European Journal of Medicinal Chemistry 44 (2009) 3201–3208

Contents lists available at ScienceDirect

European Journal of Medicinal Chemistry

journal homepage: http://www.elsevier.com/locate/ejmech

Original article

Synthesis and antimicrobial properties of polymerizable quaternary ammoniums

Laurent Caillier [a], Elisabeth Taffin de Givenchy [a], Richard Levy [b], Yves Vandenberghe [b], Serge Géribaldi [a], Frédéric Guittard [a,*]

[a] Université de Nice-Sophia Antipolis, Laboratoire de Chimie des Matériaux Organiques et Métalliques (CMOM), Equipe Chimie Organique aux Interfaces, Parc Valrose, 06108 Nice Cedex 2, France
[b] Rohm and Haas France, Laboratoires Européens, Département Process Chemicals and Biocides, 371, rue Beethoven, Sophia Antipolis, 06565 Valbonne, France

ARTICLE INFO

Article history:
Received 16 July 2008
Received in revised form
13 March 2009
Accepted 19 March 2009
Available online 1 April 2009

Keywords:
Quaternary ammonium compounds
Surfactants
Preservatives
Biocides
Monomers
Surfmers

ABSTRACT

Introduction of biocide monomers during the process of polymerization is a promising approach in the development of new permanent non leaching biocide materials. Two series of surfactants monomers, with a quaternary ammonium group as polar head and an acrylic function as the polymerizable moiety, were synthesized and tested to evaluate their surface active properties alongside with their antibacterial and antifungal properties. Four microbial strains were used to perform the study: *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Candida albicans* and *Aspergillus niger*. The biocidal efficacy measured by bacterial and fungal growth inhibition expressed as MIC (Minimal Inhibitory Concentration) and MLC (Minimal Lethal Concentration) values was discussed as a function of molecular parameters. All the synthesized surfactant monomers presented bactericidal and fungicidal activities. Increasing the spacer between the acrylic part and the ammonium group has a favourable effect on the MIC and MLC results.

1. Introduction

The battle against nosocomial infections such as, among others, surgical infections, remains one of the major actual challenges of the hospital. If cautions are numerous to avoid any pollution of inert surfaces (catheters, implants, medical equipments, floors…), the phenomena of resistance developed by the most part of pathogenic organisms require, on one hand, the elaboration of new biocide agents and, on the other hand, completion of long-term bactericidal treatments of surfaces or, in an ideal case, a permanent biocide effect of the surfaces without releasing of the antimicrobial active agents. The implementation of biocide polymeric coatings with a permanent effect introduces not negligible advantages: a non release of antibacterial agents in the surrounding environment and, consequently, a reduction of the resistance phenomena with an attenuation of the development of multi resistant germs [1]. As compared with conventional antibacterial agents of low molecular weight, polymeric antibacterial agents have also the advantages to be non volatizable, chemically stable and hard to permeate through the skin. Moreover, increased efficiency, selectivity, and handling safety are additional benefits.

In the field of disinfection, quaternary ammonium surfactants (QAS) are well-known effective antimicrobial agents and are used in a number of domains such as cosmetics, common antiseptics, sanitizers in hospitals and disinfectants for contact lenses [2]. The efficacy of such agents is conditioned by the amphiphilic nature of the molecule [3] and consequently by its surfactant properties [4]. These products possess properties such as reduction of surface tension and a ready attraction for negatively charged surfaces like bacteria. These characteristics promote their adsorption onto bacteria surfaces. Although, the mode of action cannot be reduced to surface activity only, a cytolytic damage is the primary lesion caused by such cationic surfactants and a major contribution to the cell death. Consequently, there is a well-established relationship between cytolytic action and surface tension [5].

In the perspective to elaborate biocide polymeric materials, we therefore chose to synthesize quaternary ammonium surfactants

Abbreviations: CMC, critical micellar concentration; MIC, minimal inhibitory concentration; MLC, minimal lethal concentration; Surfmers, surfactants monomers.

