

Measurement of Gas–Liquid Partition Coefficient and Headspace Concentration Profiles of Perfume Materials by Solid-Phase Microextraction and Capillary Gas Chromatography–Mass Spectrometry

Z. Liu* and M.J. Wene

Laundry & Cleaning Products, Product Safety, Regulatory and Analytical Sciences, Sharon Woods Technical Center, The Procter & Gamble Company, 11520 Reed Hartman Highway, Cincinnati, OH, 45241

Abstract

An empirical model describing the relationship between the partition coefficients (K) of perfume materials in the solid-phase microextraction (SPME) fiber stationary phase and the *Linearly Temperature Programmed Retention Index (LTPRI)* is obtained. This is established using a mixture of eleven selected fragrance materials spiked in mineral oil at different concentration levels to simulate liquid laundry detergent matrices. Headspace concentrations of the materials are measured using both static headspace and SPME–gas chromatography analysis. The empirical model is tested by measuring the K values for fourteen perfume materials experimentally. Three of the calculated K values are within 2–19% of the measured K value, and the other eleven calculated K values are within 22–59%. This range of deviation is understandable because a diverse mixture was used to cover most chemical functionalities in order to make the model generally applicable. Better prediction accuracy is expected when a model is established using a specific category of compounds, such as hydrocarbons or aromatics. The use of this method to estimate distribution constants of fragrance materials in liquid matrices is demonstrated. The headspace SPME using the established relationship between the gas–liquid partition coefficient and the *LTPRI* is applied to measure the headspace concentration of fragrances. It is demonstrated that this approach can be used to monitor the headspace perfume profiles over consumer laundry and cleaning products. This method can provide high sample throughput, reproducibility, simplicity, and accuracy for many applications for screening major fragrance materials over consumer products. The approach demonstrated here can be used to translate headspace SPME results into true static headspace concentration profiles. This translation is critical for obtaining the gas-phase composition by correcting for the inherent differential partitioning of analytes into the fiber stationary phase.

* Author to whom correspondence should be addressed.

Introduction

Solid-phase microextraction (SPME) is a simple and versatile sampling technique. Its use has been demonstrated with applications for various sample matrices (1–4). The technique uses a coated fused-silica fiber as the extraction media. The coatings are normally organic polymers used in gas chromatographic (GC) columns, such as polydimethylsiloxane. The coatings are made with various film thicknesses. It has been demonstrated that the technique is useful for both liquid- and gas-phase sampling. A good review of the technique and its major applications can be found in a review paper by Pawliszyn et al. (5).

The extraction efficiency for an analyte in an SPME stationary phase is dependent upon its absorption property into the polymer coatings and the temperature at which the sampling is performed. Therefore, the peak areas generated using SPME–GC will vary according to the partition coefficient of the analyte between the polymeric stationary phase and the sample matrix. Most analyses done using SPME are either quantitative in nature, or use complicated calibration procedures regarding headspace analysis (6–8). The use of SPME for measuring physical–chemical constants (such as the octanol–water partition coefficient) has also been demonstrated in literature (9).

For quantitative headspace analysis using SPME, one needs to prepare a calibration curve using a series of standard solutions or a standard addition. Another alternative method is to determine the partition coefficient of the analytes in the SPME stationary phase at given sampling conditions (temperature and time). This coefficient can then be used to obtain quantitative information regarding the analytes of interest based on their partition coefficient. The partitioning behavior of analytes into an SPME fiber stationary phase can be described with partitioning chromatographic theory (10,11). Therefore, the chromatographic retention data can be used to predict the partition coefficients of analytes in SPME stationary phases, assuming equilibrium sampling conditions are reached. It has been shown that there is a linear rela-

tionship between $\log K$ and the *Linearly Temperature Programmed Retention Index (LTPRI)* using alkanes and aromatic hydrocarbons as a model compound mixture. Quantitation of petroleum hydrocarbons in air using this method was demonstrated (12).

