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Chemistry and Physics of Lipids
99 (1999) 21–32

CPL
CHEMISTRY AND PHYSICS OF LIPIDS

Synthesis and surface-active properties of a series of new anionic gemini compounds

Philippe Renouf [a], Dominique Hebrault [b], Jean-Roger Desmurs [b], Jean-Michel Mercier [c], Charles Mioskowski [a], Luc Lebeau [a,*]

[a] *Université Louis Pasteur-Laboratoire de Synthèse Bioorganique associé au CNRS 74, route du Rhin-BP 24, 67401 Illkirch, France*
[b] *Rhône-Poulenc Industrialisation-CRIT-Carrières 85, avenue des Frères Perret-BP 62, 69192 Saint-Fons Cedex, France*
[c] *Rhône-Poulenc-Centre de Recherche d'Aubervilliers, 52, rue de la Haie-Coq, 93308 Aubervilliers, France*

Received 17 September 1998; received in revised form 23 December 1998; accepted 05 January 1999

Abstract

The synthesis of a series of new anionic dimeric amphiphiles **1–5** is described. The CMC and both static and dynamic surface tensions have been measured using the Wilhelmy plate technique and the maximum bubble pressure method. Results are compared to those obtained with the corresponding monomeric surfactants and relevant monomeric or dimeric compounds described in the literature. The relationship between the structural features of the different compounds and their properties is discussed. In particular an increase in the length of the connecting group between the two lipophilic chains lowers the CMC of the compounds which is different from results reported in the literature for other gemini compounds.

Keywords: Amphiphiles; Critical micelle concentration; Dimeric surfactants; Dynamic surface tension; Synthesis

1. Introduction

During the last decade, the discovery of improved surface-active properties of dimeric (gemini) surfactants, when compared to amphiphilic monomers, gave rise to the molecular design of new amphiphiles far removed from the classical concept that a surfactant is made of one lipophilic moiety and one polar head connected together (Nusselder and Engberts, 1989; Cheng et al., 1992; Stein and Gellman, 1992; Wassermann et al., 1992; Menger and Littau, 1993; Menger and Yamasaki, 1993; Perez et al., 1996; Schmidt and Jankowski, 1996). Thus a considerable number of investigations have been reported on the surface

Abbreviations: b, broad; d, doublet; m, multiplet; q, quintuplet; s, singlet; t, triplet.

* Corresponding author. Tel.: +33-3-88676857; fax: +33-3-88678891.
E-mail address: lebeau@aspirine.u-strasbg.fr (L. Lebeau)

0009-3084/99/$ - see front matter
PII: S0009-3084(99)00003-1

and aggregation properties of a variety of gemini surfactants containing two hydrophobic and two hydrophilic groups in the molecule (Devinski et al., 1986; Okahara et al., 1988; Menger and Littau, 1991; Zana et al., 1991; Zhu et al., 1991a; Masuyama et al., 1992; Rosen et al., 1992; Menger and Littau, 1993; Song and Rosen, 1996; Zana et al., 1991) so as to develop new functions of surfactants or improve their properties.

In this work, we describe the preparation of a series of new dimeric anionic surfactants and their surface-active properties in water (Fig. 1). These compounds contain a flexible hydrophilic linkage of two different lengths between the hydrophilic groups. We compare these dimeric surfactants

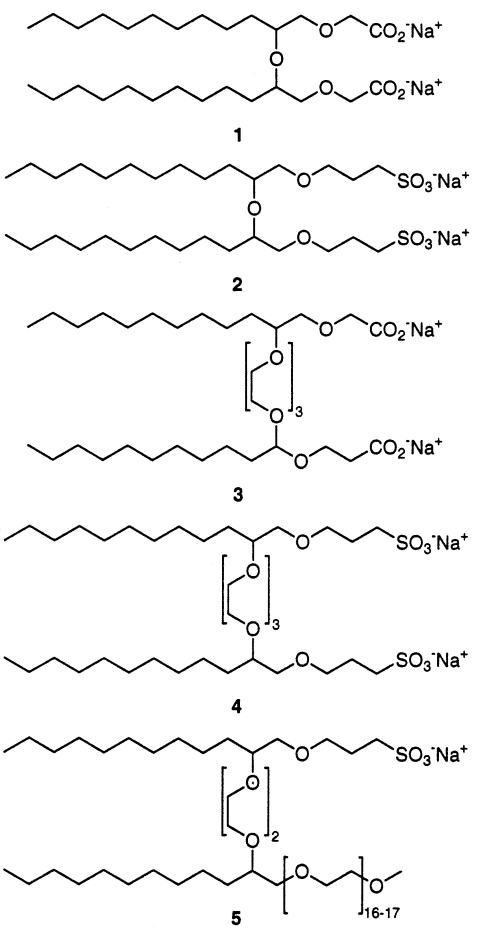


Fig. 1. Structure for the anionic gemini compounds synthesized.