* Corresponding author. Tel.: +33 4 92 07 6159; fax: +33 4 92 07 6156.
E-mail addresses: laurent.caillier@unice.fr (L. Caillier), elisabeth.taffin-de-givenchy@unice.fr (E.T. de Givenchy), rlevy@rohmhaas.com (R. Levy), yvandenberghe@rohmhaas.com (Y. Vandenberghe), serge.geribaldi@unice.fr (S. Géribaldi), frederic.guittard@unice.fr (F. Guittard).

0223-5234/$ – see front matter © 2009 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ejmech.2009.03.031

with an additional polymerizable acrylic moiety. The synthesized compounds are represented Fig. 1.

Some of this kind of compounds has already been described in literature for their surfactant properties [6–8].

Indeed, surfmers (for SURFactant monoMERS) have been extensively studied [9–14] because their reactive functionalities give to these surfactants the potentiality to control overall material properties as they polymerize into the bulk polymer network [15,16]. They can be charged easily for the incorporation of proper biological ligand [17,18] and controllable drug release [19] or they can serve as carrier for gene delivery [20,21].

However, to our knowledge, the antibacterial activity of such fundamental precursors has not been investigated. So in this paper, we report on the synthesis of two series of quaternary ammonium monomers and discuss the chemical–biological relationships, mainly the bond between molecular structure and biological activity as precursor of bioactive materials.

2. Results and discussion

2.1. Chemistry

Because of the poor solubility of quaternary ammonium compounds in common organic solvents, the strategy to get ammonium compounds is to introduce the quaternary nitrogen as far as possible along the synthesis. Moreover, this minimizes the need of difficult manipulations due to the surfactant nature of the compounds and simplifies many isolation and purification problems [22,23]. Our general synthetic pathway is described in Scheme 1.

The molecules were coded H·*m*·*n* where *m* is the number of carbon atoms in the spacer linking the ammonium head to the acrylic moiety and *n* is the number of carbon atoms in the side hydrocarbon chain (see Scheme 1). The benzylic compounds were coded H·*m*·Bz. For the ethylenic spacer compounds, the starting material was the commercial 2-(dimethylamino)ethyl acrylate on which a bromoalcane is added. On the other hand, the undecylenic spacer compounds need to prepare the corresponding 11-(dimethylamino)undecyl acrylate. To do so, a tertiary amino-alcohol intermediate is first prepared from commercially available 11-bromoundecanol using a nucleophilic substitution with *N*,*N*-dimethylamine stabilized in ethanol. Then, the corresponding polymerizable acrylic tertiary amine is prepared using an esterification reaction in the presence of acryloyl chloride. The reaction is conducted in dry acetonitrile to avoid the precipitation of the tertiary ammonium formed during the esterification reaction. The final polymerizable tertiary amine is finally recovered after a soft basic treatment. The formation of the quaternary ammonium species was performed by reacting the polymerizable amine with different commercial alkyl or benzyl bromide. The Menschutkin reaction was conducted in solvent-free condition, to give the products with good yields and purity.

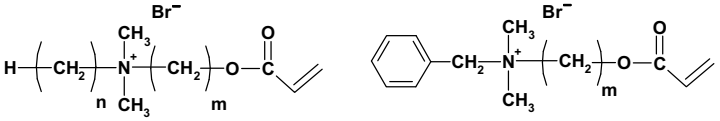
2.2. Surface active properties

2.2.1. Critical micellar concentrations (CMC)

Keeping in mind many other parameters (molecular structure, concentration of the sample, temperature, ionic force), it is generally admitted that the driving force of the micellization phenomenon is mainly governed by the hydrophobicity of the structures [24]. Aggregation of surfactant compounds in water is largely controlled by hydrophobic interaction generated by the non-polar chains of the surfactant. The formation of micelles is a balance between the inherent hydrophobicity of the surfactant and its ability to generate intermolecular interactions. The values of the critical micellar concentrations (CMC) measured for the prepared hydrocarbon polymerizable surfactants are shown in Table 1.

