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Maltose-Based Fluorinated Surfactants for Membrane-Protein

Extraction and Stabilization

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Abstract

Two new surfactants, F₅OM and F₅DM, were designed as partially fluorinated analogs of \( n \)-dodecyl-\( \beta \)-D-maltoside (DDM). The micellization properties and the morphologies of the aggregates formed by the two surfactants in water and phosphate buffer were evaluated by NMR spectroscopy, surface tension measurement (SFT), isothermal titration calorimetry (ITC), dynamic light scattering (DLS), small-angle X-ray scattering (SAXS), and analytical ultracentrifugation (AUC). As expected, the critical micellar concentration (CMC) was found to decrease with chain length of the fluorinated tail from 2.1–2.5 mM for F₅OM to 0.3–0.5 mM for F₅DM, and micellization was mainly entropy-driven at 25°C. Close to their respective CMC, the micelle sizes were similar for both surfactants \( i.e. \) 7 and 13 nm for F₅OM and F₅DM, respectively and both increased with concentration forming 4 nm diameter rods with maximum dimensions of 50 and 70 nm, respectively, at a surfactant concentration of \(~30\) mM. The surfactants were found to readily solubilize lipid vesicles and extract membrane proteins (MPs) directly from \( Escherichia \) coli membranes. They were found more efficient than the commercial fluorinated detergent F₆H₂OM over a broad range of concentrations (1–10 mM) and even better than DDM at low concentrations (1–5 mM). When transferred into the two new surfactants, the thermal stability of the proteins bacteriorhodopsin (bR) and FhuA were higher than in the presence of their solubilization detergents and similar to that in DDM; furthermore, bR was stable over several months. The membrane enzymes SpNOX and BmrA were not as active as in DDM micelles but similarly active as in F₆OM. Together, these findings indicate both extracting and stabilizing properties of the new maltose-based fluorinated surfactants, making them promising tools in MPs applications.
Introduction
Membrane proteins (MPs) are encoded by 20–30% of all genes in most genomes, and they perform a variety of vital functions like solute transport, signal transduction, intercellular recognition and cell adhesion, to name but a few. Moreover, MPs are of great importance since they represent the majority of current drug targets. MPs are usually extracted from native membrane bilayers using a detergent that, ideally, should combine both solubilizing and stabilizing properties so as to preserve the native structures of MPs in non-native environments. Sugar-based surfactants are widely considered mild detergents and have been commonly used as solubilizing and non-denaturing detergents for MP applications including n-octyl-β-D-glucoside (OG), n-decyl-β-D-maltoside (DM), n-dodecyl-β-D-maltoside (DDM), lactobionamides, and thioglycoside such as n-octyl-β-D-thioglucopyranoside (OTG). Recently, some sugar-based surfactants with branched polar headgroups or branched hydrophobic tails have been described for the same objective, namely, alkyl diglucosides (DigluM), CALX-173-GK, and laurylmaltose neopentylglycol (LMNG). Fluorinated surfactants (FSs) bear several perfluorinated carbon atoms in their hydrophobic tail. The presence of such CF₂ groups makes them more hydrophobic and more surface-active than their fully hydrogenated analogues. Moreover, fluorinated chains have a lower affinity for hydrogenated chains, which makes FSs less denaturing towards MPs as they hardly compete with protein–protein and protein–lipid/hydrophobic cofactor interactions. However, earlier neutral FSs were not able to solubilize membrane lipid bilayers, nor extract MPs, rendering classical detergents mandatory for solubilisation, while FSs came into play only at a later stage to stabilize MPs after extraction, when they might already have suffered from irreversible denaturation. Recently, we have demonstrated that fluorination per se does not prohibit detergency, with a fluorinated octyl maltoside derivative (F₆OM) showing mild detergency. This nonionic fluorinated surfactant readily interacts with and completely
solubilizes phospholipid vesicles in a manner reminiscent of conventional detergents without,
however, compromising membrane order at subsolubilizing concentrations, that is, well below
its critical micellar concentration (CMC).

Several series of sugar-based fluorinated surfactants have been synthesized and tested for
handling MPs in aqueous solutions. For example, a series of derivatives with various chain
lengths, and branched diglucose polar headgroups, showed solubilization of preformed
vesicles and efficient extraction of MPs from E. coli membranes.\textsuperscript{20} Fluorinated analogues of
DDM with a maltose polar headgroup were synthesized and found to stabilize the model MP
bacteriorhodopsin (bR) over extended periods of time.\textsuperscript{21-22} However, to the best of our
knowledge, in the literature, none of the earlier sugar-based FSs has been studied for both
solubilization and stabilization of MPs.

Currently, however, only a limited number of FSs are available from commercial sources, and
their biochemical properties have not been thoroughly investigated. To render FSs more
widely accessible and useful, our long-term project is intended to synthesize a range of related
compounds in which both head group and tail properties are modified rationally with the aim
of tailoring them to the specific needs of MP solubilization, purification, and handling. In this
work, we have developed two new maltose-based fluorinated surfactants, called F\textsubscript{5}OM and
F\textsubscript{5}DM, which are analogues of the gold standard DDM (Figure 1). The length of the
fluorinated and hydrogenated segments within the hydrophobic chain were chosen in line with
our previous observations that the stabilization of the model MP bR is sensitive to the fluorine
content,\textsuperscript{22} whereas increasing the fluorine content in the hydrophobic chain tends to favor the
formation of rod-like large and poorly defined micelles\textsuperscript{19} and/or large protein–surfactant
complexes.\textsuperscript{21} The micellization properties and morphology of aggregates formed by the two
surfactants in water were evaluated by NMR spectroscopy, surface tension measurement
(SFT), isothermal titration calorimetry (ITC), dynamic light scattering (DLS), small-angle X-
ray scattering (SAXS), and analytical ultracentrifugation (AUC). The efficiency of the synthesized compounds for the extraction and stabilization of MPs were also investigated, on a variety of different MPs: the *E. coli* multidrug transporter, BmrA\textsuperscript{23}; a prokaryotic analog of the eukaryotic NADPH oxidases, SpNOX\textsuperscript{24}; the *E. coli* outer membrane transporter, FhuA\textsuperscript{25}; and bR.\textsuperscript{26} The new detergents showed great potency to solubilize lipid vesicles and to extract different proteins from *E. coli* membranes. They also imparted stability to model MPs bR and FhuA, the former protein being still correctly folded after a year of incubation.

**Figure 1.** Chemical structures of the new maltoside derivatives.

**Experimental Section.**

All the fluorinated maltoside derivatives studied in this work are named following the common nomenclature used for their hydrogenated analogs: F\textsubscript{n}#M, where \( n \) indicates the number of the perfluorinated carbons within the chain starting from the last carbon atom, # indicates the length of the alkyl chain (O for octyl, N for nonyl, D for decyl, UD for undecyl and DD for dodecyl), and M indicates the maltoside polar head. F\textsubscript{5}OM indicates the fluorinated analog of octylmaltoside where the last five carbon atoms of the chain are perfluorinated whereas F\textsubscript{5}DM indicates the fluorinated analog of decylmaltoside with the last five carbon atoms of the chain being perfluorinated.

All starting materials were commercially available and used without further purification. All solvents were of reagent grade and used as received unless otherwise indicated. CH\textsubscript{3}OH was dried over Na under argon atmosphere. CH\textsubscript{2}Cl\textsubscript{2} was dried over molecular sieves and stored
under argon. The progress of the reactions was monitored by thin-layer chromatography. The compounds were detected either by exposure to ultraviolet light (254 nm) or by spraying with sulfuric acid (5% ethanol), followed by heating at ~150 °C. $^1$H, $^{13}$C and $^{19}$F-NMR analyses were performed at 400, 100 and 376 MHz, respectively. Chemical shifts are given in ppm relative to the solvent residual peak as a heteronuclear reference for $^1$H and $^{13}$C. Abbreviations used for signal patterns are: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; dd, doublet of doublet; and dt, doublet of triplet. HRMS (ESI+) was determined on a QStar Elite mass spectrometer. Milli-Q water (resistivity, 18.2 MΩ cm; surface tension, 71.45 mN/m at 25°C) was employed for all physical–chemical experiments.

