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Organophosphate Ester Flame Retardants and Plasticizers in the Indoor Environment: Analytical Methodology and Occurrence

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Nine organophosphate esters, which are commercially used as plasticizers and/or flame retardants, were identified and quantified in air samples from some common indoor work environments, *i.e.*, an office building, a day care center, and three school buildings. One of the compounds was identified as tri(2-chloroethyl) phosphate, a substance that has been shown to be a neurotoxic and genotoxic agent. The concentration levels of this substance were found to be as high as 250 ng/m^3. In order to examine whether the organophosphates were transferred from the outdoor air, the occurrence of organophosphates in outdoor ambient air was investigated. The levels of the individual compounds in the outdoor air samples were found to be less than 1 ng/m^3, which indicates that the main sources of organophosphates in indoor air were located indoors. A comparison between the studied indoor environments showed large differences in the concentration profiles of the nine identified compounds. This was most probably due to the large variation in indoor materials, furniture, and equipment between the different indoor work environments. A method for sampling and analysis is described and evaluated. Samples were collected by pumping air through filter and polyurethane foam plugs. At a low sampling rate, 3 L/min, the organophosphates were strongly associated with the filter, by polar interactions either directly to the filter or to the particulate phase adsorbed on the filter. Ultrasonication was shown to be a fast and efficient extraction method for all of the organophosphates studied.

Introduction

Organophosphorus compounds are utilized on a large scale as flame retarding agents and/or plasticizers in a variety of products, such as plastic materials, rubbers, varnishes, lubricants, hydraulic fluids, and other industrial applications. Current consumption in Europe is estimated to be greater than 10^4 ton/year (*1*). This family of chemicals consists of alkylated and arylated phosphate or phosphonate esters and related compounds such as phosphites, phosphines, and related dimeric forms as well as ionic forms. Volatilization and leaching into indoor environments to significant levels has been described previously (*2*).

In this study, the occurrence of organophosphates in indoor air was investigated. A general structure for those compounds is presented in Figure 1. Rather little is known so far about the health effects of those compounds on humans. In some references in the toxicological literature, alkylated and arylated phosphate esters were shown to have significant biological effects. Tritolyl phosphate and butylated triphenyl phosphate have been shown to be reproductive toxicants (*3*, *4*). In studies on rats and mice, tri(2-chloroethyl) phosphate has shown neurotoxic and cancerogenic properties (*5*) and has been distributed to all parts of the brain (*6*), causing lesions on the brain tissue of hippocampus (*7*−*9*). Among workers exposed to a mixture of arylated phosphate esters, a decrease in the number of monocytes could be observed (*10*). Some cases of contact allergy to triphenyl phosphate have also been reported (*11*−*13*).

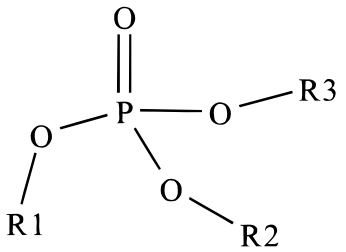

FIGURE 1. General structure of organophosphate esters. R_1, R_2, and R_3 are either similar or different organic substituents.

According to the literature, organophosphates can be considered as widely spread chemicals in the environment. Their occurrence in both the aquatic environment (*14*, *15*) and in drinking water (*16*, *17*) has been demonstrated. Organophosphates have also been detected in ambient air, both outdoors and indoors. For instance, alkyl phosphates were identified as some of the major components in particulate organic matter collected in Antarctica (*18*). Quantitative analyses of organophosphate esters in outdoor air samples showed concentrations at the low nanogram per cubic meter level of triethyl, tributyl, tri(2-chloroethyl), tri(chloropropyl), tri(dichloropropyl), and triphenyl phosphate (*19*, *20*). A few particle-associated organophosphates have also been identified and quantified in air samples from indoor environments (*21*−*23*). In one of these studies, the air in two office buildings was investigated (*21*). The concentration of tri(butoxyethyl) phosphate in one of the buildings was 25 ng/m^3, and the main source of this substance was shown to be the floor finish. In the other building, the concentration of both tri(2-ethylhexyl) phosphate and tri(butoxyethyl) phosphate was reported to be about 5 ng/m^3. However, there seems to be no extensive qualitative and quantitative analysis of indoor air, with respect to a larger number of organophosphates, described so far in the literature.

