Scalable Synthesis of Salt-free Quaternary Ammonium Carboxylate Catanionic Surfactants

Žiga Medoš, Miha Virant, Urša Štanfel, Boštjan Žener, Janez Košmrlj* and Marija Bešter-Rogač*

Faculty of Chemistry and Chemical Technology, Večna pot 113, University of Ljubljana, SI-1000 Ljubljana, Slovenia

* Corresponding author: E-mail: janez.kosmrlj@fkkt.uni-lj.si
Tel: +386 1 479 8558
E-mail: marija.bester@fkkt.uni-lj.si
Tel: +386 1 479 8537

Received: 07-16-2019

Abstract

Surfactants in commercial products commonly contain catanionic mixtures thus many studies of aqueous surfactant mixtures have been carried out. However, hardly any studies have been dedicated to pure catanionic surfactants often termed salt-free catanionic surfactants. One of the difficulties is in acquisition of samples with required purity due to difficult separation of these compounds from inorganic salts. In this work we present an alternative method of synthesis using dimethyl carbonate as the alkylating agent in order to obtain alkyl trimethylammonium alkanecarboxylates with medium alkyl chain lengths (6–10).

Keywords: Synthesis; surfactants; salt-free; catanionics; quaternization

1. Introduction

Commercial surfactants are commonly a mixture of cationic, anionic and non-ionic surfactants due to their enhanced performance as mixtures.1,2 Therefore, along the studies of non-ionic and ionic surfactants in their pure form as well as in binary aqueous solutions, significant focus has been dedicated to aqueous mixtures of cationic and anionic surfactants – catanionic mixtures. An interesting group of catanionic surfactants are salt-free catanionics, where often the challenge of preparing these surfactants in their pure form is the removal of all inorganic salts upon mixing the parent cation and anion salts. There are three main methods to remove inorganic salts from equimolar catanionic mixtures: (1) ion-exchange columns are used to prepare acids and hydroxides and subsequently mixed; (2) liquid-liquid extraction in organic phase and (3) precipitation method.3 When surfactants are poorly soluble in organic solvents precipitation is generally easily achieved. On the contrary, if solubility is limited in polar solvents liquid-liquid extraction is possible. However, many surfactants, especially those interesting for application, are soluble in both, organic and aqueous media. This limits the separation techniques to ion-exchange columns or the precipitation of silver halides from water solutions. Unfortunately, these two approaches are not economically viable and some contamination with inorganic salt can still occur. This can have significant impact on some of the surfactant’s properties and can crucially affect studied physical and aggregation properties of aqueous solutions.4–6 Thus, the development of novel and more effective methods of synthesis is required.

In this work we present two synthetic procedures to prepare alkyltrimethylammonium alkanecarboxylate catanionic surfactants (Figure 1). Generally, the synthesis of quaternary ammonium surfactants starts with ammonia or substituted amine precursor. It is alkylated in two or more steps with the last step being quaternization. Most studied and produced quaternary ammonium surfactants are alkyltrimethylammonium halides followed by dialkyldimethylammonium halides (gemeni surfactants).7 Their aqueous solutions are generally more stable than quaternary ammonium surfactants with remaining hydrogen(s) on quaternary ammonium. Quaternization can be achieved by the Menshutkin reaction where tertiary amine is reacted with haloalkane. However, halide free methods are preferred for industrial application.
Recently, Jiang et al. presented a synthetic procedure for the preparation of salt-free quaternary ammonium carboxylates using dimethyl carbonate (DMC) as alkylating agent of appropriate tertiary amines, with one or two alkyl chains exceeding 12 carbon atoms and a short-chain carboxylate anion (acetate, propionate, lactate). They expanded the scope to long-chain catanionic surfactants in the follow-up papers, namely tetradecyltrimethylammonium alkane carboxylates (hexanoate, octanoate, decanoate, docanoate, tetradecanoate) and alkyl (decyl, dodecyl, tetradecyl, hexadecyl, octadecyl) trimethylammonium decanoates. DMC represents an attractive eco-friendly alternative to methyl halides.