**Synthesis.**

**Allyl-2,3,6-tri-O-acetyl-4-O-(α-D-2′,3′,4′,6′-tetra-O-acetyl-glucopyranosyl)-β-D-glucopyranoside (2a).** Under argon, octa-O-acetyl-β-D-maltose (3.20 g, 4.71 mmol, 1.0 equiv) was dissolved in dry dichloromethane (10 mL) and the resulting solution was cooled down using an ice bath. Allyl alcohol (0.437 g, 7.54 mmol, 1.6 equiv) was first added followed by the dropwise addition of boron trifluoride diethyl ether complex (0.87 mL, 7.07 mmol, 1.5 equiv). The mixture was stirred at 0 °C for 2 h and kept at room temperature overnight. Dichloromethane (20 mL) was added, then the mixture was washed with saturated NaHCO$_3$ (2×20 mL) and brine (2×20 mL). The organic phase was collected and dried over anhydrous Na$_2$SO$_4$, filtered, and the solvent was removed under reduced pressure. The crude compound was purified by column chromatography on silica gel (cyclohexane/ethyl acetate, 4:6, v/v) to get 2a (1.88 g, 59%) as a white powder. $R_f$ (cyclohexane/ethyl acetate, 5:5, v/v) = 0.28. $^1$H NMR (CDCl$_3$, 400 MHz): $\delta$/ppm 5.89-5.78 (m, 1H), 5.40 (d, $J = 3.9$ Hz, 1H), 5.35 (t, $J = 9.4$ Hz, 1H), 5.28-5.17 (m, 3H), 5.04 (t, $J = 9.7$, 1H), 4.87-4.82 (m, 2H), 4.57 (d, $J = 7.9$ Hz, 1H), 4.47 (m, 1H), 4.33-4.19 (m, 3H), 4.11-3.93 (m, 4H), 3.67(m, 1H), 2.14 (s, 3H), 2.09 (s, 3H), 2.03 (s, 3H), 2.01 (s, 6H), 1.99 (s, H). $^{13}$C NMR (CDCl$_3$, 100 MHz): $\delta$/ppm 170.5,
Pent-4-en-1-yl-2,3,6-tri-O-acetyl-4-O-(α-D-2′,3′,4′,6′-tetra-O-acetyl-glucopyranosyl)-β-D-glucopyranoside (2b). 2b was synthesized following the same procedure as for 2a, from octa-O-acetyl-β-D-maltose (3.0 g, 4.42 mmol, 1.0 equiv), pentyl alcohol (0.571 g, 6.63 mmol, 1.5 equiv), and boron trifluoride diethyl ether complex (0.82 mL, 6.63 mmol, 1.5 equiv). After purification by column chromatography on silica gel (cyclohexane/ethyl acetate, 3:7, v/v) compound 2b (1.16 g, 37%) was obtained as a white powder. \( R_f \) (cyclohexane/ethyl acetate, 3:7, v/v) = 0.21. \( ^1H \) NMR (CDCl\(_3\), 400 MHz): \( \delta/\text{ppm} \) 5.76 (m, 1H), 5.40 (m, 1H), 5.35 (t, \( J = 9.6 \) Hz, 1H), 5.25 (t, \( J = 9.0 \) Hz, 1H), 5.09-4.93 (m, 3H), 4.87-4.79 (m, 2H), 4.50 (d, \( J = 7.9 \) Hz, 1H), 4.46 (dd, \( J = 2.6 \) Hz, \( J = 12.1 \) Hz, 1H), 4.25 (m, 2H), 4.05-3.93 (m, 3H), 3.85 (m, 1H), 3.66 (m, 1H), 3.48 (m, 1H), 2.13 (s, 3H), 2.09 (s, 3H), 2.06 (m, 2H), 2.04 (s, 3H), 2.01 (s, 6H), 1.99 (s, 6H), 1.62 (m, 2H). \( ^{13}C \) NMR (CDCl\(_3\), 100 MHz): \( \delta/\text{ppm} \) 170.5, 170.5, 170.3, 170.0, 169.6, 169.4, 137.8, 115.1, 100.3, 95.5, 75.5, 72.8, 72.2, 72.0, 70.0, 69.3, 69.3, 68.5, 68.0, 62.9, 61.5, 29.8, 28.5, 26.9, 20.9, 20.8, 20.7, 20.6, 20.6, 20.5. HRMS (ESI+) \( m/\text{z} \): [M +H]\(^+\) calculated for C\(_{31}\)H\(_{45}\)O\(_{18}\): 705.2605, found 705.2600. HRMS (ESI+) \( m/\text{z} \): [M+Na]\(^+\) calculated for C\(_{31}\)H\(_{44}\)NaO\(_{18}\): 727.2420, found 727.2393.

4,4,5,5,6,6,7,7,8,8,8-undecafluoro-2-iodo-octyl-2,3,6-tri-O-acetyl-4-O-(α-D-2′,3′,4′,6′-tetra-O-acetyl-glucopyranosyl)-β-D-glucopyranoside (3a). To a solution of 2a (1.84 g, 2.72 mmol, 1.0 equiv) in dichloromethane (10 mL), perfluoropentyl iodide (0.71 mL, 3.67 mmol, 1.35 equiv) and triethyl borane 1M in hexane (0.5 mL, 0.5 mmol, 0.2 equiv) were added. The mixture was flushed with air and stirred at room temperature for 1 h. 50 mL of a diluted solution of Na\(_2\)S\(_2\)O\(_3\) was added and the aqueous solution was extracted with CH\(_2\)Cl\(_2\) (2×50mL). The organic fractions were collected, dried over anhydrous Na\(_2\)SO\(_4\), filtered, and
the solvent was removed under reduced pressure. The crude compound was purified by column chromatography on silica gel (cyclohexane/ethyl acetate, 3:7, v/v) to give compound 3a (2.51 g, 86%) as a white powder. Rf (cyclohexane/ethyl acetate, 3:7, v/v) = 0.24. 1H NMR (CDCl3, 400 MHz): δ/ppm 5.41 (m, 1H), 5.36 (td, J = 1.3 Hz, J = 10.2 Hz, 1H), 5.26 (td, J = 0.8 Hz, J = 9.2 Hz, 1H), 5.06 (td, J = 2.2 Hz, J = 9.9 Hz, 1H), 4.88-4.82 (m, 2H), 4.59 (dd, J = 2.5 Hz, J = 7.9 Hz, 1H), 4.48 (m, 1H), 4.40-4.17 (m, 3H), 4.11-3.93 (m, 4H), 3.78 (m, 1H), 3.69 (m, 1H), 2.98 (m, 1H), 2.66 (m, 1H), 2.13 (s, 3H), 2.10 (s, 3H), 2.03 (s, 6H), 2.02 (s, 3H), 2.00 (s, 6H). 19F NMR (CDCl3, 376 MHz): δ/ppm –80.7 (td, J = 2.7 Hz, J = 9.5 Hz, 3F, CF3), –113.8 (m, 2F, CF2), –122.6 (m, 2F, CF2), –123.7 (d, J = 52 Hz, 2F, CF2), –126.3 (t, J = 13.6 Hz, 2F, CF2). 13C NMR (CDCl3, 100 MHz): δ/ppm 170.7, 170.5, 170.3, 170.1, 169.7, 169.6, 100.8, 99.8, 95.7, 75.3, 74.9, 73.9, 72.7, 72.5, 71.9, 70.2, 69.5, 68.7, 68.2, 62.7, 61.7, 37.4, 21.0, 20.9, 20.8, 20.8, 20.7, 20.6, 13.5. HRMS (ESI+) m/z: [M+H]+ calculated for C34H41F11O18: 1073.1162, found 1073.1156.

