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Jouni Jurvelin [a] , Matti Vartiainen [a] , Matti Jantunen [a] & Pertti Pasanen [b]
[a] Division of Environmental Health , KTL-National Public Health Institute , Kuopio , Finland
[b] Department of Environmental Sciences , University of Kuopio , Kuopio , Finland
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Jouni Jurvelin, Matti Vartiainen, and Matti Jantunen
Division of Environmental Health, KTL-National Public Health Institute, Kuopio, Finland

Pertti Pasanen
Department of Environmental Sciences, University of Kuopio, Kuopio, Finland

ABSTRACT

Personal 48-hr exposures to formaldehyde and acetaldehyde of 15 randomly selected participants were measured during the summer/autumn of 1997 using Sep-Pak DNPH-Silica cartridges as a part of the EXPOLIS study in Helsinki, Finland. In addition to personal exposures, simultaneous measurements of microenvironmental concentrations were conducted at each participant's residence (indoor and outdoor) and workplace. Mean personal exposure levels were 21.4 ppb for formaldehyde and 7.9 ppb for acetaldehyde. Personal exposures were systematically lower than indoor residential concentrations for both compounds, and ambient air concentrations were lower than both indoor residential concentrations and personal exposure levels. Mean workplace concentrations of both compounds were lower than mean indoor residential concentrations. Correlation between personal exposures and indoor residential concentrations was statistically significant for both compounds. This indicated that indoor residential concentrations of formaldehyde and acetaldehyde are a better estimate of personal exposures than are concentrations in ambient air. In addition, a time-weighted exposure model did not improve the estimation of personal exposures above that obtained using indoor residential concentrations as a surrogate for personal exposures. Correlation between formaldehyde and acetaldehyde was statistically significant in outdoor microenvironments, suggesting that both compounds have similar sources and sinks in ambient urban air.

IMPLICATIONS

The study presented here was a part of the European Union 4th framework RTD Programme-funded EXPOLIS study. Objectives of the EXPOLIS study included assessment of European urban population exposures to major air pollutants and analysis of personal and environmental determinants of these exposures. Results from this study confirm that indoor residential air is the most important determinant of personal exposures to formaldehyde and acetadehyde in Helsinki.

INTRODUCTION

The two most abundant aldehydes in ambient air—formaldehyde and acetaldehyde—are of concern because of their adverse effects on human health and their influence on photochemical smog processes.[1-5] Formaldehyde is a confirmed animal carcinogen and a suspected human carcinogen.[6] Acetaldehyde and its oxidation products, such as peroxyacetylnitrate, have been studied for suspected mutagenic and carcinogenic effects.[7] Additionally, both compounds are eye and respiratory irritants. In ambient urban environments, formaldehyde and acetaldehyde are both emitted directly by traffic and formed in situ by photochemical processes.[8] Inside buildings, sources of formaldehyde include cigarette smoke, insulating materials, chipboard or plywood furniture, water-based paints, fabrics, household cleaning agents, disinfectants, particle board, and other construction materials.[9] Indoor acetaldehyde concentrations in residences may be related to emissions from smoking, combustion appliances, cosmetic products, and some hobby supplies such as photographic chemicals and special adhesives.[10] Since acetaldehyde is a product of human metabolism and is present in human expired air, with higher levels observed in smokers and abstinent alcoholics, indoor residential concentrations may be related to direct emissions from humans.[11,12] In addition, some indoor activities such as cooking and baking increase indoor air concentrations of both formaldehyde and acetaldehyde.[13]

Exposure is quantified as the amount of agent/substance available at the exchange boundary of the receptor organism per specified time period.[14] It is related

directly to the pollutant of interest, to the individual, and to the time and duration of exposure. Several studies have shown that personal exposures to many pollutants correlate much better with indoor than with outdoor concentrations.[15,16] These findings can partly be explained by the high proportion of time that people spend indoors (about 85–95%).[17,18]

There have been few studies of formaldehyde and acetaldehyde where nonoccupational levels of personal exposure have been directly measured and compared to microenvironmental concentrations (such as indoor residential, outdoor, and workplace).[19,20] Personal 48-hr exposures to formaldehyde and acetaldehyde of 15 randomly selected participants in the Helsinki metropolitan area, Finland, together with microenvironmental concentrations in participants' residences (indoor and outdoor) and in workplaces, were measured as a part of a European study of air pollution exposures, EXPOLIS. This paper introduces personal and microenvironmental sampling and analysis techniques for formaldehyde and acetaldehyde together with personal exposures and microenvironmental concentrations measured in Helsinki.

