Investigation of the Release of Bioactive Volatiles from Amphiphilic Multiarm Star-Block Copolymers by Thermogravimetry and Dynamic Headspace Analysis

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ABSTRACT: Amphiphilic multiarm star-block copolymers with a hydrophobic inner and a hydrophilic outer shell have been used to encapsulate hydrophobic bioactive volatiles in aqueous media under realistic application conditions. The release rates of the bioactive compounds have been investigated for a series of fragrances by thermogravimetry and dynamic headspace analysis. An increasing amount of ethanol present in an aqueous solution linearly reduces the long-lastingness of the fragrance evaporation, which seems to particularly affect nonencapsulated fragrances. An improved controlled release effect is also obtained in the presence of surfactants, where a boosting effect was observed for the fragrance evaporation. Amphiphilic core–shell structures based on hyperbranched polymers were thus found to be suitable delivery systems for the controlled release of bioactive volatiles under typical application conditions. The fundamental understanding of the parameters influencing the release of bioactive compounds is of major interest for the development of tailor-made core–shell structures as efficient delivery systems in various areas of life-science research.

Introduction

Since the performance of perfumed consumer articles is often judged on the fragrance perception, the controlled release of fragrances has recently become an important area of interdisciplinary research. Both a boosting effect and an increased longevity of the fragrance perception improve the performance of perfumed consumer articles. Perfumes are complex mixtures of highly volatile molecules with particular physicochemical properties. Specific delivery systems have been developed to protect volatiles against degradation during storage and to control their release during application. In these systems, fragrances are hereby released either by diffusion of the encapsulated material out of a polymer matrix[1] or, alternatively, by chemical bond cleavage of suitably designed precursors.[2]

The ease of structural modification combined with specific material properties make polymers an interesting class of substrates to modulate the evaporation of volatiles, for both physical (entrapping)[1] and chemical (bond cleaving)[2] release pathways. Glassy hydrophilic copolymers with different degrees of cross-linking[3] as well as micelle or gel forming triblock copolymers[4] have successfully been applied to increase the longevity of fragrance evaporation from matrix encapsulates. A series of polymer conjugates with a multitude of backbone structures were also investigated as delivery systems for the release of volatiles by chemical bond cleavage.[5]

Recently, the use of dendritic macromolecules[6] as delivery systems for the controlled release of bioactive matter has attracted considerable interest for a broad variety of applications.[7] As a consequence of their globular architecture and their high number of end groups, dendrimers constitute highly stable "unimolecular" micelles,[8] which are readily adaptable to the requirements of use in different media. Besides encapsulation inside the dendrimer structure,[7] bioactive compounds can also be released by chemical bond cleavage at the dendrimer surface,[9] as was recently shown for the controlled release of fragrances.[2,10]

Nevertheless, with the cost of the highly symmetric dendrimers being prohibitive for many applications, research interest has been directed toward the design of hyperbranched polymers (HBPs).[11] Their synthesis is less complex and time-consuming than that of perfect dendrimers but leads to comparable globular architectures and specific chain end densities. Because of their limited size, dendrimers and HBPs have only a limited loading capacity, and a strategy to generate unimolecular containers with loading capacities higher than those of dendrimers or HBPs is to prepare amphiphilic multiarm star-block copolymers. Dendrimers and HPBs are ideal core molecules upon which such multiarm architectures can be constructed. As a consequence of their lower cost, HPBs are particularly attractive to be used as the central core for structures targeted for practical applications. Multiarm star polymers can be prepared in the so-called "grafting from" strategy, by using a multifunctional core as the initiator for controlled polymerization reactions or in a "grafting onto" procedure, where end-reactive polymers are directly grafted onto a suitably functionalized core.[11] A multitude of controlled polymerization reactions such as ring-opening polymerization (ROP)[12] or atom transfer radical polymerization (ATRP)[13] as well as combinations thereof[14] have been described for the preparation of hyperbranched multiarm star-block copolymers.[15–18] Amphiphilic core–shell structures, schematically represented in Figure 1, are of particular interest for the encapsulation of a broad variety of guest molecules.[19] For the encapsulation of hydrophilic molecules in an organic environment, core–shell structures with an inner hydrophilic and an outer hydrophobic shell are most appropriate (Figure 1, top),[20] whereas amphiphilic multiarm star-block copolymers with a hydrophobic inner and hydrophilic outer shell are suitable for

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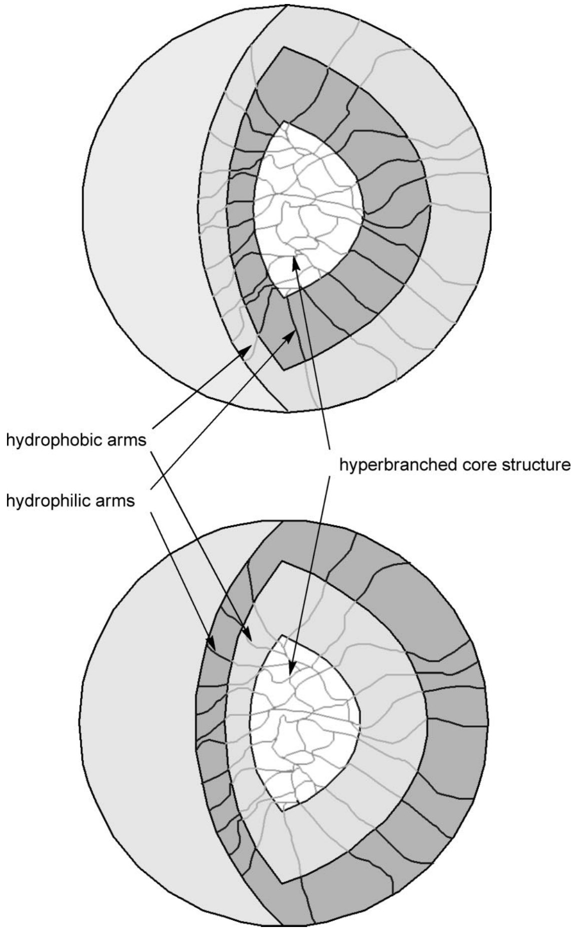


Figure 1. Schematic representation of amphiphilic multiarm star-block copolymers with a hydrophilic inner and hydrophobic outer shell (top) and with a hydrophobic inner and hydrophilic outer shell (bottom).