In gas-phase sampling using SPME, the partition coefficient of an analyte between the fiber stationary and the gas phases can be expressed as:

$$K = \frac{C_{\text{fiber}}}{C_{\text{vapor}}} \quad \text{Eq. 1}$$

where K is the partition coefficient at equilibrium conditions and C_{fiber} and C_{vapor} are the analyte concentrations in the fiber liquid stationary phase and gas phase, respectively. Equation 1 requires that the sampling time be long enough to establish partitioning equilibrium. Therefore, the vapor-phase concentration (C_{vapor}) can be calculated using C_{fiber} if K is known and C_{fiber} is experimentally measured. To obtain C_{fiber} , equation 2 can be used:

$$C_{\text{vapor}} = \frac{n_{\text{fiber}}}{V_{\text{fiber}}} \quad \text{Eq. 2}$$

where n_{fiber} is the analyte quantity (weight) extracted into the stationary phase and V_{fiber} is the volume of the stationary phase. Critical to using this approach is the determination of the K values under experimental conditions. In most headspace SPME–GC analyses, one can perform the extraction long enough to allow the analytes to reach partition equilibrium between the stationary and vapor phases. Infinite dilution and ideal behavior of the gas phase are assumed for both equations 1 and 2. These conditions are closely approached in the practice of GC and static SPME sampling processes. A linear relationship between $\log K$ and *LTPRI* has been derived by Pawliszyn and co-workers based on known chromatographic theory. The relationship is cited below as equation 3. A detailed derivation can be found in reference 12.

$$\log K = a + b(\text{LTPRI}) \quad \text{Eq. 3}$$

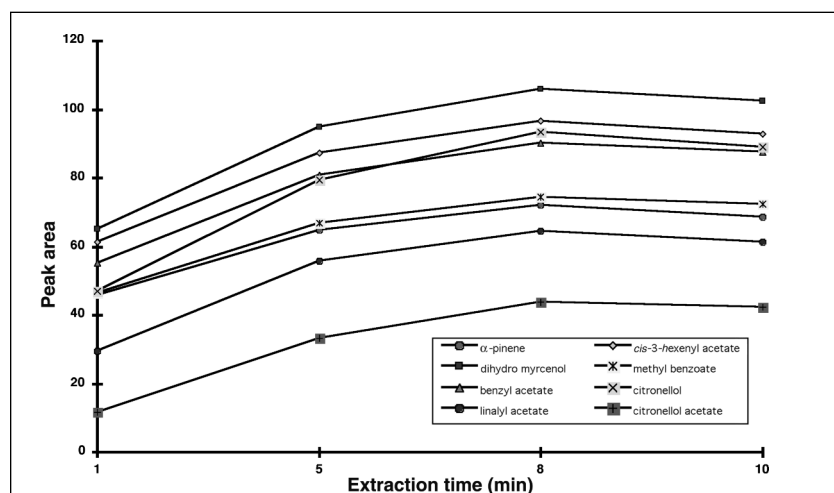


Figure 1. Determination of time required for reaching partitioning equilibrium for various perfume materials (selected compounds).

where a is the slope and b is the intercept of the line defined by equation 3. Both a and b are constant for a given system. Equation 3 should be applicable to all compound categories in gas-phase sampling, provided that the stationary phase on the SPME fiber is not drastically different than that in the GC column from which the *LTPRI* used in equation 3 is derived. This approach and our in-house generated *LTPRI* database for various fragrance materials were used to quantitate aroma and other volatiles in the headspace of various consumer products. A standard mixture covering the retention window of interest and including several common chemical functionalities was chosen to represent a typical perfume composition. K values were measured using static headspace and were compared with the calculated values using equation 3 for perfume materials. A mathematical expression was then developed for the $\log K$ and *LTPRI* of perfume compounds. K values for other materials can then be calculated using the model with known values of a and b in equation 3.

