J Incl Phenom Macrocycl Chem (2012) 74:251–256
DOI 10.1007/s10847-012-0107-y

ORIGINAL ARTICLE

Novel glucose derived non-ionic gemini surfactants as reverse micellar systems for encapsulation of D- and L-enantiomers of some aromatic α-amino acids in *n*-hexane

Lalit Sharma · Saroj

Received: 1 November 2010 / Accepted: 4 January 2012 / Published online: 28 January 2012

Abstract Novel glucose-based non-ionic gemini amphiphiles comprising two sugar head groups, two hydrophobic tails having chain length of C_{12}, C_{14}, and C_{18} and a $–CH_2–Ar–CH_2–$ spacer have been synthesized. The head groups of the geminis consist of glucose entities (with reducing function blocked in cyclic acetal group) connected through C-6 to tertiary amines. These amphiphiles were explored as reverse micellar systems, for the encapsulation of D- and L-enantiomers of ultraviolet-absorbing aromatic α-amino acids histidine (H), phenylalanine (F), tyrosine (Y) and tryptophan (W) in *n*-hexane, without any added water. Reverse micellar studies revealed that aromatic α-amino acids were encapsulated in the sequence H > F > Y > W. In most cases, specifically for F, D-enantiomer was found better encapsulated than L-enantiomer in the reverse micellar probes of the gemini surfactants.

Keywords Non-ionic gemini surfactants · 5,6-Anhydro-1,2-*O*-isopropylidene-α-D-glucofuranose · Amino acids · Reverse micelles

Introduction

Gemini surfactants or dimeric surfactants are novel class of amphiphilic molecules, first appearing in literature in 1971 [1]. Geminis possess two hydrophilic head groups and two hydrophobic alkyl tails linked by a flexible [2] or rigid [3] spacer, which can be hydrophilic or hydrophobic [4]. The nature of head group characterizes the geminis as anionic, cationic, non-ionic or zwitterionic in nature. Different types of geminis have been synthesized and because of their unique properties, have opened a new field of research within surfactant chemistry [5]. Recently, their application as gene transfection agents have been reviewed [6, 7].

Carbohydrate based non-ionic gemini surfactants are relatively new comers. Current interest in these amphiphiles is growing rapidly as besides their proven physical properties, these are biocompatible and posses broad spectrum of molecular architecture. Different types of carbohydrate based non-ionic gemini surfactants have been reported [8–31].

Herein, we describe the synthesis of some new carbohydrate based tertiary amino non-ionic gemini surfactants derived from 6-amino-6-deoxy-D-glucose and their use as reverse micellar systems for the encapsulation of D- and L-enantiomers of some aromatic α-amino acids histidine (H), phenylalanine (F), tyrosine (Y), and tryptophan (W) in *n*-hexane, without any added water.

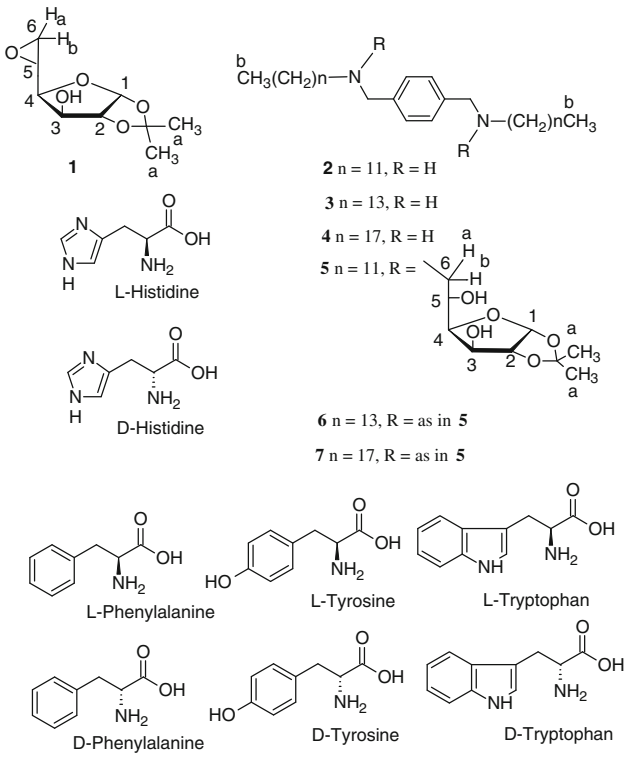
Results and discussion

Synthesis and characterization

Structures of glucose derived non-ionic geminis are given in Scheme 1. Diamines **2**–**4** were synthesized by refluxing terephthaldehyde and appropriate amine in the ratio 1:2 in ethanol for 3–4 h, followed by reduction of corresponding Schiff's base with $NaBH_4$ for 30 h at room temperature.