In the literature, there are several references related to indoor air analysis that present investigations of the impact of volatile and semivolatile organic compounds (VOC and SVOC) on air quality and physiological effects, like the sick building syndrome. In this discussion, little attention has been paid to particle-associated organic pollutants, such as organophosphates, and how they may affect the physical health. Additional data are needed to support assessments of human health risks associated with exposure to these compounds in indoor environments. Thus, the objective of this work was to investigate the occurrence of organophosphates, both qualitatively and quantitatively, in different common indoor work environments. This work also included development of an analytical method to more accurately sample and detect organophosphates in ambient air.

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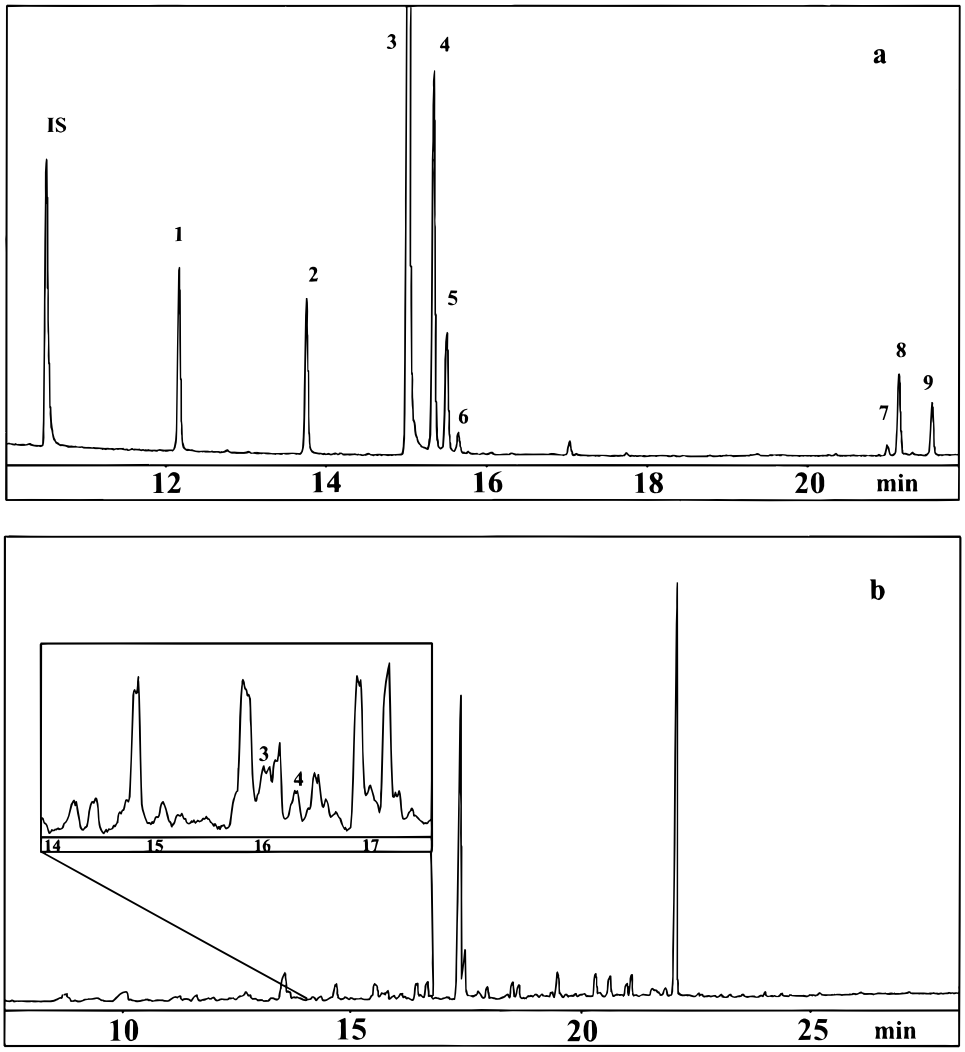

FIGURE 2. (a) GC—NPD chromatogram of an air sample, collected in an office building. IS, tripropyl phosphate (internal standard); 1, a tributyl phosphate isomer; 2, tri(*n*-butyl) phosphate; 3, tri(2-chloroethyl) phosphate; 4—6, isomers of tri(chloropropyl) phosphate; 7, triphenyl phosphate; 8, tri(2-butoxyethyl) phosphate; 9, tri(2-ethylhexyl) phosphate. For GC parameters, see Experimental Section. (b) GC—MS—EI chromatogram of the same sample as in panel a. The peaks marked 3 and 4 are tri(2-chloroethyl) phosphate and isomers of tri(chloropropyl) phosphate, respectively.