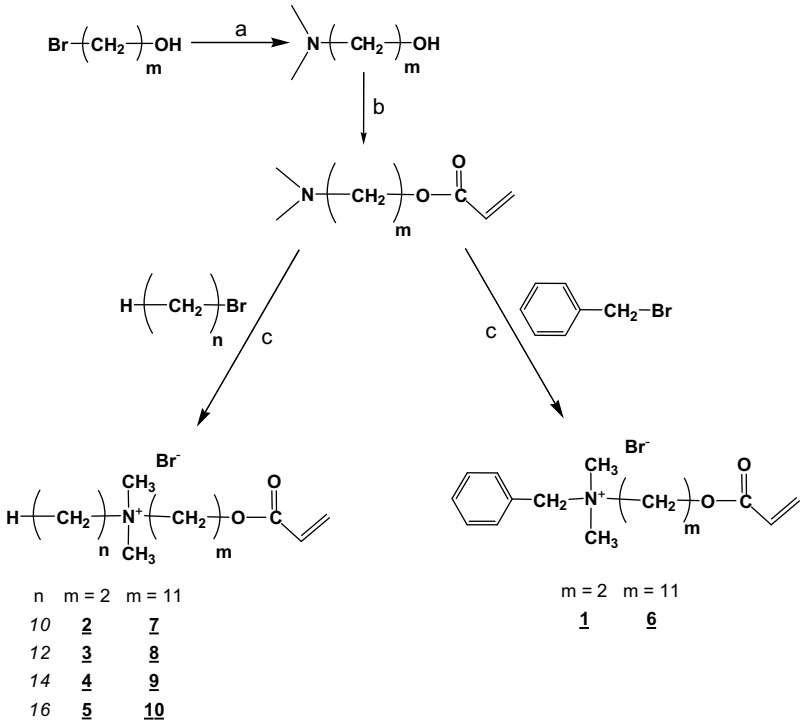
For ionic surfactants, the variation of the CMC vs. the number of carbons (n) of the hydrophobic chain generally follows the empirical Klevens equation: Log (CMC) = $A - Bn$ where A and B are specific values for a homologous series [25]. The A coefficient varies according to the nature of the hydrophilic groups of the surfactant while B, the slope of the curve Log (CMC) vs. n, characterizes the variation of the CMC according to the length of the hydrophobic chains [25]. The B coefficient gives a real indication of the impact on the general hydrophobicity of the studied hydrophobic tail. As shown in Fig. 2, both series of the studied surfactants (the short spacer series with $m = 2$ and the long spacer series with $m = 11$) follow the Klevens relation Log (CMC) = $A - Bn$. Indeed, in both cases, increasing the length of the alkyl chain involves a linear decrease of the logarithm of the measured CMC values. In all cases, for the same alkyl side chain, the surfactant with a long spacer ($m = 11$) connecting the acrylic part to the polar head of the surfmer shows a lower CMC value than the surfactant with a short spacer ($m = 2$). The calculated B coefficients are respectively 0.13 for ethylenic spacer surfmers and 0.20 for undecylenic spacer surfmers. Increasing the spacer enhances the hydrophobic influence of the addition of methylene units and tends to join the values observed in the literature for *n*-alkane hydrocarbon surfactants (about 0.29) having one ionic head [26].