Gemini amphiphiles **5**–**7** were synthesized by dry heating of the appropriate diamine with 5,6-anhydro-1,2-*O*-isopropylidene-α-D-glucofuranose (**1**) at 120–130 °C for 1 h. They possess a tertiary amino group linked to C-6 of each glucose moiety with its reducing function blocked in a

L. Sharma (✉) · Saroj
Department of Applied Chemistry, SBS College of Engineering & Technology, Ferozepur 152 004, India
e-mail: s.lalit@lycos.com; srjverma@rediffmail.com



Scheme 1 Structures of glucose derived gemini surfactants and aromatic amino acids

cyclic acetal group. Oxirane ring opening of **1** by secondary amine is expected to proceed by exclusive nucleophilic attack on C-6 and without inversion at C-5 [32].

The NMR signal assignments were based on previous studies by Hall et al. [33] (for ^{1}H NMR) and Vyas et al. [34] (for ^{13}C NMR) on *O*-isopropylidene-D-hexoses. Diamines **2–4** depict nearly identical spectra. In ^{1}H NMR spectra of diamines, methyl signal was found at δ 0.88, signal due to methylene (directly attached to nitrogen) at 2.60–2.61 and signal due to methylene (directed attached to phenyl) at 3.76, respectively. Signal due to aromatic protons was found at 7.26 for all diamines.

Gemini amphiphiles **5–7** also show identical spectra. In ^{1}H NMR spectra, the chemical shifts for sugar hydrogen H-1 (5.91–5.92), H-2 (4.46), and H-3 (4.17–4.18) were found constant and characteristic of these protons. Signals for H-4 and H-5 were found overlapping at 3.87–3.93, respectively. The most prominent shift was found in H-6 signals. The methyl signal for alkyl chain was found at δ 0.88 and methylene signals at 1.26–1.36 but merged with one of sugar isopropylidene signals. The signal at δ 1.46 was assigned to other sugar isopropylidene-methyl group. The position of methylene (directly attached to nitrogen) could not be assigned due to overlapping signals. Aromatic protons for gemini amphiphiles were found at 7.25–7.26, respectively.

^{13}C NMR signal assignments are supported by INEPT data. For diamines **2–4**, methyl signals of alkyl chains were found at δ 14.2. Signals for methylene (attached to nitrogen and to phenyl ring) were found at 49.6 and 53.9, respectively. Aromatic carbons were found at 128.1–128.2 and at 139.2–139.3, respectively. Later signals disappeared in INEPT spectra to confirm that these were of aromatic quaternary carbons.

In 5,6-anhydro-1,2-*O*-isopropylidene-α-D-glucofuranose **1** and gemini amphiphiles **5–7**, the signals for the anomeric carbon, the isopropylidene-acetal carbon and the isopropylidene-methyl groups were found invariant at δ (104.9 ± 0.1), (111.6 ± 0.0), and (26.5 ± 0.3), respectively. The chemical shifts for sugar carbons C-2, C-3, C-4, and C-5 were also found constant at (85.2 ± 0.1), (75.3 ± 0.1), (81.5 ± 0.0), and 66.6 ± 0.2), respectively. The C-5 and C-6 signals for gemini amphiphiles **5–7** were found downfield as compared to those in **1**. The chemical shifts for aromatic carbons (except the quaternary carbons) were found downfield in **5–7** compared to those in **2–4** but signals due to aromatic quaternary carbons were found upfield in geminis compared to those in diamines. The methyl signal of the long alkyl tails was found at 14.2 ppm and methylene carbons (except the directly attached to nitrogen) at 22.8–32.0 ppm as multiplets. The methylene (directly attached to nitrogen) signal was also found invariant at (55.5 ± 0.1) ppm.

Synthesis was also confirmed by ESI-MS spectra and elemental analysis

Solubilization of α-amino acids in apolar media

Reverse micelles formation by gemini surfactants **5–7** was studied by solubilization of D- and L-enantiomers of ultraviolet-absorbing aromatic amino acids H, F, Y, and W in *n*-hexane, without any added water, using UV monitoring. The critical micelle concentrations (cmc's) of surfactants are documented in Table 1 and were determined by method of Gratzer and Beaven [35]. The surfactant concentration was kept well above cmc for reverse micellar studies.