However, additional challenges emerge when both alkyl chains are shorter than 10 carbon atoms. Mainly, due to increased solubility in majority of polar and non-polar solvents the usual purification methods of precipitation, recrystallization and liquid-liquid extraction become less efficient or impossible. Additionally, the commercial price of tertiary amines, required in the most common synthesis approach, increases with shorter chains. Therefore, in this work we present low cost synthetic alternative starting with a secondary amine to produce quaternary ammonium carboxylate surfactants with alkyl chains between 6 and 10 carbon atoms long.

Synthesis of decyltrimethylammonium alkane carboxylates (acetate, butanoate, hexanoate, octanoate, nonanoate, decanoate, undecanoate) has also been reported by reacting quaternary ammonium halides with silver hydroxide. After precipitation of the silver halide salts, the resulting hydroxide solutions were reacted with carboxylic acid. For large scale application silver salts are not economically viable, therefore we present a competitive approach through precipitation of KCl from ethanol. We compare the thermal properties of products obtained by both procedures.

2. Experimental

2.1. General Information

The reagents and solvents in general procedures were used as obtained from the commercial sources (Merck), unless noted otherwise. Octanoic acid (4b) and decanoic acid (4c) were recrystallized from ethanol by addition of acetone. IR spectra were obtained with a Perkin–Elmer Spectrum 100, equipped with a Specac Golden Gate Diamond ATR as a solid sample support. High resolution mass spectra (HRMS) were recorded on Agilent 6224 time-of-flight (TOF) mass spectrometer equipped with a double orthogonal electrospray source at atmospheric pressure ionization (ESI) coupled to an HPLC instrument. 1H, 13C and 15N NMR spectra were recorded with a Bruker Avance III 500 MHz NMR (at 500 MHz, 126 MHz and 51 MHz, respectively) instrument at 296 K in DMSO-d6 using TMS as an internal standard. Proton and carbon spectra were referenced to the residual chloroform shifts of 7.26 ppm and 77.16 ppm, respectively. Assignments of proton, carbon and nitrogen resonances were performed by 2D NMR techniques (1H−1H gs-COSY, 1H−13C gs-HSQC, 1H−13C gs-HMB and 1H−15N gs-HMBC). Carbon resonances without labels belong to the chain carbons and could not have been differentiated. Thermogravimetric (TG) measurements were performed on a Mettler Toledo TGA/DSC1 Instrument in the temperature range from 25 to 400 °C under dynamic air flow (100 cm3 min−1) with a heating rate of 5 K min−1. Approximately 3–5 mg of sample was weighed into a 150 μL platinum crucible and the baseline was subtracted. Differential scanning calorimetry (DSC) measurements were performed separately on a Mettler Toledo DSC 1 Instrument in 40 μL aluminium crucibles under the same conditions.

2.2. Synthesis

Alkyltrimethylammonium Chlorides 3a–c

In a 200 mL autoclave chloroalkanes 2a–c (0.21 mol, 1 eq) were mixed with 33% trimethylamine solution in ethanol (1, 100 mL, 2 eq). The mixture was stirred in an oil bath at 80 °C for 3 days. Excess 1 and solvents were removed under reduced pressure. Products were dissolved in minimal amount of ethanol required (approx. 5 mL) and recrystallized by addition of ethyl acetate (100 mL). The precipitates were filtered and washed with diethyl ether (50 mL) and subsequently dried under reduced pressure to yield products in 50% average yield. Products 3 are very hygroscopic which reduces the yield of recrystallization in open air (3a 26%, 3b 53%, 3c 55%).

Alkyltrimethylammonium Carboxylates 5a–e According to Procedure A

In the next step, alkyltrimethylammonium chlorides 3a–c as prepared above (0.07 mol) were dissolved in ethanol (20 mL) and weighed precisely. The exact amount of chloride ions was determined by AgNO3 titration of small samples and the required equimolar amounts of carboxylic acids 4a–c were weighed and added. 95% of KOH, required for neutralization, was weighed as solid pellets. After all of the added solid KOH dissolved and KCl precipitated (1 hour), the remaining KOH was titrated as an approximate 0.25 M solution of KOH in ethanol until potential of glass electrode dropped below −250 mV which was previously determined as the potential of the inflection point. Solutions were filtered to separate the filtrate containing the products from the precipitated KCl. Filtrates were concentrated under reduced pressure subsequently precipitating more KCl which was filtered to obtain filtrate.
containing desired alkyltrimethylammonium carboxylates 5a–e in quantitative yields. Solutions were dried first under reduced pressure and followed by high vacuum. However, due to increased solubility of KCl in the presence of the products up to 3% of KCl remains in the final product as determined by AgNO₃ titration and TG analysis.