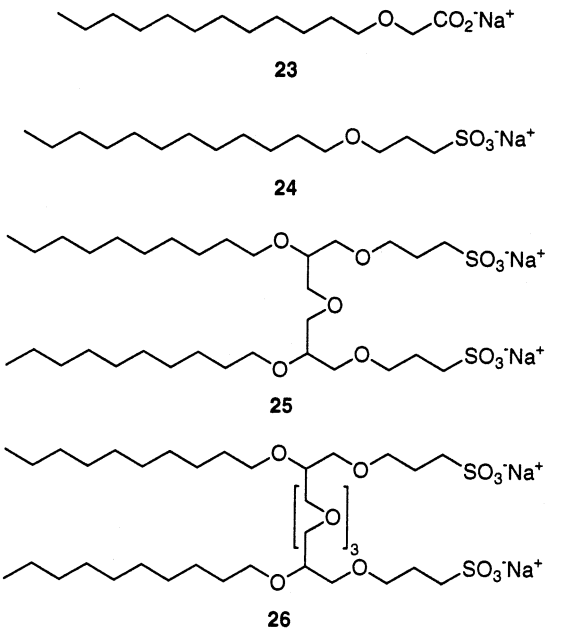


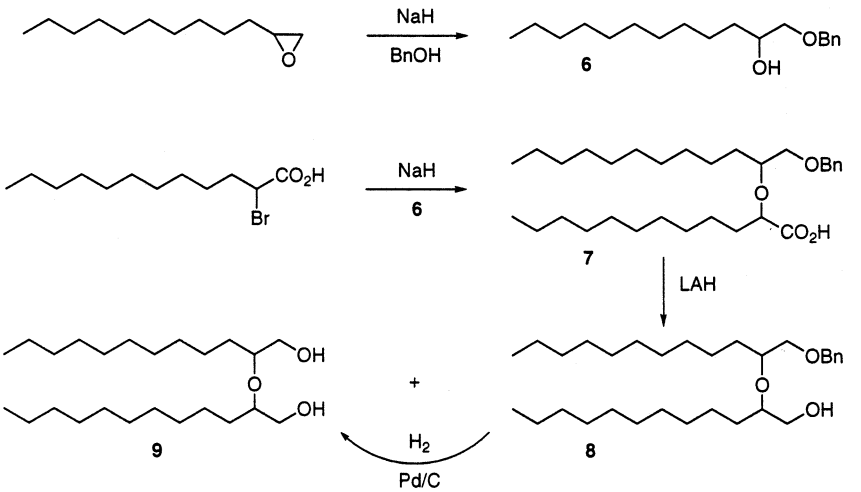
Fig. 2. Previously described surficants that are compared to the gemini compounds prepared in this work.

with the related monomeric surfactants and with other related compounds described in the literature and try to clarify the relationship between structural features and the surface-active and aggregation properties (Fig. 2).

2. Results

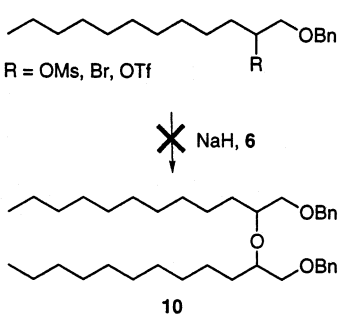
2.1. Synthesis of the gemini compounds

The synthetic routes to **1–5** are as follows. All compounds were obtained starting from 1,2-epoxydodecane. The basic solvolysis of the oxirane in benzyl alcohol produced the β-hydroxyether **6** (Scheme 1). Compound **6** was then condensed with α-bromodecanoic acid in the presence of sodium hydride to give **7**. The reduction of the carboxyl group in compound **7** using lithium aluminium hydride led to a mixture of the expected compound **8** together with diol **9**, resulting from partial debenzylation of the protected hydroxyl group in **8** (Kutney et al., 1970). Complete debenzylation of the latter compound was

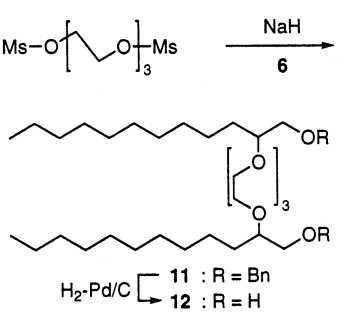


Scheme 1.

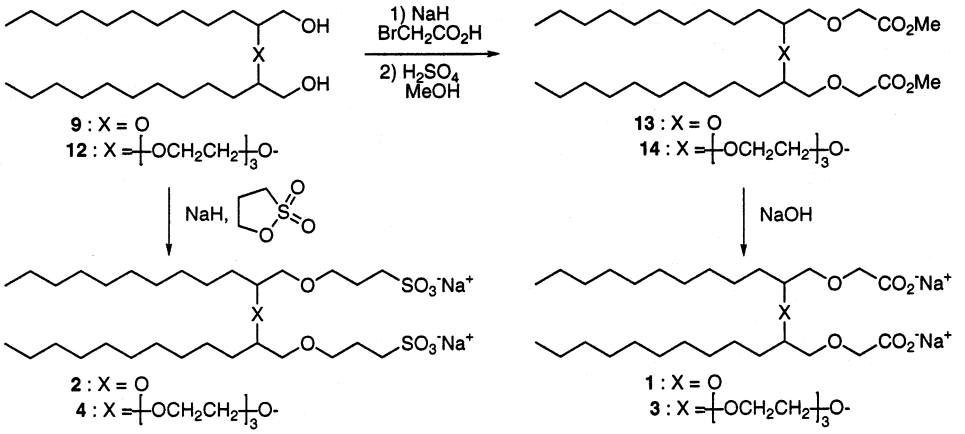
achieved by catalytic hydrogenolysis over Pd/C. Diol **9** was obtained as a mixture of 2 diastereomers that are separable by chromatography over silica gel. All attempts to achieve the direct condensation of **6** with the corresponding secondary methanesulfonate, bromide, or trifluoromethanesulfonate invariably failed to produce compound **10** (Scheme 2). The condensation of two molar equivalents of the secondary alcohol **6** with triethyleneglycol bis-methanesulfonyl ester in refluxing THF provided dibenzyl ether **11** (Scheme 3). Further debenzylation by hydrogenolysis over Pd/C produced the bis-hydroxyl compound **12**. Diols **9** and **12** reacted with sodium hydride and bromoacetic acid in THF to yield the corresponding bis-carboxylic acid compounds that could not be purified satisfactorily on silica gel (Scheme 4). Further esterification of the crude extracts in methanol, isolation of the diesters, and subsequent hydrolysis produced the two gemini compounds **1** and **3** in a pure form. The sulfonate compounds **2** and **4** were directly prepared by reacting the diols **9** and **12** with propane sultone and sodium hydride in refluxing dioxane (Suga et al., 1968; Carrea et al., 1988). The dissymetrical gemini compound **5** was prepared via monodebenzylation of **15** (obtained similarly as **11**, from diethylene glycol bis-methanesulfonyl ester and **6**) into **16** by catalytic hydrogenolysis (Scheme 5). The hydroxyl function in **16** was alkylated through reaction of the sodium salt with an oligomer of polyethyleneglycol methyl ether methanesulfonyl ester and produced compound **17**. Removal of the second benzyl protective group yielded the hydroxyl compound **18** that was further transformed into **5** using propane sultone.



Scheme 2.

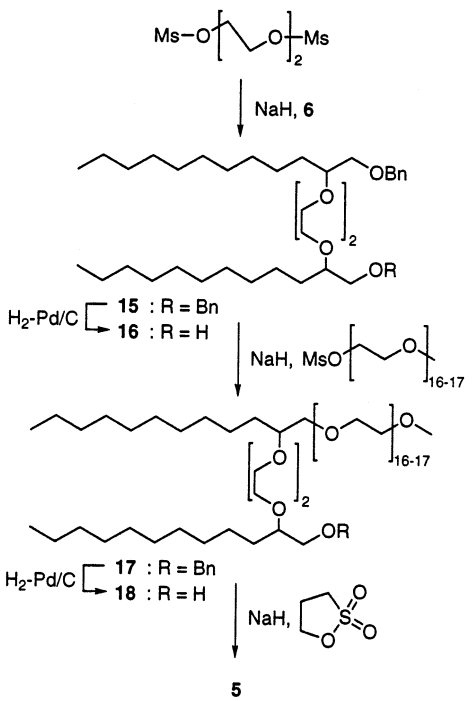


Scheme 3.