Solubilization studies for D- and L-enantiomers of aromatic amino acids in *n*-hexane in presence of gemini surfactants are documented in Tables 2, and 3, respectively. From these solubilization studies it was found that both

Table 1 HLB (hydrophilic–lipophilic balance) values and critical micelle concentration (cmc) of the surfactants

Surfactant	HLB value	cmc (moles L^{-1})
5	9.2	5.0×10^{-4}
6	8.7	1.6×10^{-4}
7	7.7	5.0×10^{-5}

Table 2 Solubilization of L-aromatic amino acids in *n*-hexane with the help of reverse micelles formed by surfactants

Surfactant	Micellar ratio (amino acid:molecules of micelle)			
	L-Histidine	L-Phenylalanine	L-Tyrosine	L-Tryptophan
5	1:7.2	1:21.6	1:37.0	1:213.7
6	1:11.1	1:12.3	1:17.1	1:128.0
7	1:20.0	1:35.0	1:44.2	1:331.0

Table 3 Solubilization of D-aromatic amino acids in *n*-hexane with the help of reverse micelles formed by surfactants

Surfactant	Micellar ratio (amino acid:molecules of micelle)			
	D-Histidine	D-Phenylalanine	D-Tyrosine	D-Tryptophan
5	1:6.7	1:18.1	1:35.7	1:109.4
6	1:12.7	1:9.0	1:14.9	1:129.0
7	1:31.0	1:23.2	1:56.0	1:232.5

enantiomers of aromatic amino acids were solubilized in the order H > F > Y > W. Comparison of Tables 2, and 3 indicate a difference in the encapsulation of D- and L-enantiomers of aromatic amino acids in reverse micellar phases of gemini amphiphiles in *n*-hexane. In most cases, specifically for F, it was found that D-enantiomer was better encapsulated than its antipode, i.e., L-enantiomer.

Hydrophilic–lipophilic balance (HLB) values [37] of the surfactants are documented in Table 1. Hydrophilicity of the surfactants used in this study is of the order **5** > **6** > **7**. Size of the aromatic amino acids is of the order H < F < Y < W. Tables 2 and 3 clearly show that more hydrophilic surfactant gives better micellar ratio for encapsulation of aromatic amino acids which are better recognized by the reverse micellar phase in order of their smaller size, i.e., smaller is the amino acid better is its encapsulation. Thus, H being smallest is best encapsulated and W being largest is least encapsulated. The high propensity of H towards encapsulation may also be facilitated by its all available nitrogen atoms involved in hydrogen bond formation with surfactant head groups.

The main driving force for encapsulation of aromatic amino acids by surfactants **5**–**7** is the electrostatic interactions between aromatic amino acids and glucose head groups of the gemini surfactants at the reverse micellar interface. A glucose hydroxyl can interact with aromatic amino acid both as hydrogen bond donor as well as acceptor. As donor it possesses added advantage of having rotational freedom about C–OH torsional angle, thus enabling it to attain the best possible linear bond with amino acid, which is important in imparting specificity. Hydrophobic portions, created due to steric disposition of the hydroxyl groups, on sugar surfaces can form contacts with hydrophobic side chain of the amino acids [36].

The better encapsulation of a particular enantiomer of aromatic amino acids than its antipode is attributed to a pronounced shape complementarity with the reverse micellar phase of surfactant and thus difference in their structure fit. In such cases, there is more enough 'chiral face' to interact with that enantiomer than its antipode.

Conclusions

The dissolution of solid aromatic α-amino acids in apolar media provides valuable means of study amino acids recognition by carbohydrate derived non-ionic gemini surfactants. The present investigation shows that glucose derived non-ionic gemini surfactants (**5**–**7**) act as reverse micellar systems in *n*-hexane, without any added water. These amphiphiles also show different propensity towards encapsulation of D- and L-enantiomers of aromatic α-amino acids H, F, Y, and W. The propensity was specific in case of F, thus better encapsulation of D- than L-enantiomer of F by all these amphiphiles. This study may also lead to potential applications of reverse micelles in such environments where the absence of water is required for extremely aggressive chemistry [38].

Experimental

Melting point determinations were performed in capillaries and are uncorrected. NMR spectra were recorded on a Bruker Avance II 400 Spectrometer with $SiMe_4$ as an internal reference. *J*-values are given in Hz. UV spectra were recorded with an EC 5704 SS spectrophotometer. ESI-MS spectra were measured on a Waters Micromass Q-Tof micro mass spectrometer coupled with Waters 2795 HPLC system. Optical rotations were measured with a JASCO DIP-360 digital polarimeter in a 1 dm cell. Specific rotations are reported in degrees. Elemental analyses were performed by Perkin Elmer 2400 CHN elemental analyser.