EXPERIMENTAL METHODS

Population Sample

The target populations of EXPOLIS were European adult urban inhabitants.[21] In Helsinki, a base sample of 2523 adults (25–55 years of age) was randomly selected from the population census of the Helsinki metropolitan area. A short screening questionnaire was completed and returned by 1881 participants of this base population sample. A subsample of 15 participants was drawn at random from these 1881 participants for measurement of formaldehyde and acetaldehyde exposures.

In Table 1, some characteristics of the subsample are presented and compared to the 1881 respondents of the Helsinki base sample. The evaluation of the population sampling bias between the 1881 respondents and the Helsinki metropolitan area population has been presented elsewhere.[22] The subsample consisted of 11 women and 4 men between 31 and 54 years of age. Two of the participants were unemployed and four smoked during the 48-hr sampling period. One of the smokers smoked indoors in the residence and three participants reported that smoking occurred in their workplace. One participant lived in a single-family house, six in attached houses, and eight in apartment buildings. None of the single-family or attached houses had an attached garage.

Table 1. Subsample of 15 participants (n = 15) vs. respondents of Helsinki base sample.

	Study Sample (n = 15) %	Respondents (25–55 years) (n = 1881) %
Gender		
Men	27	44
Women	73	56
Age		
25–34 Years	27	32
35–44 Years	33	32
45–55 Years	40	36
Self Smoking		
Yes	27	28
No	73	72
Marital Status		
Married	80	68
Not married	7	21
Divorced	13	10
Unemployed or Working at Home		
Yes	20	16
No	80	84
Home Type		
Single family or attached house	47	33
Block of flat	53	65
Home Area		
≤60 m^2	27	37
>60 m^2	73	62

Personal and Microenvironmental Measurements

Personal exposure levels and microenvironmental concentrations of formaldehyde and acetaldehyde were measured during the summer and autumn of 1997 (May 14–September 26, 1997). Formaldehyde and acetaldehyde were sampled in addition to $PM_{2.5}$, NO_2, and volatile organic compounds (VOCs), which were the core analytes of the EXPOLIS study. Personal exposures were measured by personal exposure monitors (PEMs) carried by each participant for 48 hr. Microenvironmental monitors (MEMs) were placed inside and outside of each participant's residence and in each participant's workplace and were programmed to run for self-reported nonworking hours and self-reported working hours, respectively. The total number of outdoor measurements at residences was 13, as there were no suitable locations for two participants to install the outdoor MEM. In addition, microenvironmental concentrations at workplaces (indoor) were measured for 10 participants, as it was not possible to measure in the workplace for three participants and two participants were unemployed. One workplace measurement was carried out in the residence, as one participant worked at home.

Formaldehyde and acetaldehyde were sampled using Sep-Pak DNPH-Silica cartridges (Waters). Air was drawn through the cartridge using the vacuum generated by the $PM_{2.5}$ pump. An aldehyde sampling line was connected to the $PM_{2.5}$ sampling line by a T-joint, and diffusive flow

during nonsampling periods was limited by small-pore Teflon tubes (350 mm in length, 1.6-mm i.d.) placed in front of and behind the sampling cartridge. Airflow through the cartridge was measured before and after each sampling period with a bubble flow meter (Mini Buck Calibrator M-1, A.P. Buck Inc.). Sample volumes were calculated using the average of pre- and postsampling flow rates. In personal exposure measurements, the average sampling volume was 66.4 L with a standard deviation (SD) of 14.9 L. In microenvironmental measurements, the average sampling volume was 122.6 L (SD 46.0 L). The average sample flow rate was 23.6 mL/min (SD 5.3 mL/min) in personal exposure measurements and 91.6 mL/min (SD 21.4 mL/min) in microenvironmental measurements. To avoid a negative interference from O_3, a copper tube (500 mm in length, 4-mm i.d.) with KI coating was used as an O_3 scrubber for all samples.[23]