Scheme 4.

The monomeric surfactants **21** and **22** corresponding to the gemini compounds were prepared as well (Scheme 6). The secondary hydroxyl group in **6** was alkylated using methyl iodide. Debenzylation of the resulting methoxy benzylether **19** produced the primary alcohol **20** that was then condensed either with bromoacetic acid or propane sultone to provide **21** or **22**, respectively.



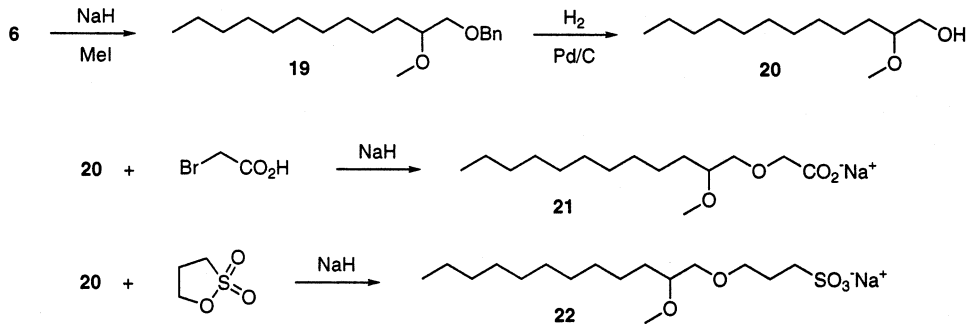
Scheme 5.

2.2. Surface-active properties

The critical micelle concentration (CMC), static surface tension (the surface tension at CMC, γ_S), and surfactant concentration in the solution phase that will reduce the surface pressure of the solvent by 20 mN/m (C_{20}) were determined in water, according to the procedures described in the experimental section. The dynamic behavior of the compounds has been characterized by dynamic surface tension measurements realized as previously described (Fainerman and Miller, 1994; Miller et al., 1997). It is related to dynamic properties as wetting power, detergency power, emulsifying power… Results are listed in Tables 1 and 2, along with some additional data related to typical or relevant detergents (Suga et al., 1968; Hato et al., 1976; Dahanayake et al., 1986; Zhu et al., 1991b).

3. Discussion

Preparation of the title compounds was easy and they could be isolated on the multigram scale in good yields. All the synthesized gemini compounds were readily soluble in water. Their CMC values were much smaller than that of the corre-



Scheme 6.

sponding monomeric surfactants (**23**, **24**). The disodium dicarboxylates (**1** and **3**) exhibit a CMC value that is lower by roughly an order of magnitude lower than that of the corresponding disodium disulfonates (**2** and **4**). Interestingly, increasing the length of the connecting group between the two lipophilic chains decreases the CMC value in both carboxylate and sulfonate series. That is definitely different from the results obtained by Zhu et al. (1991b) revealing a higher CMC for compounds with a longer spacer (see Table 1, compounds **25** and **26**). That discrepancy is not actually understood. The CMC value of the heterodimeric gemini surfactant **5** is lower than that of disodium disulfonate **4**. That is to be connected to the excellent micelle forming property of surfactants containing a poly(ethylene oxide) moiety (e.g. Igepal NP10) when compared to sulfonates (SDS, **24**).

Compounds **21** and **22** were prepared in order to determine the true contribution of the spacer group to the properties of the dimeric surfactants, independently of the way it is connected to the two constitutive monomers. However, the sodium carboxylate **21** could not be tested as it is completely insoluble in water up to 60°C in the pH range 7–11. The introduction of a methoxy group on the alkyl chain in the sulfonate series decreases the CMC value by an order of magnitude (compare compound **22** with **24**). Thus the sole introduction of a 'minor' structural change near the polar head of the monomeric surfactant can account for about half the micelle forming property variations observed in geminis.

Table 1
Surface active properties of the synthesized detergents and some typical surfactants

Surfactant	CMC (mol/l)	γ_S (mN/m)	C_{20} (mol/l)	pC_{20}
1	1.3×10^{-5}	26.4	2.4×10^{-6}	5.4
2	9.3×10^{-5}	31.4	10.8×10^{-6}	8.6
3	0.8×10^{-5}	38.7	1.8×10^{-6}	4.4
4	4.8×10^{-5}	35.5	7.4×10^{-6}	6.5
5	1.5×10^{-5}	39.8	2.3×10^{-6}	6.5
21[a]				
22	7.2×10^{-4}	31.3	1.1×10^{-4}	6.5
23[b]	7.5×10^{-3}			
24[c]	5.0×10^{-3}	38.9	2.0×10^{-3}	2.4
SDS[d]	8.0×10^{-3}	37.6	4.4×10^{-3}	2.2
25[e]	3.3×10^{-5}	28.0	8.0×10^{-6}	4.1
26[e]	6.0×10^{-5}	36.0	10.1×10^{-6}	5.9
Igepal NP10	6.5×10^{-5}	31.3	3.4×10^{-6}	19.1

[a] The compound was completely insoluble below 60°C.
[b] At 55°C (Hato et al., 1976).
[c] At 40°C (Suga et al., 1968).
[d] At 25°C (Dahanayake et al., 1986).
[e] At 20°C (Zhu et al., 1991b).

Table 2
Dynamic surface tension of the synthesized gemini surfactants

Surfactant	γ_m (mN/m)	t^* (s)	n
1	34.4	6.2	0.86
2	42.8	1.1	1.0
3	40.9	3.1	0.60
4	39.7	2.1	1.3
5	42.3	0.52	1.03
22	35.7	0.011	0.87
Igepal NP10	31.5	0.044	0.89

Concerning the ability of gemini compounds to lower surface tension (γ_S), as already observed by others with compounds **25** and **26** (Zhu et al., 1991b), the shortest connecting groups provide the maximum efficiency (compare **1** to **3** and **2** to **4**). In this respect, compound **1** definitely is the most powerful of all the compounds in this work.

The tendency of the surfactants to adsorb at the surface and consequently reduce the surface tension is quantified by the C_{20} value. Once again, the gemini surfactants prove to be far more powerful than conventional surfactants. Compounds **1-5** lower the surface tension of aqueous media by 20 mN/m in the micromolar range whereas monomeric carboxylate and sulfonates act in the millimolar range.