Materials

Column chromatography was performed on silica gel (60–120 mesh) and TLC plates were coated with silica G. The spots were developed in iodine and/or charring with 1% sulfuric acid in water. Doubly distilled water and analytical grade *n*-hexane were used for spectroscopy. Distilled solvents were used for column chromatography. Other chemicals were of AR grade and used without further purification.

*Preparation of 5,6-anhydro-1,2-O-isopropylidene-α-D-glucofuranose (**1**)*

The compound was synthesized as described in literature [39], m.p. 133 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.32 and 1.48 (s, 3H, *CH_3-a*), 2.87 (dd, 1H, $J = 2.9, 2.8$, H-6_a), 2.99 (dd, 1H, *H-6_b*), 3.24 (s, 1H, OH), 3.42 (m, 1H, *H-5*), 4.00 (dd, 1H, H-4), 4.27 (dd, 1H, *H-3*), 4.52 (d, 1H, $J = 3.6$, *H-2*), 5.99 (d, 1H, $J = 3.6$, *H-1*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 26.2 and 26.8 (*CH_3-a*), 46.1 (*C-6*), 50.2 (*H-5*), 75.2 (*C-3*), 79.6 (*C-4*), 85.1 (*C-2*), 105.0 (*C-1*), 111.9 (*Me_2**C**); Inept: δ 26.2, 26.8 (+ve), 46.1 (−ve), 50.2, 75.2, 79.5, 85.1, 105.0 (+ve). ESI-mass *m/z* 224.7 $(M - H + Na)^+$.

General method for the synthesis of long tailed diamines (**2–4**)

Terephthaldehyde (670 mg, 5 mmol) and appropriate long chain amine (10 mmol) were dissolved in EtOH (30 mL) and refluxed for 4 h. The mixture was cooled to room temperature and $NaBH_4$ (570 mg, 15 mmol) was added during 10 min. The mixture was stirred for additional 24 h at room temperature. Excess $NaBH_4$ was decomposed with water and the solvent evaporated under diminished pressure. The residue was recrystallized from ethanol. The yields and spectroscopic data for resulted compounds are given below:

*N,N′-Di(dodecyl)-p-phenylenediamine (**2**)*

Colorless solid in 81% yield (1.91 g); m.p. 49–50 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3*), 1.25 (s, 36H, *CH_2*), 1.48 (br, 4H, ***CH_2**CH_2N*), 1.65 (brs, 2H, *NH*), 2.60 (t, 4H, *N**CH_2**CH_2*), 3.76 (s, 4H, ***CH_2**Ph*), 7.26 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.2 (*CH_3*), 22.8–32.0 (*CH_2*), 49.6 (*CH_2**CH_2**N*), 53.9 (***CH_2**Ph*), 128.2 (*Ar–C*), 139.3 (*Ar–C*); Inept: δ 14.2 (+ve), 22.8, 27.4, 29.4, 29.7, 30.2, 32.0 (−ve), 49.6 (−ve), 53.9 (−ve), 128.2 (+ve). ESI-mass *m/z* 473.2 $(M + H)^+$, 511.2 $(M + K)^+$. Anal. calc. for $C_{32}H_{60}N_2$: C 81.29, H 12.39, N 5.92; found C 80.73, H 12.63, N 5.98.

*N,N′-Di(tetradecyl)-p-phenylenediamine (**3**)*

Colorless solid in 80% yield (2.11 g); m.p. 65–67 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3*), 1.25 (s, 46H, *CH_2* and NH), 1.50 (br, 4H, ***CH_2**CH_2N*), 2.61 (t, 4H, *N**CH_2**CH_2*), 3.76 (s, 4H, ***CH_2**Ph*), 7.27 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1 (*CH_3*), 22.7–31.9 (*CH_2*), 49.6 (*CH_2**CH_2**N*), 53.9 (***CH_2**Ph*), 128.1 (*Ar–C*), 139.2 (*Ar–C*); Inept: δ 14.1 (+ve), 22.7, 27.4, 29.4, 29.6, 29.7, 30.1, 31.9 (−ve), 49.6 (−ve), 53.9 (−ve), 128.1 (+ve). ESI-mass *m/z* 551.4 $(M + Na)^+$. Anal. calcd. for $C_{36}H_{68}N_2$: C 81.75, H 12.96, N 5.30; found C 82.03, H 13.18, N 5.62.