Using this mathematical expression and the flame ionization detector (FID) response factor obtained separately, the equilibrium headspace concentration of the analytes can be obtained using equations 1 and 2 by headspace SPME–GC. This approach eliminates the potential discrimination by SPME for headspace applications caused by differential partitioning of analytes in the fiber coatings that lead to a sensitivity differences. The relationship developed here allows for the determination of the equilibrium headspace concentration of perfumes by SPME–GC.

Experimental

Instrumentation

An HP 6890 GC equipped with an FID was used throughout the experiment. Unknown identifications were accomplished using a Varian Saturn 2000 GC–MS system (Varian, Walnut Creek, CA) and an in-house built fragrance MS library. A capillary column (30-m \times 0.25-mm i.d.) with a 1.0- μ m DB-5 stationary phase from J&W Scientific (Folsom, CA) was used for these analyses. The

same kind of column was used to generate all *LTPRI* in the database. An SPME manual injection holder was purchased from Supelco (Supelco, College Park, PA) The extraction fiber was composed of a fiber 1 cm in length coated with 7- μ m polydimethylsiloxane polymer, which was also purchased from Supelco and used throughout the experiment.

Materials

A test perfume mixture containing 11 compounds was made in-house and diluted in mineral oil to simulate liquid laundry detergent matrices. Mineral oil was chosen as a test matrix because it is odorless with minimal levels of volatile impurities. Also, it was used often in our research because of its good stability and viscosity. Concentration levels of total perfume in the range of 0.1 to 2.3% were tested for their extraction-time

response and partition coefficient behavior. The concentration ranges that were tested cover the most common perfume levels in liquid laundry and cleaning products.

SPME sampling

Samples were placed in a 50-mL headspace sampling vial with a septum seal. The samples were equilibrated at room temperature for at least 30 min before SPME sampling. SPME sampling was performed at various absorption times ranging from 1 to 30 min to determine the minimum time required for establishing equilibrium. The SPME fibers were desorbed into the GC injection port directly at 250°C. The desorption time used was 5 min for all experiments. The SPME fiber was preconditioned at 260°C for 20 min before each sampling.

GC conditions

Oven temperature started at 50°C without hold, was programmed to 300°C at 4°C/min, and then held at 300°C for 5 min. The injector was kept at 250°C. The FID temperature was maintained at 325°C. All peak integration was done using either TurboChrom or HP Chemstation software. Peak identification was accomplished using an MS library built in-house on an HP Chemstation platform.

External calibration

Injected in triplicate without split was 200 ng of diphenyl oxide (DPO) (Aldrich, Milwaukee, WI) in 1 μ L of acetone. A response factor was calculated using the average peak area of DPO. The response factor was then used to calculate analyte concentrations whenever appropriate.

Results and Discussion

Determination of equilibrium sampling time

Figure 1 is a plot of peak areas against the headspace SPME sampling time at 1.1% total perfume concentration. Ten grams of a 1.1% (w/w) concentration of an eleven-component mixture in mineral oil was placed in a 50-mL headspace vial. The sample was equilibrated at room temperature for at least 30 min before sampling. SPME sampling was conducted at room temperature with gentle agitation for a predetermined time, and the extracted analytes were injected directly onto GC using a 240°C injector temperature. As shown for the 7- μ m film of dimethylpolysiloxane-coated fiber, it takes about 10 min for most of the components to reach partition equilibrium. Figure 2 shows the same effect at a perfume level of 0.11%. Ten grams of a 0.11% (w/w)

concentration of an eleven-component mixture in mineral oil was placed in a 50-mL headspace vial. The sample was equilibrated at room temperature for at least 30 min before sampling. SPME sampling was conducted at room temperature with gentle agitation for a predetermined time, and the extracted analytes were injected onto GC directly using a 240°C injector temperature. It appears that within this concentration range, the time it takes to reach the partition equilibrium is independent of the analytical concentration in the sample. A 10-min sampling time can be used for the 7- μ m SPME fiber across the concentration range of interest.