PEMs were packed into aluminum briefcases (5.2 kg total), which could be carried in the hand, as shoulder bags, or as backpacks by the participants during their daily activities. The modified PEM pump (Buck I.H., A.P. Buck) was equipped with a volumetric flow control and could be operated for the entire 48-hr sampling period on a single set of batteries. MEMs were packed into portable sound-absorbing containers (MDF-board coated with a low-emission paint). The MEM pump (BGI PQ100, BGI Inc.) could be operated for up to 36 hr on an internal lead-acid battery. The pump was equipped with a mass flow control and timing. In microenvironmental measurements, MEMs were located in central representative locations at least 1 m away from the wall and 50 cm from the floor/ground level. Air was sampled outside of the boundary layer of the PEM case or the MEM container for both personal and microenvironmental sampling. Both temperature and relative humidity (Extech 445922, Extech Inc.) were measured when MEMs were delivered and collected from the residence or workplace. Sampling data were recorded in the EXPOLIS database after each measurement.[21]

Sample Analysis

Hydrazone derivatives of formaldehyde and acetaldehyde were eluted from Sep-Pak DNPH-Silica cartridges with 3-mL acetonitrile (ACN) (HPLC grade). The mass of solvent that was recovered from the silica cartridge in 2 min was weighed for exact volume determination. An automatic injector injected 15 μL into an HPLC pumping system (HP 1050, Hewlett Packard GmbH) with a Hypersil BDS C18 (3 μm, 100 × 4 mm) column at a flow rate of 1.3 mL/min, coupled with UV detection (Hewlett Packard). An isocratic run was used for the first 2 min with 60% water, 35% ACN, and 5% tetrahydrofuran (THF). Subsequently, gradient elution was used (from min 2 to 15 of each run), where the percentage of THF was decreased to 0% and ACN was increased to 73%. Finally, ACN was increased to 90% and maintained for 2 min (from min 15 to 20 of each run). Analytical and reference wavelengths were 360 and 450 ηm, respectively.

Pure 2,4-dinitrophenylhydrazine (DNPH) derivatives of formaldehyde and acetaldehyde were synthesized separately for standards by reaction with DNPH. Saturated DNPH solution was prepared in 2 M HCl and the solution was filtered through a hydrophilic membrane filter (0.45-μm pore size). Formaldehyde and acetaldehyde were added and stirred for 30 min. The formed solid derivative was filtered and washed 3 times with 2 M HCl and 3 times with water and dried overnight in an oven at 60 °C. Subsequently, it was dissolved in hot ethyl alcohol and recrystallized, filtered, and dried in the oven. A series of standard solutions were prepared in ACN. The percent relative standard deviation (RSD) for 56 standard solutions was 4.0% for formaldehyde and 4.6% for acetaldehyde.

Questionnaires and Time-Activity Monitoring

Questionnaires were used in the EXPOLIS study to obtain information on factors thought to affect personal exposure levels or the quality of indoor air in the participant's residence and workplace. A time-microenvironment-activity diary was used to assess the times that participants spent in each microenvironment and the activities performed during the 48-hr measurement period.[21]

Partial Model of Average Exposure

Data collected in EXPOLIS are used to develop and test models for predicting personal exposure. A partial model of average exposure for formaldehyde and acetaldehyde was used, which consisted of proportionally weighting the time spent in microenvironments where concentration measurements were carried out by concentrations in each respective microenvironment.

$$E = (C_I T_I + C_O T_O + C_W T_W)/(T_I + T_O + T_W) \qquad (1)$$

where E is the estimated average personal exposure concentration, C is the concentration in measured microenvironments (I is indoor residential, O is outdoor residential, and W is workplace), and T is the time spent in the respective microenvironments.