*N,N′-Di(octadecyl)-p-phenylenediamine (**4**)*

Colorless solid in 81% yield (2.60 g); m.p. 75–77 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3*), 1.25 (s, 54H, *CH_2* and *NH*), 1.49 (br, 4H, ***CH_2**CH_2N*), 2.61 (t, 4H, *N**CH_2**CH_2*), 3.76 (s, 4H, ***CH_2**Ph*), 7.27 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1 (*CH_3*), 22.7–32.0 (*CH_2*), 49.6 (*CH_2**CH_2**N*), 53.9 (***CH_2**Ph*), 128.1 (*Ar–C*), 139.2 (*Ar–C*); Inept: 14.1 (+ve), 22.7, 27.4, 29.4, 29.5, 29.6, 29.7, 30.2, 32.0 (−ve), 49.6 (−ve), 53.9 (−ve), 128.1 (+ve). ESI-mass *m/z* 640.4 $(M)^+$, 683.5 $(M + 2H + Na + H_2O)^+$. Anal. calcd. for $C_{44}H_{84}N_2$: C 82.43, H 13.21, N 4.37; found C 82.52, H 13.42, N 4.62.

General method for the synthesis of glucose derived non-ionic gemini surfactants (**5–7**)

Appropriate diamine **2–4** (2 mmol) was heated to 100 °C and to this was added **1** (808 mg, 4 mmol). The temperature was raised to 120–130 °C and kept for 1 h. Purification of the residue by column chromatography on silica gel (1:2 EtOAc–CH_2Cl_2) resulted desired product. The yields and spectroscopic data for resulted surfactants are given below:

*[6,6′-(N,N′-Di(dodecadecyl)-p-phenylenediamino)] bis(6-deoxy-1,2-O-isopropylidene-α-D-glucofuranose) (**5**)*

Syrup in 84% yield (1.47 g); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3-b*), 1.26–1.34 (m, 46H, *CH_2* and *CH_3-a*), 1.46 (s, 6H, CH_3-*a*), 1.52 (br, 4H, *OH*), 2.52–2.62 (m, 6H, *NCH_2* and *H-6_b*), 2.74 (dd, 2H, $J = 4.2$, 4.6 Hz, H-6_a), 3.57–3.69 (AB system, 4H, $J = 3.3$ Hz, ***CH_2**Ph*), 3.87–3.93 (m, 4H, *H-5* and *H-4*), 4.18 (d, 2H, $J = 2.4$ Hz, *H-3*), 4.46 (d, 2H, $J = 3.7$, *H-2*), 5.91 (d, 3.7, *H-1*), 7.25 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.2 (*CH_3-b*), 22.7–31.9 (*CH_2* and *CH_3*-a), 55.4 (*N**CH_2**CH_2*), 57.4 (***CH_2**Ph*), 58.8 (*C-6*), 66.4 (*C-5*), 75.2 (*C-3*), 81.5 (*C-4*), 85.2 (*C-2*), 105.0 (*C-1*), 111.6 (*Me_2**C**), 129.7 (Ar–C), 137.1 (Ar–C), Inept: 14.2 (+ve), 22.8 (−ve), 26.2, 26.8 (+ve), 26.4, 27.3, 29.4, 29.6, 29.7, 32.0, 55.4, 57.4, 58.8 (−ve), 66.3, 75.1, 81.5, 85.2, 105.0, 129.7 (+ve); ESI-mass *m/z* 898.1 $(M–H + Na)^+$.

*[6,6′-(N,N′-Di(tetradecyl)-p-phenylenediamino)] bis(6-deoxy-1,2-O-isopropylidene-α-D-glucofuranose) (**6**)*

Syrup in 82% yield (1.53 g); $[\alpha]_D^{27} = -1.4°$ (c 0.6, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3-b*), 1.26–1.34 (m, 54H, *CH_2* and *CH_3-a*), 1.46 (s, 6H, *CH_3-a*), 1.53 (br, 4H, *OH*), 2.52–2.62 (m, 6H, *NCH_2* and *H-6_b*),

