

# Surface Properties of Surfactants Derived from Natural Products. Part 1: Syntheses and Structure/Property Relationships—Solubility and Emulsification

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**ABSTRACT:** Several novel and some previously known, mostly sugar-based, surfactants have been synthesized and some of their surface properties have been characterized and compared with those of commercial nonylphenol ethoxylates. The surfactant solubility in water, ethanol, and dodecane was studied. The properties of these compounds as emulsification agents in systems composed of the surfactant with water/isopropyl myristate, water/rapeseed oil, and water/dodecane are presented. The aqueous solubility of the surfactants follows the general trend expected from their hydrophilic-lipophilic balance according to Griffin (HLBG), but it is also clear that the nature of the headgroup and the structure of the nonpolar part affect the solubility in a manner not captured in the standard HLBG concept. An ester or amine group as the connecting unit between the hydrophile and the hydrophobe produces a more water-soluble surfactant than the corresponding amide derivative. Some effective emulsifiers were found. For instance, the surfactants with a dehydroabietic nonpolar group appear to be promising emulsifiers. Most sugar-based surfactants were able to form macroemulsions of up to around 2 wt/vol% of oil. The stability of many of these emulsions was very high, extending for months.

Paper no. S1377 in *JSD* 7, 147–159 (2004).

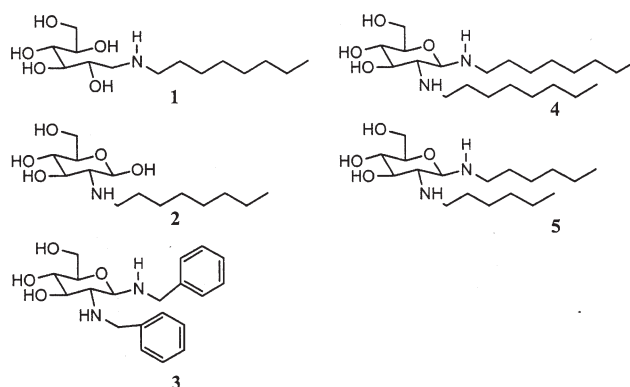
**KEY WORDS:** Emulsification, HLBD, HLBG, natural products, solubility, structure/property relationships, surface properties, surfactants.

Awareness of the ecological impacts of surfactants is growing owing to increased interest in environmental issues. This is one reason why sugar-based surfactants, including sugar esters, sugar amides, glycosides, and similar sugar-based surfactants, are being evaluated (1). These types of compounds can

be obtained in a range of structures, some of which have a large array of useful surfactant properties. Furthermore, they often degrade relatively fast under natural conditions (2). Sorbitan esters (3), sucrose esters (4), alkyl glucamides, and alkyl polyglucosides (APG) (5,6) are produced in significant quantities (25, 4, 40, and 80 thousand tons, respectively, worldwide in 1997) (7). Surfactants with sugar as polar headgroup, in comparison with analogous ethylene oxide-based surfactants, have properties that are relatively insensitive to temperature changes (8). Sugar-based surfactants are often nontoxic and noncumulative (9). They are not sensitive to hard water (10), and some of the sugar surfactants are moderate foaming agents (11). They are mild toward the skin (12) and possess lower hemolytic activity than many other types of surfactants (Söderlind, E., Astra Zeneca, Sweden, personal communication). However, these properties are also dependent on the nature of the hydrophobic moiety and, unfortunately, some sugar-based surfactants possess rather high hemolytic activity.

Here we present a study of a large number of sugar-based surfactants, some of which have been or are being commercially used and others that are novel. To screen the properties of the surfactants, a set of simple test methods was used to characterize their interfacial behavior.

*Surfactant structures.* By using a new synthetic method, a set of glucose amine surfactants, **2–5** (Scheme 1), was prepared and characterized (13). The previously known analog, compound **1**

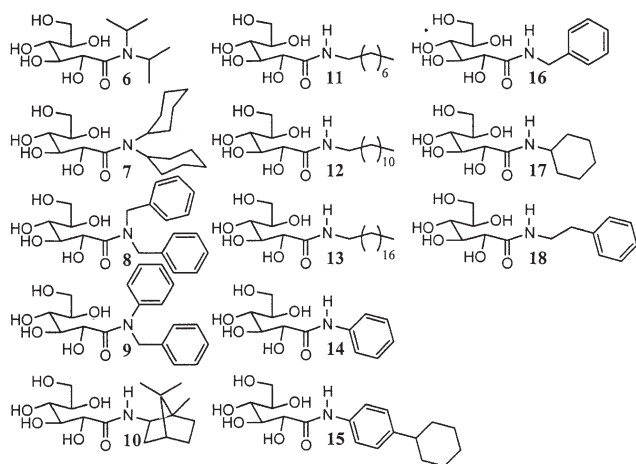


**SCHEME 1.** Glucose amine surfactants.

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Abbreviations: 2D, two-dimensional; DMSO, dimethylsulfoxide; HLB, hydrophilic-lipophilic balance; HLBD, HLB according to Davies; HLBG, HLB according to Griffin; IR, infrared; lit., literature; MeOH, methanol; m.p., melting point; MW, molecular weight; NMR, nuclear magnetic resonance; NP-6, NP-10, and NP-20, nonylphenolethoxylates of 6, 10, and 20 ethylene oxide units; O/W, oil in water; PEG, polyethylene glycol; PIT, phase inversion temperature; W/O, water in oil.



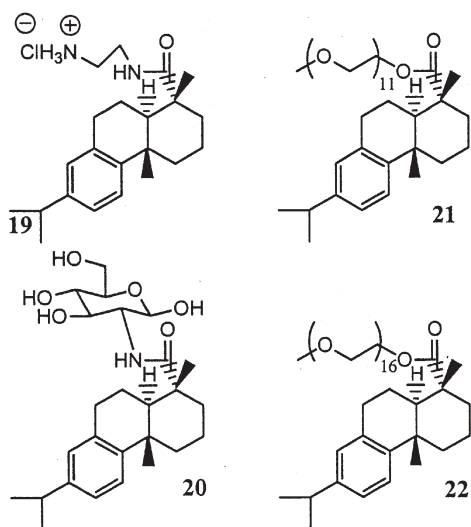
SCHEME 2. D-Gluconamides.

(14), was prepared for comparison. These surfactants contain one or two amine groups that are protonated at low and moderate pH, giving the surfactants a cationic character. At high pH, however, they should be considered as nonionic.

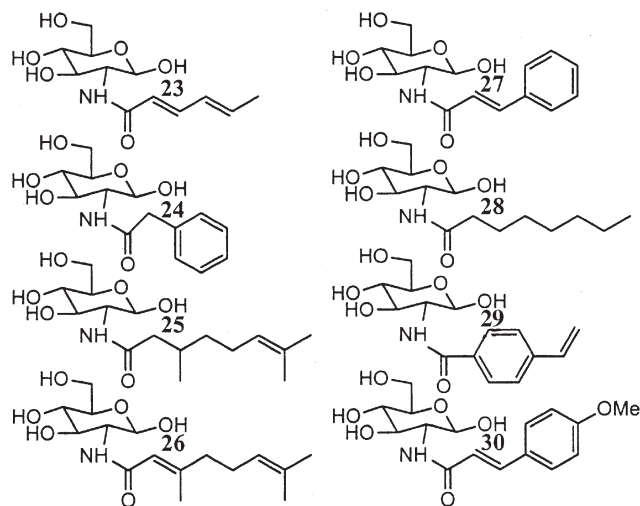
A range of nonionic D-gluconamides, compounds **6–18** (Scheme 2), some of which, **11–14**, have been described previously (15), also were prepared and characterized. Gluconamides have previously been used in commercial products as hydrotropes (16).

Four surfactants using dehydroabietic acid as the hydrophobic building block, compounds **19–22**, also were synthesized and evaluated (Scheme 3). The cationic surfactant **19** and the previously reported ethylene oxide-based surfactants **21** and **22** (17) were included for comparison with the novel sugar-based surfactant, **20**.

Further, a number of nonionic surfactants (**23–30**) were prepared from the monomer of chitosan, commonly referred to as “amino glucose” (Scheme 4). One of these, **28**, has previously been reported (18).



SCHEME 3. Dehydroabietic acid-based surfactants.



SCHEME 4. Amino glucose amides.

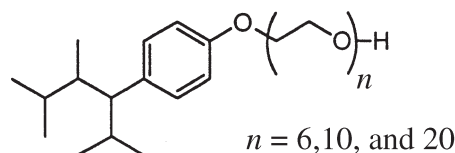
Three very common sugars are used as the basis for the hydrophilic moiety in the surfactants of our study: D-fructose, D-gluconic acid, and 2-deoxy-2-amino-D-glucose. Further, dehydroabietic acid, an easily attainable product from tall oil, a by-product from the pulping industry, is available in large quantities, making it interesting to use as a hydrophobe in surfactant synthesis. Hence, some surfactants of this type were included in this investigation.