The CMC/C_{20} ratios (pC_{20}) for each surfactant were also reported (Table 1). The larger the pC_{20} the greater the tendency of the surfactant to adsorb at the surface of aqueous media, relative to its tendency to form micelles (Rosen, 1989). Conventional monomeric surfactants generally exhibit pC_{20} values less than 3. It has been proposed that large pC_{20} values reflect the difficulty of packing the hydrophobic chains in the micelle (due to the high curvature of its surface) (Rosen, 1993). Compounds **1-5** present pC_{20} values extending from 4.4 (compound **3**) to 8.6 (compound **2**), which is extremely high. It is noteworthy that sodium sulfonate **22** has a high pC_{20} too, that can be clearly related to the presence of the methoxy substituent on the alkyl chain (compare with **24** or SDS).

The dynamic surface tension measurements for the different compounds are displayed at Fig. 3. The dynamic surface tension at time t, γ_t at a constant surfactant concentration can be represented by the relaxation function described by Rosen (Gao and Rosen, 1994; Hua and Rosen, 1988):

$$\gamma_t = \gamma_m + (\gamma_o - \gamma_m)/[1 + (t/t^*)^n]$$

where γ_m is the mesoequilibrium surface tension of the solution (where γ_t shows only a small change with time), γ_o is the equilibrium surface tension of the solvent (72.1 mN/m at 23°C for water), t^* is the time when the variation of γ_t is maximum and n is a dimensionless constant. The values for t^*, n and γ_m were obtained using a classical curve fitting software and are reported in Table 2. In comparison with monomeric surfactant Igepal NP10, the gemini compounds exhibit very poor dynamic surface tension properties and are slower by one to two orders of magnitude (considering the t^* values). This implies properties related to dynamics (wetting, detergency…) to be moderate for these compounds. Additionally, compound **22** appears more powerful than Igepal NP10 that can stand as a matter of reference for surfactant dynamic properties.

4. Experimental procedures

4.1. Materials

Unless otherwise stated, all chemicals used were of commercial sources. THF, Et_2O and dioxane were distilled over Na/benzophenone and CH_2Cl_2 over CaH_2, just before use. Methanol and ethanol were dried over 3 Å molecular sieves previously heated for 12 h at 180°C under reduced pressure (0.1 mmHg). Reactions were monitored by TLC (Merck precoated plates 0.25 mm, silica gel 60 F_{254}, 0.040–0.060 mm, 230–400 mesh ASTM). Liquid chromatography was performed on silica gel 60 (Merck, 0.040–0.060 mm, 230–400 mesh ASTM). ^{1}H- and ^{13}C-NMR spectra were recorded on Brucker-WP-200-Sy and Brucker-Avance-DPX-300 spectrometers, and chemical shifts δ are in ppm relative to an internal reference (^{1}H: $CHCl_3$ at 7.27 ppm or CD_2HOD at 3.31 ppm, the latter for $CDCl_3/CD_3OD$ solutions, ^{13}C: $CDCl_3$ at 77.0 ppm or CD_3OD at 49.0 ppm, the latter for $CDCl_3/CD_3OD$ solutions). IR spectra were recorded on a Perkin-Elmer-1600-FT spectrometer, and absorption values are in cm^{-1}.

[2-(1-Carboxymethoxymethyl-undecyloxy)-dodecyloxy]-acetic acid bis sodium salt (**1**). Dimethyl ester **13** (1.52 g, 2.87 mmol) and sodium hydroxide (0.23 g, 5.74 mmol) are refluxed in anhydrous ethanol (15 ml) for 6 h. The solvent is removed in vacuo to yield **1** quantitatively (two diastereomers, 1.56 g, 100%). ^{1}H-NMR (CD_3OD, 300 MHz) δ 3.95–3.71 (m, 4H); 3.70–3.35 (m,

6H); 1.67–1.30 (m, 36H); 0.90 (t, $J = 6.8$ Hz, 6H). ^{13}C–NMR (CD_3OD, 75 MHz) δ 177.7; 177.4; 76.3; 75.1; 72.3; 71.8; 71.4; 33.0; 32.3; 30.9; 30.8; 30.7; 30.5; 30.1; 26.4; 23.7; 14.5. IR (film) ν 3401; 2915; 2850; 1601; 1110.

3-{2-[1-(3-Sulfo-propoxymethyl)-undecyloxy]d-odecyloxy}-propane-1-sulfonic acid bis sodium salt (**2**). Sodium hydride (60% in oil, 0.41 g, 10.34 mmol) is added to a mixture of diol **9** (1.33 g, 3.44 mmol) and propane sultone (1.0 ml, 12.40 mmol) in anhydrous dioxane (10 ml). The suspension is refluxed for 24 h before methanol (20 ml) is added at room temperature. The solvents are removed in vacuo, water (150 ml) is added and the solution is extracted with *n*-butanol (3×150 ml). The organic layer is dried over $MgSO_4$ and evaporated under reduced pressure. The crude solid obtained is successively washed with *n*-hexane (50 ml) and diethyl ether (50 ml) to yield analytically pure compound **2** (two diastereomers, 2.13 g, 92%). ^{1}H-NMR (CD_3OD, 300 MHz) δ 3.69–3.62 (m, 2H); 3.54 (t, $J = 11.8$ Hz, 2H); 3.46–3.35 (m, 4H); 2.95–2.89 (m, 4H); 2.09–2.00 (m, 4H); 1.50–1.31 (m, 36H); 0.90 (t, $J = 6.8$ Hz, 6H). ^{13}C-NMR (CD_3OD, 75 MHz) δ 77.2; 73.8; 69.6; 48.6; 32.5; 31.9; 29.8; 29.6 (b); 29.3; 25.3; 22.5; 13.3. IR (film) ν 2920; 2855; 1460; 1185; 1115; 1045.