4,4,5,5,6,6,7,7,8,8,8-undecafluoro-4-iodo-decyl-2,3,6-tri-O-acetyl-4-O-(α-D-2′,3′,4′,6′-tetra-O-acetyl-glucopyranosyl)-β-D-glucopyranoside (3b). Compound 3b was synthesized following the same procedure as for 3a, from 2b (1.16 g, 1.64 mmol, 1.0 equiv), perfluoropentyl iodide (0.88 g, 2.22 mmol, 1.35 equiv) and triethyl borane 1M in hexane (0.3 mL, 0.3 mmol, 0.2 equiv). After purification by column chromatography on silica gel (cyclohexane/ethyl acetate, 2:8, v/v), compound 3b (1.70 g, 94%) was obtained as a white powder. Rf (cyclohexane/ethyl acetate, 3:7, v/v) = 0.31. 1H NMR (CDCl3, 400 MHz): δ/ppm 5.41 (m, 1H), 5.34 (t, J = 10.2 Hz, 1H), 5.23 (t, J = 9.2 Hz, 1H), 5.06 (t, J = 9.9 Hz, 1H), 4.85-4.76 (m, 2H), 4.50 (d, J = 7.9 Hz, 1H), 4.47 (m, 1H), 4.30 (m, 1H), 4.25-4.17 (m, 2H), 4.05-3.94 (m, 3H), 3.85 (m, 1H), 3.65 (m, 1H), 3.52 (m, 1H), 2.80 (m, 2H), 2.12 (s, 3H), 2.08 (s, 3H), 2.02 (s, 3H), 2.00 (s, 3H), 1.98 (2s, 9H), 1.84 (m, 4H). 19F NMR (CDCl3, 376 MHz): δ/ppm –80.8 (t, J = 9.9 Hz, 3F, CF3), –111.7 (d, J = 270 Hz, 1F, CF2), –114.7 (d, J = 270 Hz,
$^{13}$C-NMR (CDCl$_3$, 100 MHz): $\delta$/ppm 170.5, 170.4, 170.2, 170.0, 169.6, 169.5, 100.1, 95.5, 75.4, 72.7, 72.2, 72.1, 70.0, 69.3, 68.5, 68.0, 62.8, 61.5, 41.6, 36.8, 29.8, 20.9, 20.8, 20.6, 20.6, 20.5, 20.0, 19.8. HRMS (ESI+) m/z: [M+H]$^+$ calculated for C$_{36}$H$_{45}$F$_{11}$IO$_{18}$: 1101.1475, found 1101.1476.

4,4,5,5,6,6,7,7,8,8,8-undecafluorooctyl-4-O-(\(\alpha\)-D-glucopyranosyl)-\(\beta\)-D-glucopyranoside (4a). Compound 3a (1.24 g, 1.15 mmol, 1.0 equiv) was dissolved in methanol and 50 mg of Pd/C and sodium acetate (0.310 g, 3.77 mmol, 3.3 equiv) were added portion-wise. The resulting solution was stirred under H$_2$ (g) (6 bars) overnight. The resulting mixture was filtered over a pad of celite and the solvent was evaporated under reduced pressure. The crude product was dissolved in CH$_2$Cl$_2$ (50 mL) and washed with a diluted solution of Na$_2$S$_2$O$_3$ (50 mL). Then the aqueous phase was extracted with CH$_2$Cl$_2$ (2 × 50 mL). The organic fractions were collected, dried over anhydrous Na$_2$SO$_4$, filtered, and the solvent was removed under reduced pressure. The resulting compound was dissolved in methanol, then a catalytic amount of sodium methoxide (27 mg, 0.50 mmol) was added portion-wise. The mixture was stirred overnight at room temperature. The reaction mixture was neutralized by addition of Dowex 50W×8-100 ion exchange resin (2.0 g). The ion exchange resin was filtered off and the solvent was removed under reduced pressure. The crude compound was purified by column chromatography on silica gel (CH$_2$Cl$_2$/CH$_3$OH, 85:15, v/v) to give compound 4a (0.695 g, 91%) as a white powder. R$_f$ (CD$_3$OD/ethyl acetate, 2:8, v/v) = 0.27. $^1$H NMR (CD$_3$OD, 400 MHz): $\delta$/ppm 5.18 (m, 1H), 4.30 (d, $J = 7.8$ Hz, 1H), 3.98 (m, 1H), 3.94-3.78 (m, 3H), 3.71-3.60 (m, 5H), 3.55 (m, 1H), 3.45 (m, 1H), 3.38 (m, 1H), 3.27 (m, 2H), 2.44-2.25 (m, 2H), 1.92 (m, 2H). $^{19}$F NMR (CD$_3$OD, 376 MHz): $\delta$/ppm –82.5 (td, $J = 2.7$ Hz, $J = 10.2$ Hz, 3F, CF$_3$), –115.5 (q, $J = 17$ Hz, 2F, CF$_2$), –123.8 (s, 2F, CF$_2$), –124.7 (s, 2F, CF$_2$), –127.5 (s, 2F, CF$_2$). $^{13}$C NMR (CD$_3$OD, 100 MHz): $\delta$/ppm 104.2, 102.9, 81.3, 77.8, 76.6, 75.1, 74.8, 74.6,
Compound 4b was synthesized following the same procedure as for 4a, from 3b (1.69 g, 1.54 mmol, 1.0 equiv), 50 mg of Pd/C and sodium acetate (0.404 g, 4.93 mmol, 3.2 equiv) under H₂(g) (6 bars) overnight, followed by deprotection using sodium methoxide (27 mg, 0.50 mmol) to give compound 4b (0.786 g, 75%) as a white powder. R₆ (CD₃OD /ethyl acetate, 2:8, v/v) = 0.32. ¹H NMR (CD₃OD, 400 MHz): δ/ppm 5.16 (d, J = 3.8 Hz, 1H), 4.27 (d, J = 7.8 Hz, 1H), 3.94-3.78 (m, 4H), 3.71-3.51 (m, 6H), 3.44 (dd, J = 3.8 Hz, J = 9.6 Hz, 1H), 3.36 (m, 1H), 3.27 (t, J = 9.4 Hz, 1H), 3.24 (m, 1H), 2.25-2.0 (m, 2H), 1.65 (m, 4H), 1.53 (m, 2H). ¹⁹F NMR (CD₃OD, 376 MHz): δ /ppm -82.5 (td, J = 2.3 Hz, J = 10.4 Hz, 3F, CF₃), -115.5 (q, J = 17 Hz, 2F, CF₂), -123.8 (s, 2F, CF₂), -124.8 (s, 2F, CF₂), -127.5 (s, 2F, CF₂). ¹³C-NMR (CD₃OD, 100 MHz): δ/ppm 104.3, 102.9, 81.4, 77.9, 76.6, 75.1, 74.8, 74.7, 74.2, 71.5, 70.4, 62.8, 62.2, 31.7 (t, J = 22.0 Hz), 30.4, 26.6, 21.1. HRMS (ESI+) m/z: [M+H]⁺ calculated for C₂₂H₂₄F₁₁O₁₁: 681.1769, found 681.1774.
CMC determination by $^{19}$F-NMR measurements. Seven samples of each detergent at different concentrations were prepared from stock solutions (4.0 g/L for F$_5$DM and 6.0 g/L for F$_5$OM). All samples were dissolved in D$_2$O/H$_2$O (10:90, v/v). CF$_3$COONa was used as an internal reference (30 µL of a solution at 1 g/L was added). The chemical shifts of the terminal CF$_3$ group of F$_5$DM and F$_5$OM were plotted as a function of the concentration to derive the CMC linear fitting. Below the CMC, the observed chemical shift ($\delta_{obs}$) is the chemical shift of the monomer ($\delta_{mon}$), whereas above the CMC, $\delta_{obs}$ is the weighted average of the monomer, and micelle chemical shift, assuming the exchange between the bulk solution and the micelle, is fast on the NMR time scale. If the monomer concentration is constant above the CMC, the observed chemical shift can be written as follows:

$$\delta_{obs} = \delta_{mic} - \left(\frac{CMC}{C}\right)(\delta_{mic} - \delta_{mon})$$

CMC determination by Surface Tension Measurements. The surface activity of detergents in solution at the air/water interface was determined using a K100 tensiometer (Kruss, Hamburg, Germany). Surface tensions were determined by dilution of stock solutions (0.70 g/L for F$_5$DM and 5.8 g/L for F$_5$OM, ~5×CMC) using the Wilhelmy plate technique. In a typical experiment, 20–30 concentration steps were used with ca. 5–10 min between each concentration step. All measurements were performed at (25.0 ± 0.5) °C.