These surfactants have been characterized as foaming agents, dispersion agents, emulsification agents, and wetting agents by using a set of rapid test methods suitable for screening surfactant properties. The properties of the synthesized surfactants are compared with properties of some commercial surfactants of the nonylphenol ethoxylate type (Scheme 5). The tests made may serve as a first guide to their use in various applications.

In this investigation, the synthesis as well as solubility and emulsification properties is reported, and differences in the properties of polyoxyethylene-based surfactants and sugar-based surfactants are discussed.

## EXPERIMENTAL PROCEDURES

*General.* All melting points (m.p.) are uncorrected and were measured in open-glass capillaries on a Gallenkamp Melting Point Apparatus.  $^1\text{H}$  nuclear magnetic resonance (NMR) spectra were measured at 400 MHz with a Bruker AM-400



SCHEME 5. Commercial reference surfactants: nonylphenol ethoxylates of 6, 10, and 20 ethylene oxide units (**NP-6**, **NP-10**, and **NP-20**, respectively).

spectrometer. The solvent was the reference in all measurements. Only the protons that are significant to the derivatives are reported. All mass spectra were recorded on a Finnigan SSQ 7000 mass spectrometer. Infrared (IR) spectra were recorded on an ATI Mattson Infinity Series Fourier transform IR spectrometer, and all samples were prepared with KBr. Only the characteristic spectral peaks of new compounds are presented. More analytical data are found in other sources (13–22).

The properties of all the studied compounds have been compared with those of three common reference surfactants: nonylphenol ethoxylates consisting of 6, 10, and 20 ethylene oxide units (Akzo Nobel Surface Chemistry, Stenungsund, Sweden). Stock solutions of 1 wt/vol% of the surfactant, and references, in distilled water were prepared and used within the individual measurements unless other concentrations are stated.

**Solubility.** Solutions of the surfactant in water, ethanol, and dodecane, respectively, with concentrations of 1 wt/vol%, were prepared and studied. The surfactant (0.05 g) was diluted with the chosen solvent up to a total volume of 5 mL. If all surfactant was clearly dissolved, the solubility limit was determined to be over 1 wt/vol%. In cases where the solubility limit was below concentrations of 1 wt/vol%, the outcome was studied gravimetrically for aqueous solutions. These equilibrated solutions were decanted and saved for use in other measurements.

The remaining nonsolved particles were dried at 60°C for several days. The dried surfactant was weighed, and the saturation concentrations of the samples were thus calculated. Solubility in organic solvents was studied at three different concentrations: 0.01, 0.15, and 1 wt/vol%. The solubility of these samples was studied by visual opacity and thus resulted in an approximate solubility limit. The criterion for full solubility was set by the requirement for complete visual opacity of the solution with no nonsoluble residue.

**Emulsification.** The emulsification performances of the surfactants were studied by preparing emulsions made from the surfactant, distilled water, and an organic phase. The organic phases used were rapeseed oil [composition of triglycerides of 16:0/16:1/18:0/18:1/18:2/18:3/20:0–2 (4–6:0.2:1.5–2.0:60–70:15–20:10:2, by vol, carboxylic acids)]; isopropyl myristate (tetradecanoic acid isopropyl ester), and dodecane (all provided by Akzo Nobel Surface Chemistry). The surfactant (0.25 g) was dissolved in the oil (4.75 g) in a test tube with a screw cap. A graduated cylinder was filled with distilled water (90 mL), and the surfactant/oil mixture was added. The test tube was rinsed with additional water (5 mL) and poured into the cylinder. This results in a solution of 100 mL liquid with the composition water/oil/surfactant of 95/4.75/0.25 wt/vol%. The cylinder is turned 10 times at a rate of one turn per second. The volume of the upper organic phase is recorded immediately, after 15 min, and after 1 h to determine emulsion stability. All samples were kept at room temperature and checked again after 2 mon. The volume of the upper organic phase generally increased with

time. The volume fraction of separated oil remained almost the same beyond the first hour.

The emulsification degree was defined as the volume fraction of the organic phase that is emulsified at any given moment. Hence, the emulsification degree will range from 0% (no emulsion formed at all, with the organic and water phases fully separated) to 100% [a one-phase emulsion, with all oil included in the oil-in-water (O/W) emulsions].

The experimental procedures of the syntheses of the surfactants (1–30) are reported below.

*1-Deoxy-1-octylamino-D-glucitol (1).* In a 50-mL round bottle with stirrer D-glucose (2.00 g, 1 eq) and *n*-octylamine (1.43 g, 1 eq) are dissolved in a mixture of MeOH (30 mL) and water (10 mL). To the mixture is added NaB(CN)H<sub>3</sub> (95%, 0.74 g, 1.01 eq) in small portions. The mixture is stirred at room temperature for 1 d. The reducing agent is quenched by dropwise addition of hydrochloric acid (conc.) until no more bubbles are produced. The methanol is evaporated on a rotary evaporator, and the water content is increased by addition of water (10 mL). The pH of the solution is made basic by addition of solid NaHCO<sub>3</sub>. Unreacted amine is decanted away using diethylether (20 mL). The pH of the solution is adjusted to strongly acidic using hydrochloric acid (conc.), and the product is separated by addition of solid NaOH until basic pH is reached. A pure sample can be isolated by extracting the solution with chloroform (25 mL), which is then washed, dried, and evaporated. The product is ground and dried in a vacuum desiccator, yielding a fine, white powder (0.48 g; 14.7%) (14).

*1,2-Dialkylamino-1,2-dideoxy-D-(N)-β-glucosides (3–5) and 2-deoxy-2-*n*-octylamino-D-glucose (2).* The surfactants 3–5 are prepared by using a novel method, from D-fructose in appropriate neat *n*-alkyl amine using ZnCl<sub>2</sub> or ZnBr<sub>2</sub> as catalyst (13). Compound 2 is prepared from compound 4 by ultrasound-promoted hydrolysis. All analytical data are identical to those previously reported (13) and reported below.

*2-Deoxy-2-*n*-octylamino-D-glucose (2).* Total yield: 95%. IR (KBr)  $\bar{\nu}$  3300, 3200, 1470, 1275, 1230, 1200, 1170, and 710 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$ : 0.90 (*t*, 3 H, *J* = 6 Hz), 1.20–1.30 (*m*, 10 H), 1.40–1.50 (*m*, 2H), 2.20–2.85 (*m*, 6H), 3.25 (*s*, 1H), 3.55 (*t*, 2H, *J* = 7 Hz), 3.70 (*s*, 1H), 3.95 (*s*, 1H), 4.55 (*s*, 1H), 4.75 (*d*, *J* = 9 Hz, 1H).

*1,2-Dibensylamino-1,2-dideoxy-D-(N)-β-glucoside (3).* Total yield ~100%, literature (lit.): 28% (22); melting point (m.p.) 119–120°C, lit.: m.p. 119–120°C (22); IR (KBr)  $\bar{\nu}$  3300, 3200, 3050, 1600, 1510, 1500, 1470, 1275, 1225, 1180, 730, and 715 cm<sup>-1</sup>; <sup>1</sup>H NMR (CDCl<sub>3</sub>)  $\delta$ : 2.30–2.85 (*m*, 6H), 3.25 (*s*, 1H), 3.61 (*s*, 2H), 3.7 (*s*, 1H), 3.81 (*s*, 2H), 3.95 (*d*, 1H, *J* = 9 Hz), 7.06–7.14 (*m*, 10H).

*1,2-Dideoxy-1,2-di-*n*-octylamino-D-(N)-β-glucoside (4).* Total yield ~100%, lit.: 23% (21) m.p. 98.0–99.0°C (from acetone), lit.: m.p. 99–100°C (21); IR (KBr)  $\bar{\nu}$  3300, 3200, 1510, 1500, 1470, 1275, 1225, 1180, and 715 cm<sup>-1</sup>; <sup>1</sup>H-<sup>13</sup>C two dimensional (2D)-NMR (HMQC; CDCl<sub>3</sub>)  $\delta$ : 0.90 (*t*, 6 H, *J* = 6 Hz), 1.20–1.30 (*m*, 20 H), 1.40–1.50 (*m*, 4H), 2.30–2.85 (*m*, 6H), 3.25 (*s*, 1H), 3.55 (*t*, 2H, *J* = 7 Hz), 3.7 (*s*, 1H), 3.85 (*t*, 2H, *J* = 7 Hz), 3.95 (*d*, 1H, *J* = 9 Hz); <sup>13</sup>C  $\delta$ : 14.5, 23.1, 27.3, 27.8, 29.8,

30.0, 30.4, 30.8, 30.9, 32.3, 33.8, 46.4, 47.2, 62.2, 63.3, 70.2, 71.3, 75.8, and 90.2.