2.2.1.1. Free energy. The micellization phenomenon is spontaneous from the CMC. It is thus characterized by a negative Gibbs micellization free energy (ΔG^0_M). ΔG^0_M is associated with the transfer of a surfactant from the aqueous phase to the micellar pseudophase. The calculation of the micellization free energy, according to the structural parameters of surfactant, is carried out starting from the general equation suggested by Zana [27]. For an ionic surfactant



Cpds	Codes	m	Alkyl or aryl chain	Cpds	Codes	m	Alkyl or aryl chain
1	H.2.Bz	2	$C_6H_5CH_2$	**6**	H.11.Bz	11	$C_6H_5CH_2$
2	H.2.10	2	$C_{10}H_{21}$ (n = 10)	**7**	H.11.10	11	$C_{10}H_{21}$ (n = 10)
3	H.2.12	2	$C_{12}H_{25}$ (n = 12)	**8**	H.11.12	11	$C_{12}H_{25}$ (n = 12)
4	H.2.14	2	$C_{14}H_{29}$ (n = 14)	**9**	H.11.14	11	$C_{14}H_{29}$ (n = 14)
5	H.2.16	2	$C_{16}H_{33}$ (n = 16)	**10**	H.11.16	11	$C_{16}H_{33}$ (n = 16)

Fig. 1. Schematic structures of the investigated surfmers.



Scheme 1. Synthetic pathway for the quaternized ammonium bromides; (a): dimethylamine, ethanol, 6 h, rt; (b): acryloyl chloride, acetonitrile, 12 h rt; (c): solvent free, 12 h, 50 °C. ((a) and (b) only for surfmers with an undecylenic spacer).

where i is the number of charged groups, Zs is the valence of the charged groups, j the number of alkyl chains and Zc the valence of counter-ions, the Zana's equation proposed for the calculation of micellization free energy is:

$$\Delta G_M^0 = RT\left(\frac{1}{j} + \beta\frac{i}{j}\left|\frac{Zs}{Zc}\right|\right)\ln \mathrm{CMC} + \mathrm{RT}\left(\frac{i}{j}\left|\frac{Zs}{Zc}\right|\beta \ln\left(\frac{i}{j}\left|\frac{Zs}{Zc}\right|\right) - \frac{\ln(j)}{j}\right)$$

where β is the fraction of charges of micellized univalent surfactant ions neutralized by micelle-bound univalent counter-ions.

For short spacer surfmers, it is generally admitted that only the alkyl chain takes part in the hydrophobicity of the structures. In this case we will thus use the following parameters in the general equation of Zana:

- Number of charged groups (i) = 1
- Number of hydrophobic chains (j) = 1
- Valence of the charged groups |Zs| = 1
- Valence of counter-ions |Zc| = 1

The simplified general equation is then, $\Delta G_M^0 = \mathrm{RT}(1+\beta)\ln(\mathrm{CMC})$, in which β is calculated according to the formula $(\alpha+\beta=1)$ starting from the ionization coefficient α accessible from the conductimetry measurements. However, the value of α depends on the method used for its determination:

- The Evans equation [28] incorporates the contribution of the micellar aggregate to conductance and requires the knowledge of the aggregation number N_{ag}.
- Frahm's method [29] admits that α can be calculated as the ratio of the slope of the conductance vs. C curves respectively above and below the CMC. This approach appears very useful but gives values of α which are little over-estimated because the conductance above the CMC is attributed only to the counter-ion. However, this method is a very useful approximation [30,31] when N_{ag} is not available and was used in our study.

For monomers having an undecylenic spacer, the previous simplified equation is invalid. Indeed, the literature specifies that

Table 1
Physicochemical properties and MIC results obtained for the synthesized surfmers.