CMC determination by ITC. Demicellization experiments were performed at 25°C on a VP-ITC (Malvern Instruments) by titrating 28 mM F$_5$OM and 5 mM F$_5$DM, respectively, from the injection syringe into the sample cell containing triple-distilled water or phosphate buffer. Experimental settings included injection volumes of 5–10 µL, a reference power of 58 µJ/s, a filter period of 2 s, and time spacings of 5 min to allow the signal to reach the baseline before the next injection. Automated baseline adjustment and peak integration were done with NITPIC,$^{30}$ and the first injection was always excluded from further analysis. Nonlinear least-
squares fitting was performed in an Excel (Microsoft, Redmond, USA) spreadsheet using the Solver add-in (Frontline Systems, Incline Village, USA), as explained elsewhere.\textsuperscript{31}

**Analysis of thermodynamic properties.** ITC demicellization experiments directly calculates the CMC and the molar enthalpy of micelle formation, $\Delta H_S^{0,\text{aq-m}}$. From the CMC, the partition coefficient for micellization, $K_{S}^{\text{aq-m}}$, can thus be derived as the ratio of the mole fractions of the surfactant in the micellar (m) and the aqueous (aq) phases: $K_{S}^{\text{aq-m}} = \frac{X_s^m}{X_s^{aq}}$. The micellar phase consists only of surfactant molecules, $X_s^m=1$, whereas $X_s^{aq} = (C_M |_{C_W} + \text{CMC}) \approx \text{CMC} / 55.5 \, M$, where $C_W$ denotes the water concentration (55.5 M). From this, the standard molar Gibbs free energy change upon micellization was derived as $\Delta G_S^{0,\text{aq-m}} = -RT \ln(K_{S}^{\text{aq-m}}) = RT \ln(\text{CMC} / 55.5 \, M)$ and the entropic contribution to micellization as $-T \Delta S_S^{0,\text{aq-m}} = \Delta G_S^{0,\text{aq-m}} - \Delta H_S^{0,\text{aq-m}}$, with $\Delta S_S^{0,\text{aq-m}}$ denoting the standard molar entropy change upon micellization.

**Dynamic light scattering (DLS).** DLS measurements were carried out with a Nano Zetasizer S90 (Malvern, Herrenberg, Germany), utilizing a He–Ne laser at a wavelength of 633 nm as light source and a detection angle of 90°. Samples were transferred to a 45-μL quartz glass cuvette (Hellma, Munich, Germany) and equilibrated for 2 min prior to each measurement. The attenuator was fixed to the maximum position to ensure comparable results for light scattering intensity measurements while in case of the determination of size distributions, attenuator settings were automatically set by the software.

**Sedimentation velocity experiments.** Sedimentation velocity experiments were performed in a Beckman XL-I analytical ultracentrifuge with a rotor Anti-50 (Beckman Coulter, Palo Alto, USA) and double-sector cells of optical path length 12 mm equipped of Sapphire windows (Nanolytics, Potsdam, DE). Samples were centrifuged at 42000 rpm (130 000 g), at 20°C. Sedimentation velocity profiles were acquired in interference, every 1 min. Data were
analyzed in terms of continuous size distribution $c(s)$ of sedimentation coefficients, $s$,\textsuperscript{27} by using SEDFIT. Peak integration and figures were done with the GUSSI software\textsuperscript{28} (http://biophysics.swmed.edu/MBR/software.html). Standard equations and protocols described in \textsuperscript{29} were used to derive the refractive index increment, the CMC, the sedimentation coefficient at infinite dilution, $s_0$. We used the Svedberg equation to derive from $s$, micelle molar masses, $M_{\text{mic}}$, from which were derived aggregation numbers, $N_{\text{agg}}$, using the information on the calculated surfactant molar masses and partial specific volumes reported on Table 1, and estimates on the hydrodynamic diameters from DLS.

**SAXS experiment.** Five samples of each detergent at different concentrations were prepared from stock solutions in H$_2$O (33.3 mM for F$_5$DM and 29.5 mM for F$_5$OM). SAXS experiments were conducted on the BM29 beamline at the European Synchrotron Radiation Facility (Grenoble, France). The data were recorded for $0.004<Q<0.5$ Å$^{-1}$ ($Q=(4\pi/\lambda)\sin\theta$ is the modulus of the scattering vector, with $2\theta$ being the scattering angle, and $\lambda$ the wavelength), using a two-dimensional 1M Pilatus detector, at 20 °C, with a monochromatic X-ray beam with $\lambda = 0.9919$ Å and a sample to detector distance of 2.864 m. Measurements were performed with 50 µL loaded sample, in a quartz capillary, with a continuous flow. 10 acquisitions with 0.5 s irradiation (flows of 5 µL/s), were recorded for the samples and water. Data reduction was performed using the automated standard beamline software (BSxCuBE),\textsuperscript{30} and data processing, including the elimination of data suffering from radiation damage, averaging, buffer subtraction, Guinier plots, and pair distribution functions, using PRIMUS (V3.1) of the software suite ATSAS.\textsuperscript{31} Absolute scales were obtained using the scattering of water. The radii of gyration ($R_g$) and the intensities scattered in the forward direction ($I(0)$) were extracted by the Guinier approximation, with $R_gQ \leq 1.0$. The molar mass of the micelle, $M_{\text{mic}}$, was derived from $M_{\text{mic}} = (I(0)/c_{\text{mic}}) N_A (\partial \rho_v/\partial c)^2$, with $N_A$ Avogadro’s number, $c_{\text{mic}}$ the micelle concentration (g mL$^{-1}$), calculated using the CMC-values from ITC, and $\partial \rho_v/\partial c$ (cm
Aggregation numbers $N_{agg}$ were then derived from $M_{mic}$. The maximum dimensions ($D_{max}$) were estimated from the pair distribution functions. Shape analysis were done using shape-dependent models in SASview (V4.2.1) (https://www.sasview.org/). We investigated the cylinder models. Theoretical SLD values are given in table S1. The form factor included size polydispersity on radius (fixed at 15 %, this value resulting from preliminary fits) using a gaussian distribution. The scale factor (i.e. the surfactant concentration in vol/vol unit), and the SLD of the solvent were constrained (table S1). The core radius and cylinder length were adjusted. Note that for F3DM scattering curves, we also performed an analysis with core shell cylinder model. The scale factors, the core and solvent SLDs were fixed (table S1) and core radius, thickness and SLD shell, and cylinder length were adjusted. The two fits in the cylinder and core shell cylinder models were equivalent in terms of quality, as evaluated by the chi2 values. But the later provided inconsistent values for the lowest concentrations; for the three largest concentrations, the radius and the thickness were constant: 1.79 ± 0.09 and 1.16 ± 0.1 nm, respectively, thus the sum (radius + thickness) was rather large (2.95 nm). The mean value of the fitted SLD shell (1.07 ± 0.02 $10^{-5}$ Å$^{-2}$) corresponded to 75 % water. The very large dimension of the total radius associated to overestimated hydration in the core-shell cylinder model can be due to the fact that the SLDs of the anhydrous head and tail are rather close (1.51 $10^{-5}$ Å$^{-2}$ and 1.44 $10^{-5}$ Å$^{-2}$) compared to water (9.53 $10^{-6}$ Å$^{-2}$), which argues in favor of the simple cylinder model.

**Preparation of lipid vesicles.** To prepare LUVs, POPC in powder form was weighed on a high-precision XP Delta Range microbalance (Mettler Toledo, Greifensee, Switzerland) and suspended in phosphate buffer (10 mM Na$_2$HPO$_4$/NaH$_2$PO$_4$, 150 mM NaCl, pH 7.4). The solution was vortexed for 15 min at room temperature and extruded in a LiposoFast extruder (Avestin, Mannheim, Germany) with at least 35 extrusion steps through two stacked
polycarbonate membranes with a pore diameter of 100 nm (Avestin). The hydrodynamic
diameter of the LUVs was distributed around 120–130 nm, as shown by DLS.

**Kinetics of vesicle solubilization.** For vesicle solubilization kinetics, measurements were
conducted by adding a high concentration (5 mM) of the respective surfactant above its CMC
to 100 μM POPC LUVs in a 3 mm×3 mm quartz glass cuvette. Measurements were started
immediately after mixing the vesicle suspension to monitor changes in light scattering
intensity, \( I_{\text{scatter}} \).