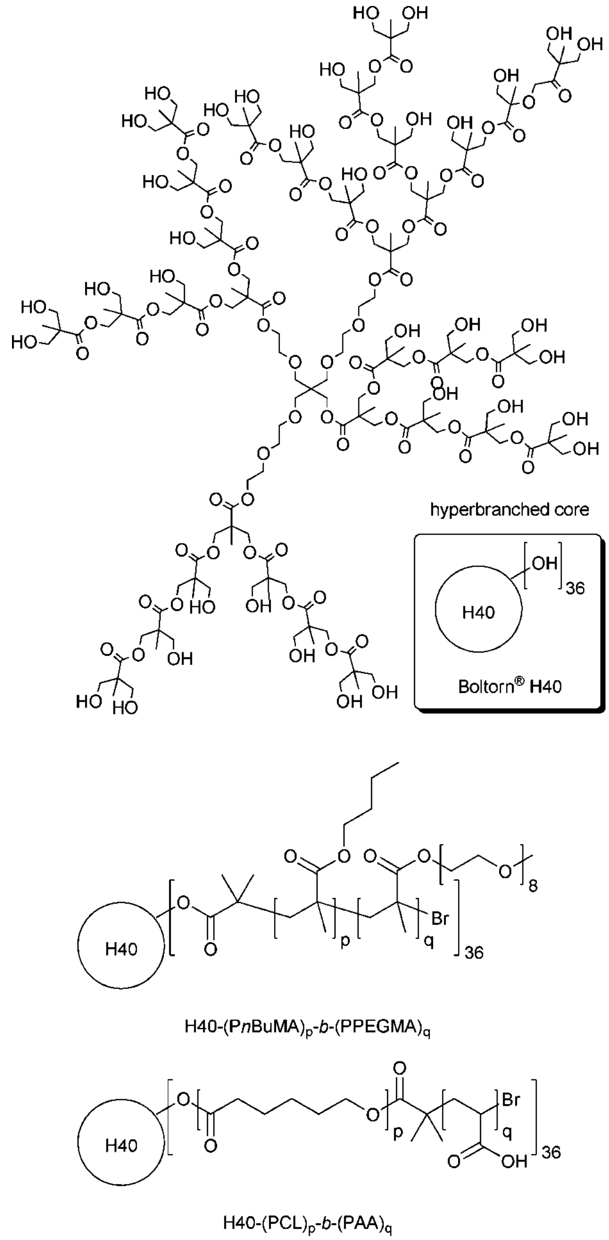


Figure 2. Average structures of the Boltorn H40 core and amphiphilic multiarm star-block copolymers H40-(P*n*BuMA)$_p$-*b*-(PPEGMA)$_q$ and H40-(PCL)$_p$-*b*-(PAA)$_q$.

the encapsulation of hydrophobic guests in an aqueous environment (Figure 1, bottom).[16−18,21,22] Most fragrances are only slightly soluble in water (as expressed by high log $P_{o/w}$ values),[23,24] which is the most commonly used solvent for most perfumery applications. To disperse them in an aqueous environment and to ensure an efficient encapsulation inside the molecular containers, we investigated amphiphilic multiarm star-block copolymers with a hydrophobic inner and hydrophilic outer shell as possible fragrance delivery systems.[17,18,25]

In our previous work we described the preparation of amphiphilic multiarm star-block copolymers based on a commercially available hyperbranched polyester core (Boltorn H40), which was functionalized by consecutive ATRP with *n*-butyl methacrylate (*n*BuMA) and poly(ethylene glycol) methyl ether methacrylate (PEGMA) to give the amphiphilic multiarm star-block copolymer H40-(P*n*BuMA)$_p$-*b*-(PPEGMA)$_q$ (Figure 2).[17] Alternatively, the H40 polyester core was functionalized by ROP with ε-caprolactone to give a semicrystalline poly(ε-caprolactone) (PCL) inner shell, which was then functionalized by ATRP with *tert*-butyl acrylate (*t*BuA) to give block copolymer H40-(PCL)$_p$-*b*-(P*t*BuA)$_q$. To obtain a hydrophilic outer shell, the *tert*-butyl esters were then hydrolyzed to the corresponding poly(acrylic acid) (PAA), resulting in the final core−shell block copolymer H40-(PCL)$_p$-*b*-(PAA)$_q$ (Figure 2).[18] The Boltorn H40 used as the core of the HBP has an average of 36 terminal hydroxyl groups,[18] all of which were successfully functionalized with the corresponding diblock copolymer to give an average of 36 arms. A series of polymers with different ratios of p and q have been prepared and fully characterized.[17,18] Self-diffusion NMR spectroscopy and relaxation studies in aqueous media have shown that fragrances are successfully encapsulated inside the water-soluble core−shell structure and mainly located in the hydrophobic part of the HBP.[25] The degree of encapsulation was found to depend on the log $P_{o/w}$ values of the fragrance molecules with hydrophobic, high log $P_{o/w}$ molecules being preferentially dissolved by the polymer.

In this contribution we now complete our work on the investigation of the release of fragrances from the amphiphilic multiarm star-block copolymers under typical conditions found in perfumery applications.[26] Fundamental understanding of the parameters influencing the release of bioactive compounds is an important prerequisite for the use of core−shell structures as delivery systems. To our surprise, this aspect has often been neglected in previous studies. Besides the encapsulation and release of one single compound, we were particularly interested to understand the behavior of compound mixtures. The evaporation of the fragrances from copolymers H40-(P*n*BuMA)$_p$-*b*-(PPEGMA)$_q$ and H40-(PCL)$_p$-*b*-(PAA)$_q$ in the presence of anionic, nonionic, and cationic surfactants as well as the influence of the ethanol concentration on the evaporation rate was thus monitored by thermogravimetry (TGA)[27] or dynamic headspace analysis.[28]

Experimental Section

General. Boltorn H40 was obtained from Perstorp Chemicals. Amphiphilic multiarm star-block copolymers H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$, H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$, and H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$ were prepared as described previously.[17,18] All fragrance compounds were used as obtained without further purification. Percentages are indicated in percent by weight (w/w) if not stated otherwise. Thermogravimetric analyses (TGA) were carried out on a Mettler Toledo thermogravimetric analyzer (module TGA/SDTA 851e) under a constant flow of nitrogen gas (20 mL/min).[29] Dynamic headspace analyses were performed on a Perkin-Elmer TurboMatrix ATD desorber coupled to a Carlo Erba MFC 500 gas chromatograph equipped with a J&W Scientific DB-1 capillary column (30 m × 0.45 mm i.d., film thickness 0.42 μm) and a FID detector using a temperature gradient from 70 to 130 °C (at 3 °C/min) and then to 260 °C at 35 °C/min. The injection temperature was fixed at 240 °C and the detector temperature at 260 °C.[30] Headspace concentrations (in ng/L) were obtained by external standard calibration of the corresponding fragrances using six different concentrations in ethanol. Each calibration solution (0.2 μL) was injected onto clean Tenax TA cartridges, which were desorbed and analyzed under the same conditions as the collected samples.

TGA for the Fragrance Release from Water/Ethanol Mixtures. Amphiphilic multiarm star-block copolymers H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ or H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ (0.04 g, 2%) were each solubilized in ethanol (1.70 g, 85%). After stirring, pure water (0.16 g, 8%) and either one of the fragrances 4-*tert*-butyl-1-cyclohexyl acetate (Vertenex), benzyl acetate, (*E*)-3,7-dimethyl-2,6-octadienol (geraniol), or decanal (0.10 g, 5%) were added. Solutions were obtained for both polymers. The sample was left stirring at room temperature for 1 day. A reference sample using the unfunctionalized Boltorn H40 core instead of the amphiphilic multiarm star-block copolymer was prepared in a similar way. Each solution (10 μL) was placed in an aluminum oxide crucible and analyzed by TGA. The samples were heated from 25 to 50 °C at 5 °C/min, kept at 50 °C for 115 min, then heated to 130 °C at 4 °C/min, and kept at 130 °C for 15 min. All analyses were carried out in duplicate.