2.75 (dd, 2H, $J = 4.2$, 4.6 Hz, *H-6$_a$*), 3.55–3.69 (AB system, 4H, $J = 3.3$ Hz, *CH_2Ph*), 3.87–3.92 (m, 4H, *H-5* and *H-4*), 4.18 (d, 2H, $J = 2.4$ Hz, *H-3*), 4.46 (d, 2H, $J = 3.6$, *H-2*), 5.92 (d, 3.6, *H-1*), 7.26 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.2 (*CH_3-b*), 22.8–32.0 (*CH_2* and *CH_3-a*), 55.4 (*NCH_2CH_2*), 57.3 (*CH_2Ph*), 58.8 (*C-6*), 66.4 (*C-5*), 75.2 (*C-3*), 81.5 (*C-4*), 85.1 (*C-2*), 105.0 (*C-1*), 111.6 (*Me_2C*), 129.6 (Ar–C), 137.1 (Ar–C), Inept: 14.2 (+ve), 22.8 (−ve), 26.2, 26.8 (+ve), 26.4, 27.3, 29.4, 29.6, 29.7, 32.0, 55.4, 57.3, 58.8 (−ve), 66.4, 75.2, 81.5, 85.1, 105.0, 129.6 (+ve); ESI-mass *m/z* 934.1 $(M + H)^+$, 956.0 $(M + Na)^+$, 972 $(M + K)^+$.

*[6,6′-(N,N′-Di(octadecyl)-p-phenylenediamino)] bis(6-deoxy-1,2-O-isopropylidene-α-D-glucofuranose) (**7**)*

Colorless solid in 82% yield (1.71 g); m.p. 61–62 °C. $[\alpha]_D^{27} = +21.3°$ (c 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, 6H, *CH_3-b*), 1.26–1.36 (m, 70H, *CH_2* and *CH_3-a*), 1.46 (s, 6H, *CH_3-a*), 1.52 (br, 4H, *OH*), 2.52–2.62 (m, 6H, *NCH_2* and *H-6$_b$*), 2.76 (dd, 2H, $J = 4.4$, 4.7 Hz, H-6$_a$), 3.54–3.69 (AB system, 4H, ***CH_2Ph***), 3.87–3.93 (m, 4H, *H-5* and *H-4*), 4.17 (d, 2H, $J = 2.4$ Hz, *H-3*), 4.46 (d, 2H, $J = 3.6$, *H-2*), 5.92 (d, 3.6, *H-1*), 7.24 (s, 4H, *Ar–H*); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.2 (*CH_3-b*), 22.8–32.0 (*CH_2* and *CH_3-a*), 55.6 (*NCH_2CH_2*), 57.4 (*CH_2Ph*), 58.9 (*C-6*), 66.8 (*C-5*), 75.4 (*C-3*), 81.5 (*C-4*), 85.3 (*C-2*), 104.9 (*C-1*), 111.5 (*Me_2C*), 129.4 (*Ar–C*), 137.9 (*Ar–C*), Inept: 14.2 (+ve), 22.8 (−ve), 26.2, 26.8 (+ve), 26.4, 27.4, 29.4, 29.6, 29.8, 32.0, 55.6, 57.4, 58.9 (−ve), 66.8, 75.4, 81.5, 85.3, 104.9, 129.4 (+ve); ESI-mass *m/z* 1045 $(M + H)^+$, 1068 $(M + H + Na)^+$. Anal. calcd. for $C_{62}H_{112}N_2O_{10}$: C 71.22, H 10.79, N 2.68; found C 71.07, H 10.98, N 2.83.

Determination of the cmc of surfactants **5**–**7**

The critical micelle concentration was determined by adding known volumes of a concentrated gemini surfactant solution, to a volume of *n*-hexane. After each addition the contents were mixed thoroughly and absorbance determined by electronic absorption spectroscopy (218.5 for **5**, 220.5 for **6**, and 216.5 nm for **7**). Plots of absorbance against concentration of surfactant were constructed and a clear discontinuity gave the cmc value.

Solubilization of aromatic amino acids in *n*-hexane, without any added water

The surfactant (5 mmol) in *n*-hexane (10 mL) was shaken at room temperature with the aromatic amino acid (20 mg) for 20 min and filtered. The filtrate was extracted with water (2 × 10 mL) and amino acid concentration in water determined by electronic absorption spectroscopy (211 for H, 257 for F, 274 for Y and 280 nm for W). Solubilities thus obtained were corrected for the solubilities of aromatic amino acids in *n*-hexane without surfactant found in the same way.

Acknowledgments The financial support of this work (Grant SERC/OC-17/2006) and research fellowship to Srj from the Department of Science and Technology, Government of India, New Delhi was gratefully acknowledged. Spectroscopic analysis by SAIF, Panjab University, Chandigarh is highly appreciated.