Experimental Section

Chemicals. Triethyl, tri(*n*-propyl), tri(*n*-butyl), tri(2-chloroethyl), triphenyl, tri(2-butoxyethyl), triethylhexyl, and tritolyl phosphate were purchased from Aldrich Chemicals, Germany.

Tri(2-chloropropyl) phosphate was kindly provided by Akzo Nobel, Sweden.

Tri(n-propyl) phosphate was used as internal standard and added to the samples prior to the extraction procedure. Azabenzo[*a*]pyrene, purchased from Larodan AB, Sweden, was used as an external standard and was added to the samples prior to GC analysis.

For quantitative analysis, a standard consisting of the organophosphates at a concentration of about 0.4 ng/μL of each compound was used. To each sample 48.8 ng of internal standard (IS) and 1324 ng of external standard (ES) were added. The difference in concentrations between the two standards is due to the much lower sensitivity of the NPD detector for the nitrogen-containing azabenzo[*a*]pyrene (ES) than for the phosphorus containing tri(*n*-propyl) phosphate (IS).

Cleaning Procedures. Since organophosphates seem to be ubiquitous indoor air pollutants, extensive cleaning procedures had to be applied. Prior to sampling, the glass fiber filters were ultrasonicated for 20 min in methanol, acetone, and dichloromethane, respectively. The PUFs were first boiled in water for 4 h in order to eliminate compounds containing nitrogen, such as isothiocyanates. They were then washed with water, acetone, and dichloromethane and finally Soxhlet-extracted for 12 h in dichloromethane.

All the glassware had to be soaked in a solution of 5% (w/w) sodium hydroxide in ethanol for at least 12 h and then extensively rinsed with water, ethanol, and finally acetone. After performing this procedure, no chemical background of organophosphates originating from glassware could be detected.

The glass wool used during the cleanup procedure was cleaned by washing in methanol and acetone and finally by ultrasonication several times in dichloromethane until no chemical background of organophosphates was detected.

Sampling. Stationary air sampling was performed with a personal sampler, as previously described (*24*). The sampler holder was made of anodized aluminium. A 25-mm binder-free A/E borosilicate glass fiber filter (Gelman Sciences Inc., Ann Arbor, MI) and two 15 $\times$ 15mm cylindrical polyurethane foam (PUF) plugs (Specialplast AB, Gillinge, Sweden) were used to trap the particulate and the semivolatile associated fractions, respectively. Air was pumped through the sampler using a battery-operated personal sampler pump (224-PCXR7, SKC Inc., Eighty Four, PA). The flow rate was set to 3.0 L/min,

and samples were collected for 700 min, yielding a total air volume of 2.1 m^3.

Sampling at higher flow rates, at 17.5 L/min, was also performed in order to examine (a) the distribution between the particulate and the semivolatile phase and (b) how the result, in terms of total concentrations of organophosphates, was affected. In this case, a larger pump (KNF, Neuburger, Freiburg, Germany) was used, but with the same sampler as described above. These samples were collected after 15−17 h, which yielded a total air volume of about 16−18 m^3. Cellulose AP10 support filters (Millipore, USA) were used during sampling at higher flow rates.

Sample Extraction and Analysis. Extraction efficiencies for the organophosphates using either Soxhlet extraction or ultrasonication, respectively, were studied. Filters and PUFs spiked with 100 μL of the organophosphate standard were used as samples. In both methods, dichloromethane was used as solvent. In the case of Soxhlet extraction, the samples were extracted for 15 h in 50 mL of solvent, and the time of one extraction cycle was 1.5−2 min. When using ultrasonication, the extraction was performed during 20 min in 5 mL of solvent and was repeated once with fresh solvent. The ultrasonic bath was a Bransonic 220 instrument, with an output power of 50 W and a frequency of 48 kHz.