TGA for the Fragrance Release from Water/Ethanol Mixtures with a Varying Amount of Ethanol. H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$ (0.02 g, 2%) was solubilized in water (0.93 g, 93%) before benzyl acetate or geraniol (0.05 g, 5%) was added. The sample was stirred at room temperature overnight. Equivalent samples were prepared by solubilizing the polymer in ethanol/water mixtures of 5:88, 20:73, 40:53, and 60:33, respectively, before adding the benzyl acetate or the geraniol to each sample. In the case of H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$, samples with low ethanol content were obtained as solutions; those with an ethanol content of ca. 60% and above formed an emulsion. Each sample (10 μL) was placed in an aluminum oxide crucible and analyzed by TGA. The temperature was kept at 30 °C for 300 min (5 h). A sample of the pure fragrance molecule without polymer in the corresponding ethanol/water mixtures was measured as the reference.

Dynamic Headspace Analysis for the Fragrance Release from Water/Ethanol Mixtures.[26] A model perfume consisting of 15 fragrance molecules with different chemical functionalities (aldehydes, ketones, alcohols, nitriles, and esters) was obtained by mixing equimolecular amounts (0.2 mol) of (*Z*)-3-hexenol (2.00 g), (±)-3,5,5-trimethylhexanal (2.84 g), 2,6-dimethyl-2-heptanol (dimetol, 2.88 g), acetophenone (2.40 g), ethyl (*E*)-2,4-dimethyl-2-pentenoate (3.12 g), benzyl acetate (3.00 g), (±)-2-propylheptanenitrile (3.06 g), decanal (3.12 g), 4-phenyl-2-butanone (benzylacetone, 2.96 g), (±)-2-pentylcyclopentanol (3.12 g), geraniol (3.08 g), 4-cyclohexyl-2-methyl-2-butanol (3.40 g), 10-undecenal (3.36 g), Vertenex (3.96 g), and allyl 3-cyclohexylpropanoate (3.92 g). Amphiphilic multiarm star-block copolymer H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ (0.04 g, 2%) was solubilized in ethanol (1.70 g, 85%). After stirring, water (0.16 g) and the model perfume (0.10 g, 5%) were added. Amphiphilic multiarm star-block copolymer H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$ (0.04 g, 2%) was solubilized in water (either 1.06 g, 53% or 0.66 g, 33%). After stirring, ethanol (0.80 g, 40% or 1.20 g, 60%) and the model perfume (0.10 g, 5%) were added. The sample was left stirring at room temperature for at least 1 day. The sample (2 μL) was then placed in a homemade headspace sampling cell (ca. 160 mL of inner volume), thermostated at 25 °C, and exposed to a constant air flow of ca. 200 mL/min.[30] The air was filtered through activated charcoal and aspirated through a saturated solution of NaCl to give a constant humidity of ca. 75%.[31] The volatiles were continuously adsorbed onto Tenax TA cartridges (0.10 g), which were changed after 3.5, 4.5, 6, 8, 10, 13, 16, 20, 30, 45, and 60 min. The cartridges were then thermally desorbed and the volatiles analyzed by gas chromatography (GC). As a reference, the same experiment was repeated using the pure model perfume (2 μL) without the amphiphilic multiarm star-block copolymer. All data are the average of two measurements.

Dynamic Headspace Analysis for the Fragrance Release from an Aqueous Surfactant Solution. An aqueous surfactant solution was prepared by weighing sodium dodecylbenzenesulfonate (Marlon A, 10.85 g, 75% in water) as an anionic surfactant and poly(ethylene glycol) monoundecyl ether (Neodol 25-7, 15.00 g) as a nonionic surfactant in water (24.15 g). The aqueous surfactant solution (0.10 g) was added to amphiphilic multiarm star-block copolymer H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$ (0.02 g, ca. 5.59×10^{-5} mmol) and water (0.87 g), providing a mixture containing 4.7% of surfactant and 2% of the copolymer. The above-described model perfume (0.01 g) was added and the mixture stirred for 1 day. Similarly, a reference sample without the polymer was prepared. For the measurements, the above prepared samples (200 μL) were each placed in the above-described headspace sampling cell. The headspace cell was thermostated at 25 °C and exposed to a constant flow of air of ca. 200 mL/min, which was filtered through activated carbon and aspirated through a saturated solution of NaCl. The volatiles were adsorbed onto clean Tenax cartridges from 4.5 to 19 min at increasing time intervals varying from 1.5 to 3 min, and then for 5 min every 5 min for 1 h. Further data points (5 min of sampling) were collected after 110, 150, and 265 min. Between the samplings, the volatiles were trapped onto a waste Tenax cartridge which was discarded after the experiment. All the other cartridges were thermally desorbed and the volatiles analyzed by GC.

Size distribution measurements of the perfume containing surfactant solutions were carried out by dynamic light scattering on a Malvern Nano SZ instrument in the presence and absence of H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$.

Dynamic Headspace Analysis for the Fragrance Release from an Aqueous Surfactant Solution on Cotton.[26,30] A solution (3.3 mL) of equimolar amounts (0.45 mmol) of 4-phenyl-2-butanone (benzylacetone, 63.8 mg), allyl 3-cyclohexylpropanoate (86 mg), 4-cyclohexyl-2-methyl-2-butanol (78.7 mg), and benzyl acetate (69.3 mg) in 10 mL of ethanol was added to amphiphilic multiarm star-block copolymer H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ (0.04 g, ca. 1.33×10^{-4} mmol, corresponding to a copolymer content of 1.2%) and stirred for 1 day. This solution (1.0 mL) was added in a small vial to an aqueous surfactant emulsion (1.80 g) consisting of a quaternized triethanolamine ester of fatty acids (TEA-esterquat) (Stepantex VK90 or VHR90, 16.5%), calcium chloride (0.2%), and water (83.3%). A reference sample consisting of the fragrance solution in ethanol (1.0 mL) without the copolymer and the surfactant emulsion (1.80 g) was prepared in a second vial. Both vials were closed and left stirring at room temperature for 4 days. The samples were then dispersed in a beaker with 600 mL of demineralized cold tap water. One cotton sheet (Eidgenössische Materialprüfanstalt (EMPA) cotton test cloth Nr. 221, prewashed with an unperfumed detergent powder and cut to ca. 12 × 12 cm pieces) was added to each beaker and agitated manually for 3 min, left standing for 2 min, then wrung out by hand, and weighed to

Table 1. Remaining Amount of Fragrances (in wt %) after 80 min at 50 °C in the Presence and Absence of the H40 Core or Amphiphilic Multiarm Star-Block Copolymers As Determined by TGA

	pure fragrance	Boltorn H40 core	H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$	H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$
geraniol	3.42	4.35	5.65	5.90
decanal	2.52	2.55	2.65	4.62
benzyl acetate	2.00	2.64	2.65	2.46
Vertenex	2.48	2.54	3.39	3.08

obtain a constant quantity of residual water. The two sheets (one with the amphiphilic multiarm star-block copolymer and one without) were analyzed immediately after treatment with the softener. For the measurements, one sheet was put into the above-described headspace sampling cell. The headspace cell was thermostated at 25 °C and exposed to a constant flow of air of ca. 200 mL/min, which was filtered through activated carbon and aspirated through a saturated solution of NaCl. The headspace system was equilibrated for 75 min, and then the volatiles were adsorbed for 5 min on a clean Tenax cartridge. The sampling was repeated 7 times every 50 min. The cartridges were then thermally desorbed and the volatiles analyzed by GC. A similar experiment using amphiphilic multiarm star-block copolymer H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ was carried out as described above, after equilibrating the headspace system for 15 min.