Quality Assurance/Quality Control

Microenvironmental samples for four participants were accompanied by field blanks. These consisted of complete formaldehyde and acetaldehyde sampling assemblies, which underwent all sample procedures, except that they were not connected to a sampling pump. Determination of formaldehyde and acetaldehyde

sampling precision was based on field duplicate measurements (n = 3) collected in the field along with the normal sample.

RESULTS AND DISCUSSION

Quality Assurance/Quality Control

Aldehyde and $PM_{2.5}$ samples were drawn simultaneously using the same pump. Flow resistance of $PM_{2.5}$ filters increased with loading of particles during the sampling periods. Consequently, there was a potential for increased flow through aldehyde sampling cartridges in microevironmental measurements as a mass flow-controlled pump was used to draw air for both samples using a T-joint in the sample lines. Thus, it was possible for formaldehyde and acetaldehyde concentrations to be somewhat over-represented toward the end of each sample relative to the beginning. Measured differences in pre- and postsampling flow rates for microenvironmental measurements, however, were small, with a mean change of 7.5% (SD 4.8%) due to the low $PM_{2.5}$ masses collected. Personal exposure measurements used a volumetric flow-controlled pump, which kept the pump speed constant as the particle load on $PM_{2.5}$ filters increased. Consequently, flow rate changes for personal samples were minimal (mean –1.1%, SD 7.0%) when the $PM_{2.5}$ filters got loaded during the sampling period. The combined effect of these flow-rate change differences resulted in less than 10% differences in concentrations in side-by-side PEM and MEM VOC sampling comparisons carried out as a part of the EXPOLIS, and therefore did not introduce significant error.

Mean contamination levels found in field blanks were 0.80 ppb (0.68-1.03 ppb) for formaldehyde and 0.67 ppb (0.32-1.04 ppb) for acetaldehyde (using an assumed sampling volume of 100 L). Limits of detection were defined as 3 times the standard deviation of the field blanks and were 0.50 ppb for formaldehyde and 1.00 ppb for acetaldehyde. One-half of the detection limit was used for data below the limit of detection in statistical analyses.[24]

Percentages of samples above the limit of detection for formaldehyde were 100% (15/15) for personal exposure samples, 100% (15/15) for indoor residential samples, 85% (11/13) for outdoor residential samples, and 100% (10/10) for workplace samples. Respective percentages for acetaldehyde were 100% (15/15), 100% (15/15), 62% (8/13), and 90% (9/10). The mean RSD for microenvironmental duplicate pairs was 2.7% (0.1–4.3%) for formaldehyde and 1.6% (0.7–3.2%) for acetaldehyde.

The sensitivity of current methods was adequate for the measurement of personal exposures and microenvironmental concentrations of formaldehyde and acetaldehyde. In this study, percentages of samples above the limits of detection were greater than 90% for all microenvironments except outdoor residential samples. A part of the outdoor residential samples was below limits of detection due to low concentration levels of these compounds in this microenvironment. Comparison with other studies that used Sep-Pak cartridges indicated similar detection limits and precision, although the number of field blanks and duplicates in this study were small.[3-5,8,11,25,26]

Time Activities of the Sampled Participants

Participants of this study spent, on average, 62% of the 48-hr sampling period at the residence (Table 2), 88% indoors, and 4% outdoors. Time spent in traffic and transportation (inside a vehicle or in close proximity to road traffic) is not included in these percentages. These values are similar to those found in other studies.[17]

Concentration Levels

Mean 48-hr personal exposure levels (including smokers) of formaldehyde and acetaldehyde were 21.4 (7.6–40.3 ppb) and 7.9 ppb (1.4–13.9 ppb), and mean indoor residential concentrations (including the home where smoking occurred indoors) of formaldehyde and acetaldehyde were 33.3 and 10.1 ppb, respectively (Table 3). Comparison of smokers with nonsmokers is not supported by this study, as the numbers of smokers (n = 4) and residences (n = 1) or workplaces (n = 3) where smoking occurred indoors were very small, which precluded meaningful comparison. Personal exposure levels of active smokers reflect concentrations of formaldehyde and acetaldehyde in the air around each study participant and not the dose received from actively inhaling smoke directly from a cigarette. Measured doses from directly inhaling cigarette smoke were not measured or estimated in our study because there is a wealth of literature already available on this topic.