[2-(2-{2-[2-(1-Carboxymethoxymethyl-undecyloxy)-ethoxy]-ethoxy}-ethoxy)-dodecyloxy]-acetic acid bis sodium salt (**3**). Compound **3** (two dia-

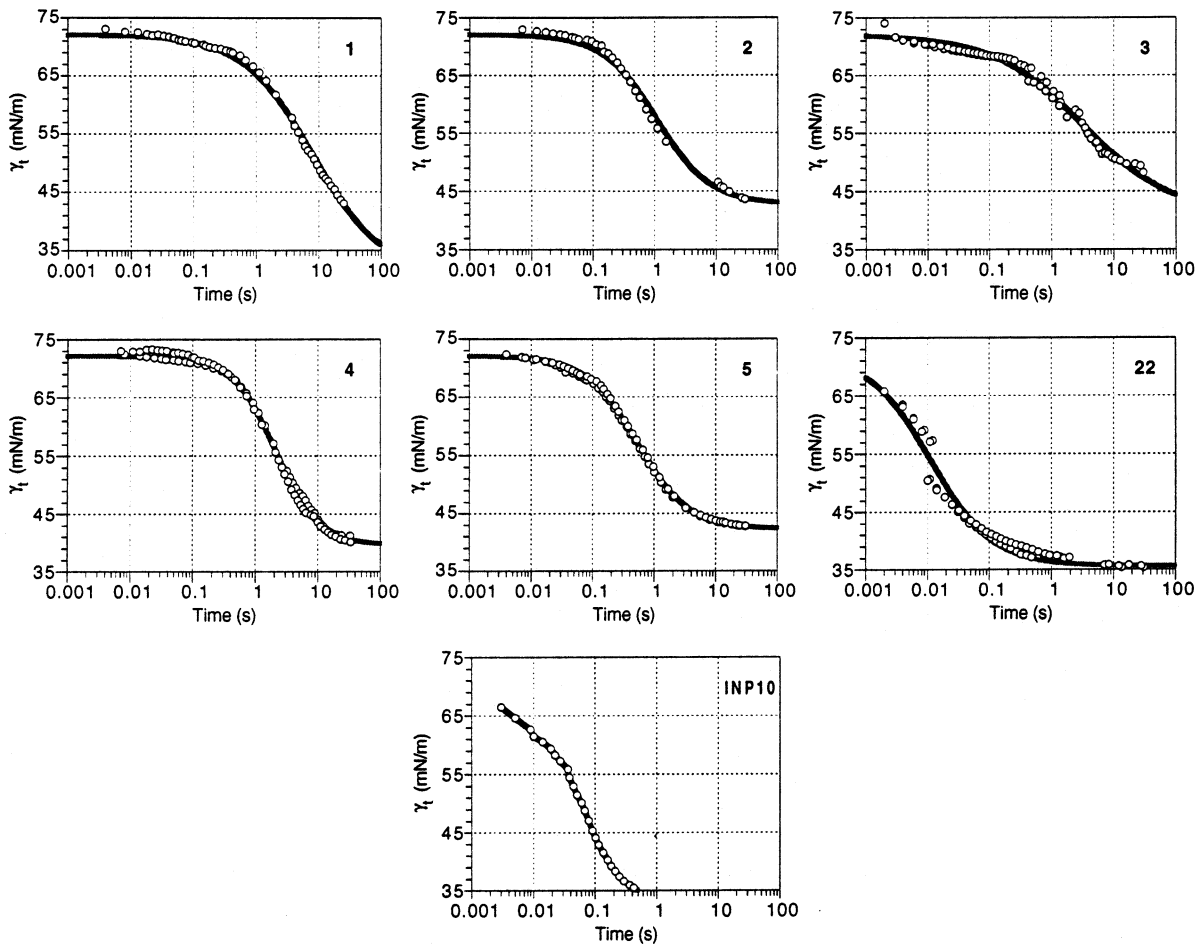


Fig. 3. The dynamic surface tension measurements for the different compounds (see Section 4.2.2).

stereomers, 1.72 g, 99%) is obtained from dimethyl ester **14** following the same procedure as for **1**. ^{1}H-NMR (CD_3OD, 300 MHz) δ 3.87 (t, $J = 6.8$ Hz, 4H); 3.72–3.45 (m, 18H); 1.67–1.44 (m, 4H); 1.38–1.26 (m, 32H); 0.90 (t, $J = 6.8$ Hz, 6H). ^{13}C-NMR ($CDCl_3/CD_3OD$: 1/1, 50 MHz) δ 176.8; 78.4 and 78.1; 71.3; 70.6; 69.5 and 69.3; 68.8; 66.3 and 65.9; 32.3; 30.5; 30.1; 29.7; 25.9; 23.0; 14.3. IR (film) *v* 3404; 2923; 2854; 1606; 1466; 1416; 1322; 1116.

3-{2-[2-(2-{2-[1-(3-Sulfo-propoxymethyl)-undecyloxy]-ethoxy}-ethoxy)-ethoxy]-dodecyloxy}-propane-1-sulfonic acid bis sodium salt (**4**). Compound **4** (two diastereomers, 1.22 g, 81%) is obtained from diol **12** following the same procedure as for **2**. ^{1}H-NMR (CD_3OD, 300 MHz) δ 3.81–3.48 (m, 22H); 2.99–2.91 (m, 4H); 2.12–1.98 (m, 4H); 1.48–1.28 (m, 36H); 0.90 (t, $J = 6.7$ Hz, 6H). ^{13}C-NMR (CD_3OD, 75 MHz) δ 80.3; 74.2; 71.8; 71.4; 70.8; 70.1; 49.3; 33.0; 32.7; 30.9; 30.8; 30.5; 26.5; 26.3; 23.7; 14.5. IR (film) *v* 2925; 2855; 1205; 1045.

3-[2-(2-{2-[1-methyl(PEG)oxymethyl-undecyloxy]-ethoxy}-ethexy)-dodecyloxy]-propane-1-sulfonic acid sodium salt (**5**). Compound **5** (two diastereomers, 1.12 g, 80%) is obtained from **18** following the same procedure as for **2**. ^{1}H-NMR ($CDCl_3$, 200 MHz) δ 3.65–3.58 (m, 76H); 3.54–3.49 (m, 6H); 3.42–3.38 (m, 2H); 2.92–2.84 (m, 2H); 2.07–1.99 (m, 2H); 1.43–1.21 (m, 36H); 0.83 (t, $J = 6.4$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 79.0; 78.9 and 78.8; 73.3 and 73.2; 73.0; 71.7; 70.6; 70.5; 70.3; 70.2; 69.7; 68.7; 68.4; 68.2; 58.9; 48.2; 31.8; 31.4; 31.0 and 30.9; 29.7; 29.5; 29.2; 25.4 and 25.3; 25.2 and 25.0; 22.6; 14.0. IR (film) *v* 3502 (b); 2923; 2859; 1458; 1348; 1299; 1245; 1112; 1045.