### Alkyltrimethylammonium Carboxylates

#### Bromoalkanes 7a–c
Bromoalkanes 7 (bromohexane 7a 2.3 mol; bromooctane 7b 1.9 mol; bromodecane 7c 1.6 mol; 1 eq) were mixed with toluene (300 mL) in a 3 L autoclave. Then 40% N,N-dimethylamine (6) solution in water (500 mL, approx. 2 eq) was added. An excess amount of NaOH (200 mL) was added as a 50% aqueous solution. The mixtures were stirred and heated to 60 °C for 3 days. After the reaction was completed the reaction mixture separated in two layers. The organic phase containing products was separated from water phase and concentrated under reduced pressure. The products were washed several times with water (5 × 20 mL) and distilled under reduced pressure to remove toluene (8a 70%, 8b 90%, 8c 95%). While amine 8c can be dried on a vacuum line with minimal loss due to evaporation, the distillation results in better overall yield. The presence of toluene in product is not problematic, as it can be dried on a vacuum line with minimal loss due to increased solubility of KCl in the presence of the products up to 3% of KCl remains in the final product as determined by AgNO₃ titration and TG analysis.

#### Alkyldimethylamines 9a–c

Prepared according to the general procedure B. White solid (11.5 g, 35%). IR 3473, 3393, 3020, 2920, 2852, 1717, 1657, 1569, 1380, 972, 756 cm–¹. 1H NMR (500 MHz, CDCl₃) δ 3.42–3.35 (m, 2H, CH₂-2'), 3.32 (s, 9H, NMe₃), 2.14–2.06 (m, 2H, CH₂-2'), 1.75–1.64 (m, 2H, CH₂-2), 1.59–1.48 (m, 2H, CH₂-3'), 1.38–1.15 (m, 18H, CH₂-chain), 0.92–0.78 (m, 6H, CH₃-10' and CH₃-6). 13C NMR (126 MHz, CDCl₃) δ 179.8 (COO), 66.9 (30.21), 53.2 (NMe₃), 39.4 (C-2'), 32.0, 31.4, 30.2, 29.9, 29.8, 29.5, 27.3, 26.0, 23.2, 22.8, 22.5, 14.2 (CH₃-6/CH₃-10'), 14.0 (CH₃-6/CH₃-10'). 15N NMR (51 MHz, CDCl₃) δ 49.5 (NMe₃). HRMS (ESI+): calcd. for C₆H₁₃N²⁺ [M⁺] 144.1747, found 144.1749. HRMS (ESI–): calcd. for C₁₅H₁₄O₂⁻ [M⁻] 171.1391, found 171.1389.

Prepared according to the general procedure B. White solid (14.7 g, 63%). IR 3317, 3119, 3032, 2919, 2851, 1572, 1377, 1055, 963, 643 cm–¹. 1H NMR (500 MHz, CDCl₃) δ 4.00–3.94 (m, 2H, CH₂-1'), 3.92–3.87 (m, 9H, NMe₃), 1.98–1.90 (m, 2H, CH₂-2'), 1.67–1.58 (m, 2H, CH₂-2), 1.46–1.33 (m, 2H, CH₂-chain), 0.91–0.79 (m, 6H, CH₃-10' and CH₃-6). 13C NMR (126 MHz, CDCl₃) δ 179.6 (COO), 66.9 (C-1), 53.2 (NMe₃), 39.2 (C-2'), 32.1, 31.4, 30.2, 29.9, 29.8, 29.5, 29.3, 29.1, 27.3 (C-3'), 26.4, 23.2, 22.5, 14.2 (CH₃-8/CH₃-10'), 14.1 (CH₃-8/CH₃-10'). 15N NMR (51 MHz, CDCl₃) δ 49.7 (NMe₃). HRMS (ESI+): calcd. for C₁₂H₂₂N⁺ [M⁺] 172.2060, found 172.2057. HRMS (ESI–): calcd. for C₁₆H₁₉O₂⁻ [M⁻] 171.1391, found 171.1386.