For all organophosphates studied, except tri(2-butoxyethyl) phosphate, recoveries were higher than 95%. For tri(2-butoxyethyl) phosphate, the recovery was clearly different depending on the extraction method used. It was found to be as low as 37% using Soxhlet extraction, but higher than 95% when applying ultrasonication. Regarding Soxhlet extraction, the low recovery was shown to be due to adsorption to the large glass surfaces of the equipment and of the rotary evaporator flask used subsequently to the extraction. Due to this as well as to the high yields for all of the tested organophosphates and to the small time consumption using ultrasonic extraction, the latter method was chosen for extraction of the air samples.

Prior to the extraction of air samples, tri(*n*-propyl) phosphate was added to the filters and to the PUFs as an internal standard. Subsequent to extraction, the samples were filtered through a clean glass wool wad plugged in a Pasteur pipet. After filtration, samples were evaporated at room temperature using a gentle stream of nitrogen. Azabenzo[*a*]pyrene was added to the samples as an external standard prior to GC analysis.

Instrumentation. *GC−NPD.* Quantitative GC analysis was performed using a Varian 3700 gas chromatograph equipped with a DB-5 column (J&W, 30 m × 0.25 mm, 0.1 μm thickness of stationary phase), a nitrogen−phosphorus detector (NPD), and a split/splitless injector. Nitrogen was chosen as the carrier gas since some degradation of the phosphates was observed when using hydrogen. This was most probably due to hydrolysis of the phosphate esters to phosphoric acid in the injector. Samples were introduced into the injector kept at a temperature of 280 °C, having the split closed for 2 min. Temperature programming of the GC oven was as follows: 45 °C for two minutes, followed by a linear temperature increase of 10 °C/min up to 300 °C. An ELDS laboratory data system (Chromatography Data System Inc., Sweden) was used for registering, storing, and processing the detector signals.

GC−AED. An HP 5890 Series II gas chromatograph (Hewlett-Packard, Wilmington, DE) equipped with an HP 7673A automatic sample injector was used in this study. The capillary GC column (J&W Scientific, DB-5, 40 m, 0.25 mm i.d., 0.1 μm film thickness) was provided with a deactivated retention gap (HP, 0.3 m length × 0.53 mm i.d.). Helium was used as the carrier gas at a linear velocity of 0.3 m/s. The final part of the GC column was used as a transfer line to the detector. The HP 5921A atomic emission detector was operated at the emission wavelengths of 495.7 nm (carbon), 486.1 nm (hydrogen), 479.4 nm (chlorine), 777.3 nm (oxygen), and 178.1 nm (phosphorus) for selective detection, with reagent gas flows adjusted as recommended by the manufacturer. All detector parts were heated to 300 °C. The reagent gases hydrogen and oxygen were kept at a pressure of 70 and 30 psi, respectively. Nitrogen was used as spectrometer purge gas at a flow of 2 L/min. Makeup gas flow through the cavity was set to 150 mL/min for optimal phosphorus response and to 50 mL/min for the other elements. The solvent venting time in the AED detector was set to 4.7 min. The GC−AED analyses require separate injections for oxygen, phosphorus, and carbon/chlorine, respectively, to be analyzed. The GC−AED chromatogram in Figure 3 is thus a composite of three separate injections of the sample.

GC−MS. The gas chromatography/mass spectrometry (GC−MS) system consisted of a Varian 3400 GC and a Finnigan Incos 50 quadrupole mass spectrometer. The GC was equipped with a DB-5 column (the same type as used in the GC−NPD), and helium was used as the carrier gas. Injections were made using a Varian SPI-injector and on-column technique. Temperature programing of the GC oven was the same as for the GC−NPD. During injection, the SPI injector was held at 35 °C for 1 min and then programed up to 295 °C with a rate of 180 °C/min. The temperature of the transfer line between the GC and the mass spectrometer was held at 310 °C. Analyses were made in both electron impact mode (EI) as well as in positive ion chemical ionization mode (PICI). In EI, an electron energy of 70 eV was applied. In the case of PICI, the electron energy was set to 110 eV. Methane of >99.995% purity was utilized as reagent gas, and the temperature of the ion source was held at 80 °C. The instrument was tuned in PICI by optimizing the ratio of the reactant ions (CH_5^+, $C_2H_7^+$, and $C_3H_8^+$) to approximately 5:4:1. In both PICI and EI mode, full-scan spectra were recorded, using a scan cycle from 35 to 500 in 1 s in EI and from 50 to 500 in 1 s in PICI.