**Solubilization of MPs from native *E. coli* membranes.** *E. coli* BL21(DE3) cells were
transformed with an empty pET-24 vector and selected by kanamycin resistance. After
incubation in 400 mL lysogeny broth overnight at 37°C under constant agitation (150 rpm),
cells were harvested by centrifugation and washed twice with saline (154 mM NaCl). Cell
pellets were resuspended in ice-cold buffer (100 mM Na₂CO₃, pH 11.5) and subjected to
ultrasonication in an S-250A sonifier (Branson Ultrasonics, Danbury, USA) twice for 10 min
each. To remove cell debris, the lysate was centrifuged at 4°C for 20 min at 3000 g. The
supernatant was ultracentrifuged at 4°C for 1 h at 100,000 g to separate membrane fragments
from soluble and peripheral proteins. Membrane pellets were washed and suspended in
working buffer, ultracentrifuged again at 4°C for 1 h at 100,000 g to remove any residual
soluble or peripheral proteins. The resulting pellets were resuspended in buffer (50 mM Tris,
200 mM NaCl, pH 7.4) to a final concentration of 100 mg wet-weight pellet per 1 mL of
buffer and mixed in a 1:1 volume ratio with stock solutions of DDM or FSs in buffer.
Surfactant concentrations were chosen on the basis of the CMC values determined in this
study to ensure comparable extraction conditions. All samples were incubated for at least 16 h
at 20°C under constant, gentle agitation (500 rpm) and subsequently ultracentrifuged at 4°C
for 1 h at 100,000 g. The solubilized supernatant containing micelles was analyzed using
SDS-PAGE.
Sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE). The solubilization efficiency of the two FSs on biological membranes was assessed by SDS-PAGE using a NuPAGE Bis–Tris system (Life Technologies, Carlsbad, USA) with a polyacrylamide gradient of 4–12%. 14-μL samples were mixed with 5 μL 4x SDS sample buffer (106 mM Tris HCl, 141 mM Tris base, 2% (w/v) SDS, 10% (w/v) glycerol, 0.51 mM EDTA, 0.22 mM SERVA Blue G250, and 0.175 mM Phenol Red, pH 8.5) and 1 μL 1 M dithiothreitol (DTT) and boiled at 95°C for 10 min. 12 μL of each sample was loaded on a ready-to-use NuPAGE. As reference, a standard-weight marker (Roti-Mark 10–150, Carl Roth, Karlsruhe, Germany) was used, and the working buffer was used as negative control. Gel electrophoresis was performed for 45 min in MES buffer (50 mM MES, 50 mM Tris base, 0.1% (w/v) SDS, 1 mM EDTA) at 200 V and 50 W. Subsequently, gels were fixed for 20 min (10% (w/v) acetic acid, 40% (w/v) ethanol), stained for 30 min (0.025% (w/v) Coomassie brilliant blue G250, 10% (w/v) acetic acid) and destained overnight in water. For quantification of solubilization efficiencies, gels were photographed with a C4000Z camera (Olympus, Tokyo, Japan), and protein bands were analyzed with ImageJ.

Thermal denaturation assays. Thermal unfolding analysis were performed by differential scanning fluorimetry coupled to back scattering using a Prometheus NT.48 instrument (Nanotemper Technologies, Munich, DE), and the provided software PR.thermocntrol v2.0.4. Up to 48 capillary containing 10 μL of sample are sequentially illuminated at 280 nm, and fluorescence intensity at 350 (F350) and 330 (F330) nm, and back scattering measured as a function of temperature. The temperature was increased by 1 °C/min from 15 °C up to 90 or 95°C °C. The derivatives of F350/F330 and of the back scattering were used to estimate the melting temperature, \( T_m \), and the onset of aggregation, \( T_{agg} \), respectively. FhuA and bR samples are described in Breyton et al.
**bR solubilization and detergent exchange by sucrose gradient.** Sucrose gradients are a convenient means to perform both detergent exchange and evaluate the colloidal homogeneity of the protein-detergent complex. We routinely use this method to evaluate the potentialities of fluorinated surfactants in the biochemistry of MPs. BR retinal molecule, whose visible absorption spectrum is very sensitive to its local environment, is a convenient reporter of the state of the protein: the trimeric protein in its native membrane reveals a visible absorption spectrum with a maximum at $\lambda_{\text{max}} = 570$ nm; when solubilized in detergent, the protein monomerizes and displays $\lambda_{\text{max}} \sim 550$ nm; the protein appears purple/pink. When the protein denatures, the retinal is released, and $\lambda_{\text{max}}$ shifts to 400–380 nm: the protein solution turns yellow. We have reported that when the solubilized monomeric protein is transferred into a fluorinated surfactant, fluorinated surfactant migrates deeper in the gradients, due to the higher density of the surfactant, and $\lambda_{\text{max}}$ can shift to $\sim 610$ nm, giving a blue color to the protein-surfactant complex. Diffusion of the absorption curve is a witness of the appearance of larger particles in the solution, suggesting either aggregation of the protein or the formation of membrane patches.

Purified purple membrane was solubilized for 40 h at 4°C with 89mM OTG (CMC = 9 mM) at a membrane concentration of 1.5 g L$^{-1}$ in 20mM sodium phosphate buffer, pH 6.8. Samples were diluted to reach a final OTG concentration of 15 mM, supplemented with 2 mM of the surfactant to be tested, and incubated 15 min prior to being loaded onto a 10–30% (w/w) sucrose gradient containing 20 mM sodium phosphate buffer pH 6.8 and 6 mM of either DDM as a control, or the surfactant to be tested. Gradients were centrifuged for 5 h at 55,000 rpm (200,000 g) in the TLS55 rotor of a TL100 ultracentrifuge (Beckman). Bands containing the colored protein were collected with a syringe, and protein samples were kept at 4°C in the dark for UV–visible spectrophotometry.
Results and Discussion.

Synthesis. The detergents were synthesized in four steps, as illustrated in Scheme 1. The synthetic route is inspired by that previously used for the preparation of the poorly fluorinated analog of undecylmaltoside with two perfluorinated carbons F$_2$UDM (also called F$_2$H$_9$Malt).$^{22}$ Compounds 2a and 2b were prepared starting from peracetylated maltose by glycosylation reaction with allyl alcohol and penten-1-yl alcohol, respectively. The double bonds of the obtained compounds (2a and 2b) were then subjected to free radical reaction with perfluoropentyl iodide in the presence of 1 M BEt$_3$ in hexane.$^{33}$ The addition of the fluoroalkyl chain to the double bonds was confirmed by $^1$H- and $^{13}$C-NMR, which showed the disappearance of the signals corresponding to the double bond and the formation of new signals of -CHI. The iodine group of compounds 3a and 3b was reduced under H$_2$ gas and in the presence of Pd/C as catalyst. The obtained compounds were then deprotected under Zemplén conditions,$^{34}$ using a catalytic amount of MeONa in MeOH to obtain the desired detergents 4a and 4b. The crude detergents were purified by chromatography and freeze−dried to give the pure detergents in satisfactory global yields of 46% and 26% for F$_5$OM and F$_5$DM, respectively.

Scheme 1. Synthesis of F$_5$OM (4a) and F$_5$DM (4b).
Micellization. Micellization of the two surfactants was characterized by means of ITC, $^{19}$F-NMR, and SFT, from which we derived micellar parameters (Table 1). The critical micelle concentration (CMC) values were in very good agreement among the three techniques (Figure 2 and Figure S1). While F$_5$OM exhibited a CMC around 2.3 mM, the longer-chain derivative F$_5$DM had a CMC of ~0.4 mM. Thus, addition of two more methylene groups to the chain led to a decrease in CMC by a factor of ~5, which is only half the effect predicted by Traube’s rule$^{35}$ for adding two methylene groups to an alkyl chain.

The changes in Gibbs free energy $\Delta G_{m/aq}^{m}$, enthalpy $\Delta H_{m/aq}^{m}$, and entropy $-T\Delta S_{m/aq}^{m}$, accompanying the transfer of surfactant monomers from the aqueous solution into micelles are also summarized in Table 1. These data showed that micellization was almost exclusively driven by entropy, with enthalpy making only a minor contribution that decreased with increasing chain length. The Gibbs free energy of micellization increased in magnitude by –4.2 kJ/mol upon increasing the chain length by two CH$_2$ groups. In addition, the fluorinated maltoside-based surfactants displayed a higher tendency to form micelles at lower concentration than their hydrogenated analogues bearing the same number of carbon atoms in their hydrogenated chains. The hydrophobic contribution to micelle formation, that is, the contribution of the alkyl tail of F$_5$DM (CMC = 0.39 mM), which contains 10 carbon atoms, was greater than that of its decyl hydrogenated analogue DM (CMC = 2.0 mM) and fall between that of the undecyl derivative UDM (CMC = 0.59 mM) and DDM (CMC = 0.17 mM).$^{36}$ Similarly, the alkyl tail of F$_5$OM (CMC = 2.21 mM), which contains 8 carbon atoms, had almost similar hydrophobic contribution as DM. The hydrophobic contribution of CF$_2$ in highly fluorinated surfactants follows the rule that 1.0 CF$_2$ moiety has about the same effect as 1.5 CH$_2$ moieties;$^{37}$ hence, the CMC of F$_6$OM (0.71 mM) is similar to that of UDM (0.59 mM). This is once again confirmed with the two F$_5$DM and F$_5$OM where 1CF$_2$ = 1.3-1.6×CH$_2$. By contrast, sparingly fluorinated FSs do not obey this rule. Indeed, it has been
observed that the hydrophobic contribution of a CF$_2$ unit depends on the length of the fluorinated tip at the end of the aliphatic chain.$^{37}$ For instance, F$_2$H$_9$Malt,$^{22}$ the fluorinated analog of UDM with two perfluorinated carbons (F$_2$UDM following our nomenclature) has a CMC of 1.14 mM which is close to that of DM (1.8 mM) and would correspond to 1CF$_2 = 0.5\times$CH$_2$.