n	Code	CMC (mol L^{-1})	ΔG^0_M (kJ mol^{-1})	MIC (μmol L^{-1})			
				P. aeruginosa	*C. albicans*	*A. niger*	*S. aureus*
Ref	BAK	–	–	93.0 ± 1.8	8.3 ± 0.2	4.7 ± 0.2	3.2 ± 0.1
1	H·2·Bz	4.60×10^{-2}	–	>2000	>2000	506.7 ± 7.4	>2000
2	H·2·10	1.16×10^{-2}	−12.7	355.8 ± 3.8	277.6 ± 3.0	175.2 ± 1.9	355.8 ± 3.8
3	H·2·12	6.45×10^{-3}	−18.6	71.1 ± 1.8	63.8 ± 1.6	63.8 ± 1.6	71.1 ± 1.8
4	H·2·14	2.99×10^{-3}	−23.5	112.4 ± 1.9	18.1 ± 0.3	178.1 ± 3.0	178.1 ± 3.0
5	H·2·16	1.95×10^{-3}	−24.3	237.3 ± 6.4	24.0 ± 0.7	237.3 ± 6.4	275.0 ± 7.4
6	H·11·Bz	3.34×10^{-2}	–	153.9 ± 3.2	153.9 ± 3.2	153.9 ± 3.2	243.8 ± 5.0
7	H·11·10	2.79×10^{-3}	−12.6	79.9 ± 1.0	19.0 ± 0.3	19.0 ± 0.3	64.8 ± 0.8
8	H·11·12	9.66×10^{-4}	−14.2	58.4 ± 3.4	14.8 ± 0.5	14.8 ± 0.5	34.7 ± 1.2
9	H·11·14	4.68×10^{-4}	−15.3	44.8 ± 0.6	16.8 ± 0.2	24.9 ± 0.3	104.4 ± 1.2
10	H·11·16	1.66×10^{-4}	−17.0	131.7 ± 2.7	27.1 ± 0.6	31.4 ± 0.6	208.6 ± 4.3

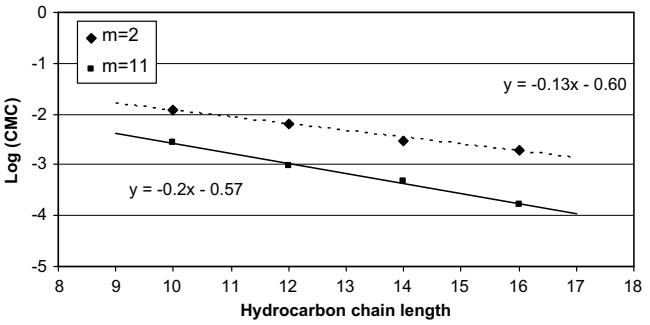


Fig. 2. Application of the Klevens relation Log (CMC) = $A - Bn$ for the studied surfmers.

the hydrophobic impact of the couple long spacer/acrylic part cannot be neglected [22,23,32]. In this case, it must be considered that the surfactant presents two hydrophobic chains and it has to be taken into account when simplifying the general equation of Zana [27]. Thus, for long spacer surfmers, the number of hydrophobic chains (j) = 2 and the simplified equation becomes:

$$\Delta G_M^0 = \frac{1}{2}RT(1+\beta)\ln(CMC) + \frac{1}{2}RT\left(\beta \ln\frac{1}{2} - \ln 2\right)$$

Table 1 summarizes the values of micellization free energy calculated for the different synthesized surfmers. It appears that increasing the length of the alkyl chains linked to the nitrogen atom, involves a lowering of micellization free energy values: as expected, the aggregation phenomena i.e. formation of micelles is thus favoured.

The surfmers with an ethylenic spacer form aggregate more stable than their counterparts presenting an undecylenic spacer. The spacer thus has an unfavourable impact on the phenomenon of micellization of polymerizable hydrocarbon surfactants.

2.3. Antimicrobial properties

Evaluations of the antibacterial and antifungal properties of the surfmers prepared in this work were conducted using MIC (Minimal Inhibitory Concentration) and MLC (Minimal Lethal Concentration) measurements vs. four different microorganisms: *Pseudomonas aeruginosa* (Gram −ve bacteria, ATCC 9027), *Staphylococcus aureus* (Gram +ve bacteria, ATCC 6538), *Aspergillus niger* (fungi, ATCC 6275) and *Candida albicans* (yeast, ATCC 10231). In Table 1, the MIC values obtained for all the synthesized molecules are reported. For comparison, the commercially available preservative BAK (aqueous solution of a mixture of dodecyl (40%), tetradecyl (50%) and hexadecyl (10%) benzyldimethyl ammonium chlorides) has been tested within the same conditions. All the results are from independent triplicates measurements for each compound. The strains used are ubiquitous, opportunistic and commonly encountered in industrial processes or health services. These strains are generally encountered in nosocomial infections.