Results and Discussion

Indoor Air Pollutants Identified as Organophosphate Esters. In a simplified pilot study, the settling particulate material (defined as the material recovered from open petri dishes exposed to the air) was investigated with respect to the presence of organophosphate esters. Samples were collected in a number of office, laboratory, and home indoor environments. The results indicated that organophosphates are ubiquitous indoor air pollutants. They were also shown to contaminate glassware, solvents, extraction equipment, etc. due to their presence in the laboratory indoor environment. Many of the investigated compounds were detected when analyzing extracts from the laboratory glassware and thus constituted a strong, disturbing background in the analytical procedure. This necessitated the cleaning procedures described in the Experimental Section. In order to further investigate the occurrence of organophosphate esters in indoor environments, analytical methods in combination with air sampling utilizing personal-carried equipment were developed. The same compounds were identified using either Petri dishes or the developed sampling method.

Chemical Analysis. Gas chromatography with nitrogen−phosphorus detection (NPD) was chosen for the analysis of organophosphate esters in air samples. The NPD detector in this study was demonstrated to be sensitive toward organophosphates, with a limit of detection (LOD) less than 5 pg at three times the noise level. Figure 2a shows the GC−NPD chromatogram of an air sample collected in an office building. The sensitivity and selectivity is illustrated by comparing the GC−NPD chromatogram with the full-scan GC−MS−EI chromatogram of the same sample, shown in Figure 2b. In the latter chromatogram, all of the dominating peaks were identified as phthalates and other non-phosphorus

TABLE 1. Concentrations (in ng/m^3) of Individual Organophosphates in Air Samples from Three Different School Buildings, a Day Care Center, and an Office Building[a]

	school 1		school 2		school 3		day care		office	
compound	mean	CV[b]	mean	CV	mean	CV	mean	CV	mean	CV
tributyl phosphate	35	19	27	16	17	30	7.6	25	25	5
tri(*n*-butyl) phosphate	64	20	40	16	9.8	18	13	18	18	7.5
tri(2-chloroethyl) phosphate	250	12	18	22	45	19	144	19	11	37
tri(chloropropyl) phosphate:1[d]	14	24	41	23	35	28	34	0.5	31	11
tri(chloropropyl) phosphate:2[d]	5.1	41	15	29	12	28	16	0.3	12	9.1
tri(chloropropyl) phosphate:3[d]	det[c]		1.5	24	1.1	19	2.9	3	1.4	11
triphenyl phosphate	det		0.8	24	0.5	15	det		0.7	23
tri(2-butoxyethyl) phosphate	2.9	8.0	1.4	11	3.0	21	5.9	31	2.2	23
tri(2-ethylhexyl) phosphate	det		det		det		10	6	det	

[a] Each value is defined as the mean value of at least four measurements. [b] CV, coefficient of variation. [c] det, compounds detected at concentrations below 0.5 ng/m^3 and not quantified. [d] Not identified isomers of tri(chloropropyl) phosphate, with unknown positions of chlorine.