In general, personal exposure levels were lower than indoor residential concentrations. This suggests that concentrations of formaldehyde and acetaldehyde in indoor residential environments were higher than those found in other microenvironments in which participants spent significant portions of the day, and that participants spent only a small amount of time in nonresidential microenvironments where concentrations were high (e.g., traffic) and more time in locations where concentrations were low (e.g., workplace, outdoors).

Ambient air concentrations measured outside each participant's residence were low compared with indoor (indoor residential and workplace) concentrations and personal exposure levels. Mean outdoor concentrations of formaldehyde and acetaldehyde were 2.6 and 1.5 ppb, respectively. The ratio of mean indoor to mean outdoor concentrations was 12.8 for formaldehyde and 6.7 for acetaldehyde, and individual indoor/outdoor ratios were greater than unity for almost every measurement pair (Table 4).

Table 2. Time activities of the participants (n = 15) during the 48-hr sampling period.

	Microenvironment								
	In Transit			Not in Transit					
% of Time	Walk or Bike	Car or Taxi	Bus or Tram	Residence		Work		Other	
				In	Out	In	Out	In	Out
Mean	3.5	3.5	0.8	61.7	3.1	22.3	0.4	4.1	0.6
Min	0	0	0	24.4	0	0	0	0	0
Max	18.4	20.3	6.3	87.3	13.5	53.8	2.9	26.8	4.2

Table 3. The 48-hr personal exposure levels and indoor residential, outdoor residential, and workplace concentrations of formaldehyde and acetaldehyde (in ppb). The analysis of workplace concentrations does not include the participant who worked at home.

	Personal (n = 15)		Residential-In (n = 15)		Residential-Out (n = 13)		Workplace (n = 9)	
	Formald.	Acetald.	Formald.	Acetald.	Formald.	Acetald.	Formald.	Acetald.
Mean	21.4	7.9	33.3	10.1	2.6	1.5	12.0	2.6
SD[a]	11.1	3.9	17.9	5.4	2.9	1.6	6.1	1.2
50th[b]	18.0	7.1	33.0	9.1	1.5	1.2	11.1	3.3
75th[c]	29.1	10.5	47.8	12.0	3.2	1.3	12.3	3.6
Min	7.6	1.4	6.5	2.0	0.3	0.5	7.3	0.5
Max	40.3	13.9	62.3	22.7	10.9	6.5	26.4	4.0

[a]Standard deviation; [b]50th percentile; [c]75th percentile.

Mean indoor workplace concentrations of formaldehyde and acetaldehyde (including workplaces where smoking occurred indoors) were 12.0 and 2.6 ppb, respectively. Analysis of workplace concentrations does not include one participant who worked at home. Generally, concentrations of formaldehyde and acetaldehyde were lower in workplaces than in residences. This suggests that there were more indoor sources of formaldehyde and acetaldehyde in residences (e.g., building materials which emit formaldehyde and acetaldehyde) and/or workplaces had better ventilation. It is also possible that there were additional formaldehyde and acetaldehyde sinks at workplaces compared with residences.

Dingle et al.[20] reported personal exposures and indoor and outdoor residential concentrations (all 5-day average concentrations) of formaldehyde for 80 volunteers from 250 randomly selected residences in Perth, Western Australia. The mean personal exposure level (17.5 ppb) was lower than that measured in Helsinki due to lower indoor residential concentrations in Perth. Mean indoor residential concentration in Perth (19.7 ppb) was higher than respective mean personal exposure concentration and 10 times higher than respective mean outdoor residential concentration (2.0 ppb).

Table 4. Statistics of the I/O ratios of formaldehyde and acetaldehyde in residential air (n = 13).