References

1. Bunton, C.A., Robinson, L.B., Schaak, J., Stam, M.F.: Catalysis of nucleophilic substitutions by micelles of di cationic detergents. J. Org. Chem. **36**, 2346–2350 (1971)
2. Zana, R., Talmon, Y.: Dependence of aggregate morphology on structure of dimeric surfactants. Nature **362**, 228–230 (1993)
3. Menger, F.M., Littau, C.A.: Gemini surfactants: a new class of self-assembling molecules. J. Am. Chem. Soc. **115**, 10083–10090 (1993)
4. Zana, R.: Specialist surfactants. In: Robb, I.D. (ed.) p. 81. Chapman Hall Ltd., London (1996)
5. Mbadugha, B.N.A., Keiper, J.S.: Production of gemini surfactants. In: Handbook of detergents/Part F: production, pp. 561–577. Taylor & Francis Group LLC, Philadelphia (2009)
6. Wettig, S.D., Verrall, R.E., Foldvari, M.: Gemini surfactants: a new family of building blocks for non-viral gene delivery systems. Curr. Gene Ther. **8**, 9–23 (2008)
7. Bombelli, C., Giansanti, L., Luciani, P., Mancini, G.: Gemini surfactant based carriers in gene and drug delivery. Curr. Med. Chem. **16**, 171–183 (2009)
8. Sharma, L., Singh, S.: Synthesis, characterization and reverse-micellar studies of some *N*-substituted derivatives of 6-amino-6-deoxy-1,2-*O*-isopropylidene-D-glucose. Carbohydr. Res. **270**, 43–49 (1995)
9. Castro, M.J.L., Kovensky, J., Cirelli, A.F.: Gemini surfactants from alkyl glucosides. Tetrahedron Lett. **38**, 3995–3998 (1997)
10. Castro, M.J.L., Kovensky, J., Cirelli, A.F.: New dimeric surfactants from alkyl glucosides. Tetrahedron **55**, 12711–12722 (1999)
11. Castro, M.J.L., Kovensky, J., Cirelli, A.F.: New family of non-ionic gemini surfactants. Determination and analysis of interfacial properties. Langmuir **18**, 2477–2482 (2002)
12. Castro, M.J.L., Kovensky, J., Cirelli, A.F.: Structure-properties relationship of dimeric surfactants from butyl glucosides. Molecules **5**, 608–609 (2000)
13. Castro, M.J.L., Kovensky, J., Cirelli, A.F.: Ecologically safe alkyl glucoside-based gemini surfactants. Arkivoc **12**, 252–267 (2005)
14. Castro, M.J.L., Cirelli, A.F., Kovensky, J.: Synthesis and interfacial properties of sugar-based surfactants composed of homo- and heterodimers. J. Surfactant Deterg. **9**, 279–286 (2006)
15. Gao, C., Millqvist-Fureby, A., Whitcombe, M.J., Vulfson, E.N.: Regioselective synthesis of dimeric (gemini) and trimeric sugar based surfactants. J. Surfactant Deterg. **2**, 293–302 (1999)
16. Gao, C., Millqvist-Fureby, A., Whitcombe, M.J., Vulfson, E.N.: Enzymatic synthesis of dimeric and trimeric sugar-fatty acid esters. Enzym. Microb. Technol. **25**, 264–270 (1999)
17. Menger, F.M., Mbadugha, B.N.A.: Gemini surfactants with a disaccharide spacer. J. Am. Chem. Soc. **123**, 875–885 (2001)
18. Pestman, J.M., Terpstra, R., Stuart, M.C.A., van Doren, H.A., Brisson, A., Kellogg, R.M., Engberts, J.B.F.N.: Non-ionic bola-amphiphiles and gemini surfactants based on carbohydrates. Langmuir **13**, 6857–6860 (1997)