*1,2-Dideoxy-1,2-di-n-hexylamino-D-(N)-glucoside (5)*. Total yield ~100%, lit.: 20% (21); m.p. 99.0–100.0°C (from diethyl ether), lit.: 99–100°C (21); IR (KBr)  $\bar{\nu}$  3300, 3200, 1510, 1500, 1470, 1275, 1225, 1180, and 715  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$ : 0.90 (*t*, 6 H, *J* = 6 Hz), 1.20–1.30 (*m*, 12H), 1.40–1.50 (*m*, 4H), 2.30–2.85 (*m*, 6H), 3.25 (*s*, 1H), 3.55 (*t*, 2H, *J* = 7 Hz), 3.7 (*s*, 1H), 3.85 (*t*, 2H, *J* = 7 Hz), 3.95 (*d*, 1H, *J* = 9 Hz) (21).

*Alkyl/aryl-D-gluconamides (6–18) (14,19)*. In a 50-mL round bottle with stirrer D-(+)-glucono-1,5-lactone (1.78 g, 10 mmol, 1 eq) and a primary or secondary amine (20.0 mmol, 2 eq) are dissolved in dimethylsulfoxide (DMSO) (20 mL). The mixture is stirred at 60–80°C for 20–80 h under a nitrogen atmosphere. When using a low-boiling amine, the reaction is performed with reflux. Larger, sterically hindered amines require the longer reaction times. The solution is cooled to room temperature. The solvent and any low-boiling remaining amines are removed by evaporation in vacuum with heat, using a Kugelrohr distillation apparatus. Care should be taken with the heating, since the products quickly are colored or even polymerize at high temperatures. The remaining white-yellowish (sometimes green or red) oil or solid is recrystallized from methanol (10–40 mL). Several recrystallizations may be necessary, in methanol (MeOH) or other pure solvents (such as water or diethylether) or mixtures of solvents (such as MeOH/water or MeOH/diethylether), to acquire a pure product. All products were ground and dried in a vacuum desiccator, yielding mostly fine, white powders. The following spectral data are all common for D-gluconamides 6–18;  $^1\text{H}$  NMR (400 MHz; DMSO)  $\delta$ : 7.59 (*s*, 1 H, –CONH– if primary), 5.37 (*s*, 1H, C2-OH), 4.33–4.60 (*s*, 4H, C3–6-OH), 3.11–4.00 (*m*, 6H, C2-6H); (additional signals for compounds 8, 9, and 18) 7.05–7.40 (*d* or *t*, 5 or 10 H, Ar-H); IR (KBr):  $\bar{\nu}$  695 (monosub. aromatic) (compounds 8, 9, 14, 16, and 18 only), 2950 (Ar-H) (compounds 8, 9, 14, 15, 16, and 18 only), 1000 (C–H), 1430 (N–H if primary), 1630 (C=O), 3295 (N–H if primary) and 3300–3400  $\text{cm}^{-1}$  (–OH). All further analytical data of  $^1\text{H}$  NMR and IR are in accordance with those presented elsewhere and will not be repeated here in detail (14,19).

Below are the yields of pure compounds acquired in the syntheses. All compounds are white powders, although they may be yellowish oils before crystallization.

*N,N-Diisopropyl-D-gluconamide (6)*. Yield: 11%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 1.27 (*d*, *J* = 6Hz, 6H, –CH<sub>3</sub>), 1.30 (*d*, *J* = 6Hz, 6H, –CH<sub>3</sub>), 3.63 (*septet*, *J* = 6Hz, 1H, N-CH), 4.2 (*septet*, *J* = 6Hz, 1H, N–CH).

*N,N-Dicyclohexyl-D-gluconamide (7)*. The product was purified chromatographically using acetylcellulose as stationary phase with MeOH as eluent. The clearly red fractions were pooled, and the solvent evaporated on a rotary evaporator, yielding the product in pure form (a yellowish oil). Total yield: 83%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 1.20–1.93 (*m*, 20H, –CH), 3.63 (*q*, 2H, N–CH), 4.2 (*q*, 2H, N–CH).

*N,N-Dibenzyl-D-gluconamide (8)*. Yield: 6%.

*N-Benzyl-N-phenyl-D-gluconamide (9)*. Yield: 24%.

*N-Camphyl-D-gluconamide (10)*. Yield: 67%.

*N-Octyl-D-gluconamide (11)*. Yield: 85%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 0.86 (*t*, *J* = 6Hz, 3H, –CH<sub>3</sub>), 1.16–1.40 (*m*, 12H, –(CH<sub>2</sub>)<sub>6</sub>–), 3.07 (*t*, *J* = 6Hz, 2H, –NHCH<sub>2</sub>–).

*N-Dodecyl-D-gluconamide (12)*. Yield: 71%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 0.86 (*t*, *J* = 6Hz, 3H, –CH<sub>3</sub>), 1.16–1.40 (*m*, 20H, –(CH<sub>2</sub>)<sub>10</sub>–), 3.07 (*t*, *J* = 6Hz, 2H, –NHCH<sub>2</sub>–).

*N-Octadecyl-D-gluconamide (13)*. Yield: 90%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 0.86 (*t*, *J* = 6Hz, 3H, –CH<sub>3</sub>), 1.16–1.40 (*m*, 32H, –(CH<sub>2</sub>)<sub>16</sub>–), 3.07 (*t*, *J* = 6Hz, 2H, –NHCH<sub>2</sub>–).

*N-Phenyl-D-gluconamide (14)*. Total yield: 19%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 7.79 (*s*, 1H, –NH), 7.49 (*d*, 2H, Ar-H), 7.30 (*t*, 2H, Ar-H), 7.10 (*t*, 1H, Ar-H).

*N-(4-Cyclohexylphenyl)-D-gluconamide (15)*. Yield: 20%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 1.40 (*m*, 5H, –CH–), 1.85 (*m*, 5H, –CH–), 2.47 (*m*, 1H, Ar-CH), 7.36 (*d*, 2H, Ar-H), 7.08 (*d*, 2H, Ar-H), 7.79 (*s*, 1H, –NH).

*N-Benzyl-D-gluconamide (16)*. Yield: 73%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 4.31 (*s*, 2H, N–CH<sub>2</sub>-Ar), 7.25 (*t*, 1H, Ar-H), 7.27 (*d*, 2H, Ar-H), 7.33 (*t*, 2H, Ar-H), 8.52 (*s*, 1H, –NH).

*N-Cyclohexyl-D-gluconamide (17)*. Yield: 66%.  $^1\text{H}$  NMR (additional signals)  $\delta$ : 1.20–1.71 (*m*, 10H, –CH<sub>2</sub>–), 3.35 (*h*, 1H, N–CH), 7.30 (*d*, 1H, –NH).

*N-Phenethyl-D-gluconamide (18)*. Yield: 91%.

*N-(2-Aminoethyl)-dehydroabiatic amide hydrochloride (19)*. Into a 100-mL round bottle with a magnetic stirrer was added previously synthesized dehydroabiatic acid aminoethylamide (20) (1.00 g, 2.92 mmol, 1 eq) and 50 mL of dry ethanol. Concentrated hydrochloric acid (3.5 mL, 40.9 mmol, 14 eq) was added dropwise with stirring until the product crystallized out quantitatively as fine white crystals. The product was filtered and washed carefully with cold ethanol. Total yield 1.106 g (100%),  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ )  $\delta$ : 3.04–3.06 (*m*, 2 H, –CH<sub>2</sub>NH<sub>3</sub><sup>+</sup>), 2.90–2.92 (*m*, 2H, –CH<sub>2</sub>–O–CO–); IR:  $\bar{\nu}$  1510 and 1630 (–CONH–), 1585 and 2850  $\text{br}$  (–NH<sub>3</sub><sup>+</sup>)  $\text{cm}^{-1}$ .

*2-Deoxy-2-dehydroabietyl-amido-D-glucopyranose (20)*. To a 50-mL round bottle with stirrer is added 2-deoxy-2-aminoglucose hydrochloride (1.075 g; 5 mmol; 1 eq), sodium bicarbonate (1.55 g; 18.4 mmol; 3.68 eq), and distilled water (5 mL). When everything has been solubilized, with stirring, the mixture is cooled to around 0°C using an ice-water bath. A solution of dehydroabiatic acid chloride (1.645 g; 5.175 mmol; 1.03 eq) in 1,4-dioxane (5 mL) is added dropwise. The reaction then proceeds, with stirring, for 22 h, during which time the temperature is slowly increased toward room temperature. The solution is then again cooled to 0°C, and the crystals obtained are filtered off. The remaining solution then separates into two phases, and the lower, oil-like, yellow phase is separated and collected. Upon drying on a rotary evaporator, the oil crystallizes into the product, a yellowish powder. The product consists of a kinetically controlled mixture of the amide and corresponding esters. This is also what has been reported from similar reactions (20). The exact composition or purity cannot be determined from  $^1\text{H}$  NMR alone. Yield: 1.602 g; IR:



$\bar{\nu}$  1510 and 1630 (–CONH–), 1725  $\text{cm}^{-1}$  (C=O ester), 3295 (N–H), 2950 (Ar–H) and 3300–3400  $\text{cm}^{-1}$  (–OH).