2.3.1. Microbiostatic activity

2.3.1.1. Influence of the alkyl chain. The variation of the biological activity according to the length of the alkyl chain for the two types of spacers is presented against the four microorganisms tested in Fig. 3.

All the synthesized compounds are active towards the four microorganisms studied with the exception of H·2·Bz which shows only an activity towards *A. niger*.

The antimicrobial activity of quaternary ammonium salts being strongly influenced by the micellization properties [33–36], the MIC values were compared with the CMC values (Fig. 3a and b). The measured CMC values are systematically higher than the corresponding inhibition concentrations and thus cannot explain the variations of the biological activity. However, a parabolic dependence of the biological activity with respect to the length of the hydrophobic chain can be observed for all the synthesized compounds (except H·2·Bz). This type of dependence is called the "cut off effect". The origin of this latter is not well explained. Among the various assumptions proposed by Balgavy and Devinsky [37], the concept of free volume could be applied to quaternary ammonium salts. In solution, the polar ammonium heads interact with those of phospholipids and the hydrocarbon chains are parallel to those of the phospholipids of the cells. At this level, the density of hydrophobic area of the bilayer is necessarily modified and a free volume is formed. When the length of the hydrocarbon side chain of the ammonium salts is smaller than that of phospholipids, the total free volume created in the bilayer is small. When the length of the surfactant tail becomes comparable to that of phospholipids, the free volume decreases and tends towards zero. Molecules bearing chains between these two extremes lead to the most important free volume inside the bilayer. The more the free volume is large, the more the membrane is expected to be destabilized and the bactericidal activity increases.

For the short spacer surfmers (see Fig. 3a), the "cut off effect" is particularly marked for the microbiostatic activity against *P. aeruginosa*, *A. niger* and *S. aureus*. For these three microorganisms, a loss of activity is observed for C_{10} and C_{16} alkyl chains and an optimum of activity for C_{12} chains is measured. For *C. albicans* the optimum seems centred on C_{14}.

For long spacer surfmers the trends obtained are compiled in Fig. 3b. As previously, an optimum of activity is found for C_{12} alkyl chains against *C. albicans*, *A. niger* and *S. aureus*. Regarding *P. aeruginosa*, the best microbiostatic activity is observed for the C_{14} alkyl chain derivatives. According to Fig. 3b, the values of MIC are lower than the measured CMC except for the C_{16} derivative for which MIC tops CMC values (even if the two values remain extremely close).

2.3.1.2. Influence of the spacer length. To our knowledge, there are no studies related to the biological impact of the length of the spacer connecting the acrylic part to the quaternary nitrogen. We thus compare in this work, for a given alkyl chain, the biological activity of the short spacer vs. long spacer homologues against the four studied microorganisms. It appears clearly that the length of the spacer plays an important role in terms of microbiostatic activity. Indeed, the MICs of the undecylenic spacer surfmers are systematically lower than the values recorded for the ethylenic spacer surfmers.

As an example, in the case of the most active dodecylenic alkyl chain surfactants (H·2·12, H·11·12), the MIC decreases by a factor 1.2, from H·2·12 to H·11·12, for *P. aeruginosa*, and a factor 4.3 for *C. albicans* and *A. niger*. The increase in the biological activity is even more important for the compounds presenting a decylenic alkyl chain (H·2·10 and H·11·10): the MIC decreases, from H·2·10 to H·11·10, by a factor 4.5 for *P. aeruginosa* and a factor 14.5 for *C. albicans*.

The microbiostatic performances are improved by increasing the length of the hydrocarbon spacer connecting the quaternary ammonium function to the acrylic part. However, from ethylenic to undecylenic, the spacer length does not seem to modify the optimum of activity which corresponds to about dodecyl alkyl chains.