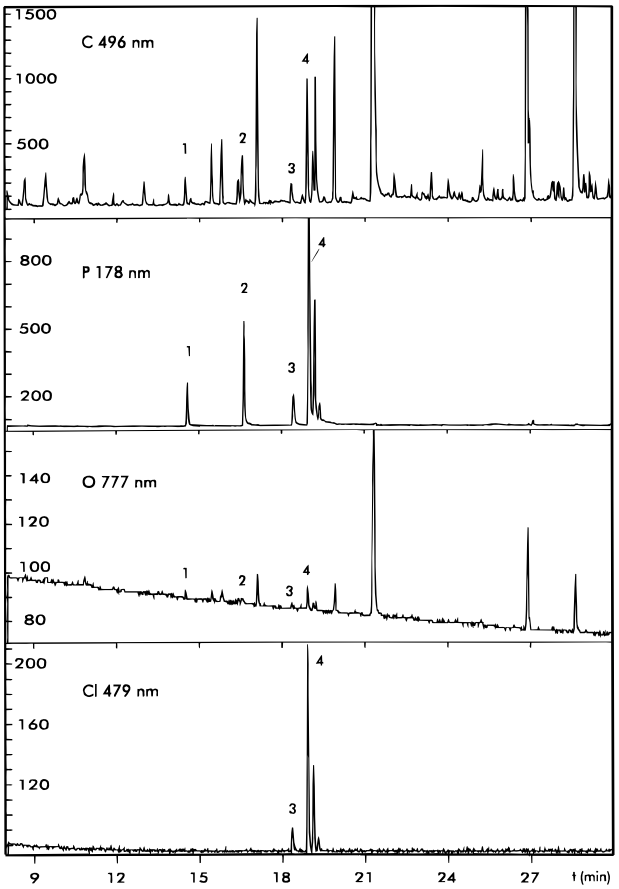

FIGURE 3. Element selective chromatograms of compounds present in an indoor air sample, collected in an office building. The chromatograms were obtained from the GC−AED selective channels for carbon (496 nm), phosphorus (178 nm), oxygen (777 nm), and chlorine (479 nm). Solute identification: 1, isomer of tributyl phosphate; 2, tri(*n*-butyl) phosphate; 3, tri(2-chloroethyl) phosphate; 4, tri(chloroisopropyl) phosphate.

containing organic compounds by aid of their mass spectra. Only the most abundant of the organophosphorus esters in the sample, could be identified as as being a phosphate in this way.

GC−AED with multichannel detection using the carbon, hydrogen, phosphorus, oxygen, and chlorine selective lines was used. By applying compound-independent calibration (*27*), it was possible to obtain preliminary elemental compositions for the detected organophosphate esters. Figure 3 demonstrates four GC−AED element selective chromatograms of an air sample collected in the investigated office building.

By use of selected ion monitoring (SIM), the selectivity and thereby the sensitivity of the MS for organophosphates was enhanced. For alkylated phosphates, no or very weak molecular ions were observed, while a m/z 99 fragment corresponding to protonated phosphoric acid was shown to be characteristic. Due to the extensive fragmentation of alkylated phosphates using GC−MS−EI, it was necessary to apply the GC−MS−PICI technique for identification. Arylated phosphates, on the other hand, exhibit an intense molecular ion and do not show the fragment of m/z 99 in their MS-EI spectra.

By combining the GC−MS and the GC−AED data, all but one of the detected organophosphate compounds could be identified by using reference compounds. The phosphate ester, numbered as compound 2 in Figure 2, was identified as tri(*n*-butyl) phosphate by the aid of the reference compound, while the first was unknown. An abundant m/z 99 fragment in its EI mass spectrum indicated that the substance was an alkylated phosphate. Due to this and to an intense $[M + 1]^+$ ion at m/z 267 and three losses of neutral m/z 56 fragments in its PICI mass spectrum, the compound was identified as a tributyl phosphate isomer, either iso- or tertiary butyl. This was further supported by GC−AED analysis (*25*).

Investigation of five indoor environments. By using the described analytical methods, a number of indoor environments were investigated. This included three school buildings, a day care center, and an office building. One room in each building was investigated, and four samples were collected at each occasion. All samples were taken at night when the ventilation systems were switched off. Organophosphates could be identified in all air samples from the indoor work environments. In the whole body of samples two isomers of tributyl phosphate, *i.e.*, tri(*n*-butyl) phosphate and an unknown isomer (iso- or tertiary), were present as well as tri(2-chloroethyl) phosphate, three isomers of tri(chloropropyl) phosphate, triphenyl phosphate, tri(2-butoxyethyl) phosphate, and tri(2-etylhexyl) phosphate. One of the most dominating compounds in the air samples was tri(2-chloroethyl) phosphate (Table 1). In one of the school buildings, the concentration of this substance was as high as 250 ng/m^3. This is of interest since tri(2-chloroethyl) phosphate has (according to the literature) shown several biological effects when tested on rats and mice (*5*−*9*). Its effect on man is unknown.