*Monomethyl polyethyleneglycol (PEG-550) ester of dehydroabiatic acid (21)*. The compound was prepared as previously described (17); total yield: 100%; m.p. approximately 35–40°C;  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ )  $\delta$ : 3.17 (s, 3 H,  $\text{CH}_3\text{O}$ –), 3.30–3.50 (m, 44 H, – $\text{OCH}_2\text{CH}_2\text{O}$ –), 3.65 (t,  $J = 7\text{Hz}$ , 2H, – $\text{CH}_2$ – $\text{CH}_2$ – $\text{O}$ – $\text{CO}$ –), 3.77 (t,  $J = 7\text{Hz}$ , 2H, – $\text{CH}_2$ – $\text{O}$ – $\text{CO}$ –); IR:  $\bar{\nu}$  1725  $\text{cm}^{-1}$  (C=O ester).

*Monomethyl polyethyleneglycol (PEG-750) ester of dehydroabiatic acid (22)*. The compound was prepared as previously described (17); Total yield: 100%; m.p. approximately 40–45°C;  $^1\text{H}$  NMR (400 MHz;  $\text{CDCl}_3$ )  $\delta$ : 3.17 (s, 3 H,  $\text{CH}_3\text{O}$ –), 3.30–3.50 (m, 64 H, – $\text{OCH}_2\text{CH}_2\text{O}$ –), 3.65 (t,  $J = 7\text{Hz}$ , 2H, – $\text{CH}_2$ – $\text{CH}_2$ – $\text{O}$ – $\text{CO}$ –), 3.77 (t,  $J = 7\text{Hz}$ , 2H, – $\text{CH}_2$ – $\text{O}$ – $\text{CO}$ –); IR:  $\bar{\nu}$  1725  $\text{cm}^{-1}$  (C=O ester).

*2-Deoxy-2-alkylamido-D-glucopyranoses (23–30) (18)*. In a 25-mL round bottle with stirrer 2-amino-2-deoxy-D-glucose hydrochloride (1.075 g, 5 mmol) and solid  $\text{NaHCO}_3$  (1.55 g, 18.4 mmol) are dissolved in water (5 mL). After stirring at room temperature for some minutes, the solution is cooled to 0–4°C using an ice-water bath. A solution of the appropriate acid chloride (79 mmol) in 1,4-dioxane (2.5 mL) is added dropwise. The solution is strongly stirred for 1–1.5 h while immersed in the ice-water bath. The precipitated product is collected and washed with cold water and diethyl ether and is then recrystallized from small amounts of water (unless stated otherwise) or other appropriate solvents into a fine, white powder. If consecutive recrystallization is performed, the product is dried and ground between each step. The solvent used for recrystallization, if other than water, is given below as are the total yields of the syntheses. More information can be found elsewhere (14). The following spectral data are all common for 2-deoxy-2-alkylamido-D-glucopyranoses **23–30**;  $^1\text{H}$  NMR (400 MHz; DMSO)  $\delta$ : 7.59 (s, 1 H, –CONH–), 5.37 (s, 1H, C2–OH), 4.33–4.60 (s, 4H, C3–6–OH), 3.11–4.00 (m, 6H, C2–6H), (additional signals compounds **23**, **25**, **26**, **27**, **29**, and **30**) 4.0–5.0 (1–4H, alkene H); IR (KBr):  $\bar{\nu}$  1000 (C–H), 1430 (N–H), 1630 (C=O), 2950 (Ar–H) (compounds **24**, **27**, **28**, and **30** only), 3295 (N–H) and 3300–3400  $\text{cm}^{-1}$  (–OH).

Below are the yields of the pure compounds as well as any noncommon purification method used for these compounds:

*2-Deoxy-2-sorbinamido-D-glucopyranose (23)*. Caution: This compound is soluble in water, and hence much material is lost in any water recrystallization. Methanol works better as the recrystallization medium. Total yield: 10%.

*2-Deoxy-2-phenacetamidamido-D-glucopyranose (24)*. The compound is recrystallized from water, methanol, and diethyl ether, respectively, yielding a fine white powder. Total yield: 71%.  $^1\text{H}$  NMR (400 MHz; DMSO)  $\delta$ : 7.327 (t, 2H, Ar–H), 7.27 (d, 2H, Ar–H), 7.25 (t, 1H, Ar–H), 4.311 (s, 2H, – $\text{CH}_2$ –Ar). IR (KBr):  $\bar{\nu}$  695 (monosub. aromatic).

*2-Deoxy-2-citronellamido-D-glucopyranose (25)*. Total yield: 46%.

*2-Deoxy-2-geranamido-D-glucopyranose (26)*. The compound is recrystallized from diethylether into a fine, white powder. Total yield: 40%.

*2-Deoxy-2-trans-cinnamonamido-D-glucopyranose (27)*. Total yield: 55%.  $^1\text{H}$  NMR (400 MHz; DMSO)  $\delta$ : 7.59 (t, 2H, Ar–H), 7.47 (d, 1H, Ar–CH), 7.24 (t, 2H, Ar–H), 7.39 (t, 1H, – $\text{CH}_2$ –Ar), 6.67 (d, 1H, CH–CO).

*2-Deoxy-2-octanamido-D-glucopyranose (28)*. Total yield: 53%.

*2-Deoxy-2-p-vinylbenzoylamido-D-glucopyranose (29)*. Total yield: 99%.

*2-Deoxy-2-p-methoxycinnamonamido-D-glucopyranose (30)*. Total yield: 83%.

## RESULTS AND DISCUSSION

*Hydrophilic-lipophilic balance (HLB) values*. It is a well-known fact that surfactant properties are influenced by the relative sizes of the hydrophilic and hydrophobic moieties. To better understand the HLB of each surfactant, the HLB values according to Griffin (23) (the HLBG) and Davies (24) (the HLBD) were calculated. These values serve as a guide to surfactant properties at room temperature, e.g., aqueous solubility, and they can be used as a first suggestion for potential applications (25). The HLBG value, which is restricted to nonionics, is defined for alcohol ethoxylates, alkylphenol ethoxylates, and polyol ethoxylates as the weight percentage of the hydrophilic part of the surfactant divided by 5 (23). Hence, higher values indicate a more hydrophilic surfactant.

The empirically determined HLBD values, developed after the publication of HLBD, take into account the contribution from each individual group and are calculated as  $7 + \Sigma$  (hydrophilic group numbers) +  $\Sigma$  (lipophilic group numbers) (26). HLBD group numbers have not yet been determined for amine and amide functional groups. Since practically all of our tested surfactants contain amide or amine groups, we have chosen to use the HLBG values for our analyses, in which the HLBD values have been calculated using seemingly appropriate values for the amide and amine groups. To estimate these values, we used recent measurements of the cloud point for the amide-containing surfactants, tetra(oxyethylene)dodecyl amide, which suggest that the amide group has a hydrophilicity corresponding to two ethylene oxide groups (Kjellin, U.R.M., unpublished results). Hence, we assign a value of 0.66 for this group. A similar estimate based on the cloud point of an ethoxylated amine suggests that the group number for the uncharged amine is around 0.55 (27). The hydrophilicity of the amine group will, however, depend on the pH. At low pH, the charged ammonium form will dominate, and this form is considerably more hydrophilic than the amine group. For this group, we have used the value for the ammonium form, 9.4. Following the suggestion of Davies, the OH-groups for ring-opened sugars have been assigned a value of 1.9, and those in sugar rings a value of 0.5. We note that this is a simplification since the mutual orientation of the OH-groups will influence the interaction with water and thus the properties of the polar

headgroup. It also should be noted that the calculated HLBG and HLBD values in some cases are rather different, which emphasizes that these values only should be seen as rough guides to the HLB of the surfactant. This is particularly so when hydrophobic groups other than linear alkyl chains are used. This will become apparent from the discussion below.

Griffin proposed that surfactants with HLBG values in the range 3.5–6 are suitable as water-in-oil (W/O) emulsifiers, 7–9 as wetting agents, 8–18 as O/W emulsifiers, 13–15 as detergents, and 15–18 as solubilizers (24). This should, however, be regarded as a first guide, and more detailed investigations are necessary before the suitability of a surfactant in a given application area can be judged. As can be seen in Table 1, most of the surfactants have HLBG values within the range of 8 to 13, with the majority of the surfactants found around 11. Thus, many of the surfactants may have the potential to act as good O/W emulsifiers and have rather high aqueous solubilities. These predictions were to some extent verified in our experimental studies. However, the results presented here also clearly demonstrate the limitations of the simplified HLB concept for complex surfactant structures.