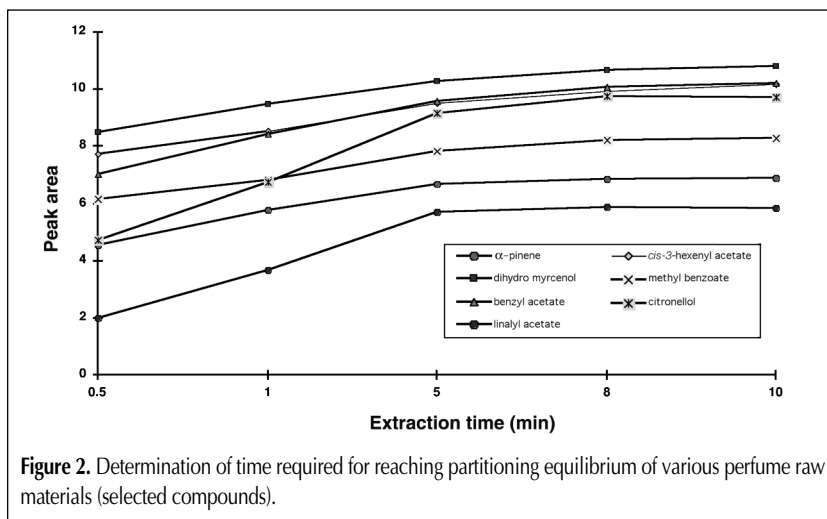


Figure 2. Determination of time required for reaching partitioning equilibrium of various perfume raw materials (selected compounds).

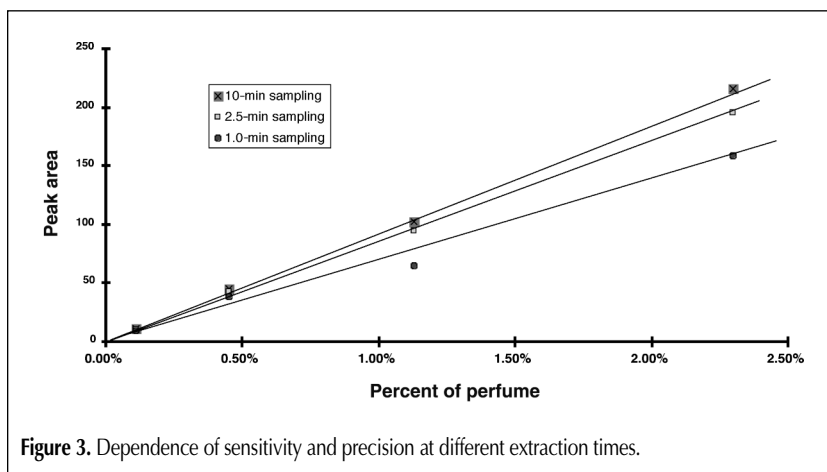


Figure 3. Dependence of sensitivity and precision at different extraction times.

Table I. Measurement of SPME Reproducibility*

Compound	RSD at 0.11% perfume levels		RSD at 1.13% perfume levels	
	1 day	3 days	1 day	3 days
cis-3-Hexenyl acetate	2.53	2.03	1.04	1.87
Dihydro myrcenol	2.66	3.19	1.12	1.90
Methyl benzoate	2.10	3.27	0.95	1.74
Benzyl acetate	1.34	2.25	1.24	2.19
Citronellol	1.86	2.72	1.18	2.06