2.3.1.3. Influence of the benzylic group. The MIC values for the benzylic compounds, **1** (H·2·Bz) and **6** (H·11·Bz), are presented in Table 1. Both H·2·Bz and H·11·Bz present poor biological activities

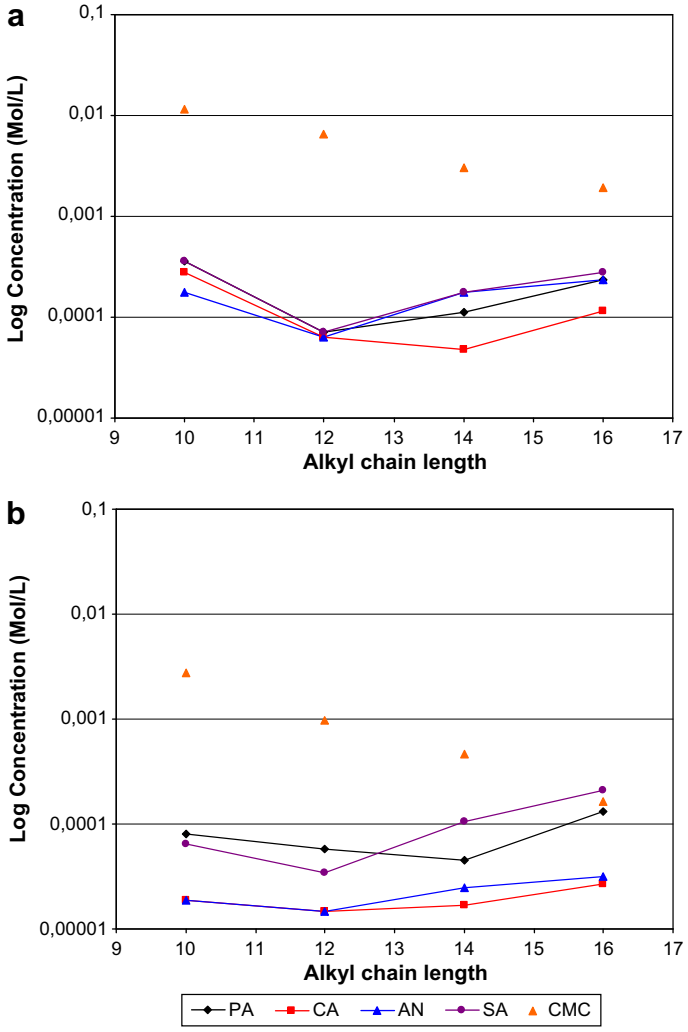


Fig. 3. MIC results vs. alkyl chain length (a) for surfmers with an ethylenic spacer (b) for surfmers with an undecylenic spacer.

if compared to their homologues presenting long alkyl chains (H·2·*n* and H·11·*n*). This is notable if compared to the well-known activity of the commercially available alkylbenzyldimethyl ammonium chlorides currently used in industrial process as biocide agents.

- H·2·Bz presents a reduced activity spectrum to the only strain *A. niger* with an MIC of 506.7 μmol L^{-1} to compare with the 237.3 μmol L^{-1} of H·2·16 (least powerful among compounds with alkyl chains) or 63.8 μmol L^{-1} of H·2·12 (most powerful).
- H·11·Bz presents an activity spectrum extended to the four studied microorganisms. The MIC values are close, but always higher than those measured for the counterparts with long alkyl chains. In comparison with H·2·Bz, the improvement of the biological properties could be explained by an increase in the hydrophobicity of the structure.