Compound	Mean	50th[a]	75th[b]	Min	Max
Formaldehyde	44.8	25.7	39.6	1.5	217.5
Acetaldehyde	14.2	10.9	19.5	0.8	43.2

[a]50th percentile; [b]75th percentile.

In another study carried out in New Jersey,[11] simultaneous indoor and outdoor residential measurements of aldehydes were made for six suburban houses during the summer of 1992. In this study, the mean indoor concentrations of formaldehyde and acetaldehyde were 54.6 and 3.0 ppb and mean outdoor concentrations were 12.5 and 2.6 ppb, respectively. Mean indoor/outdoor concentration ratios were 7.20 for formaldehyde and 1.38 for acetaldehyde. Reiss et al.[26] measured indoor residential and outdoor concentrations of carbonyl compounds in the greater Boston, MA, area during the winter (n = 4 residences) and summer (n = 9 residences). During the summer, mean indoor and outdoor formaldehyde concentrations were 16.1 and 2.6 ppb, and mean indoor and outdoor acetaldehyde concentrations were 5.1 and 1.1 ppb, respectively.

Indoor residential concentrations of acetaldehyde in Helsinki were generally higher than indoor concentrations in New Jersey and Boston. No such difference was observed

in outdoor concentrations. In addition, mean indoor/outdoor concentration ratios of both formaldehyde and acetaldehyde were higher in Helsinki than in New Jersey. The higher indoor residential concentrations of acetaldehyde observed in Helsinki may result from differences in physical properties of the buildings (e.g., lower air-exchange rates in Helsinki), building materials, and chemical processes governing the generation, accumulation, and removal of this compound in the indoor environments.[11]

Correlation between 48-hr Personal Exposure Levels and Microenvironmental Concentrations

Personal 48-hr exposures to formaldehyde and acetaldehyde were correlated with indoor residential concentrations of these compounds (Table 5). There was no significant correlation, however, between personal exposure levels and indoor workplace concentrations ($n = 9$) for formaldehyde ($r_s = 0.150$) and acetaldehyde ($r_s = 0.151$) or between personal exposures and concentrations in ambient air (outdoor residential). Dingle et al.[20] reported a correlation ($r = 0.780$) between personal exposures and indoor residential concentrations of formaldehyde that was similar to the current study. These findings indicate that for formaldehyde and acetaldehyde, outdoor air concentrations are a poor proxy of personal exposure levels.

Table 5. Summary of Spearman correlation coefficients between personal exposure ($n = 15$) levels and indoor residential ($n = 15$) and outdoor residential ($n = 13$) concentrations of formaldehyde and acetaldehyde.

Measurement	Personal Exposure	Formaldehyde Residential-In Conc.	Residential-Out Conc.
Personal exposure	1.0		
Residential-in conc.	0.804[a]	1.0	
Residential-out conc.	–0.300	–0.386	1.0
Measurement	**Personal Exposure**	**Acetaldehyde Residential-In Conc.**	**Residential-Out Conc.**
Personal exposure	1.0		
Residential-in conc.	0.819[a]	1.0	
Residential-out conc.	–0.154	–0.393	1.0

Note: The significance level of the correlations are denoted as follows: [a]Probability < 0.001.

Measured 48-hr Personal Exposure Levels Versus Partial Model of Average Exposure

It is important to note that the partial model of average exposure only covered the monitored microenvironments and the time spent in these environments. It did not cover nonmonitored microenvironments such as shops, restaurants, and traffic even if the participants could visit these environments during their 48-hr sampling period. The model explained 54% of the variation in formaldehyde personal exposures and 59% of the variation in acetaldehyde personal exposures using logarithmically transformed data (Figure 1). Interestingly, measured indoor residential concentrations predicted measured personal exposures better than the used model did (for formaldehyde, $R^2 = 0.61$ and for acetaldehyde, $R^2 = 0.78$) (Figure 2). Dingle et al.[20] also reported that the time-weighted formaldehyde exposure model did not improve estimation of personal exposures compared with prediction using indoor residential concentrations. These results emphasize the importance of residential formaldehyde and acetaldehyde concentrations for personal exposures. Other studies on personal exposure to NO_2 have reported that time weighting is of minor importance for estimating personal NO_2 exposures.[27,28]