N-DeCyN, N,N′,N′-trimethylammonium Decanoate (5c)

Prepared according to the general procedure B. White solid (25.3 g, 72%). IR 3429, 3348, 3195, 3119, 3032,
3. Results and Discussion

A series of quaternary ammonium carboxylates – N-alkyl-N,N,N,N-trimethylammonium alkane carboxylates were prepared according to two general procedures as presented on Figure 2.

In the first step of procedure A, where the reaction mixture was heated at 80 °C for 3 days, alkyltrimethylammonium chlorides (alkyl = hexyl, 3a; octyl, 3b; decyl, 3c) were obtained. Procedure A is followed by a cost effective approach to anion exchange in ethanolic solutions of KOH through precipitation of KCl (see Experimental Section for details) yielding alkyltrimethylammonium alkane carboxylates (5a–e, Table in Figure 2). Even though the reported solubility of KCl in ethanol is very low (0.034%) the final products of procedure A shown in Table 1 contained up to 3% of inorganic salt as determined by AgNO₃ titration (0.6 ± 0.5% Cl⁻) and TG analysis (2 ± 1%). Presumably the presence of the product significantly increases solubility of KCl in ethanol. In fact, products are soluble in polar (water, methanol, ethanol, 1-butanol, acetone, ethyl acetate) and most non-polar (diethyl ether, n-hexane, toluene, dichloromethane, chloroform) solvents, making complete separation from KCl by precipitation impossible.

Therefore, the procedure B was developed as an alternative. Starting from dimethylamine (6) the long alkyl chain is introduced in the step before quaternization. Therefore, the soluble halide salts are easily washed away with water. Quaternization was successfully achieved with dimethyle carbonate (Me₂CO₃), a common methylating agent enabling a facile purification method. The side products, methanol and CO₂, are easily removed under reduced pressure. Preparation according to the general procedure B. White solid (2.2 g, 13%). IR 3359, 3021, 2922, 2854, 1572, 1377, 973, 918, 766, 644 cm⁻¹. ¹H NMR (500 MHz, CDCl₃) δ 3.45–3.37 (m, 2H, CH₂-1), 3.38–3.30 (m, 9H, NMe₃), 2.21–2.03 (m, 2H, CH₂-2’), 1.76–1.61 (m, 2H, CH₂-2), 1.61–1.50 (m, 2H, CH₂-3’), 1.38–1.15 (m, 18H, CH₂-chain), 0.92–0.78 (m, 6H, CH₃-8 and CH₂-8’). ¹³C NMR (126 MHz, CDCl₃) δ 179.6 (COO), 66.9 (C-1), 53.2 (NMe₃), 39.2 (C-2’), 32.4, 31.9, 29.50, 29.46, 29.3, 26.9 (3’). ¹⁵N NMR (51 MHz, CDCl₃) δ 49.8 (NMe₃). HRMS (ESI+): calcd. for C₁₃H₃₆N⁺ [M⁺] 200.2373, found 200.2370, HRMS (ESI–): calcd. for C₁₃H₃₆O⁻ [M⁻] 171.1391, found 171.1386.
recrystallized from ethyl acetate or ethyl acetate-acetone mixture\textsuperscript{9,10} however compounds with shorter alkyl chains are soluble in both subsequently limiting recrystallizations to acetonitrile.

The compounds synthesized according to procedure B were characterized using standard NMR spectroscopy techniques, IR spectroscopy, HRMS.

The two methods thus enable the preparation of the same products in different number of reaction steps and of different purity. A simpler method A is more suitable for quick preparation of products in which the presence of inorganic salt does not affect its application. However, the first step of method B can be industrially replaced by catalytic alkylation of dimethylamine with alcohols\textsuperscript{15–17} thus method B can produce desired catanionic surfactants using a more environmentally friendly approach. Nevertheless, in the case where salts in final product could result in undesired properties, procedure B is the method of choice.