*Solubility in water, ethanol, and dodecane.* To better understand the HLB of each surfactant, their solubilities were studied. Three solvents with different dielectric constants were used. Thus, solutions in water ( $\epsilon_{25^\circ\text{C}} = 80$ ), ethanol ( $\epsilon_{25^\circ\text{C}} = 24$ ), and dodecane ( $\epsilon_{25^\circ\text{C}} = 1.9$ ) were prepared to determine the solubility limit of the surfactants. The results are summarized in Table 2.

From Table 2 it is apparent that the trend is for aqueous solubility to increase with an increased HLBG value, whereas dodecane solubility decreases with an increased HLBG value. However, it is equally clear that knowledge of the HLBG value is not sufficient for predicting the solubility. The general trend is expected and well in accordance with the HLB concept, as well as with Bancroft's rule (28,29). The exceptions,

compounds with high aqueous solubility but with low HLBG values, share some common structural elements. They either possess a secondary amide bond instead of a primary amide bond, such as surfactant **7**, or have a heavily branched and unsaturated hydrophobe, such as surfactants **25** and **26**. For sugar-based surfactants, such as gluconamides, containing an amide bond, exchanging the hydrogen atom on the amide group with an alkyl group is known to increase the solubility, primarily due to the disturbed packing in the crystalline state (30). This is demonstrated by the observation that surfactants containing a primary amide as the connecting bond have lower aqueous solubilities than their secondary amide analogs; such is the case for compound pairs **7–12** and **9–15**, respectively. Branching and unsaturation of the hydrophobic moiety are expected to increase solubility for similar reasons.

Solubility in ethanol, a solvent of intermediate polarity, seems to be lower for surfactants containing an amide bond, as compared with those with an amine or ester bond. Compare, for instance, compound **21** containing an ester group with compound **20** that contains an amide group or compounds **1** and **2** containing an amine group with compounds **11** and **28**, which contain an amide group. The same trend is observed with water as solvent. This may be related to the higher dipole moment of the amide group. Dipole moments have been given for the amide  $\text{HCONHCH}_3$  (3.83 D), the ester  $\text{HCOOCH}_3$  (1.77 D), and the amines  $\text{CH}_3\text{NH}_2$  (1.31 D) and  $\text{CH}_3\text{NHCH}_3$  (1.01 D), facilitating comparison between these functional groups (31).

Sugar-based surfactants, in contrast to polyoxyethylene-based surfactants, are known for being lipophobic and are not well-solubilized by nonpolar solvents (32). Consistent with this, polyoxyethylene-based surfactants of a given HLBG value are more soluble in dodecane than their respective sugar-based equivalents, as exemplified by compounds **21** and **22**. The presence of a highly polar connecting bond, such as a primary

**TABLE 1**  
HLB Values According to Griffin and Davies<sup>a</sup>

Surfactant number	HLBG	HLBD	Surfactant number	HLBG	HLBD	Surfactant number	HLBG	HLBD
<b>1</b>	11.3	13.3–22.1	<b>11</b>	11.7	13.4	<b>21</b>	11.9	15.9
<b>2</b>	11.2	7.1–15.9	<b>12</b>	9.9	11.5	<b>22</b>	14.4	22.4
<b>3</b>	8.2	6.6–24.3	<b>13</b>	8.0	8.6	<b>23</b>	13.0	8.6
<b>4</b>	7.3	3.3–21.0	<b>14</b>	13.2	15.5	<b>24</b>	12.0	8.8
<b>5</b>	8.4	5.2–22.9	<b>15</b>	10.1	12.6	<b>25</b>	10.8	6.7
<b>6</b>	12.8	14.3	<b>16</b>	12.6	15.0	<b>26</b>	10.8	6.7
<b>7</b>	10.0	11.5	<b>17</b>	12.9	14.3	<b>27</b>	11.5	8.3
<b>8</b>	9.5	12.9	<b>18</b>	12	14.5	<b>28</b>	11.7	7.6
<b>9</b>	9.9	13.4	<b>19</b>	5.0	9.2	<b>29</b>	11.5	8.3
<b>10</b>	10.8	12.4	<b>20</b>	7.1	3.1	<b>30</b>	10.5	7.9
<b>NP-6</b>	11.6	10.8	<b>NP-10</b>	13.8	16.0	<b>NP-20</b>	16.3	29.0

<sup>a</sup>HLBG is the hydrophilic-lipophilic balance (HLB) calculated according to Griffin (23) and HLBD is the HLB calculated according to Davies (24). The value for the amide group is estimated to be that of two ethylene oxide groups, 0.66. The group number for the amine group has not been calculated previously since it can have either a protonated or an unprotonated form. We estimate the group numbers of the unprotonated amine (0.55) and the protonated amine to be that of the ammonium ion (9.4). Thus, the HLBD values for amine-containing compounds **1–5** show the range from nonprotonated to fully protonated compound. The hydroxides of a ring-closed sugar were assigned group numbers of 0.5, whereas those of an open sugar were assigned group numbers of 1.9. **NP-6**, **-10**, **-20**, nonylphenoethoxylates of 6, 10, and 20 ethylene oxide units.

**TABLE 2**  
**Surfactant Solubility in Water, Ethanol, and Dodecane<sup>a</sup>**

Surfactant number	MW	HLBG	Hydrophobic carbon atoms	Solubility limits (wt/vol%)		
				Aqueous	Ethanol	Dodecane
19	379	5.0	20	0.44	0.15–1	0.15–1
20	461.6	7.1	20	0.15	0.01–0.15	0.15–1
4	402.6	7.3	16	0.15	0.15–1	0.15–1
13	447.7	8.0	18	0.1	0.15–1	0.01–0.15
3	358.4	8.2	14	0.15	0.15–1	0.15–1
5	346.5	8.4	12	0.15	0.15–1	0.01–0.15
8	375.4	9.5	14	0.94	>1	0.01–0.15
12	363.5	9.9	12	0.1	0.15–1	0.01–0.15
9	361.5	9.9	13	0.06	0.15–1	0.01–0.15
7	359.5	10.0	12	>1	>1	0.01–0.15
15	353.4	10.1	12	<0.01	0.15–1	0.01–0.15
30	339.3	10.5	10	<0.01	<0.01	0.01–0.15
25	331.4	10.8	10	>1	0.15–1	0.15–1
10	331.4	10.8	10	0.88	>1	0.01–0.15
26	329.4	10.8	10	>1	0.15–1	0.15–1
2	291.4	11.2	8	0.15	0.15–1	0.15–1
1	293.4	11.3	8	>1	>1	0.15–1
27	309.3	11.5	9	0.64	<0.01	0.01–0.15
29	309.3	11.5	9	0.89	0.15–1	0.01–0.15
11	307.4	11.7	8	0.12	0.15–1	0.01–0.15
28	305.4	11.7	8	0.69	0.01–0.15	0.01–0.15
21	843.1	11.9	20	>1	>1	0.15–1
18	299.3	12.0	8	>1	0.15–1	<0.01
24	297.3	12.0	8	>1	0.01–0.15	<0.01
16	285.3	12.6	7	>1	0.15–1	<0.01
6	279.3	12.8	6	>1	>1	<0.01
17	277.3	12.9	6	>1	0.15–1	<0.01
23	273.3	13.0	6	>1	0.01–0.15	<0.01
14	271.3	13.2	6	>1	0.15–1	<0.01
22	1063	14.4	20	>1	>1	0.15–1
NP-6	498.7	11.6	15	0.15–1	>1	0.15–1
NP-10	674.9	13.8	15	>1	>1	0.01–0.15
NP-20	1115	16.3	15	>1	>1	<0.01

<sup>a</sup>The solubility was determined up to concentrations of 1 wt/vol% of surfactant in the solvent. Compounds having solubility limits in excess of 1 wt/vol% are given >1 as their values. Aqueous solubility was gravimetrically determined. Ethanol and dodecane solubilities were determined at concentrations of 0.01, 0.15, and 1 wt/vol% with the result indicating in which concentration the surfactant was fully soluble. From these tests the solubility range was determined for each surfactant. MW, molecular weight; see Table 1 for other abbreviations.

amide, also gives lower solubility in dodecane, which is apparent when comparing the gluconamides and amino glucose amides with compounds 1–5 (amine-containing).

Thus, the solubility of nonionic surfactants is dependent not only on their HLB as calculated by, e.g., Griffin, but also on other aspects of the headgroup and nonpolar group structures not accounted for by the HLBG concept.