Two sampling locations were also investigated with respect to organophosphates in the outdoor environment. This was made simultaneously with the indoor sampling. This was done to establish that the organophosphate esters originate from emissions within the indoor environment. One sampling site was located outside the office building, and the other was outside one of the school buildings. All organophosphate esters were detected at concentrations below 1 ng/m^3. This confirms that the organophosphates observed

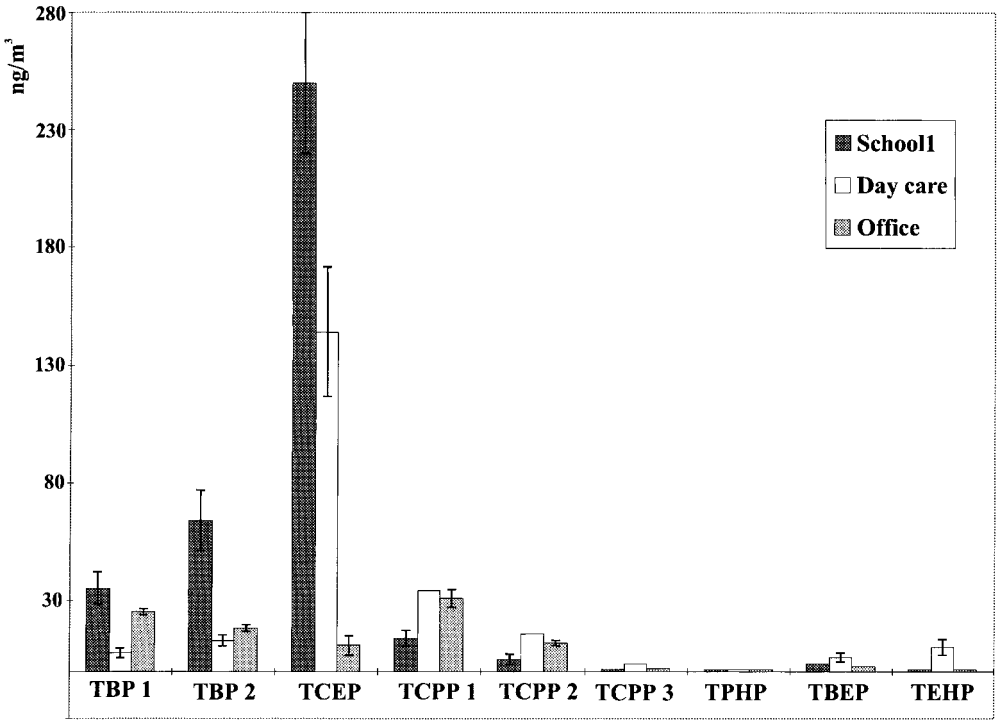

FIGURE 4. Concentration profiles for air from the office building, one of the school buildings, and the day care center, respectively. Abbreviations: TBP1, the first on DB-5 GC stationary phase eluting isomer of tributyl phosphate; TBP2, tri(*n*-butyl) phosphate; TCEP, tri-(2-chloroethyl) phosphate; TCPP1, the first eluting tri(chloropropyl) phosphate isomer; TCPP2 and TCPP3, the second and third eluting isomers of tri(chloropropyl) phosphate; TPHP, triphenyl phosphate; TBEP, tri(2-butoxyethyl) phosphate; TEHP, tri(2-ethylhexyl) phosphate. In some cases, the values of the standard deviation were too low to be drawn in the diagram, see Table 1.

in indoor air originate from materials present in the indoor environment.

There was a large difference in concentration between the individual organophosphates in all the five indoor environments studied, as shown in Table 1. One reason is that the emission rate is dependent on the volatility of the added organophosphates and their migration rate in the material to which they have been added. The large difference in boiling points, ranging from below 290 °C for tri(*n*-butyl) phosphate up to about 400 °C for triphenyl phosphate, is a probable reason for the constant dominance of the tributyl phosphates and the chlorinated trialkyl phosphates in the samples. These compounds correspond to the six earliest eluting compounds in the GC−NPD chromatogram shown in Figure 2a.

There were also significant differences in concentration profiles between the buildings, as shown in Figure 4. For instance, tri(2-ethylhexyl) phosphate occurred in the day care center at a concentration level at least 20 times higher than in the other buildings examined. An obvious reason to this difference in emission is the amounts of the individual plasticizers/flame retardant additives added during their manufacturing processes to the various emitting materials present in the indoor environment as well as the mass and surface area of these materials. That is, every indoor environment exhibits an unique concentration profile of emitted plasticizers/flame retardants depending on the furniture, building materials, electronic equipment, etc.