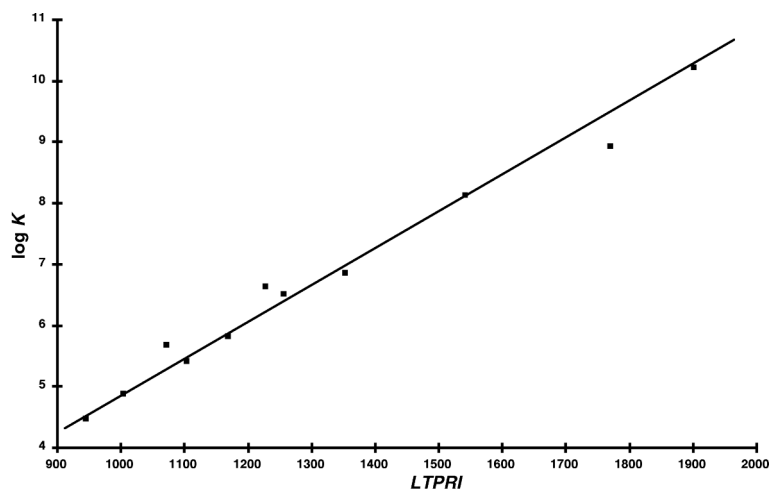
* The percent perfumes in this table refers to the total perfume concentration in sample. Some of the eleven compounds were not detectable by headspace SPME-GC at the 0.11% level; therefore, only 5 out of 14 were reported here.

Table II. Calculated and Measured K Values in SPME Fiber Stationary Phase

Compound	LTPRI	K (Calculated)	K (Measured)	% Difference
Hexanol	865	1.64E + 04	1.89E + 04	13
α -Pinene	945	4.62E + 04	2.97E + 04	56
<i>cis</i> -3-Hexenyl acetate	1005	1.00E + 05	7.54E + 04	33
Dihydro myrcenol	1072	2.39E + 05	4.71E + 05	49
Methyl benzoate	1104	3.62E + 05	2.56E + 05	41
Benzyl acetate	1169	8.39E + 05	6.50E + 05	29
α -Terpineol	1203	1.30E + 06	1.32E + 06	2
Citronellol	1228	1.80E + 06	4.34E + 06	59
Linalyl acetate	1257	2.62E + 06	3.22E + 06	19
Citronellyl acetate	1353	9.08E + 06	7.26E + 06	25
Undecalactone	1542	1.05E + 08	1.65E + 08	36
Hexyl cinnamic aldehyde	1770	2.01E + 09	4.02E + 09	50
Tonalid	1902	1.11E + 10	2.55E + 10	56
Ethylene brassylate	2060	8.57E + 10	7.03E + 10	22

Table III. Partition Coefficients of Perfume Materials in Mineral Oil Measured by SPME-GC

Compound	In mineral oil (ng/L)	In the gas phase (ng/L)	Liquid-Gas (K)
α -Pinene	7.74E + 08	2.44E + 01	3.17E + 07
<i>cis</i> -3-Hexenyl acetate	9.44E + 08	1.01E + 01	9.31E + 07
Dihydro myrcenol	9.41E + 08	9.74E - 01	9.66E + 08
Methyl benzoate	1.03E + 09	1.82E + 00	5.64E + 08
Benzyl acetate	1.03E + 09	7.26E - 01	1.42E + 09
Citronellol	8.3E + 08	1.07E - 01	7.78E + 09
Linalyl acetate	8.49E + 08	9.22E - 02	9.21E + 09
Citronellol acetate	9.45E + 08	4.09E - 02	2.31E + 10
Undecalactone	8.51E + 08	8.64E - 08	9.84E + 15
Hexyl cinnamic aldehyde	9.73E + 08	4.09E - 09	2.38E + 17
Tonalid	8.36E + 08	7.10E - 10	1.18E + 18

**Figure 4.** Relationship of LTPRI and log K used for the selected model mixture. The compounds used were: α -pinene, *cis*-3-hexenyl acetate, dihydro myrcenol, methyl benzoate, benzyl acetate, citronellol, linalyl acetate, citronellyl acetate, undecalactone, hexyl cinnamic aldehyde, and tonalid. All had approximately the same concentration and were prepared in mineral oil.**Calibration at different sampling times**

If the extraction time is controlled precisely, analysis can actually be performed using a shorter extraction time than what is required for reaching equilibrium extraction (13,14). Figure 3 shows the calibration curves obtained across the concentration range at three different extraction times. The eleven-component mixture was analyzed using SPME at sampling times of 1.0, 2.5, and 10 min for samples at total perfume concentrations of 0.0%, 0.45%, 1.13%, and 2.33%, respectively. Dihydro myrcenol was used in this calibration. All extractions were performed in the same manner as that used in Figures 1 and 2. The linearity is held for all three sampling times. The R^2 values for the calibration curves shown in Figure 3 are 0.9954, 0.9977, and 0.9993 for the 1.0-, 2.5-, and 10-min sampling times, respectively. Better sensitivity (greater slope) and precision (R^2 value) were achieved with longer sampling times. For this study, a 10-min sampling time was chosen throughout the experiments.