**Emulsification.** The emulsification ability of the surfactants was tested using three different oils with different polarity increasing in the order: dodecane < rapeseed oil < isopropyl myristate. A large excess of water was used, and the test thus probes the ability of the surfactant to emulsify the oil. The emulsions formed are O/W macroemulsions (not thermodynamically stable), and we observed that most emulsions phase-separated partly or completely over time. The samples exhibit either one phase (water with emulsified oil) or two phases (water with emulsified oil in equilibrium with an oil

phase). The results obtained, expressed as emulsification degree (i.e., the percentage of the oil emulsified) immediately after shaking the samples (i.e., the emulsion ability), are summarized in Table 3. The maximal amount of oil emulsified, under our conditions, for each surfactant is presented in Table 4. A study of emulsion stability immediately, after 15 min, and after 1 h, is presented in Table 5. The degree of emulsification after 2 mon in most cases was similar to that found after 1 h.

Before discussing these results, we recapitulate that it is the nature of the surfactant that governs the stability and type of emulsion formed. Stable emulsions are formed when the surfactants adsorbed to the O/W interface are able to generate repulsive interactions between the emulsion droplets and also provide a barrier against rupture. The type of emulsion formed can conveniently be expressed in terms of the spontaneous curvature of the surfactant film at the O/W interface (33). A

**TABLE 3**  
**Correlations Between the Surfactants' HLBG Value and Emulsification Properties<sup>a</sup>**

Surfactant number	MW	Hydrophobic carbon atoms	Emulsification degree (%)			Emulsion sample conc. (mM)	Approx. CMC value (mM)	Solubility limit, if less than 0.25 wt/vol%	Applications acc. to HLBG
			Rapeseed oil	Isopropyl myristate	Dodecane				
<b>19</b>	379	5.0	20	28	44	31	6.6		W/O emulsifier wetting agent
<b>20</b>	461.6	7.1	20	81	<i>100</i>	<i>100</i>	3.25	0.15	
<b>4</b>	402.6	7.3	16	81	61	53	6.21		
<b>13</b>	447.7	8.0	18	100	56	28	2.23	0.000065	
<b>3</b>	358.4	8.2	14	61	53	44	6.97		
<b>5</b>	346.5	8.4	12	72	<i>100</i>	56	7.21		
<b>8</b>	375.4	9.5	14	22	81	44	6.66	0.0065	
<b>12</b>	363.5	9.9	12	100	61	72	2.75	0.065	
<b>9</b>	361.5	9.9	13	<u>44</u>	<u>39</u>	<u>44</u>	1.66	0.02	
<b>7</b>	359.5	10.0	12	44	<i>100</i>	33	6.95	0.065	
<b>15</b>	353.4	10.1	12	64	50	<i>100</i>	0.28	0.065	
<b>30</b>	339.3	10.5	10	<u>17</u>	<u>44</u>	<u>11</u>	0.29	6.5	
<b>25</b>	331.4	10.8	10	75	<i>100</i>	81	7.54	2	
<b>10</b>	331.4	10.8	10	100	<i>100</i>	44	7.54	0.65	
<b>26</b>	329.4	10.8	10	22	44	44	7.59	2	
<b>2</b>	291.4	11.2	8	61	—	—	8.58		
<b>1</b>	293.4	11.3	8	100	89	0	8.52		
<b>27</b>	309.3	11.5	9	22	28	0	8.08	6.5	
<b>29</b>	309.3	11.5	9	<u>100</u>	<u>100</u>	<u>100</u>	8.08	6.5	
<b>11</b>	307.4	11.7	8	<u>22</u>	<u>44</u>	<u>0</u>	3.9	6.5	
<b>28</b>	305.4	11.7	8	81	81	53	8.19	20	
<b>21</b>	843.1	11.9	20	100	<i>100</i>	<i>100</i>	2.97	0.071	
<b>18</b>	299.3	12.0	8	33	61	28	8.35	6.5	
<b>24</b>	297.3	12.0	8	—	—	—	8.41	20	
<b>16</b>	285.3	12.6	7	<u>33</u>	<u>53</u>	<u>22</u>	8.76	20	
<b>6</b>	279.3	12.8	6	<u>81</u>	<u>72</u>	<u>22</u>	8.95	65	
<b>17</b>	277.3	12.9	6	<u>44</u>	<u>33</u>	<u>61</u>	9.02	65	
<b>23</b>	273.3	13.0	6	<u>33</u>	—	—	9.15	215	
<b>14</b>	271.3	13.2	6	<u>44</u>	<u>44</u>	<u>22</u>	9.22	65	
<b>22</b>	1063	14.4	20	80	80	90	2.35	0.069	
<b>NP-6</b>	498.7	11.6	15	100	100	100	5.01	0.0401	
<b>NP-10</b>	674.9	13.8	15	100	100	95	3.7	0.0444	
<b>NP-20</b>	1115	16.3	15	100	100	100	2.24	0.0896	

<sup>a</sup>HLBG values are calculated according to Griffin (23). Composition of emulsification systems is water/oil/surfactant 95:4.75:0.25 wt/vol%. Surfactants with lower aqueous solubility limits than 0.25 wt/vol% were studied at their saturation concentrations (water was added to receive the same volume for all samples). Thus, the underscored emulsification degree numbers have been measured below the approximated CMC value of that surfactant. Maximal attainable emulsification degree, 100%, has been highlighted in italics. CMC, critical micelle concentration; O/W, oil-in-water, W/O, water-in-oil; see Tables 1 and 2 for other abbreviations.

positive curvature favors formation of O/W emulsions (Winsor I), zero curvature formation of bicontinuous microemulsions (Winsor II), and a negative curvature formation of W/O emulsions (Winsor III). This indicates that hydrophilic surfactants having a large polar group and a small nonpolar group will form O/W emulsions and vice versa. This line of thought is consistent with earlier concepts. For instance, Bancroft stated that oil-soluble surfactants form W/O emulsions and water-soluble surfactants form O/W emulsions (28,29). In another descriptive approach, Shinoda determined the phase inversion temperature (PIT), i.e., the temperature at which a given emulsion converts from an O/W emulsion at low temperature to a W/O emulsion above the PIT (31–34). This concept is useful for ethylene oxide-based surfactants that become more hydrophobic at elevated temperatures. We note that the PIT increases with the hydrophilicity of the surfactant and with decreasing polarity of the oil (34–39). The PIT thus describes

the system water–surfactant–oil, whereas Bancroft's rule and the HLB concept focus solely on the surfactant.

The HLB concept, described by Griffin (23,40) and extended by Davies (24), was used in this study to describe the balance between the hydrophobic and hydrophilic moieties of the surfactants. This concept can also be used for surfactant mixtures where the HLBG value for the mixture is given as the linear, weight average of the individual HLBG values. To take into account the effect of the nature of the oil, one must define an oil HLB value based on emulsification experiments (41). The oil HLB number corresponds to the surfactant HLB number of optimal emulsification. Thus, it is a measure for estimating the stability of different emulsions. However, it cannot be used for estimating the initial emulsion ability of such systems. A more sophisticated approach is taken by Salager, who considered the nature of the surfactant, the nature of the oil, and the effect



**TABLE 4**  
**Maximum Emulsification of Three Different Oils Using the Surfactants<sup>a</sup>**

Surfactant number	MW	HLBG	Emulsification degree (%)			Solubility limit, if less than 0.25 wt/vol%	Maximal emulsification of ... (mass%)		
			Rapeseed oil	Isopropyl myristate	Dodecane		Rapeseed oil	Isopropyl myristate	Dodecane
19	379	5.0	28	44	31		1.32	2.11	1.45
20	461.6	7.1	81	100	100	0.15	3.83	4.75	4.75
4	402.6	7.3	81	61	53		3.83	2.9	2.51
13	447.7	8.0	100	56	28	0.1	4.75	2.64	1.32
3	358.4	8.2	61	53	44		2.9	2.51	2.11
5	346.5	8.4	72	100	56		3.43	4.75	2.64
8	375.4	9.5	22	81	44		1.06	3.83	2.11
12	363.5	9.9	100	61	72	0.1	4.75	2.9	3.43
9	361.5	9.9	44	39	44	0.06	2.11	1.85	2.11
7	359.5	10.0	44	100	33		2.11	4.75	1.58
15	353.4	10.1	64	50	100	0.01	3.03	2.38	4.75
30	339.3	10.5	17	44	11	0.01	0.79	2.11	0.53
25	331.4	10.8	75	100	81		3.56	4.75	3.83
10	331.4	10.8	100	100	44		4.75	4.75	2.11
26	329.4	10.8	22	44	44		1.06	2.11	2.11
2	291.4	11.2	61	—	—		2.9		
1	293.4	11.3	100	89	0		4.75	4.22	0
27	309.3	11.5	22	28	0		1.06	1.32	0
29	309.3	11.5	100	100	100		4.75	4.75	4.75
11	307.4	11.7	22	44	0	0.12	1.06	2.11	0
28	305.4	11.7	81	81	53		3.83	3.83	2.51
21	843.1	11.9	100	100	100		4.75	4.75	4.75
18	299.3	12.0	33	61	28		1.58	2.9	1.32
24	297.3	12.0	—	—	—				
16	285.3	12.6	33	53	22		1.58	2.51	1.06
6	279.3	12.8	81	72	22		3.83	3.43	1.06
17	277.3	12.9	44	33	61		2.11	1.58	2.9
23	273.3	13.0	33	—	—		1.58		
14	271.3	13.2	44	44	22		2.11	2.11	1.06
22	1063	14.4	80	80	90		3.8	3.8	4.28
NP-6	498.7	11.6	100	100	100		4.75	4.75	4.75
NP-10	674.9	13.8	100	100	95		4.75	4.75	4.51
NP-20	1115	16.3	100	100	100		4.75	4.75	4.75