Results and Discussion

A large number of amphiphilic multiarm star-block copolymers have been prepared,[15−22] and the successful encapsulation of active molecules and their controlled release have been described.[16−22] Since their release can easily be followed by UV/vis or fluorescence spectroscopy, dyes or fluorescent probes have almost exclusively been used as the model compounds to follow the encapsulation and release of guest molecules from dendritic structures.[16,20,22]

Fragrances are highly volatile, aliphatic or aromatic hydrocarbons with numerous chemical functionalities (aldehydes, ketones, alcohols, nitriles, esters, and lactones). They usually do not absorb in the visible spectrum and are rarely fluorescent. Furthermore, in practical applications, they are used as compound mixtures with up to 40 or more ingredients in different ratios and in the presence of surfactants. The proof of successful encapsulation[25] and their controlled release under realistic application conditions are therefore not trivial.

Investigation of the Fragrance Release by TGA. As a consequence of their volatility, we decided to begin our studies by following the fragrance evaporation in the presence or absence of the multiarm star-block copolymers by TGA. TGA was found to be a suitable method to study the evaporation of volatiles from polymeric nanoparticles, as recently shown for the release of Romascone from hydrolyzed vinyl acetate with different degrees of cross-linking.[29]

In a first experiment, we individually compared the evaporation of four model fragrances (benzyl acetate, geraniol, decanal, and Vertenex) in the presence or absence of amphiphilic multiarm star-block copolymers H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ and H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ as well as the unfunctionalized Boltorn H40 core as an additional reference. The measurements were carried out in an aqueous ethanol solution (with 85% of ethanol). The samples were mixed and left equilibrating for 1 day before being heated from 25 to 50 °C (at 5 °C/min), kept at 50 °C for 115 min, and then heated to 130 °C (at 4 °C/min) where the temperature was then kept for 15 min.

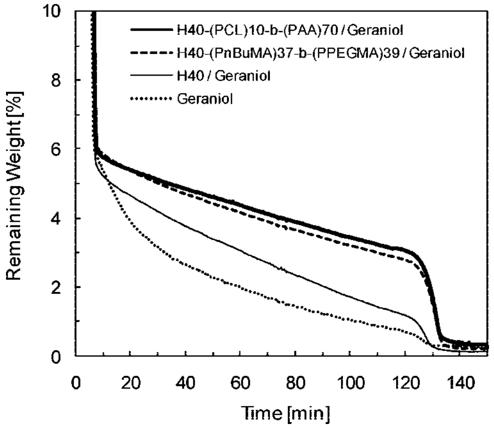


Figure 3. Weight loss (in %) of geraniol when mixed with 85% ethanol and 8% water, in the presence or absence of the H40 core or amphiphilic multiarm star-block copolymers.

Table 2. Differences of the Solubility Parameters between Fragrances and the Hydrophobic Blocks of H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ (PBuMA) and H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ (PCL)

	$[(\delta_{h1}-\delta_{h2})^2+(\delta_{p1}-\delta_{p2})^2+(\delta_{d1}-\delta_{d2})^2]^{1/2}$ [J$^{1/2}$ cm$^{-3/2}$]	
	PBuMA block	PCL block
geraniol	6.78	3.56
decanal	5.73	3.72
benzyl acetate	2.74	2.10
Vertenex	2.70	7.04

The data obtained for the evaporation of the nonencapsulated fragrances were normalized to account for the polymer content (2%) in the other samples. Table 1 compares the remaining amount of each individual fragrance (in %) after 80 min, and Figure 3 displays the data measured for the evaporation of geraniol as a typical example. In open systems (as is the case for the present investigations), the weight loss is mainly determined by the vapor pressures of the evaporating compounds.[29] With the vapor pressure of ethanol (8117.97 Pa) being more than 1 order of magnitude higher than those of the fragrances, its evaporation is expected to be well separated from that of the fragrances. The steep decrease in weight loss observed at the beginning of the experiment (Figure 3) was therefore attributed to the evaporation of ethanol (and water), which is followed by a much slower decrease in weight loss as a result of fragrance evaporation (data measured between 10 and 20 min). As previously shown for micellar copolymer structures,[4] the evaporation of the fragrance was significantly slowed down in the presence of the amphiphilic multiarm star-block copolymers, even at relatively low copolymer concentrations of 2%. As expected, this effect was much more pronounced for the core−shell structures than for the unfunctionalized H40 core.

One possibility to rationalize the affinities of the different fragrance molecules with the multiarm star-block copolymers is the comparison of their respective solubility parameters.[32] The Flory−Huggins parameter[33] (χ_{12}) between the polymer (1) and the fragrance (2) is a measure of the interaction between the polymer and the volatiles and may be expressed as

$$\chi_{12} = V_m(\delta_1 - \delta_2)^2/RT \qquad (1)$$

where δ_1 and δ_2 are the Hildebrand solubility parameters for the polymer and the fragrance, respectively, and V_m is the molar volume of a polymer "segment". The Hildebrand solubility parameters δ are often separated into hydrogen (δ_h), polar (δ_p), and dispersive (δ_d) contributions (Hansen parameters), and to assess miscibility the term $(\delta_{h1}-\delta_{h2})^2+(\delta_{p1}-\delta_{p2})^2+(\delta_{d1}-\delta_{d2})^2$ is used.[34] The values of the Hansen parameters for the fragrance molecules and the polymers have been determined using literature data.[34] Based on NMR measurements showing

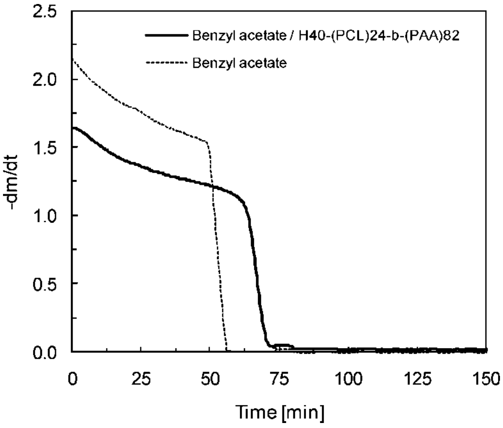


Figure 4. Comparison of the evaporation rates of benzyl acetate from an aqueous solution (containing 5% of ethanol) in the presence and absence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$.

that the fragrances are located within the hydrophobic part of the star-block copolymers,[25] only the hydrophobic blocks have been considered for the determination of the solubility parameters. Table 2 indicates the differences obtained for the solubility parameters of the hydrophobic polymer block and the fragrance molecule for each polymer/fragrance system.

