops, parking,* and *public transportation*—none of the participants had any activity segments with missing CO concentration data. For the other three METs, some of the activity segments did not have CO concentrations. However, the amount of time for those activity segments is very small. For the MET *private car,* the average amount of time per participant for which CO concentration is missing is 0.004 hours. This is less than one-half of 1 percent of the average time of 1.623 hours spent in this MET. For the MET *office*, the average amount of time without CO concentration is 0.001 hours, again very small compared with the average time of 0.269 hours in this MET. Missing concentration data is, therefore, of very little effect.

Comparison of MET Concentrations

The MET concentrations based on PM are substantially lower than the corresponding MET concentrations based on MEM, especially in the commuting METs. The most dramatic difference of all is the MET *parking*, in which there is a fourfold difference between PM and MEM. The average MET concentration for *private cars* based on MEM is more than twice the corresponding average concentration based on personal monitoring. It is suspected that incongruencies inherent in the matchups of activities to MEs, ME rush hour sampling, and monitor battery rundown contributed considerably to these differences.

Comparison of Exposure Distribution Estimates

The comparison between the two sets of summary statistics for the estimated exposures indicates that the two distributions are substantially different. The average MEM exposure is about 40 percent higher than the average PM exposure. The difference is highly significant ($t = 6.69$ for the convolution method, $t = 8.01$ for the hybrid method). The comparison between the summary statistics for the log estimated exposures also indicates major differences between the MEM and PM exposures. The average log MEM exposure is significantly higher than the average log PM exposure.

For certain situations such as qualifying the health effects of air pollution, it is only necessary that the estimated exposure be a good predictor of actual exposure. In such instances the appropriate way to assess the validity of the estimated exposure is to examine the regression relationship between the actual and estimated exposures. The slope coefficient in the regression relationship must be significant, indicating that the estimated exposure predicts the ranking of actual exposures, even though the magnitude might be off. Furthermore, the slope coefficient should be close to one, and the intercept coefficient close to zero, implying that the estimated exposures are approximately equal to the actual exposures.

As usual the actual exposures are unknown, therefore one cannot adequately define the relationship between the estimated exposures and the unobserved actual exposures. The PM exposure is used as the benchmark and the regression relationship between the two estimated exposures is tested, regressing the PM exposure on the MEM exposure.

On the original scale, the regression results show a very significant relationship between the PM and the MEM exposures. The convolution method gives a more significant slope coefficient than the hybrid method. This indicates that even though the MET concentrations from MEM and PM are substantially different, the MEM exposures are still useful for predicting the ranking of the PM exposures. In other words, given that a certain individual's MEM exposure is high, it is reasonable to expect that his PM exposure is also high.

The R^2 statistic for the convolution method is about 40 percent, indicating that the MEM exposure is not only a significant predictor for the PM exposure but is also an informative predictor, explaining an important fraction of the variability in the PM exposure. The hybrid method has a much smaller R^2. With the convolution method, the slope coefficient in this regression is about 0.5, substantially smaller than one, and the intercept coefficient is about 0.5 ppm, significantly larger than zero. For simplicity the estimated regression model may be approximated as follows:

$$\text{PM exposure} \simeq 0.5 + 0.5 \times \text{MEM exposure.}$$

At low levels (less than 1 ppm), the MEM exposure underestimates the PM exposures. For example, for an individual with MEM exposure equal to zero, the regression model predicts that his actual exposure is probably about 0.5 ppm. At higher levels (more than 1 ppm), the MEM exposure overestimates the PM exposure. For example, for an individual with MEM exposure equal to 10 ppm, the regression model predicts that his PM exposure is probably about 5.5 ppm, substantially lower than the MEM exposure. Because the average MEM exposure is about 2 ppm, for most people the MEM exposure overestimates the PM exposure according to the regression model.

On the log scale, too, the regression results show a significant relationship between the MEM exposure and the PM exposure, indicating that the MEM exposures successfully predict the ranking of the PM exposures. The R^2 statistic for the convolution method is about 60 percent, indicating that the log MEM exposure is fairly powerful in explaining an important fraction of the variability of the log PM exposure.

Conclusions

Methods for estimating population CO exposures using microenvironment monitoring (MEM) data, personal monitoring (PM) data, and activity data have been presented and results compared.

The MEM/activity data exposures averaged about 40 percent higher than the exposures estimated by the PM method. The observed difference in the estimated distributions is probably specific to this data base and should not be generalized.

Given the imperfect matches of microenvironments and problems associated with personal monitoring, it is impressive that the MEM exposure is such a successful predictor of PM exposure, especially on the log scale on which the MEM exposure derived by the convolution method has the correct span relative to the PM exposure and the drift is constant over the range.

The convolution method is preferable to the hybrid method for this data set due to the high variability within the MET concentrations.

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The complete report, entitled "Application of the Microenvironment Monitoring Approach to Assess Human Exposure to Carbon Monoxide," (Order No. PB 85-228 955/AS; Cost: $11.50, subject to change) will be available only from:

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