SFT data were used to construct Gibbs adsorption isotherms (data not shown) to determine the surface excess concentration at surface saturation, $\Gamma_{\text{max}}$. The values observed for F$_5$OM ($2.79 \times 10^{-12} \text{ mol/mm}^2$) and F$_5$DM ($2.87 \times 10^{-12} \text{ mol/mm}^2$), thus indicate similar packing of the two detergents at the air/water interface. From these values, the areas occupied per detergent molecule at the air/water interface, $A_{\text{min}}$, were determined to be close to 60 Å$^2$ for both compounds.

![Figure 2](https://via.placeholder.com/150)

**Figure 2.** (A) ITC data for F$_5$DM. Shown are an experimental isotherm (*open symbols*) and a fit based on a generic sigmoidal function (*solid line*). (B) $^{19}$F NMR peak chemical shift, $\delta_{\text{obs}}$. 

20
versus F$_5$DM concentration. We followed the signal of the terminal CF$_3$ group of the chain. The solid line represents the nonlinear fit of the experimental points.  

(C) Surface tension versus F$_5$DM concentration. The solid lines represent the linear fit of the experimental points and the intersection corresponds to the CMC.

**Size and shape of the micelles.** We next investigated the self-assembly properties of the FSs in phosphate buffer using DLS. At 10 mM, volume-weighted particle size distributions for F$_5$OM and F$_5$DM revealed unimodal distributions of rather small micelles with hydrodynamic diameters ranging from ~8 nm for F$_5$OM to ~15 nm for F$_5$DM (Figure 3A). Upon dilution to 5 mM, no significant difference in the volume-weighted distributions was observed for both compounds yet with a small decrease of the hydrodynamic diameters to ~7 nm for F$_5$OM and to ~13 nm for F$_5$DM (data not shown).

![Figure 3](image)

**Figure 3.** (A) Volume-weighted particle size distributions for F$_5$OM and F$_5$DM at 10 mM in phosphate buffer. (B) Distributions of sedimentation, c(s), for F$_5$OM at 10.5 mM and F$_5$DM at 7.7 mM. (C) SAXS patterns, and (D) pair distribution functions for F$_5$OM at 23.6 mM and F$_5$DM at 24.6 mM.
Table 1. Micellar Properties of Maltose Derivatives.

<table>
<thead>
<tr>
<th>Detergent</th>
<th>F3OM</th>
<th>F3DM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Molecular Weight g/mol</strong></td>
<td>652</td>
<td>680</td>
</tr>
<tr>
<td><strong>ITC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMC (mM)</td>
<td>2.21 ± 0.07</td>
<td>0.39 ± 0.01</td>
</tr>
<tr>
<td>$- T\Delta S_{mic}^o$ (kJ/mol)$^b$</td>
<td>-28.53 ± 0.53</td>
<td>-32.01 ± 0.04</td>
</tr>
<tr>
<td>$\Delta H_{mic}^f$ (kJ/mol)$^c$</td>
<td>3.43 ± 0.46</td>
<td>2.57 ± 0.20</td>
</tr>
<tr>
<td>$\Delta G_{mic}^o$ (kJ/mol)$^d$</td>
<td>-25.10 ± 0.08</td>
<td>-29.43 ± 0.04</td>
</tr>
<tr>
<td>$K_{mic}$</td>
<td>$2.5 \times 10^4 ± 0.08 \times 10^4$</td>
<td>$14.5 \times 10^4 ± 0.23 \times 10^4$</td>
</tr>
<tr>
<td><strong>NMR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMC (mM)</td>
<td>2.67</td>
<td>0.53</td>
</tr>
<tr>
<td><strong>ST</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMC (mM)</td>
<td>2.13 ± 0.10</td>
<td>0.34 ± 0.02</td>
</tr>
<tr>
<td>$\gamma$CMC (mN/m)$^g$</td>
<td>20.6</td>
<td>21.7</td>
</tr>
<tr>
<td>$\Delta G_{mic}^o$ (kJ/mol)$^d$</td>
<td>-25.2 ± 0.1</td>
<td>-29.7 ± 0.1</td>
</tr>
<tr>
<td>$I_{max}$ (10$^{12}$ mol/mm$^2$)</td>
<td>2.79 ± 0.01</td>
<td>2.87 ± 0.13</td>
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<tr>
<td>$A_{min}$ (Å$^2$)$^f$</td>
<td>59.6 ± 0.2</td>
<td>58.0 ± 2.6</td>
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<tr>
<td><strong>DLS</strong></td>
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<tr>
<td>$D_H$ (nm)$^f$ at 5 mM</td>
<td>7.4</td>
<td>12.8</td>
</tr>
<tr>
<td>$D_H$ (nm)$^f$ at 10 mM</td>
<td>8.3</td>
<td>14.8</td>
</tr>
<tr>
<td><strong>AUC-SV</strong></td>
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<tr>
<td>$\bar{v}$ (mL/g)</td>
<td>0.571</td>
<td>0.595</td>
</tr>
<tr>
<td>$\delta n/\delta c$ (mL/g)</td>
<td>0.064</td>
<td>0.074</td>
</tr>
<tr>
<td>CMC (mM)$^h$</td>
<td>2.5</td>
<td>0.3</td>
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<tr>
<td>$s_0$ (S)$^i$</td>
<td>12.1 ± 0.2</td>
<td>11.1 ± 0.2</td>
</tr>
<tr>
<td>$s$ (S) at CMC + 5 mM$^i$</td>
<td>12.7 ± 0.2</td>
<td>14.1 ± 0.2</td>
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<tr>
<td>$k$'s (mL/g)$^j$</td>
<td>9 ± 4</td>
<td>77 ± 12</td>
</tr>
<tr>
<td>$N_{agg}$ at CMC + 5 mM$^k$</td>
<td>200</td>
<td>380</td>
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<tr>
<td><strong>SAXS</strong></td>
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<td></td>
</tr>
<tr>
<td>C-CMC range (mM)</td>
<td>1.8 - 31</td>
<td>2.5 - 29</td>
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<tr>
<td>$R_g$ (nm) range$^l$</td>
<td>6.5 - 10</td>
<td>5.8 - 13.5</td>
</tr>
<tr>
<td>$N_{agg}$ range$^l$</td>
<td>270 - 335</td>
<td>300 - 500</td>
</tr>
<tr>
<td>$D_{max}$ (nm) range$^m$</td>
<td>27 - 50</td>
<td>30 - 70</td>
</tr>
<tr>
<td>Fitted SLD (Å$^2$)$^n$</td>
<td>13.8 ± 0.7</td>
<td>12.8 ± 0.4</td>
</tr>
<tr>
<td>Hydration (g water /g surfactant)$^n$</td>
<td>0.18 ± 0.12</td>
<td>0.34 ± 0.11</td>
</tr>
<tr>
<td>Radius (nm)$^n$</td>
<td>1.95 ± 0.03</td>
<td>2.25 ± 0.03</td>
</tr>
<tr>
<td>Length (nm) range$^n$</td>
<td>18 - 30</td>
<td>14 - 38</td>
</tr>
</tbody>
</table>

$^a$Data are averages of at least two experiments unless noted by * for one experiment only. ± indicates 95% confidence interval boundaries from a nonlinear least-squares fit for ITC. ± indicates standard errors from at least two experiments for SFT, AUC and SAXS. $^b$Entropic contribution to micelle formation. $^c$Enthalpic contribution to micelle formation. $^d$Gibbs free energy of micellization. $^e$Surface tension attained at the CMC. $^f$The surface excess ($I_{max}$) and the surface area per molecule (Å$^2$) were estimated from the slope of the surface tension curve. $^g$Hydrodynamic diameter by volume in phosphate buffer. $^h$Sedimentation coefficient at infinite dilution ($s_0$), or linearly interpolated from experimental data at CMC+ 5 mM, in water at 20 °C. $^i$Concentration dependence factor $k$'s from linear fits. $^j$Aggregation number obtained from $s$, and $D_h$. Error is estimated at 10%. $^k$Radius of gyration and aggregation numbers from Guinier analysis. $^l$Maximum distance from $P(R)$ analysis. $^m$Fitted scattering length density, derived hydration, radius and length considering a cylinder model.