As a general trend, one should expect that the lower the difference of the solubility parameters between the polymer block and the fragrance, the higher the affinity between the compounds and the slower the rate of evaporation. The data in Table 2 correctly predict the experimental values in Table 1, although the measured differences of the amount of remaining fragrances are quite small in some cases. This indicates that other physicochemical parameters, such as the volatility or the water solubility of the fragrances, have an influence on the release properties.

Previous work demonstrated that the self-assembly of block copolymers with a hydrophobic and hydrophilic part reduces the evaporation of volatiles as a consequence of micelle formation.[4] Not all, but some, star-block copolymers form unimolecular micelles,[8] and therefore the interactions between the polymer and the volatiles are not expected to be influenced by the presence of large quantities of ethanol and a low amount of polymer.

As mixtures of water and ethanol are usually used as the solvent in fine perfumery (fine fragrances and eaux de toilette), we investigated the influence of its amount on the fragrance evaporation. Five solutions with different ethanol contents (0%, 5%, 20%, 40%, and 60%) were prepared. The evolution of the evaporation rate of the fragrances ($-dm/dt$) was determined for benzyl acetate and geraniol as a function of time, in the presence or absence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$. TGA measurements were carried out at constant temperature (30 °C) for 300 min.

Figure 4 shows the curves obtained for the evaporation of benzyl acetate in 5% of ethanol. The steep decrease in evaporation rate corresponds to the onset of a constant weight plateau in the original TGA measurement. This steep decrease of the evaporation rate is representative of the copolymer−fragrance interaction. The data show that the copolymer is efficient in retaining the fragrance. Furthermore, they indicate that the rate of evaporation of benzyl acetate decreases smoothly from the beginning of the measurement and then drops to zero, which corresponds to the complete evaporation of the fragrance.

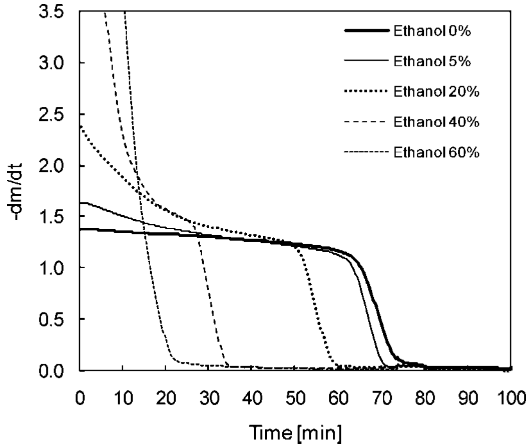


Figure 5. Comparison of the evaporation rates of benzyl acetate in the presence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ from aqueous solutions with variable ethanol content (0% to 60%).

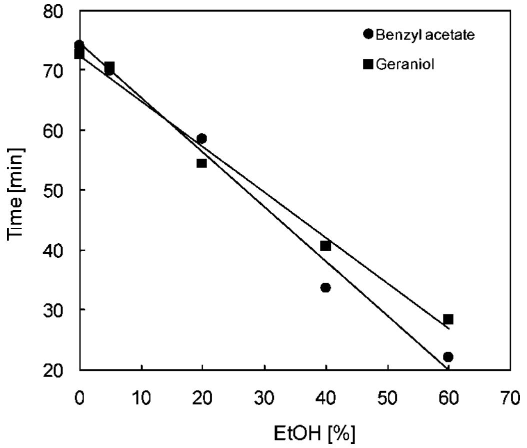


Figure 6. Influence of the ethanol fraction on the time required to reach a constant rate of fragrance evaporation (Figure 5) in the presence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ as a function of the variable ethanol concentration of the aqueous solution.

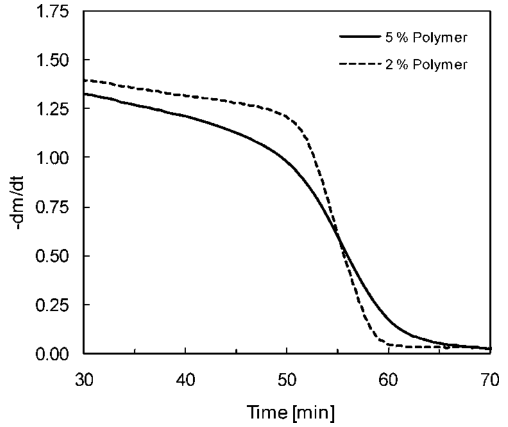
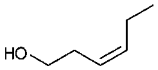
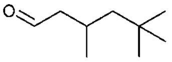
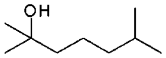
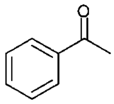
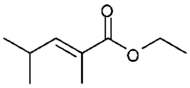
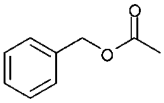
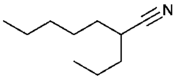
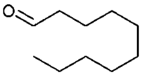
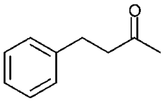
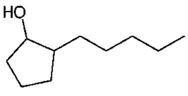
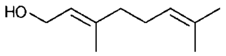
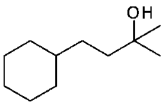
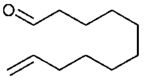
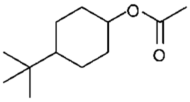
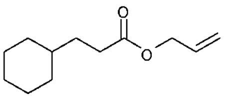


Figure 7. Influence of the polymer concentration on the evaporation profile of benzyl acetate in the presence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ from an aqueous solution containing 20% of ethanol.

An increase in the amount of ethanol in the solvent mixtures increases the evaporation rate of the fragrance as illustrated for the example of benzyl acetate in Figure 5. This is the result of preferred coevaporation of the fragrances with ethanol and was therefore observed in the presence and in the absence of the copolymer, independently of the nature of the fragrance molecule. The linearity of the effect was demonstrated by

Table 3. Physicochemical Parameters of the Fragrances Used as a Model Perfume and Evaporation Time Required To Reach a Headspace Concentration Threshold of 500 ng/L from an Aqueous Ethanol Solution in the Presence or Absence of Amphiphilic Multiarm Star-Block Copolymer H40-$(PCL)_{10}$-*b*-$(PAA)_{70}$

Fragrance Compound		Physico-Chemical Parameters		Time to Reach a Headspace Concentration of 500 ng/L	
		$\log P_{o/w}$[a]	Vapor Pressure [Pa] at 20°C[a]	pure fragrances in mixture [min]	fragrances and H40-$(PCL)_{10}$-*b*-$(PAA)_{70}$ [min]
(*Z*)-3-Hexenol		1.61	124.0	5.0	5.2
3,5,5-Trimethylhexanal		3.03	287.0	8.0	9.3
Dimetol		3.11	48.5	7.8	10.0
Acetophenone		1.58	43.4	6.0	10.3
Ethyl (*E*)-2,4-dimethyl-2-pentenoate		3.09	134.0	---[b]	6.2
Benzyl acetate		1.96	24.9	9.7	17.0
2-Propylheptanenitrile		3.71	9.1	11.6	13.6
Decanal		3.76	31.3	16.7	16.7
Benzylacetone		1.96	8.7	15.5	22.0
2-Pentylcyclopentanol		3.53	1.2	30.6	37.8
Geraniol		3.47	2.1	42.0	45.6
4-Cyclohexyl-2-methyl-2-butanol		3.98	1.3	35.8	42.6
10-Undecenal		4.12	8.7	29.2	30.6
Vertenex®		4.42	9.1	24.6	31.0
Allyl 3-cyclohexyl-propanoate		4.47	2.9	31.9	44.0

[a] Calculated with the EPIwin v. 3.10 program (US Environmental Protection Agency). [b] Measured headspace concentration always below 500 ng/L.