<sup>a</sup>HLBG values are calculated according to Griffin (23). Composition of emulsification systems is water/oil/surfactant 95:4.75:0.25 wt/vol%. Surfactants with lower aqueous solubility limits than 0.25 wt/vol% were studied at their saturation concentrations (water was added to receive the same volume for all samples). The underscored emulsification degree numbers have been measured below the approximated CMC value of that surfactant. Maximal attainable emulsification degree, 100%, has been highlighted in italics. For these solutions, including 0.25 wt/vol% surfactant, the maximal amount, in mass%, of soluble oil is given in the last three columns to the right. See Tables 1–3 for abbreviations.

of temperature and electrolyte in a considerably more elaborate way (42).

In our study, isopropyl myristate, rapeseed oil, and dodecane were emulsified in water. In comparison to existing data (42), we approximate their HLBG values to be 17, 14, and 10, respectively. Curiously, it seems that the surfactants within the range of  $10.0 < \text{HLBG} < 11.5$ , as indicated by brackets in Table 3, do show very good initial emulsification properties. The emulsion stability of these surfactants cannot be explained by using the HLBG theory. Surprisingly, we do not find any good correlation, which would be expected, between the surfactant HLBG value, the oil HLBG value and their emulsification stability. This indicates that the packing of the surfactants at the interface, spontaneous curvature of the surfactant film, and the elasticity of the surfactant film, all of which influence the rupture probability, are not well-correlated with the HLBG values. We suggest that this is due, in

many cases, to the complex hydrophobic groups. Consequently, more sophisticated investigations are needed to understand the potential of our surfactants.

It has been reported that *n*-decyl- $\beta$ -D-glucopyranoside is capable of emulsifying at most 2 wt/vol% *n*-octane in water (43). A comparison with the maximal emulsifiable amount of *n*-dodecane by the surfactants in Table 4 is interesting. It is, indeed, found that the emulsification limit of such highly hydrophobic oils is around 2 wt/vol% for most of our surfactants. Given the structural similarities, this is not unexpected.

The emulsification degree after 1 h is illustrated in Figures 1A–C, and the stability of the emulsions in Figures 2A–C. These figures clearly demonstrate the poor correlation between the HLBG values and the results of the emulsification process. Hence, rather than discussing the results in terms of the surfactant HLBG value, we focus on the structure of the surfactants that performed well in these tests. Let us first consider

**TABLE 5**  
**Emulsion Stability for Three Different Oils<sup>a</sup>**

Surfactant number	MW	HLBG	Emulsification degree (%)								
			Dodecane			Rapeseed			Isopropyl myristate		
			0 min	15 min	1 h	0 min	15 min	1 h	0 min	15 min	1 h
19	379	5.0	31	31	31	28	28	22	44	44	44
20	461.6	7.1	100	44	33	81	47	47	100	100	100
4	402.6	7.3	53	44	44	81	44	44	61	53	53
13	447.7	8.0	28	22	22	100	100	100	56	56	56
3	358.4	8.2	44	33	33	61	47	44	53	44	44
5	346.5	8.4	56	44	44	72	72	72	100	100	100
8	375.4	9.5	44	22	22	22	11	11	81	61	61
12	363.5	9.9	72	11	0	100	100	100	61	0	0
9	361.5	9.9	44	42	42	44	22	22	39	28	28
7	359.5	10.0	33	33	33	44	44	44	100	33	33
15	353.4	10.1	100	94	33	64	44	33	50	33	28
30	339.3	10.5	<u>11</u>	<u>11</u>	<u>11</u>	<u>17</u>	<u>11</u>	<u>11</u>	<u>44</u>	<u>22</u>	<u>11</u>
25	331.4	10.8	81	17	17	75	75	72	100	100	100
10	331.4	10.8	44	33	33	100	53	53	100	47	47
26	329.4	10.8	44	44	28	22	22	22	44	28	28
2	291.4	11.2	—	—	—	61	44	44	—	—	—
1	293.4	11.3	0	0	0	100	33	33	89	33	33
27	309.3	11.5	0	0	0	22	22	22	28	25	22
29	309.3	11.5	100	61	61	100	81	81	100	83	83
11	307.4	11.7	0	0	0	22	22	22	44	22	22
28	305.4	11.7	<u>53</u>	<u>33</u>	<u>33</u>	<u>81</u>	<u>11</u>	<u>11</u>	<u>81</u>	<u>22</u>	<u>22</u>
21	843.1	11.9	100	80	70	100	40	40	100	60	60
18	299.3	12.0	28	28	28	33	33	28	61	50	47
24	297.3	12.0	—	—	—	—	—	—	—	—	—
16	285.3	12.6	<u>22</u>	<u>22</u>	<u>22</u>	<u>33</u>	<u>28</u>	<u>28</u>	<u>53</u>	<u>44</u>	<u>44</u>
6	279.3	12.8	22	0	0	81	0	0	72	0	0
17	277.3	12.9	61	22	17	44	33	22	33	22	17
23	273.3	13.0	—	—	—	33	28	28	—	—	—
14	271.3	13.2	22	22	22	44	17	0	44	22	19
22	1063	14.4	90	80	80	80	40	40	80	0	0
NP-6	498.7	11.6	100	95	95	100	56	56	100	80	70
NP 10	674.9	13.8	95	0	0	100	20	20	100	80	70
NP-20	1115	16.3	100	0	0	100	15	0	100	15	0

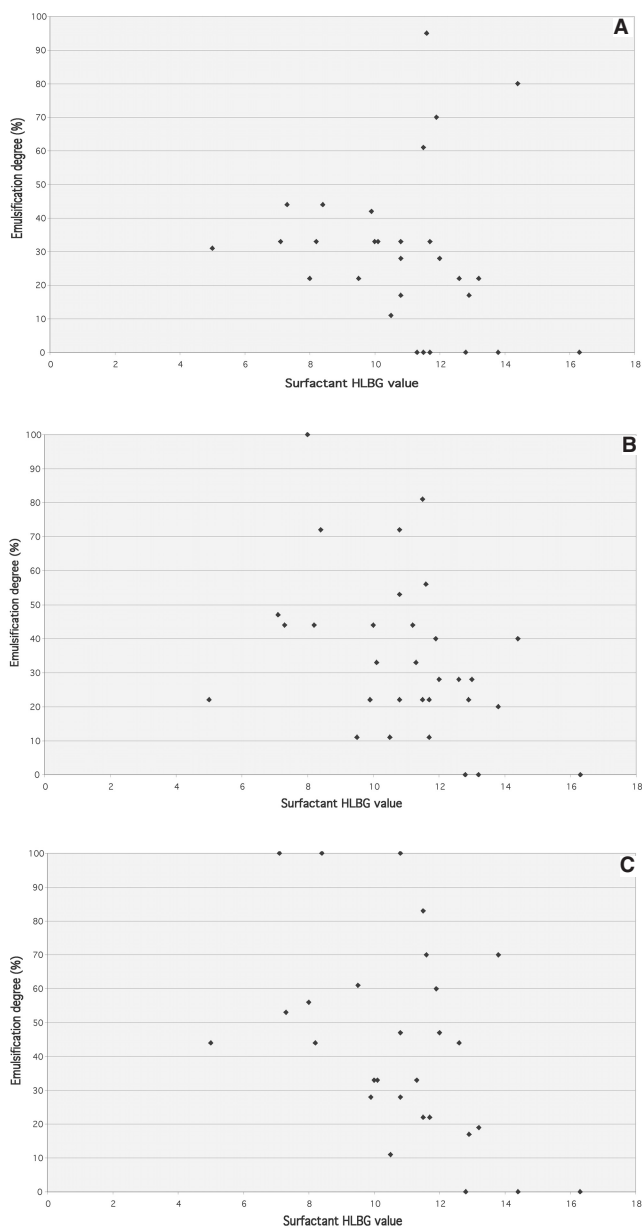
<sup>a</sup>HLBG values are calculated according to Griffin (23). Composition of emulsification systems is water/oil/surfactant 95:4.75:0.25 wt/vol%. Surfactants with lower aqueous solubility limits than 0.25 wt/vol% were studied at their saturation concentrations (water was added in order to receive the same volume for all samples). The underscored emulsification degree numbers have been measured below the approximated CMC value of that surfactant. Maximum attainable emulsification degree, 100%, has been highlighted in italics. The emulsification degree is given at 0 min, 15 min, and after 1 h for the different oils. See Tables 1–4 for abbreviations.

the results for dodecane, the most nonpolar oil. In this case the emulsification capacity after 60 min is rather poor for most surfactants. The highest emulsification capacity is found for the reference substance **NP-6**. For this surfactant, 95% of the oil is emulsified after 1 h.