19. Fielden, M.L., Perrin, C., Kremer, A., Bergsma, M., Stuart, M.C., Camilleri, P., Engberts, J.B.F.N.: Sugar-based tertiary amino gemini surfactants with a vesicle-to-micelle transition in the endosomal pH range mediate efficient transfection in vitro. Eur. J. Biochem. **268**, 1269–1279 (2001)
20. Wagenaar, A., Engberts, J.B.F.N.: Synthesis of non-ionic reduced-sugar based bola amphiphiles and gemini surfactants with an α,ω-diamino-(oxa)alkyl spacer. Tetrahedron **63**, 10622–10629 (2007)
21. Wilk, K.A., Syper, L., Domagalska, B.W., Laska, U., Maliszewska, I., Gancarz, R.: Aldonamide-type gemini surfactants: synthesis, structural analysis and biological properties. J. Surfactant Deterg. **5**, 235–244 (2002)
22. Laska, U., Wilk, K.A., Maliszewska, I., Syper, L.: Novel glucose-derived gemini surfactants with a 1,1′-ethylenebisurea spacer: preparation, thermotropic behavior, and biological properties. J. Surfactant Deterg. **9**, 115–124 (2006)
23. Komorek, U., Wilk, K.A.: Surface and micellar properties of new non-ionic gemini aldonamide-type surfactants. J. Colloid Interface Sci. **271**, 206–211 (2004)
24. Warwel, S., Brüse, F., Schier, H.: Glucamine-based gemini surfactants I: gemini surfactants from long-chain *N*-alkyl glucamines and α,ω-diepoxides. J. Surfactant Deterg. **7**, 181–186 (2004)
25. Warwel, S., Brüse, F.: Glucamine-based gemini surfactants II: gemini surfactants from long-chain *N*-alkyl glucamines and epoxy resins. J. Surfactant Deterg. **7**, 187–193 (2004)
26. Han, F., Zhang, G.: Synthesis and characterization of glucosamide-based trisiloxane gemini surfactants. J. Surfactant Deterg. **7**, 175–180 (2004)
27. Mine, Y., Fukunaga, K., Samejima, K., Yoshimoto, M., Nakao, K., Sugimura, Y.: Preparation of gemini-type amphiphiles bearing cyclitol head groups and their application as high-performance modifiers for lipases. Carbohydr. Res. **339**, 493–501 (2004)
28. Yoshimura, T., Ishihara, K., Esumi, K.: Sugar-based gemini surfactants with peptide bonds. Synthesis, adsorption, micellization, and biodegradability. Langmuir **21**, 10409–10415 (2005)
29. Takamatsu, Y., Torigue, K., Yoshimura, T., Esumi, K., Sakai, H., Abe, M.: Adsorption characteristics of sugar-based monomeric and gemini surfactants at the silica/aqueous solution interface. Colloids Surfaces A **328**, 100–106 (2008)
30. Sakai, K., Umezawa, S., Tamura, M., Takamatsu, Y., Tsuchiya, K., Torigoe, K., Ohkubo, T., Yoshimura, T., Esumi, K., Sakai, H., Abe, M.: Adsorption and micellization behavior of novel gluconamide-type gemini surfactants. J. Colloid Interface Sci. **318**, 440–448 (2008)
31. Ford, M.E., Kretz, C.P., Lassila, K.R., Underwood, R.P., Meier, I.K.: Simple catalytic synthesis of *N*,*N*′-dialkyl-*N*,*N*′-di(1-deoxyglucityl)ethylenediamines, sugar-based gemini surfactants. In: Prunier, M.L. (ed.) Catalysis of organic reactions, 22nd conference, pp. 171–174. CRC Press, Boca Raton (2009)
32. Parker, R.E., Issacs, N.S.: Mechanisms of epoxide reactions. Chem. Rev. **59**, 737–799 (1959)
33. Hall, L.D., Black, S.A., Seessor, K.N., Tracey, A.S.: Conformational studies on the 1,2:5,6-di-*O*-isopropylidene-D-hexoses. Can. J. Chem. **50**, 1912–1924 (1972)
34. Vyas, D.M., Jarrell, H.C., Szarek, W.A.: Carbon-13 nuclear magnetic resonance spectra of some dendroketose and other furanose derivatives. Can. J. Chem. **53**, 2748–2754 (1975)
35. Gratzer, W.B., Beaven, G.H.: Effect of protein denaturation on micelle stability. J. Phys. Chem. **73**, 2270–2273 (1969)
36. Quiocho, F.A.: Protein–carbohydrate interactions—basic molecular features. Pure Appl. Chem. **61**, 1293–1306 (1989)
37. Griffin, W.C.: Calculation of HLB values of non-ionic surfactants. J. Soc. Cosmet. Chem. **5**, 249–256 (1954)
38. Wilcoxon, J.P., Provencio, P.P.: Use of surfactant micelles to control the structural phase of nanosize iron clusters. J. Phys. Chem. B. **103**, 9809–9812 (1999)
39. Ohle, H., Vargha, L.v.: Über die aceton-verbindungen der zucker und ihre abkömmlinge, XV. Mitteil.: 5,6 anhydro-monoacetonglucose und der 5-methyläther der glucofuranose (glucosemethyläther). Berichte **62**, 2435–2444 (1929)