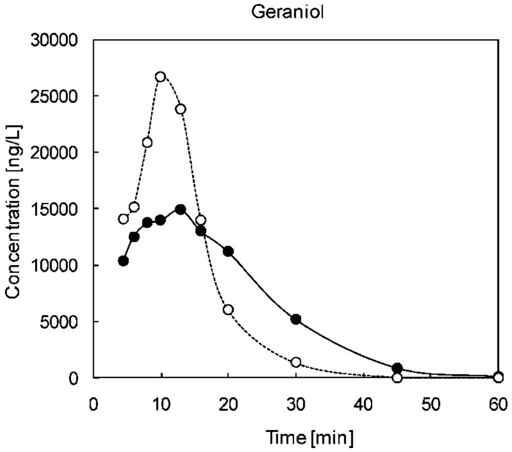


Figure 8. Dynamic headspace analysis for the evaporation of geraniol in the presence (solid line) and absence (dotted line) of amphiphilic multiarm star-block copolymer H40-$(PCL)_{10}$-*b*-$(PAA)_{70}$ from an aqueous ethanol solution.

plotting the time to reach a constant rate of fragrance evaporation ($-dm/dt = 0$) as a function of the ethanol concentration (Figure 6). In the area which is representative of the polymer−fragrance interactions, the evaporation rate is a linear function of the ethanol concentration. This was observed for the more volatile benzyl acetate as well as for the less volatile geraniol and is therefore expected to be a general trend.

The curves displayed in Figure 5 correspond to three regimes. The first regime, at the beginning of the experiment, is dominated by the evaporation of ethanol, with high amounts of ethanol accelerating the evaporation rates. The second regime corresponds to the influence of water on the evaporation rates and is typical of the rates observed for the evaporation of volatiles from an aqueous solution. This effect is more pronounced for samples with a low ethanol content (in our case less than 60%), where an inflection point can be observed in the evaporation profile. The last stage represents the evaporation of the fragrance from the polymer matrix before reaching a constant value ($-dm/dt = 0$) corresponding to complete evaporation.

To illustrate the influence of the polymer concentration on the evaporation rate of the fragrances, TGA measurements at two different polymer concentrations were carried out. Figure 7 shows the evaporation rate measured for benzyl acetate in the presence of 2 and 5 wt % of star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ and with an ethanol content of 20%. Different amounts of copolymers modify the shape of the $-dm/dt$ curve, in particular in the part of the curve relating to the polymer−fragrance interaction. A higher concentration of the amphiphilic block copolymer results in a steeper decrease of the evaporation rate prior to the complete evaporation of the fragrance.

After complete evaporation of the ethanol, TGA measurements allowed analysis of the evaporation rates of single fragrance molecules as a function of the copolymer concentration.[29] They therefore simulate the evaporation of single molecules in typical applications of fine perfumery.

Investigation of the Fragrance Release by Dynamic Headspace Analysis. Headspace sampling in combination with gas chromatography (GC) is the most currently used technique for the analysis of volatiles.[28] As long as the individual molecules are separated by GC, the technique allows to simultaneously quantify a multitude of individual volatiles in a mixture. As the volatiles are trapped in the headspace above the sample, the method usually requires a minimum of sample preparation and thus tolerates the presence of nonvolatile additives such as polymers and surfactants.

In a first experiment, we investigated the evaporation of a model perfume consisting of an equimolar mixture of 15 fragrances (Table 3) in the presence and absence of amphiphilic multiarm star-block copolymer H40-$(PCL)_{10}$-*b*-$(PAA)_{70}$ by dynamic headspace analysis. The polymer was dissolved in aqueous ethanol (containing 85% of ethanol), and the sample was stirred for 1 day. For the analysis, a small amount of the sample was placed in the headspace sampling cell. The headspace was continuously removed (by pumping air across the sample) to account for the natural convection of a sample exposed to air, and the evaporated volatiles were trapped on Tenax cartridges at given time intervals. The cartridges were thermally desorbed and the volatiles quantified by GC. Headspace concentrations were determined by external standard calibration. A reference sample without the polymer was prepared and analyzed in the same way.

Our measurements showed that, in general, higher headspace concentrations were measured in the presence of the amphiphilic multiarm star-block copolymer rather than in its absence. Table 3 lists some physicochemical parameters of the different fragrance molecules[24] and compares the times required for each molecule of the mixture to reach an arbitrarily chosen headspace concentration of 500 ng/L in the presence and absence of the amphiphilic multiarm star-block copolymer. In almost all cases it was found that the presence of the star-block copolymer prolongs the time which is needed to reach the threshold concentration, thus illustrating the desired delayed release effect of the copolymer.

The evaporation profiles of geraniol are represented as a typical example in Figure 8. As expected for a typical slow release effect, the headspace concentration curves cross each other after a certain amount of time. In the case of highly volatile compounds, such as benzyl acetate, the crossover of the release profiles may occur at a very early stage of the experiment. Because of the equilibration of the headspace sampling cell at the start of the measurement, no precise data could be recorded at the beginning of the headspace sampling. Nevertheless, at the end of the experiment, the headspace concentrations of all fragrance compounds in the mixture were found to be higher in the presence of the star-block copolymer than in its absence.

Figure 9 shows some of the headspace data obtained for the evaporation of the model perfume in the presence or absence of copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ using 40 or 60% of ethanol in water. The data show that the evaporation of the fragrances was delayed in the presence of the star-block copolymer. This delayed release effect was observed for all different ethanol concentrations in solution, confirming the results shown in Figure 8 for the analysis carried out with H40-$(PCL)_{10}$-*b*-$(PAA)_{70}$. Moreover, and in agreement with the TGA measurements discussed above, Figure 9 illustrates that an increasing ethanol content in the solution increases the evaporation rate of the free fragrances, as shown by a steeper slope of the corresponding evaporation profiles at 60% of ethanol as compared to the measurements carried out at 40%. A high ethanol content seems to affect in particular the nonencapsulated fragrances, as there is a considerable slow release effect in the presence of any of the star-block copolymers, even at a high ethanol content in the solution. Our data show that the presence of the star-block copolymer has a stronger effect on the longevity of the fragrance evaporation at higher ethanol content. Figure 9 compares the evaporation of highly volatile 3,5,5-trimethylhexanal (with a vapor pressure of 287.0 Pa) and less volatile 10-undecenal (8.7 Pa) at an ethanol content of 40 and 60%, respectively. The presence of the polymer reduces the time required for the headspace concentration curves to cross at a