Reproducibility

The SPME sampling reproducibility was measured at different concentration levels and sampling times. Table I summarizes the results. Each data point in Table I was generated from six replicate measurements, either made on the same day or across a 3-day time frame. Slightly higher relative standard deviations (RSDs) were seen at lower concentration levels. This is a result of the low signal levels of some components at low concentration levels because of their low vapor pressure. The RSD obtained across the 3-day period using the same fiber was slightly higher than that of the RSD obtained on a single day. This sampling precision is adequate for headspace analysis at trace levels. In fact, the precision in Table I with headspace SPME is better than dynamic purge-and-trap techniques at the same concentration levels. Although it was not measured in this study, a higher RSD would be expected if times less than that of the equilibrium extraction times were used.

Empirical model of log K and LTPRI for fragrance materials

Using the same calibration standard, the K values were measured experimentally at two concentration levels using static sampling of the gas phase and headspace SPME with external calibrations. Linear regression was performed to obtain the constants a and b in equation 3 using the LTPRI in our own database. A regression plot is shown in Figure 4, and the equation is given later in this section. The simple test mixture used included alcohols, aldehydes, esters, and ketones

(both aliphatic and aromatic compounds were included). The correlation coefficient between $\log K$ and $LTPRI$ was 0.9917. It should be noted that the column used to generate the $LTPRI$ was a 5% phenyl polydimethylsiloxane, which is slightly different than the stationary phase on the SPME fiber. Using identical stationary phase and more compounds in the modeling mixture should improve the correlation coefficient. The equation that describes the relationship between K and $LTPRI$ for perfume raw materials can be written as follows:

$$\log K = -0.64845 + 0.005622 (LTPRI) \quad \text{Eq. 4}$$

In reference to equation 3, slope a (-0.64845) and intercept b (0.005622) were calculated respectively from Figure 4. Table II contains the calculated K and experimentally measured K values for 14 perfume raw materials. The agreement between the calculated and the measured K values varied according to the individual compound. Using equation 4, K values for any other material can be calculated using the known $LTPRI$ database. With the K values known, SPME headspace GC data can be translated to obtain approximate gas-phase concentration profiles.

K values measurement

To evaluate the accuracy of the model for perfume materials, a 14-compound mixture was spiked into mineral oil and the K values measured using SPME and static headspace techniques. The evaluation mixture was selected to cover the most commonly used chemical functionalities and $LTPRI$ range in most fragrance compositions to create a general model. The percentage deviations between the experimental and calculated K values for the 7- μm fiber varied significantly for different compounds. This is mainly because of the diversity of the test mixture selected and the lower levels of analyte concentrations in the gas phase for static headspace analysis, especially for low vapor pressure substances. Very small deviation has been shown when using mixtures that are more uniform in chemical functionality (11). Generating accurate models is achievable when a specific category of chemicals is used (e.g., esters or aldehydes). However, for semiquantitative estimations of trace-level fragrances in the gas phase, the model developed here would be adequate.

Gas-liquid distribution constant

Mineral oil was selected as the liquid matrix to simulate the perfume material gas-liquid distribution model for liquid detergents. Eleven perfume materials were spiked into mineral oil at a total perfume concentration of 1.0%. The headspace over the spiked liquid sample was equilibrated at room temperature and analyzed via SPME-GC. The headspace concentration of each individual material was then calculated using the

concentration of the fiber stationary phase (C_{fiber}) and the K values calculated from equation 4. Table III contains the measured distribution constant for perfume materials in mineral oil. This constant is an important parameter to consider for optimizing perfume levels in the product gas phase. This approach provides a simple means for obtaining gas-liquid partition coefficients of perfume materials in liquid matrices.