Phase Distribution of Airborne Organophosphates. As described in the Experimental section, samples were collected at two different flow rates, 3 and 17.5 L/min, respectively. These samples were all collected in the same room and on the same occasion. For both sampling rates the total concentration of each phosphate in the sample, *i.e.*, the concentration in support filter, filter, and PUFs together, was almost identical, as shown in Table 2. At the sampling rates and times used in this investigation, the organophosphates were mainly detected on the filters since the part passing on into the PUFs was less than 1%. Therefore, the total concentration can be considered to be equal to the concentration in the filter or the filter/support pad combination. This together with the fact that the concentration profiles are independent of a change in the flow rate of nearly six times indicate that the compounds are either (1) strongly associated to airborne particles or (2) strongly adsorbed on the filters due to polar interactions. Our preliminary results, showing the presence of organophosphates in the dust collected in the Petri dishes, provide evidence for particulate association.

When applying the higher flow rate, the use of a cellulose support pad was necessary to avoid rupture of the glass fiber filter during sampling. The support pad was extracted in the same way as the glass fiber filter and the PUFs. When analyzing the filter and the support pad from the high flow rate sampling separately, a significant breakthrough from the

TABLE 2. Concentrations (in ng/m³) of Individual Organophosphates in Air Samples from an Office Building Collected at Two Different Pumping Flow Rates but at the Same Occasion and Locality[a]

	high		low	
compound	mean	CV[b]	mean	CV
tributyl phosphate	23	25	25	5
tri(*n*-butyl) phosphate	13	4.9	18	7.5
tri(2-chloroethyl) phosphate	9.9	13	11	37
tri(chloropropyl) phosphate:1	27	4.2	31	11
tri(chloropropyl) phosphate:2	9.7	4.9	12	9.1
tri(chloropropyl) phosphate:3	1.1	19	1.4	11
triphenyl phosphate	0.4	47	0.7	23
tri(2-butoxyethyl) phosphate	2.0	11	2.2	23
tri(2-ethylhexyl) phosphate	det[c]		det	

[a] High, 17.5 L/min; low, 3.0 L/min. Each value is defined as the mean value of at least four measurements. [b] CV, coefficient of variation. [c] det, compounds not quantified, i.e., detected at concentrations below 0.1 ng/m³ in the case of sampling at a high flow rate and below 0.5 ng/m³ when using a low flow rate.

TABLE 3. Distribution between Filter and Support Pad of Individual Organophosphates in Air Sample Collected at a Flow Rate of 17.5 L/min in the Office Building[a]

compound	filter	support
tributyl phosphate	1.5	20
tri(*n*-butyl) phosphate	1.8	11
tri(2-chloroethyl) phosphate	2.9	7.3
tri(chloropropyl) phosphate:1	4.3	22
tri(chloropropyl) phosphate:2	2.0	7.8
tri(chloropropyl) phosphate:3	0.3	0.8
triphenyl phosphate	0.2	0.2
tri(2-butoxyethyl) phosphate	1.4	0.4
tri(2-ethylhexyl) phosphate	det[b]	

[a] The values are the concentrations (in ng/m^3) of the organophosphates adsorbed on the filter and support pad, respectively. Each concentration value is defined as the mean value of at least four measurements. [b] det, compounds not quantified, i.e., detected at concentrations below 0.1 ng/m^3.

filter into the support pad could be observed. This is illustrated in Table 3. The partition seems to correlate rather well to the boiling points of the compounds, *i.e.*, a decrease in migration to the support pad with a higher boiling point was observed. The strong adsorption to the pad is somewhat surprising since this filter has very large pores. An explanation could be that the phosphates are mainly particle associated in the indoor environment. However, after being trapped on the glass fiber filter, they are transferred to the support filter if the flow is sufficiently high. They are then trapped on the cellulose support pad due to strong polar interactions between the phosphates and the cellulose surface. These results demonstrate that caution has to be taken during sampling since too high sampling flow can severely influence the partition between filter and adsorbent.

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