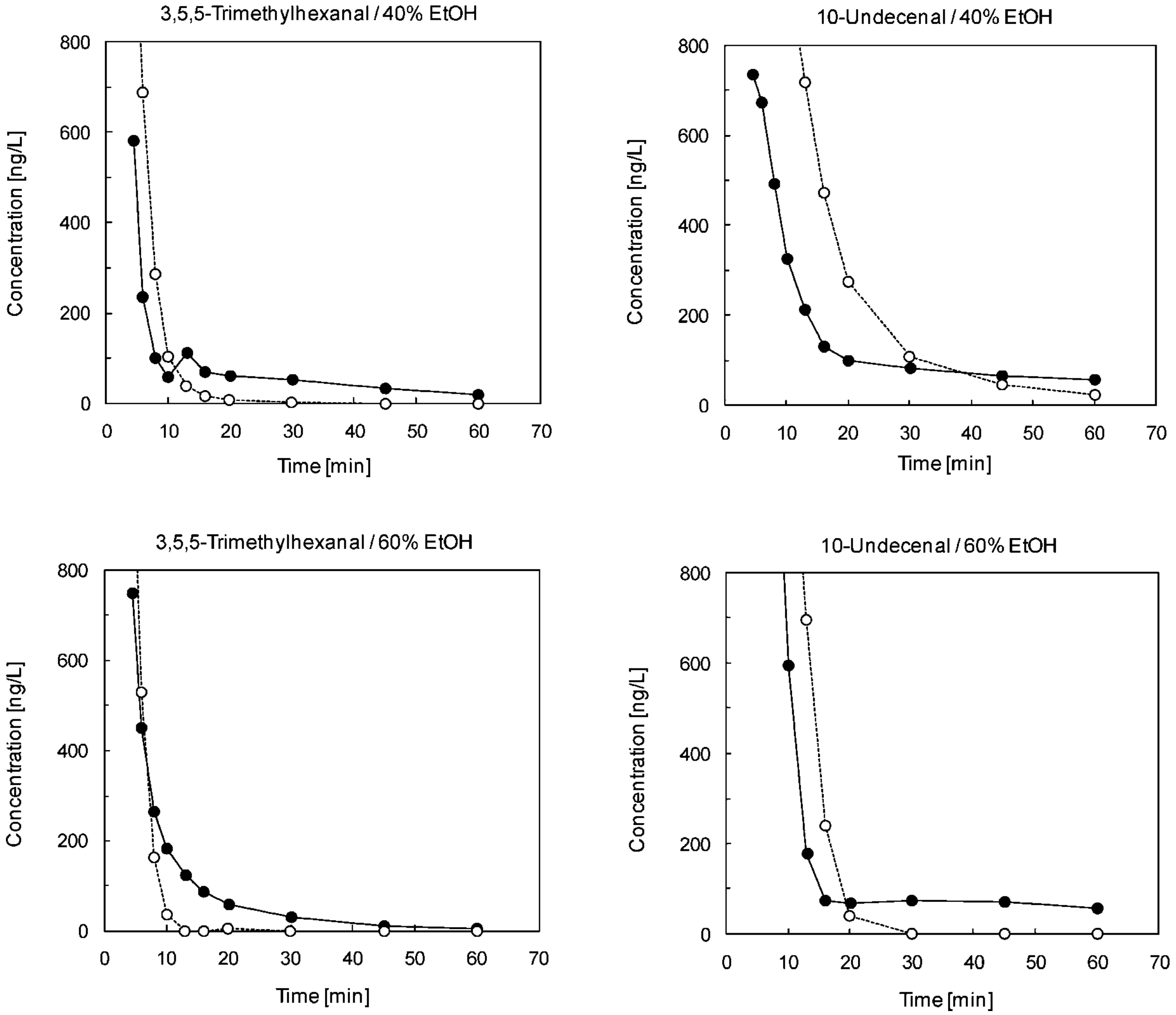


Figure 9. Dynamic headspace analysis for the evaporation of a model perfume in the presence (solid line) or absence (dotted line) of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ from an aqueous solution containing 40% (top) or 60% (bottom) of ethanol.

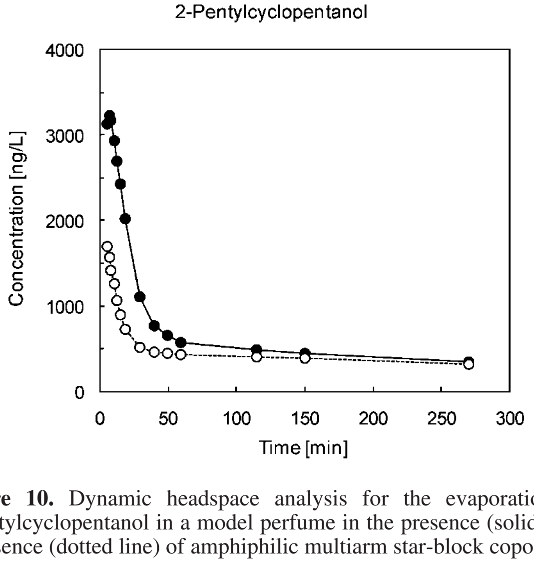


Figure 10. Dynamic headspace analysis for the evaporation of 2-pentylcyclopentanol in a model perfume in the presence (solid line) or absence (dotted line) of amphiphilic multiarm star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$ from an aqueous solution containing 4.7% of a mixture of an anionic and nonionic surfactant.

higher ethanol content of the solvent by about 4 and 18 min, respectively, and even by up to 35 min in the case of allyl 3-cyclohexylpropanoate (see Supporting Information).

Decreasing the ethanol content and/or using amphiphilic multiarm star-block copolymers to encapsulate the perfume is therefore an efficient way to increase the long-lastingness of fragrance perception.

In functional perfumery, as is the case for typical body care or household applications, surfactants are used as additional ingredients. They are responsible for the cleaning effect of detergents and all purpose surface cleaners (APCs) or the softening properties of fabric conditioners. Surfactants act as solubilizers of hydrophobic compounds in aqueous media. It can therefore be expected that the presence of surfactants influences the encapsulation and release properties of the star-block copolymers, as they are in competition with surfactant micelles as fragrance carriers. Whereas typical APCs usually contain up to 5% of a mixture of anionic and nonionic surfactants such as sodium alkylbenzenesulfonates and poly(ethylene glycol) monoalkyl ethers,[35] fabric softeners contain up to 16% of a cationic surfactant such as quaternized triethanolamine esters of fatty acids (TEA-esterquats) as the softening agent.[36]

Our model perfume was thus added to an aqueous APC formulation consisting of a mixture of sodium dodecylbenzenesulfonate as an anionic surfactant and poly(ethylene glycol) monoundecyl ether as a nonionic surfactant, with a total amount of surfactant of 4.7% (w/w) and ca. 2% of star-block copolymer H40-$(PCL)_{24}$-*b*-$(PAA)_{82}$. After 1 day, the mixture (which corresponds to the neat product in its concentrated form) was analyzed by dynamic headspace analysis by comparison to a reference sample without the copolymer. Figure 10 shows the