1-Benzyloxy-dodecan-2-ol (**6**). Sodium hydride (60% in oil, 2.90 g, 72.5 mmol) is added to 1,2-epoxydodecane (10.2 g, 55.4 mmol) in benzyl alcohol (50 ml) at 0°C. The reaction mixture is stirred at 80°C till complete consumption of the epoxide. Diethyl ether is added at room temperature and the mixture is washed with aqueous NH_4Cl, brine, and dried over $MgSO_4$. Ether and most of benzyl alcohol are removed under reduced pressure. Compound **6** crystallizes on standing at -20°C and is collected by filtration (12.8 g, 79%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.41–7.29 (m, SH); 4.58 (s, 2H); 3.86–3.81 (m, 1H); 3.54–3.50 (m, 1H); 3.37–3.31 (m, 1H); 1.46–1.27 (m, 18H); 0.89 (t, $J = 6.0$ Hz, 3H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.2; 128.6; 127.9; 74.8; 73.5; 70.6; 33.3; 32.0; 29.9; 29.8; 29.7; 29.5; 25.6; 22.8; 14.3. IR (film) v 3450; 2925; 2855; 1100.

2-(1-Benzyloxymethyl-undecyloxy)-dodecan-1-ol (**8**). Sodium hydride (60% in oil, 1.70 g, 43.0 mmol) is slowly added to 1-benzyloxy-dodecan-2-ol **6** (2.50 g, 8.6 mmol) in HMPA (2.5 ml) at 0°C. The suspension is warmed to 60°C and α-bromododecanoic acid (7.20 g, 28.0 mmol) in anhydrous THF (20 ml) is added dropwise. The reaction mixture is refluxed for 4 h before it is cooled down to 0°C, acidified with aqueous HCl (10%), and extracted with diethyl ether. The organic layer is washed with brine, dried over $MgSO_4$ and reduced in vacuo to yield compound **7** (9.42 g) that is used without further purification. Lithium aluminium hydride (1.00 g, 26.3 mmol) is added by portions at 0°C to the latter solid (9.00 g) in anhydrous THF (100 ml). The mixture is stirred at room temperature for 4 h, and then is refluxed for 48 h. Excess reagent is decomposed at 0°C by careful addition of water. The resulting solution is acidified with aqueous HCl (10%), vigorously stirred for 30 min, and extracted with diethyl ether. The organic layer is washed with brine, dried over $MgSO_4$ and reduced in vacuo. The crude residue is purified by chromatography on silica gel (diethyl ether/hexane: 1/2 to 2/1) to give compound **8** (two diastereomers, 2.43 g, 62%) followed by a portion of the debenzylation product **9** (1.21 g, 38%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.38–7.26 (m, 5H); 4.62–4.52 (m, 2H); 3.83–3.40 (m, 6H); 1.52–1.24 (m, 36H); 0.87 (t, $J = 6.8$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.1 and 137.4; 128.4 and 128.2; 127.7 and 127.5; 80.6 and 78.8; 78.4 and 76.7; 77.6; 77.0; 73.4 and 73.1; 73.2 and 73.0; 65.6 and 64.1; 36.8; 32.3; 31.8; 31.6; 29.7; 29.5; 29.3; 25.7; 25.5; 25.2; 22.6; 14.0. IR (film) *v* 2925; 2855; 1115.

2-(1-Hydroxymethyl-undecyloxy)-dodecan-1-ol (**9**). Compound **8** (2.40 g, 5.0 mmol) and Pd/C 10% (0.1 g) in methanol are stirred overnight

under hydrogen atmosphere (1 atm). The catalyst is removed by filtration over celite. The filtrate is reduced in vacuo and the residue is purified by chromatography on silica gel (hexane/ethyl acetate: 4/1 to 2/1) to yield **9** as two separated diastereomers **9a** and **9b** (1.94 g, 99%). (**9a**) ^{1}H-NMR ($CDCl_3$, 200 MHz) δ 3.69–3.61 (m, 2H); 3.54–3.43 (m, 4H); 1.55–1.26 (m, 36H); 0.90 (t, $J = 6.4$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 78.1; 64.5; 31.9; 31.3; 29.8; 29.6 (b); 29.3; 25.5; 22.6; 14.1. IR (film) ν 3317; 2917; 2851; 1467; 1086. (**9b**) ^{1}H-NMR ($CDCl_3$, 200 MHz) δ 3.73–3.65 (m, 2H); 3.55–3.43 (m, 4H); 1.55–1.27 (m, 36H); 0.90 (t, $J = 6.4$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 80.4; 65.3; 32.4; 31.9; 29.8; 29.6 (b); 29.3; 25.6; 22.7; 14.1. IR (film) ν 3336; 2925; 2857; 1460; 1069.

1-BenzylOxy-2-(2-{2-[2-(1-benzyloxylethyl-undecyloxy)-ethoxy]-ethoxy}-ethoxy)dodecane (**11**). Sodium hydride (60% in oil, 1.2 g, 30.0 mmol) is slowly added to a mixture of 1-benzyloxy-dodecan-2-ol **6** (5.0 g, 17.0 mmol), triethyleneglycol bismethanesulfonyl ester (3.1 g, 10.0 mmol), HMPA (2 ml), and sodium iodide (30 ma, 0.2 mmol) in anhydrous THF (30 ml). The mixture is stirred in refluxing THF for 16 h. Diethyl ether is then added at room temperature and the resulting solution is neutralized by careful addition of aqueous HCl (10%). The organic layer is washed with brine, dried over $MgSO_4$ and reduced in vacuo. The crude residue is purified by chromatography on silica gel (diethyl ether/hexane: l/2) to yield **11** as a mixture of two diastereomers (5.3 g, 89%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.37–7.23 (m, 10H); 4.55 (s, 4H); 3.78–3.72 (m, 2H); 3.68–3.60 (m, 10H); 3.51–3.42 (m, 6H); 1.51–1.42 (m, 4H); 1.40–1.21 (m, 32H); 0.89 (t, $J = 6.5$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.7; 129.7; 128.5; 127.8; 127.7; 79.5; 73.5; 72.9; 71.0; 70.7; 69.5; 32.1; 29.9; 29.8 (b); 29.5; 25.6; 22.8; 14.3. IR (film) ν 2925; 2860; 1110.

2-(2-{2-[2-(1-Hydroxyethyl-undecyloxy)-ethoxy1-ethoxy}-ethoxy)-dodecan-1-ol (**12**). Compound **12** (two diastereomers, 3.1 g, 99%) is obtained from **11** by catalytic hydrogenation, following the same procedure as for **9**. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 3.79–3.62 (m, 14H); 3.51–3.38 (m, 4H); 1.55–1.22 (m, 36H); 0.90 (t, $J = 6.5$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 81.4; 70.8 and 70.7; 70.2 and 70.1; 68.9 and 68.8; 64.5; 31.2; 31.1; 29.6; 29.5; 29.4 (b); 29.1; 25.5; 22.5; 13.9. IR (film) ν 3450; 2920; 2855; 1105.