Estimation of perfume materials in the gas phase of laundry detergents

Liquid and powder detergents from a local store were analyzed using SPME-GC. The perfume materials were identified using an in-house perfume MS library. A typical SPME-GC-MS chromatogram is shown in Figure 5. The concentrations of major components were determined by calculating the K values using equation 4 and the corresponding $LTPRI$ in our database. The results are summarized in Tables IV and V for liquid and powder detergents, respectively.

Table IV. Headspace Concentrations of Perfume Components in Liquid Detergent*

Compounds	$LTPRI$	K value in SPME fiber stationary phase	Gas-phase concentration (ng/L)
D-limonene	1039	1.56E + 05	5.88E + 03
Dihydro myrcenol	1072	2.39E + 05	3.08E + 01
Tetrahydro linalool	1099	3.39E + 05	1.72E + 02
2-Decenal	1267	2.98E + 06	2.82E + 01
Citronellyl nitrile	1231	1.87E + 06	3.18E + 01
Verdox	1313	5.41E + 06	1.91E + 01
Vertenex	1387	1.41E + 07	1.60E + 01
Flor acetate	1443	2.91E + 07	3.83E + 00
Ethyl dodecanoate	1593	2.03E + 08	7.97E + 00
Hexyl alicylate	1650	4.24E + 08	5.54E - 02
Hexyl cinnamic aldehyde	1770	2.01E + 09	2.89E - 02
Tonalid	1902	1.11E + 10	8.43E - 03

* Structure information found in Table V.

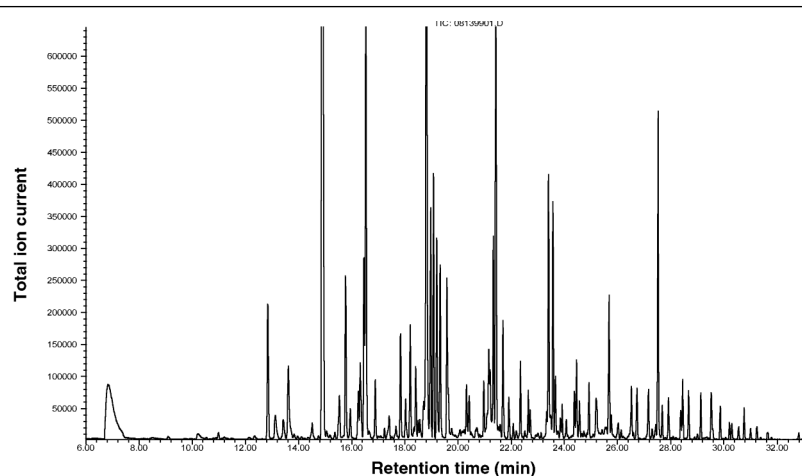


Figure 5. Headspace SPME-GC-MS chromatogram of a typical liquid laundry detergent. Conditions were as follows: 20-min absorption at room temperature; 5-min desorption at 240°C; 30-m \times 0.25-mm-i.d. column with 1.0- μm DB5 stationary phase; oven at 50°C for 1 min, then 6°C/min to 300, and held for 10 min; and Helium at 1.5-mL/min constant flow.

It is worth mentioning that this technique provided the sensitivity and precision needed for profiling the gas-phase fragrance compositions in a very efficient way without using complicated sampling procedures, such as purge-and-trap followed by thermal desorption. The SPME extraction of gas-phase volatiles followed by GC analysis also provided excellent sensitivity for most fragrance materials used in laundry and cleaning products.