To further characterize the micellar aggregates, AUC sedimentation velocity experiments were performed. Figure S2A displays the sedimentation velocity profiles. From the $c(s)$ analysis, we observed a complex boundary representing micelles in the range 9-16 S for
F₅OM and 10-18 S for F₅DM (Figures 3B, S2B and S2B’). The s value increased with concentration, with a more pronounced effect for F₅DM than for F₅OM (Figure S2D). We used the dilution series to determine, from the micelle signals versus concentration, the refractive index increment (∂n/∂c) and the CMC, as well as the s value at infinite dilution (s₀) and the concentration dependence factor (k’s) (Figure S2C and Table 1). For both detergents, AUC provided CMC values relatively similar to those obtained from NMR, SFT, and ITC (Table 1). The s₀ values are similar, but sedimentation coefficients vary with concentration to different extents for the two surfactants as illustrated by the k’s values. A realistic estimate of aggregation numbers, Nₐgg, is obtained by combining the values of s with that of the hydrodynamic diameters from DLS. Calculated Nₐgg at the CMC+5mM are lower for F₅OM compared to F₅DM (Table 1).

To complete the colloidal characterization of the two compounds, SAXS experiments were next performed. Figure 3C shows the scattering curves for F₅OM and F₅DM whose similarities in the shape suggest similar micelle organization (See Figure S3 for detailed analysis). Guinier analysis at low angle (Figure S3B) provided mean radius of gyration (Rg) and Nₐgg, which increase with concentrations, moderately for F₅OM and to a larger extent for F₅DM (Table 1 and Figure S4). Pair distribution functions, P(R), derived from the whole scattering curves (Figure 3D and S3C) present for F₅OM a main maximum at 3.5 nm which remains invariant while it increases slightly with concentration for F₅DM from 3.6 to 4.6 nm. All curves present at larger R a linear decrease, which indicates a linear rod shape for the aggregates.³⁹ The largest distance, Dₘₐₓ, corresponding to P(R) reaching zero, increases with concentration for both surfactants, and in minor extent for F₅OM compared to F₅DM (from ≈ 30 for both to 30 and 50 nm, respectively). Lastly, we analyzed the scattering curves considering a cylinder with hard sphere interaction. The fitted and experimental curves are reasonably superposed for all scattering curves (Figure S3D). Table S2 presents the detailed
results, and Table 1 reports the main conclusions. The values of the fitted scattering length density (SLD) do not depend on surfactant concentration, as expected, and are intermediate between anhydrous surfactant and water SLDs. We derived reasonable hydration of $0.18 \pm 0.12$ and $0.34 \pm 0.11$ g of water per g of surfactant. Fitted radius do not vary with surfactant concentration: 1.95 and 2.25 nm for F$_5$OM and F$_5$DM, respectively. It is comparable to the sum, determined from SAXS and SANS, of the core radius and shell thickness, for the small dimension ($\approx 2.1$ nm) of the slightly elongated DDM micelle,$^{12, 40-41}$ or for the lateral dimension (2.2 nm) of the rod-forming detergent LMNG, which also bears maltose heads and have two dodecyl chains.$^{12}$ Because the fitted SLD and radius-values are correlated with the concentration input values, the minor differences in the fitted hydration and radius for the two surfactants may be irrelevant. The length is $\approx 15$ nm at the lowest concentrations, and reaches 30 and 38 nm at $\approx 30$ mM F$_5$OM and F$_5$DM, respectively (Figure S3D). These values correspond to length/diameter ratio of $\approx 8$. We note that the fitted length is about half $D_{\text{max}}$. A tentative explanation is that there is a distribution in length. $D_{\text{max}}$ probes the largest molecules, while the fit considers the most populated dimensions.

The larger micelle size above 5 mM, for F$_5$DM versus F$_5$OM observed from AUC and SAXS is in line with what is generally observed for hydrogenated$^{42}$ and fluorinated detergents.$^{20}$ Comparing with fluorinated compounds with the same OM head-group, while the hydrogenated DDM forms small slightly elongated micelles of $\approx 60$ kDa up to at least 10 mM$^{29}$, the poorly fluorinated F$_2$UDM and the nonyl derivative with four perfluorinated carbons F$_4$NM (also called F$_4$H$_5$Malt)$^{22}$ were described to form small micelles with $N_{\text{agg}} < 100$ up to C-CMC $\approx 10$ mM ($s$ of 4 and 7 S at CMC + 5 mM), the later experiencing very slightly attractive interactions evidenced only above 30 mM. The commercial F$_6$OM forms very large rod micelles with $N_{\text{agg}} > 500$ at $\approx$ CMC + 10 mM ($s$ of 27 S at CMC + 5 mM). The propensity of highly fluorinated surfactants with a OM head to form rather large rods is in contrast with
fluorinated surfactants with a head bearing two glucose groups, which self-assemble into
compact and well-defined globular micelles of 6–8 nm in diameter with aggregation numbers
below 100.\textsuperscript{20}

**Solubilization of POPC LUVs by FSs.** The detergency reflects the ability of an amphiphilic
compound to both solubilize lipid bilayers and extract MPs. To assess the detergency of
F\textsubscript{5}OM and F\textsubscript{5}DM, we tested whether they are able to dissolve large unilamellar vesicles
(LUVs) composed of the singly unsaturated phospholipid 1-palmitoyl-2-oleyl-\textit{sn}-glycerol-3-
phosphocholine (POPC). Measurements were conducted at 25°C by adding a rather high
concentration (CMC+5 mM) of the respective FS to 100 \(\mu\)M POPC LUVs, which resulted in a
steady decrease in the light scattering intensity over time. The particle size distributions
shown in Figure 4 support the interpretation that the decreased light scattering intensity was
due to vesicle solubilization, as the vesicular peak at \(\sim120\) nm at the beginning of the
measurement completely disappeared after the intensity decreased to the level of pure mixed
micelles. Solubilization was essentially complete after \(\sim16\) h for F\textsubscript{5}DM but took longer for
F\textsubscript{5}OM. Most importantly, however, both FSs were able to solubilize synthetic POPC vesicles
at 25°C, which sets them apart from more conventional FSs such as F\textsubscript{6}OM, F\textsubscript{4}H\textsubscript{2}-DigluM,
F\textsubscript{6}H\textsubscript{2}-DigluM, and F\textsubscript{8}H\textsubscript{2}-DigluM, which require elevated temperatures and prolonged
incubation times for solubilization.\textsuperscript{19-20}
Figure 4. Kinetics of 100 μM POPC LUVs solubilization by 7.2 mM F₅OM & 5.4 mM F₅DM at 25°C as monitored in terms of the light scattering intensity recorded at an angle of 90°. The inset shows intensity-weighted size distributions obtained for a mixture of 100 μM POPC and F₅DM immediately (green) or after 16h (blue). Buffer: 10 mM phosphate, 150 mM NaCl, pH 7.4.

**Extraction of MPs from native E. coli membranes.** Next, we investigated whether F₅OM and F₅DM can also extract MPs from native E. coli membranes. To this end, we quantified the intensities (*i.e.*, pixel counts) of SDS-PAGE band patterns (Figure 5A) and compared their efficiencies with those of DDM and F₆OM. The overall protein-extraction yields were also expressed relative to the buffer without any detergent (Figure 5B). Figure 5A indicates that both F₅OM and F₅DM extracted similar patterns of MPs spanning a broad size range. Notably, at low concentrations (*i.e.*, 1–5 mM), both FSs displayed better solubilization efficiencies than DDM, although DDM was outstanding in extracting a single abundant protein of ∼35 kDa, namely, outer-membrane protein OmpA, at higher concentrations. By contrast F₆OM showed very limited solubilization.
**Figure 5.** (A) SDS-PAGE of *E. coli* membrane extracts upon exposure to various FSs with micellar concentrations as indicated. (B) Graphical representation of protein-extraction yields (symbols) when using surfactant relative to the yield obtained when no surfactant was added (i.e., only buffer; dashed line). Data are mean values from three experiments.

**FhuA and bR thermal stability.** To assess the stability of MPs in the new FSs, we investigated the thermal stability of two models proteins. Differential scanning fluorimetry (DSF) probes conformation changes with temperature. It allows measuring the melting temperature ($T_m$) of the protein by measuring the fluorescence emission ($F_{350nm}/F_{330nm}$ ratio) of the aromatic residues upon increasing temperature. Simultaneous light back-reflection measurement probes protein aggregation, $T_{agg}$ being the onset temperature for aggregation.