Table 4. Dynamic Headspace Concentrations Measured for a Mixture of Four Fragrances in the Presence or Absence of Amphiphilic Multiarm Star-Block Copolymer H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ (after 370 min of Sampling) and H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ (after 430 min of Sampling) from an Aqueous Solution Containing 16% of a Cationic Surfactant after Deposition on a Cotton Sheet

	concn of pure fragrances in mixture [ng L^{-1}]	concn of fragrances with H40-(P*n*BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ [ng L^{-1}]	concn of pure fragrances in mixture [ng L^{-1}]	concn of fragrances with H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ [ng L^{-1}]
benzyl acetate	6.3	82.1	0.0	34.7
benzylacetone	277.3	298.2	74.4	130.6
4-cyclohexyl-2-methyl-2-butanol	375.2	837.2	69.7	445.8
allyl 3-cyclohexylpropanoate	46.8	588.1	10.3	498.1

headspace concentrations for one selected fragrance. Despite the presence of the surfactants, higher (or at least comparable) headspace concentrations were measured in the samples with the star-block copolymer. A particular long-lastingness of the fragrance evaporation was observed for some of the less volatile compounds of the series (e.g., 2-pentylcyclopentanol or geraniol), whereas the effect was found to be less pronounced for highly volatile fragrances (vapor pressures >40 Pa, e.g., dimetol).

In marked contrast with the previous measurements in ethanol, one observes that in the presence of the copolymer very high headspace concentrations were measured at the beginning of the experiment with respect to the reference without polymer. In this case there is a boosting rather than a long-lasting effect of fragrance perception. Dynamic light scattering measurements of the perfume containing aqueous APC formulation showed that in the absence of the star-block copolymer two predominant peaks were observed at 18 and 440 nm corresponding to pure micelles and aggregates of micelles, respectively. Deposition of a droplet of the micellar system on a surface results in a multilayer arrangement of the surfactant molecules which reduces the surface of evaporation. In the presence of H40-(PCL)$_{24}$-*b*-(PAA)$_{82}$, the formation of large polymer aggregates was observed with an average size distribution of 1300 nm. The peak corresponding to the pure micelles on the size distribution curve of the sample without the polymer disappeared in the presence of the star-block copolymer. The deposition of the aggregated polymers on a surface results in a larger surface of evaporation as the micellar system and is therefore expected to accelerate the fragrance evaporation. Furthermore, after the initial rapid evaporation at the beginning of the experiment, the amount of remaining perfume is much higher in the presence of the polymer as compared to its absence. With higher headspace concentrations being measured for up to 150 min (e.g., for geraniol), the positive effect of the copolymer should be easily perceived in a realistic cleaner application.

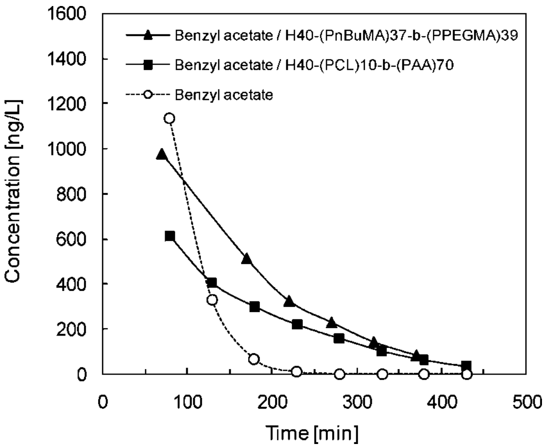


Figure 11. Dynamic headspace concentrations measured for benzyl acetate (in a mixture with three other fragrances) in the presence or absence of amphiphilic multiarm star-block copolymer H40-(P*n*-BuMA)$_{37}$-*b*-(PPEGMA)$_{39}$ (solid line, triangles) and H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ (solid line, squares) from an aqueous solution containing 16% of a cationic surfactant after deposition on a cotton sheet.

To even further increase the surfactant concentration, we investigated the performance of an equimolar mixture of four fragrances in a typical fabric softener application. For the measurements, a product formulation containing 16% of a TEA-esterquat and 1.2% of either one of the amphiphilic multiarm star-block copolymers H40-(PCL)$_{10}$-*b*-(PAA)$_{70}$ and H40-(PBMA)$_{37}$-*b*-(PPEGMA)$_{39}$ was used. The system was left equilibrating for 4 days and then dispersed in water, and the surfactants were transferred to a cotton sheet. Again the headspace concentrations were compared against a reference sample without the copolymer.

To be efficient under these application conditions (which corresponds to the diluted product form), the fragrances not only have to be encapsulated into the core—shell structure of the star-block copolymer, but the latter has also to be efficiently transferred to the cotton surface.

At the beginning of the measurement, higher headspace concentrations were recorded in the absence of the amphiphilic multiarm star-block copolymer, although this effect was less pronounced than in the previous measurements with a lower surfactant content. Nevertheless, at the end of the experiment all headspace concentrations determined in the presence of the copolymer were higher than those of the corresponding reference, thus showing the desired long-lastingness of the fragrance release. Table 4 shows the headspace concentrations measured on wet fabric after 430 min of sampling, and Figure 11 illustrates the evolution of the headspace concentrations of benzyl acetate in the presence and absence of the copolymer.

Conclusions

The encapsulation and controlled release of bioactive substances such as pharmaceuticals, agrochemicals, flavors, or fragrances are important tools to improve the performance of these compounds in their respective product formulation. In our work we have shown that amphiphilic core—shell structures of multiarm star-block copolymers are suitable delivery systems for the controlled release of fragrances under realistic application conditions. Amphiphilic core—shell structures with a hydrophobic inner shell and a hydrophilic outer shell allow trapping of relatively hydrophobic fragrances inside the polymer structure and thus dispersing them efficiently in aqueous media. The release performance was followed by thermogravimetry and dynamic headspace analysis, without relying on model compounds such as dyes or fluorescence probes.

The presence of ethanol has a strong influence on the evaporation profile of volatile organic compounds. Our data illustrate that an increasing amount of ethanol linearly increases the rate of fragrance evaporation. But as this effect seems to affect in particular the nonencapsulated fragrances, the presence of the amphiphilic core—shell structures has a strong influence on the longevity of fragrance evaporation, in particular at a high ethanol content in the solution.

Dynamic headspace analysis of fragrance mixtures showed that the presence of surfactants, and thus a competition between encapsulation into the amphiphilic multiarm star-block copolymers and surfactant micelles, does not have a negative impact on the performance of the polymers. In contrast to the ethanol/water systems, where the amphiphilic copolymer mainly contributes to the long-lastingness of the fragrance perception, its presence in surfactant-based systems results rather in a boosting effect for the fragrance evaporation.

We have shown that amphiphilic multiarm star-block copolymers efficiently encapsulate volatiles and contribute to the efficiency of fragrance evaporation under realistic application conditions. Amphiphilic core−shell structures based on HBPs are therefore suitable delivery systems for the controlled release of fragrances and other bioactive volatiles.

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Supporting Information Available: Full data (tables and figures) of the dynamic headspace measurements using the model perfume. This material is available free of charge via the Internet at http://pubs.acs.org.

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