[2-(1-Methoxycarbonylmethoxymethyl-undecyloxy)-dodecyloxy]-acetic acid methyl ester (**13**). Sodium hydride (60% in oil, 1.71 g, 41.4 mmol) is slowly added to a solution of diol **9** (two diastereomers, 2.00 g, 5.2 mmol) and HMPA (3 ml) in anhydrous THF (30 ml) at 0°C. A solution of bromoacetic acid (2.92 g, 20.8 mmol) in THF (10 ml) is added to the previous mixture which is then refluxed for 24 h. Aqueous HCl (10%) is added at 0°C and the resulting solution is extracted with ethyl acetate. The organic layer is washed with brine, dried over $MgSO_4$ and reduced in vacuo. The crude residue is stirred with sulfuric acid (0.5 ml) in refluxing anhydrous methanol (100 ml) for 16 h. Methanol is removed in vacuo, ether (50 ml) is added and the solution is washed with water and brine. The organic layer is dried over $MgSO_4$ and the residue is purified by chromatography on silica gel (hexane/ethyl acetate: 1/2) to yield the dimethyl ester compound **13** (two diastereomers, 0.88 g, 32%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 4.12 (AB syst., $J_{AB} = 16.6$ Hz, $\Delta\nu = 6.2$ Hz, 4H); 3.76 (s, 6H); 3.64–3.56 (m, 2H); 3.53–3.47 (m, 4H); 1.57–1.40 (m, 4H); 1.39–1.19 (m, 32H); 0.89 (*t*, $J = 6.0$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 170.7; 77.4; 74.1; 68.5; 51.5; 32.3; 31.7; 29.7; 29.5 (b); 29.2; 25.4; 22.5; 14.0. IR (film) ν 2925; 2855; 1760; 1145.

[2-(2-{2-[2-(1-Methoxycarbonylmethoxymethyl-undecyloxy)-ethoxy]-ethoxy}-ethoxy)dodecylaxy]-acetic acid methyl ester (**14**). Compound **14** (two diastereomers, 1.43 g, 70%) is obtained starting from diol **12**, and following the same procedure as for **13**. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 4.15 (AB syst., $J_{AB} = 16.2$ Hz, $\Delta\nu = 0.6$ Hz, 4H); 3.78–3.73 (m, 8H); 3.69–3.45 (m, 16H); 1.74–1.26 (m, 36H); 0.88 (t, $J = 6.4$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 170.5; 79.0; 73.7; 70.5; 70.2; 68.9; 68.3; 51.2; 31.5; 31.3; 29.4 (b); 29.3; 28.9; 25.0; 22.3; 13.7. IR (film) ν 2925; 2860; 1755; 1140.

1-Benzyloxy-2-{2-[2-(1-benzyloxymethyl-undecyloxy)-ethoxy]-ethoxy}-dodecane (**15**). Com-

pound **15** (two diastereomers, 4.14 g, 74%) is obtained starting from **6** and diethyleneglycol bis-methane-sulfonyl ester, and following the same procedure as for **11**. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.35–7.25 (m, 10H); 4.55 (s, 4H); 3.79–3.71 (m, 2H); 3.68–3.61 (m, 6H); 3.50–3.45 (m, 6H); 1.49–1.25 (m, 36H); 0.89 (t, $J = 6.5$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.6; 128.4; 127.7; 79.5; 73.5; 72.9; 71.0; 69.5; 32.0; 29.9; 29.8; 29.5; 25.6; 22.8; 14.3. IR (film) v 2925; 2855; 1115.

1-Benzyloxy-2-{2-[2-(1-hydroxymethyl-undecyloxy)-ethoxyI-ethoxy}-dodecane (**16**). Compound **16** (two diastereomers, 2.36 g, 70%) is obtained starting from **15**, using the same procedure as described for **12**, except that the reaction is conducted in ethanol/hexane (85:15, v/v) during a shorter period of time (4h). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.36–7.27 (m, 5H); 4.55 (s, 2H); 3.82–3.42 (m, 14H); 1.47–1.26 (m, 36H); 0.89 (t, $J = 6.5$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.2; 128.0; 127.3; 127.2; 81.3; 79.1; 73.0; 72.5; 70.7; 70.6; 69.0; 64.5; 31.7; 31.2; 29.5; 29.4; 29.1; 25.4; 22.5; 13.8. IR (film) v 3470; 2925; 2860; 1105.

1-Benzyloxy-2-(2-{2-[1-methyl(PEG)oxymethyl-undecyloxy1-ethoxy}-ethoxy)-dodecane (**17**). Sodium hydride (60% in oil, 0.50 g, 13.5 mmol) is slowly added to compound **16** (1.27 g, 2.25 mmol) and polyethyleneglycol methyl ether methane-sulfonyl ester (average MW: 830, 1.25 g, 1.5 mmol) in anhydrous dioxane (15 ml). The reaction mixture is refluxed overnight before methanol (2 ml) is added at room temperature. The solvent is removed in vacuo, water is added (100 ml) and the resulting solution is wished with n-butanol (3×100 ml). The organic layers are pulled together, dried over $MgSO_4$ and evaporated under reduced pressure. The residue is purified by flash chromatography over a silica gel pad (AcOEt/hexane: 1/1, then n-BuOH/CH_2Cl_2: 1/1) to yield **17** (1.95 g, 66%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.34–7.25m, 5H); 4.54 (s, 2H); 3.76–3.42 (m, 82H); 3.38 (s, 3H); 1.55–1.18 (m, 36H); 0.90 (t, $J = 6.5$ Hz, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.4; 128.2; 127.5; 127.4; 79.3; 79.2; 73.9; 73.2; 72.7; 71.9; 70.8; 70.7; 70.5; 69.3; 58.9; 31.8; 29.7; 29.6; 29.3; 25.4; 22.6; 14.0. IR (film) v 2920; 2855; 1115.

1-Hydroxy-2-(2-{2-[1-methyl(PEG)oxymethyl-undecyloxy]-ethoxy}-ethoxy)-dodecane (**18**). Compound **18** (two diastereomers, 2.47 g, 98%) is obtained starting from **17**, and following the same procedure as described for **12**. ^{1}H-NMR ($CDCl_3$/CD_3OD: 7/3, 300 MHz) δ 3.82–3.25 (m, 82H); 3.30 (s, 3H); 1.50–1.18 (m, 36H); 0.89 (m, 6H). ^{13}C-NMR ($CDCl_3$, 75 MHz) 6 81.3; 79.0; 73.6; 71.6; 70.6; 70.2; 68.7; 64.3; 58.7; 31.7; 31.4; 30.9; 29.6; 29.4; 29.1; 25.4; 25.3; 22.4; 13.9. IR (film) v 3420; 2920; 1110.