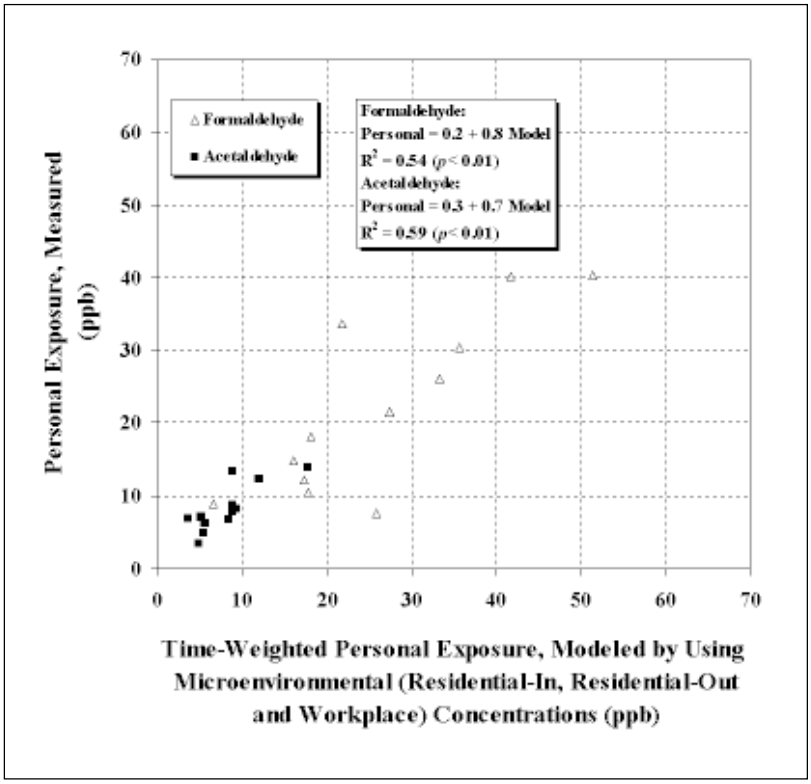

Figure 1. Measured 48-hr personal exposure levels vs. partial model of average exposure ($n = 12$). The model consisted of proportionally weighting the time spent in the microenvironments where concentration measurements were carried out by concentrations in each respective microenvironment. For regression analysis, data were logarithmically transformed.

Formaldehyde-to-Acetaldehyde Ratio

Concentration ratios of formaldehyde and acetaldehyde have been used to compare the results of carbonyl compound measurement studies in different locations.[8,29] The high correlation between formaldehyde and acetaldehyde suggests that these two compounds have similar sources and sinks. In this study, formaldehyde and acetaldehyde were correlated in outdoor air ($p < 0.001$) (Table 6). In indoor microenvironments and personal exposures, there was no correlation between compounds. Contrary to our study, Reiss et al.[26] reported significant correlation between formaldehyde and acetaldehyde in indoor residential air. Combined with higher indoor concentrations in Helsinki, this indicates there were additional but separate indoor sources of formaldehyde and acetaldehyde in residences of Helsinki compared with those of Boston. It is also possible that the numbers of sinks of both compounds were lower or that the sinks were weaker in Helsinki residents.

Mean formaldehyde-to-acetaldehyde concentration ratios (ppb/ppb) increased from outdoor residential (1.69) to personal exposure (3.46), indoor residential (4.02), and workplace (5.93). The mean outdoor formaldehyde-to-acetaldehyde concentration ratio in Helsinki is consistent with data from other urban areas.[3,8] The highest mean observed in workplaces resulted from low indoor workplace concentrations of acetaldehyde.