From the obtained TG/DSC curves the effect of impurities on the thermal properties of studied catanionic surfactants was observed, explicitly the change in the melting point and the decomposition temperature as presented in Table 1.

Thermal analysis of products reveals very similar decomposition temperature for all products regardless of alkyl chain lengths (Table 1). From the TG curves (Figures S1 and S2 in Supporting Information) it is evident from the starting % of mass that shorter alkyl chains increase hygroscopicity of the compound. However, this water is weakly bound as most samples obtained by procedure B were completely dehydrated at mere 70 °C except for 5a and 5f where water binding is stronger. Presence of KCl significantly increases the strength of binding of water as well as introduces a second step in the decomposition. This step is more pronounced the longer the alkyl chain on the anion thus we propose the formation of potassium carboxylate.

Table 1. Yields and thermal data for the prepared compounds by the two methods.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Alkyl chain length</th>
<th>Method</th>
<th>Yield/%</th>
<th>(T_m/°C)</th>
<th>(T_{dec}/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>6</td>
<td>A</td>
<td>26</td>
<td>128</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>35</td>
<td>/</td>
<td>169</td>
</tr>
<tr>
<td>5b</td>
<td>8</td>
<td>A</td>
<td>53</td>
<td>144</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>63</td>
<td>176</td>
<td>180</td>
</tr>
<tr>
<td>5c</td>
<td>10</td>
<td>A</td>
<td>55</td>
<td>/</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>72</td>
<td>172</td>
<td>181</td>
</tr>
<tr>
<td>5d</td>
<td>8</td>
<td>A</td>
<td>53</td>
<td>147</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>28</td>
<td>/</td>
<td>179</td>
</tr>
<tr>
<td>5e</td>
<td>10</td>
<td>A</td>
<td>55</td>
<td>/</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>54</td>
<td>/</td>
<td>184</td>
</tr>
<tr>
<td>5f</td>
<td>10</td>
<td>B</td>
<td>13</td>
<td>/</td>
<td>178</td>
</tr>
</tbody>
</table>
For comparison TG/DSC curve of decyltrimethylammonium chloride (3c) is also presented on Figures S1 and S2 indicating lower thermal stability of carboxylates. Stability is also somewhat lowered by KCl (Table 1). Melting point or phase transition was observed for some of the products. KCl lowers the temperature of this transition.

4. Conclusions

In the proposed salt-free procedure first alkyl trimethylammonium methylcarbonate is obtained and reacted with carboxylic acid. The side products of methanol and CO₂ are easily removed under reduced pressure. In principle, salts composed of quaternary ammonium cations and most anions can be synthesized with this procedure. Reactants are inexpensive thus the procedure is potentially applicable in industrial production. An alternative procedure applying precipitation method is a viable alternative when inorganic impurities do not affect the application of the surfactant.

Supplementary Material

Copies of the IR and NMR spectra as well as additional figures on thermal analysis are available free of charge.

5. Acknowledgements

The financial support by the Slovenian Research Agency through Grants No. P1-0201, P1-0230 and P1-0134 is gratefully acknowledged. Ž. M. is grateful to Slovenian Research Agency for the position of young researcher enabling him the doctoral study. Dr. Damijana Urankar from the Research Infrastructure Centre at the Faculty of Chemistry and Chemical Technology, University of Ljubljana, is acknowledged for HRMS analyses.

6. References


Povzetek

Površinsko aktivne snovi v komercialnih produktih pogosto vsebujejo mešanice anionskih in kationskih surfaktantov, zato so bile dosedaj večinoma preiskovane vodne raztopine mešanic površinsko aktivnih snovi, ki se pogosto imenujejo katanionski surfaktanti brez soli. V tem delu predstavljamo alternativno metodo sinteze z dimetilkarbonatom kot alkilirnem sredstvom za pripravo alkil trimetilaammonijevih alkankarboksilatov s srednjimi dolžinami alkilnih verig (6–10).