FhuA is an *E. coli* outer membrane ferrichrome-iron transporter involved in bacteriophage infection.$^{43}$ bR is a light-driven proton pump purified from the archaea *Halobacterium*. It binds a covalent cofactor, a retinal molecule that confers a purple color to the protein.$^{44}$ We use the two proteins, representatives of the two main structural classes β-barrels and α-helix bundle, of proteins, to investigate their thermal stabilities in the presence of our fluorinated derivatives. The two proteins were first extracted by lauryldimethylamine oxide (LDAO) for FhuA and OTG for bR, and then transferred into F$_5$OM and F$_5$DM, as well as in DDM and the solubilizing detergent, at CMC + 0.2 mM, and CMC + 2 mM. Final residual concentrations of the initial detergents, LDAO for FhuA and OTG for bR, were 0.05 and 0.4 CMC. FhuA shows two unfolding events (Figure 6), attributed to, first, the unfolding of the cork, at $T_{m1}$,
and then of the barrel, at $T_{m2}$, while bR shows only one transition (Figure S5). For each of the two proteins, the melting curves general appearance is similar whatever the detergent and its concentration. Table 2 presents the mean values of $T_m$ and $T_{agg}$. For FhuA and bR, in LDAO or OTG the extracting detergents, $T_m$ are lower than that in F$_5$OM, F$_5$DM or DDM suggesting a thermostabilizing effect of the three maltoside derivatives.

**Figure 6.** Thermal denaturation of FhuA by differential scanning fluorimetry. (A) Ratio of the fluorescence emitted at 350 and 330 nm, and (B) derivative (bottom panel) for FhuA at 0.04 mg mL$^{-1}$, incubated in the presence of F$_5$OM at CMC+2mM (green), F$_5$DM at CMC+2mM (red), DDM at CMC+0.2mM (blue), LDAO at CMC+2 mM (black).

**Table 2.** Melting temperatures of FhuA and bR

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<th>Protein type</th>
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$T_{m1}$, $T_{m2}$, $T_{m}$: melting temperatures measured by differential scanning fluorimetry for the first and second transition of FhuA, and the transition for bR. $T_{agg}$: onset temperature for aggregation from light back reflexion. The precision on $T_{m1}$ is estimated at 1°C, that for $T_{m2}$ and $T_{m}$, which are above $T_{agg}$, at 2°C. The precision on $T_{agg}$ is 2°C. Micelle concentrations (i.e. above the CMC concentrations) were calculated considering CMC-values of 1, 0.17, 2.8, and 0.4 mM for LDAO, DDM, F5OM, and F5DM, respectively.

**Homogeneity and stability of bR over time.** The retinal molecule bound to bR, whose visible absorption spectrum is very sensitive to its local environment, is a convenient reporter of the state of the protein.\(^{32}\) Figure 7 reports bR absorption spectra after detergent exchange, over time, in DDM, F5OM and F5DM. Pink monomeric bR in DDM displays a $\lambda_{max} = 550$ nm. In F5OM or F5DM, just after detergent exchange, the $\lambda_{max} \sim 595$ nm is compatible with the observed bR blue color, and reflects a monomeric state, as observed previously in various fluorinated surfactants.\(^{35}\) After two days incubation, $\lambda_{max}$ shifts to $\sim 575$ nm (close to the $\lambda_{max}$ of native bR), and remains unchanged for one year; the absence of $\lambda_{max} = 390$ nm, reporter of free retinal, reflects the absence of protein denaturation; over time, the spectra show scattering, witness of progressive but very minor aggregation. These three observations suggest clustering of monomeric bR into larger, native-like oligomers. Thus, the protein is extremely stable as regards its conformation, but its colloidal stability is not as good as that in DDM. When comparing with the previous fluorinated compounds of the maltose series, some differences can be noted: 1- in F2UDM and F4NM, bR was blue ($\lambda_{max} \sim 610$ nm) and remained so unless it denatured; 2- in F2UDM, bR was not stable, denatured and aggregated; 3- in F6OM, bR was not soluble and aggregated during surfactant exchange.\(^{22}\) Thus, both F5OM and F5DM appear more solubilizing than F6OM, more stabilizing than F2UDM and providing a more native environment than F4NM. Thus, an optimized F/H ratio has been found in those two compounds, providing solubility, stability and close-to-native environment in biochemistry.
Figure 7. Spectral time course of bR collected from the gradients in (A) DDM, (B) F₅OM and (C) F₅OM. Samples were incubated at 4°C in the dark and UV-visible spectra were recorded at the indicated time (given in days, D). Day 1 curve is displayed in red, day 2 in orange, day 9 in yellow, day 27 in green, day 40 in cyan and day 357 in violet. The arrow indicates the evolution of $\lambda_{\text{max}}$ with time.

Specific activity of BmrA and SpNOX

We investigated the enzymatic stability of two MPs, SpNOX, a *Streptococcus pneumoniae* protein analog to the eukaryotic NADPH oxidase and BmrA, a transporter of multiple drugs with the driving force of ATP hydrolysis. The activity results following detergent exchange are displayed on Figure S6. The specific activity of BmrA and SpNOX is partially preserved, and in the same range for F₅OM, F₅DM, and F₆OM.
Conclusion

We have designed two maltose-based fluorinated surfactants, F₅OM and F₅DM, whose hydrophobic tails are made up of linear fluoroalkyl chains. Formation of micelles in water occurred as governed by the length of the hydrophobic chain. F₅OM and F₅DM self-assembled into rod-like micelles, with hydrodynamic diameters and aggregation numbers that increased with chain length. The potencies of the new FSs to act as detergents was first demonstrated using synthetic POPC lipid vesicles and were further confirmed through the extraction of MPs from *E. coli* membranes. Both F₅OM and F₅DM showed detergency with more solubilizing activity than the commercial fluorinated compound F₆OM at all concentrations and even better protein-extraction efficiency than DDM at low concentrations. F₅DM consistently exhibited better solubilizing properties than F₅OM, towards both lipid vesicles and MPs. The detergency of the two derivatives exceeded by far that of the fluorinated DigluM derivatives F₄H₂-, F₆H₂- and F₈H₂DigluM. This suggests that the linear maltoside polar head, likely owing to its small size, may promote detergency as compared with the bulky branched diglucose polar head. BR and FhuA, representatives of α-helical and β-barrel proteins, showed remarkable thermal and, for bR, also functional stability, similar to DDM, when transferred into both F₅OM and F₅DM. These surfactants appear, for bR, better than the commercial F₆OM in which the protein aggregated more stabilizing than F₂UDM and provided a more native environment than F₄NM. This indicates that an optimized F/H ratio has been identified in those two compounds, providing solubility, stability, and a close-to-native environment for bR. The enzymatic activities of BmrA and SpNox, were by contrast rather limited when compared to DDM, and similar for F₅OM, F₅H₅OM and F₆OM. Taken together, these findings support the usefulness of this novel series of fluorinated maltoside detergents as promising molecular tools for extracting, stabilizing, and handling MPs.
ASSOCIATED CONTENT

Supporting Information

The supporting information is available free of charge on the ACS Publication website at DOI: #

ITC, $^19$F NMR and surface tension data curves of F$_5$OM; Analysis of sedimentation velocity experiments; Small Angle X-Ray Scattering complementary data of F$_5$OM and F$_5$DM including concentration dependence analysis and cylinder shape fitting; Thermal denaturation of bR by differential scanning fluorimetry; Material and Methods for BmrA and SpNox production and SpNox and BmrA activity assays; SpNox and BmrA activity data in F$_6$OM, F$_5$OM and F$_5$DM;

$^1$H and $^{13}$C NMR spectra and mass spectrometry data of compounds 2a and 2b; $^1$H, 19F and $^{13}$C NMR spectra and mass spectrometry data of compounds 3a, 3b, 4a (F$_5$OM) and 4b (F$_5$DM).

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Institute of Grenoble (IRIG, CEA) We thank Martha Brennich (ESRF) for help in SAXS data acquisition and Marine Soulié (IBMM) for carefully checking NMR data. Emmi Mikkola (UGA) participated to the biochemical evaluation during her master internships at IBS. This work benefited from the use of the SasView application, originally developed under NSF Award DMR-0520547. SasView also contains code developed with funding from the EU Horizon 2020 programme under the SINE2020 project Grant No 654000.
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Table of Graphical Content

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