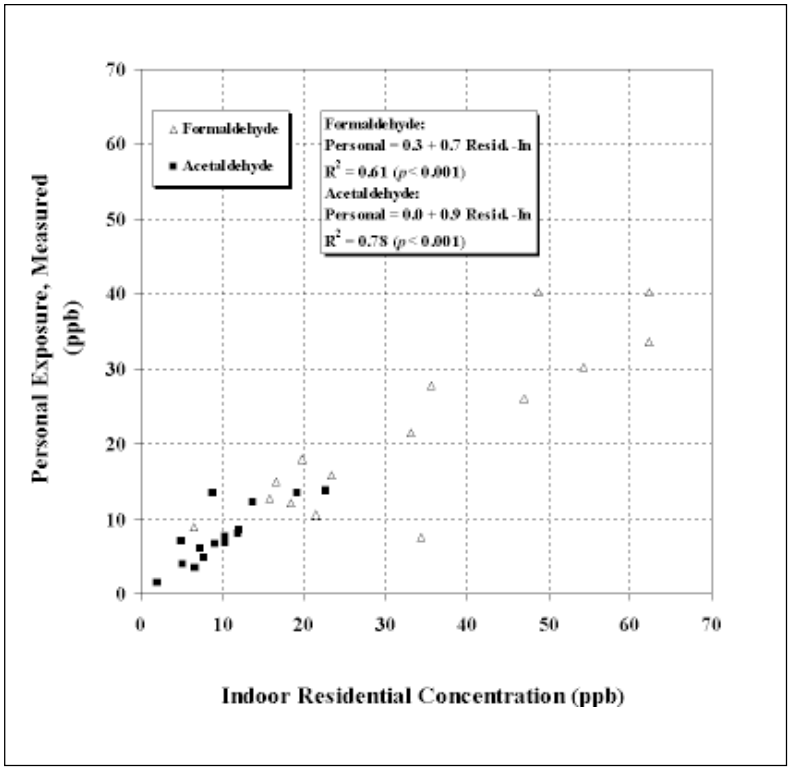

Figure 2. Measured 48-hr personal exposure levels vs. indoor residential concentrations ($n = 15$). For regression analysis, data were logarithmically transformed.

CONCLUSIONS

Mean 48-hr personal exposure was found to be 21.4 ppb for formaldehyde and 7.9 ppb for acetaldehyde among 15 participants living in the Helsinki metropolitan area. For both compounds, personal exposure levels were systematically lower than indoor residential concentrations. Outdoor residential concentrations were low compared with indoor residential concentrations and personal exposure levels. Mean concentrations of both compounds were lower indoors in workplaces than in residences. Personal exposure levels of formaldehyde and acetaldehyde were correlated with indoor residential concentrations, but not with workplace or outdoor residential concentrations. Indoor residential concentrations alone were better estimators of personal exposures than was a time-weighted exposure model. Concentration levels of formaldehyde and acetaldehyde were correlated in outdoor residential microenvironments, but not in indoor microenvironments or personal exposure samples. This suggests that both compounds have similar sources and sinks in ambient urban air, but not in indoor air, which dominates personal exposures.

Table 6. Summary of concentration ratios and Spearman correlation coefficients between formaldehyde and acetaldehyde in personal exposure and microenvironmental concentration samples. The analysis of workplace concentrations does not include the participant who worked at home.

	Formaldehyde/Acetaldehyde (ppb/ppb)		
Measurement	Mean	SD[a]	r_s[b]
Personal Exposure ($n = 15$)	3.46	2.59	0.136
Residential-in ($n = 15$)	4.02	2.82	0.438
Residential-out ($n = 13$)	1.69	0.95	0.844[c]
Workplace ($n = 9$)	5.93	4.09	0.117

[a]Standard deviation; [b]Spearman correlation coefficient; [c]The significance level of the correlations are denoted as follows: Probability < 0.001.

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About the Authors

Jouni Jurvelin, M.Sc., and Matti Vartiainen, Ph.D., are researchers and Matti Jantunen, Ph.D., is the director of the Department of Environmental Hygiene at KTL (National Public Health Institute), P.O. Box 95, FIN-70701 Kuopio, Finland. Pertti Pasanen, Ph.D., is a lecturer in environmental engineering in the Department of Environmental Sciences at the University of Kuopio, P.O. Box 1627, FIN-70211 Kuopio, Finland.