Ethoxylated dehydroabiatic acids also have a rather good emulsification capacity, with 80% of the dodecane being emulsified by compound **22** and 70% by compound **21**. The stability of the emulsion formed, evaluated as the degree of emulsification after shaking, divided by the degree of emulsification after a 60-min rest period, is illustrated in Figure 2A. The reference substance **NP-6** and compound **22** are also reasonably good in this case. However, we note that some compounds having a rather low emulsification capacity nevertheless form stable emulsions. For instance, no increase in the separated oil phase with time is observed for the cationic dehydroabiatic acid (**5**). A complete stability is also observed for

one amino glucose amide (**11**) and four D-gluconamides (**7**, **14**, **16**, **18**). However, in the latter cases, the amount of emulsified oil is rather low, about 10% for compound **5** and about 20% for compounds **7**, **14**, **16**, and **18**.

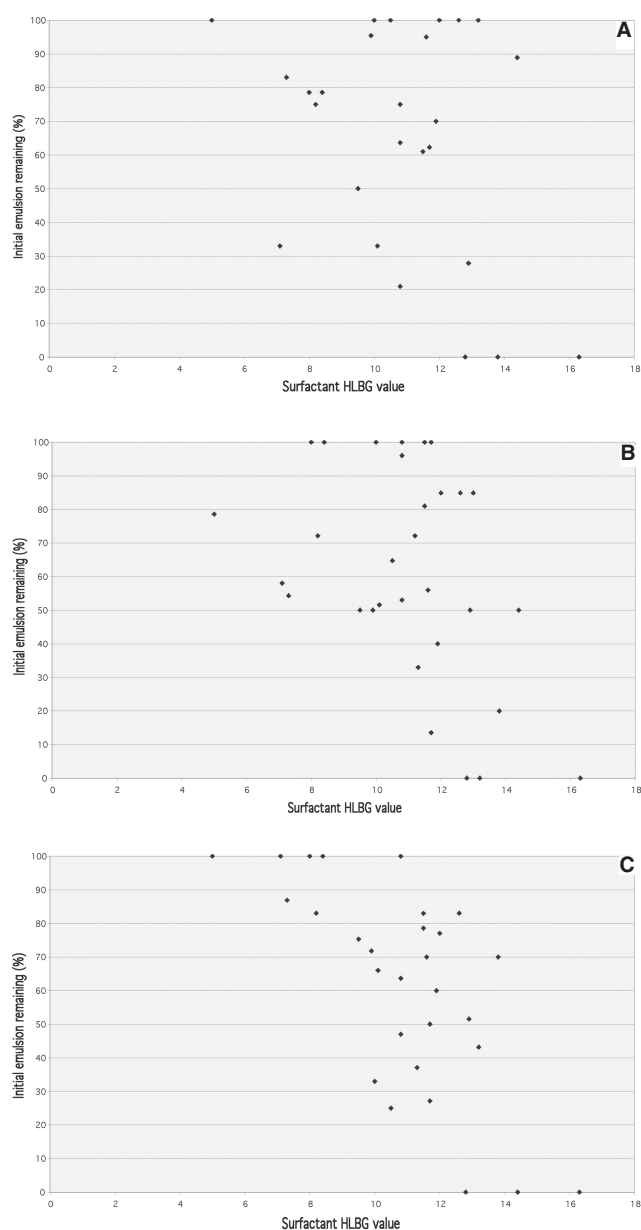
The emulsification results for rapeseed oil, having an intermediate oil polarity, are summarized in Figures 1B and 2B. Two D-gluconamides, compounds **12** and **13**, are able to emulsify all oil for more than 1 h (Table 5). These compounds are structurally similar, with a straight saturated hydrocarbon chain as the hydrophobe. The chain lengths are 12 and 18 carbons for compounds **12** and **13**, respectively. The surfactant with a shorter saturated hydrocarbon chain, compound **11**, does not have the same emulsification capacity. It only dissolves about 20% of the oil, but the emulsion formed is stable over 1 h. Compound **7**, which forms stable emulsions with dodecane, also forms stable emulsions with rapeseed oil, but again it suffers from rather poor emulsification capacity (about 40% of



**FIG. 1.** Correlations between the hydrophilic-lipophilic balance according to Griffin's (HLBG) value of the surfactants and their long-term emulsification degree for (A) dodecane, (B) rapeseed oil, and (C) isopropyl myristate emulsions in water. The emulsification degree is given after 1 h for each surfactant.

the oil was emulsified). The double-chained glucose amine surfactant, compound **5**, solubilized 72% of the rapeseed oil, and the emulsion formed was stable for more than 1 h. Several amino glucose amides formed stable emulsions (Fig. 2B), but the emulsification capacity was low except for compounds **25** and **29**, which solubilized about 70 and 80% of the oil after 60 min, respectively.

The most polar oil, isopropyl myristate, was fully solubilized after 1 h by the sugar dehydroabiatic acid (**20**), by the double-chained glucose amine surfactant, compound **5**, which also performed reasonably well with rapeseed oil, and by the amino glucose amide (**25**), which likewise performed



**FIG. 2.** A representation of emulsion stability correlating the HLBG value of the surfactant vs. the degree of the initially formed emulsion remaining after 60 min for emulsions of (A) dodecane, (B) rapeseed oil, and (C) isopropyl myristate in water. The composition is water/dodecane/surfactant 95:4.75:0.25 wt/vol%. See Figure 1 for abbreviations.

well with rapeseed oil. Stable emulsions over a period of 1 h, but with reduced emulsifying capacity, were also formed by the cationic dehydroabiatic acid (**5**) and by one D-glucosamide (**13**). These two surfactants also were able to form reasonably stable emulsions with the other two oils.

In summary, the surfactants having a large and bulky dehydroabiatic acid hydrophobe and sugar or ethylene oxide as polar group (compounds **20–22**) show good emulsification properties, but for different oils, suggesting that the use of this class of compounds as emulsifiers is worth further studies. For instance, compound **20** having a sugar headgroup is able to emulsify all isopropyl myristate, and this emulsion is

completely stable for a long period of time, up to 2 months. On the other hand, compounds **21** and **22** give reasonably stable emulsions with dodecane, i.e., the most nonpolar oil. We also note that compound **29**, consisting of a single sugar unit and a small aromatic tail, shows surprisingly good emulsification properties at short time scales, and the emulsions formed by the more polar oils are reasonably stable. The performance of this surfactant cannot be understood by considering its HLBG value, particularly since structurally similar surfactants do not have similar favorable emulsifier properties. Two of the D-gluconamides, compounds **12** and **13**, having a straight-chain C12 and C18 hydrophobe, respectively, show excellent emulsification properties of rapeseed oil.

The reference surfactants, **NP-6**, **NP-10**, and **NP-20**, with HLBG values of 11.6, 13.8, and 16.3, respectively, are all found to emulsify all three tested oils over short time scales. However, only **NP-6** gives reasonably stable emulsions and only with the most nonpolar oil.

The simple emulsification test used here has been able to identify some potentially good emulsifiers for different oils. We note, however, that even though some of the surfactants tested are found to perform poorly, they may perform well at higher surfactant concentrations or in combination with other surfactants or polymers. For instance, sugar-based surfactants with block co-polymers of poly-(ethylene propylene)-co-poly (ethylene oxide), polystyrene-co-polyethylene oxide, polybutyl methacrylate-co-poly (ethylene oxide), or poly-(ethylene butylene)-co-polyethylene oxide are suitable for forming stable emulsions and have a high solubilization capacity (44). For ethylene oxide-based surfactants, temperature is an important variable. Hence, much more work has to be done to evaluate the possible use of these surfactants as emulsifiers, but such extended tests are beyond the scope of the present work.

## ACKNOWLEDGMENTS

The study was supported by the Competence Center for Surfactants Based on Natural Products and financially supported by industry, NUTEK (now VINNOVA, the Swedish Agency for Innovation Systems) and The Royal Institute of Technology (KTH), Stockholm, Sweden.

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[Received June 17, 2003; accepted October 30, 2003]

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