References

1. D. Potter and J. Pawliszyn. Rapid determination of polyaromatic

- hydrocarbons and polychlorinated biphenyls in water using solid phase microextraction and GC-MS. *Environ. Sci. Technol.* **28**: 298-305 (1994).
2. Z. Zhang and J. Pawliszyn. Analysis of organic compounds in environmental samples using headspace solid phase microextraction. *J. High Resolut. Chromatogr.* **16**: 689-92 (1993).
3. R.J. Bartelt. Calibration of a commercial solid-phase microextraction device for measuring headspace concentrations of organic volatiles. *Anal. Chem.* **69**: 364-72 (1997).
4. M. Cisper, W. Earl, N. Nogar, and P. Hemberger. Silica-fiber microextraction for laser desorption ITMS. *Anal. Chem.* **66**: 1897-1901 (1994).
5. Z. Zhang, M.J. Yang, and J. Pawliszyn. Solid phase microextraction. *Anal. Chem.* **66**: 844A-853A (1993).
6. K.G. Furton, J.R. Almirall, and J.C. Bruna. A novel method of the analysis of gasoline from fire debris using headspace solid-phase microextraction. *J. Forensic Sci.* **41**: 12-22 (1996).
7. B. Schaefer, P. Hennig, and W. Engewald. Analysis of monoteroenes from conifer needles using solid microextraction. *J. High Resolut. Chromatogr.* **18**: 587-92 (1995).
8. V. Camel and M. Caude. Trace enrichment methods for the determination of organic pollutants in ambient air. *J. Chromatogr.* **710**: 3-19 (1995).
9. J.R. Dean, W.R. Tomlinson, V. Makovskaya, R. Cumming, M. Hetheridge, and M. Comber. SPME as a method for estimating the octanol-water partition coefficient. *Anal. Chem.* **68**: 130-133 (1996).
10. Z. Zhang and J. Pawliszyn. Studying activity coefficient of probe solute in selected liquid polymer coatings using solid phase microextraction. *J. Phys. Chem.* **100**: 17648-54 (1996).
11. J. Pawliszyn. Water analysis by solid-phase microextraction based on physical chemical properties of the coating. *Anal. Chem.* **69**: 1992-98 (1997).
12. P.A. Martos, A. Saraullo, and J. Pawliszyn. Estimation of air-coating distribution coefficients for solid-phase microextraction using retention indexes from linear temperature-programmed capillary gas chromatography. Application to the sampling and analysis of total petroleum hydrocarbons in air. *Anal. Chem.* **69**: 402-408 (1997).
13. J. Ai. Solid-phase microextraction for quantitative analysis in non-equilibrium. *Anal. Chem.* **69**: 1230-1236 (1997).
14. L. Ai. Headspace solid-phase microextraction. Dynamics and quantitative analysis before reaching a partition equilibrium. *Anal. Chem.* **69**: 3260-3266 (1997).

Table V. Headspace Concentrations of Major Perfume Components in Powder Detergent

Compounds	Structure	LTPRI	K (Cf/Cg)	Gas-Phase Concentration (ng/L)
Benzylaldehyde		967	6.14E + 04	2.35E + 02
D-limonene		1039	1.56E + 05	1.25E + 02
Dihydro myrcenol		1072	2.39E + 05	2.31E + 02
Linalool		1102	3.52E + 05	3.05E + 01
cis-Hexenyl isobutyrate		1139	5.69E + 05	4.43E + 01
Camphor		1166	8.07E + 05	4.18E + 01
Carvone		1262	2.80E + 06	6.89E + 01
Verdax		1313	5.41E + 06	3.24E + 01
Vertenex		1387	1.41E + 07	2.86E + 01
Flor acetate		1443	2.91E + 07	1.51E + 01
Cymal		1477	4.52E + 07	2.39E + 00
γ-Me-ionone		1500	6.09E + 07	1.00E + 00
Lilial		1546	1.10E + 08	2.27E + 00
Amyl salicylate		1558	1.29E + 08	4.48E - 01
Iso-E-Super		1703	8.43E + 08	2.78E - 01
Hexyl cinnamic aldehyde		1770	2.01E + 09	1.19E - 01
Galaxolide		1893	9.86E + 09	4.85E - 03
Tonalid		1902	1.11E + 10	1.29E - 02