1-Benzyloxy-2-methoxy-dodecane (**19**). Hydroxy compound **6** (1.25 g, 4.3 mmol) in anhydrous THF (10 ml) is slowly added to sodium hydride (60% in oil, 0.25 g, 6.2 mmol) previously washed twice with anhydrous THF (3 ml). Methyl iodide (0.75 ml, 12.0 mmol) is then added and the resulting mixture is refluxed overnight. The suspension is filtered and the filtrate is reduced in vacuo. The residue is dissolved in diethyl ether, washed with aqueous NH_4Cl, water and brine. The organic layer is dried over $MgSO_4$ and concentrated to yield analytically pure compound **19** (1.20, 92%). ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 7.37–7.29 (m, 5H); 4.58 (s, 2H); 3.50 (d, $J = 4.9$ Hz, 2H); 3.43 (s, 3H); 3.35 (q, $J = 5.3$ Hz, 1H); 1.54–1.25 (m, 18H); 0.91 (t, $J = 6.0$ Hz, 3H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 138.6; 128.5; 127.8; 127.7; 80.4; 73.5; 72.4; 57.7; 32.0; 31.6; 29.9; 29.8 (b); 29.5; 25.5; 22.8; 14.3. IR (film) v 2925; 2855; 1460; 1115.

2-Methoxy-dodecan-1-ol (**20**). Compound **20** (1.13 g, 96%) is obtained starting from **19**, and following the same procedure as for **9**. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 3.72–3.65 (m, 1H); 3.52–3.45 (m, 1H); 3.41 (s, 3H); 3.30–3.23 (m, 1H); 1.56–1.24 (m, 18H); 0.89 (t, $J = 6.0$ Hz, 3H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 81.8; 64.1; 57.2; 32.0; 30.4; 30.0; 29.7 (b); 29.5; 25.5; 22.8; 14.2. IR (film) v 2930; 2855; 1460; 1100.

(2-Methoxy-dodecyloxy)-acetic acid sodium salt (**21**). Sodium hydride (60% in oil, 0.76 g, 19.0 mmol) is slowly added to a solution of the hydroxy compound **20** (1.37 g, 6.3 mmol) and bro-

moacetic acid (1.39 g, 10.0 mmol) in anhydrous THF (15 ml). The reaction mixture is refluxed overnight and then decomposed by dropwise addition of methanol (1 ml). The solvent is removed in vacuo and the residue is dissolved in *n*-butanol and washed with water. The organic layer is dried over $MgSO_4$, concentrated, and the residue is purified by chromatography on silica gel (ethyl acetate/ethanol: 8/2, then chloroform/methanol/water: 10/6/1) to yield (2-methoxy-dodecyloxy)-acetic acid (1.10 g). The latter carboxylic acid is treated with aqueous sodium hydroxide (10%) and the resulting mixture is extracted with *n*-butanol. The organic layer is dried over $MgSO_4$ and concentrated to yield the sodium salt **21** (1.25 g, 67%). ^{1}H-NMR (CD_3OD, 300 MHz) δ 3.96 (s, 2H); 3.63–3.51 (m, 2H); 3.40 (s, 3H); 3.43–3.37 (m, 1H); 1.54–1.30 (m, 18H); 0.90 (t, $J = 6.8$ Hz, 3H). ^{13}C-NMR ($CD_3OD/CDCl_3$: 1/1, 75 MHz) δ 173.6; 79.3; 72.3; 70.5; 56.5; 31.2; 29.3; 29.0 (b); 28.7; 24.7; 22.0; 13.7. IR (film) v 3421; 2517; 1637; 1464; 1116.

3-(2-Methoxy-dodecyloxy)-propan-1-sulfonic acid sodium salt (**22**). Compound **22** (1.66 g, 87%) is obtained starting from **20**, and following the same procedure as for **2**. ^{1}H-NMR ($CD_3OD/CDCl_3$: 2/8, 200 MHz) δ 3.55 (t, $J = 6.4$ Hz, 2H); 3.46–3.41 (m, 1H); 3.38 (s, 3H); 3.32–3.29 (m, 2H); 2.96–2.88 (m, 2H); 2.08–2.01 (m, 2H); 1.55–1.20 (m, 18H); 0.87 (t, $J = 7.1$ Hz, 3H). ^{13}C-NMR (CD_3OD, 75 MHz) δ 80.3; 72.5; 69.6; 56.6; 48.4; 31.8; 31.2; 29.7; 29.5 (b); 29.3; 25.3; 25.2; 22.5; 13.3. IR (film) v 3427; 2924; 2854; 2533; 1187.

4.2. Methods

Igepal NP10 ((nonylphenoxy)polyethoxyethanol, nonylphenol 10 EO) was from Rhône-Poulenc and was used without further purification.

4.2.1. Surface tension measurements

Solutions of the surfactants were prepared with distilled water (specific resistivity 10^6 Ωcm at 23°C) by stepwise dilution of concentrated solutions in 200 ml volumetric flasks. Surface tension measurements were made by the Wilhelmy vertical plate technique, using a sand-blasted platinum plate or by the stirrup method, using a platinum stirrup in case of wetting problem of the plate. The plate or the stirrup were connected to an electrobalance (Tensimat n°3, Prolabo). Air-water interfaces were swept clean by suction and let rest for 20 minutes at 23°C prior to experiments. Measurements were repeated until no significant change in the surface pressure value was recorded. Critical micelle concentrations were determined using a series of aqueous solutions at various concentrations. The CMC was determined from the break point of each surface versus concentration (on log scale) curve.

4.2.2. Dynamic surface tension measurements

The dynamic surface tensions were determined with a LAUDA MPT1 surface tensiometer using the maximum bubble pressure method (Fainerman and Miller, 1994; Miller et al., 1997).The apparatus was fit out with a 77 μm capillary tube and the bubble life times were in the range 0.003–30 s. Unless otherwise stated, all experiments were realized at 1 g/l surfactant concentration, at 23°C. The bubbles were blown with surrounding air (pump included in the apparatus). The LAUDA instrument was interfaced to a computer and all data were analyzed with a software supplied by LAUDA.

Acknowledgements

The authors are thankful to Gilles Guérin (Rhône-Poulenc, Centre de Recherche d'Aubervilliers) for fruitful discussion.

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