2.3.2. Microbicidal activity

The various results of MLC measurements are compiled in Table 2 following the various studied strains. These results give interesting information concerning the mechanism of action of the studied compounds. All the surfmers present bactericidal and fungicidal activity when an MIC was highlighted. For the compounds presenting the lowest inhibition concentration, the MLC is equal to the MIC. It is the case, for H·11·12 or H·11·14. In all the other cases the values of MIC and MLC are very close. These results are in perfect agreement with the mechanism of action of quaternary ammoniums with a first phase of inhibition of the cell multiplication with relatively weak concentration (MIC) followed from one second phase of eradication to higher concentrations (MLC).

For the microbicidal activity studied here (measured by the MLC), the same general tendencies proposed for the microbiostatic activity (measured with the MIC) are observed:

- A cut off effect with an optimum activity observed for H·*m*·12 compounds in general, except for ethylenic spacer compounds

Table 2
MLC results obtained for the synthesized surfmers.

n	Code	MLC (μmol L^{-1})			
		P. aeruginosa	*C. albicans*	*A. niger*	*S. aureus*
1	H·2·Bz	>2000	>2000	599.5	>2000
2	H·2·10	416.4	359.2	280.2	359.2
3	H·2·12	71.1	63.8	63.8	71.1
4	H·2·14	114.1	18.4	231.8	231.8
5	H·2·16	282.6	24.7	282.6	282.6
6	H·11·Bz	447.4	447.4	238.3	305.5
7	H·11·10	188.2	30.4	19.3	72.6
8	H·11·12	64.7	15.4	14.8	34.7
9	H·11·14	103.3	16.8	24.9	163.7
10	H·11·16	317.4	40.4	40.4	273.8

against *C. albicans* where the cut off effect seems centred on H·2·14.
- The recorded MLC values are systematically lower for the surfactants with an undecylenic spacer (H·11·*n*).
- The benzylic derivatives present the worst activities. H·2·Bz showing only an activity towards *A. niger*.

3. Experimental section

3.1. Chemical synthesis

3.1.1. General

Confirmation of the structures of the intermediates and products was obtained by nuclear magnetic resonance (NMR), mass spectrometry (MS) and infrared spectroscopy (FT IR). NMR spectroscopy was carried out using a Bruker Advance 200 MHz or 500 spectrometer. MS was carried out using a Finnigan Matt TSQ 7000 mass spectrometer coupled with a gas chromatograph or liquid chromatography interface. Infrared spectroscopy was carried out using a Perkin Elmer Paragon 1000 FT IR spectrometer. Gas phase chromatography was done from Hewlett Packard™ HP 5890 Series II GC with HP5 column 30 m, 0.32 diameter, from 60 to 250 °C at a rate of 10 °C min^{-1}.

Benzyl bromide, 1-bromodecane, 1-bromododecane, 1-bromotetradecane, 1-bromohexadecane, 11-bromo-1-undecanol, 2-(dimethylamino)ethyl acrylate were purchased from Aldrich and used as-received. Dimethylamine solution (33% in absolute ethanol) and acryloyl chloride were purchased from Fluka Chemicals. All other reagents employed were common laboratory materials. Unless specified the solvents were of unpurified reagent grade.

3.1.2. Synthesis of 11-(dimethylamino)undecyl acrylate

3.1.2.1. Step i. 50 mmol of dimethylamine in ethanol were added dropwise to 10 mmol of 11-bromoundecan-1-ol in ethanol. After 6 h, the initial brominated compound was completely consumed. The excess of ethanol and amine was removed under reduce pressure. The crude product was dissolved in dichloromethane and washed three times using a 5% $NaHCO_3$ water solution. The solvent was removed on reduced pressure. The final product was used without any further purification. (Yield: 91%).

3.1.2.2. Step ii. To a stirred solution of 10 mmol of 11-(dimethylamino)undecan-1-ol, in anhydrous acetonitrile (10 mL), under inert atmosphere (N_2) and at the temperature of 0 °C, 10 mmol of acryloyl chloride was added dropwise. The solution was maintained at 0 °C for 2 h and then stirred for 12 h at room temperature.

The solution was then neutralized with a 5% $NaHCO_3$ water solution. The water/acetonitrile solution was extracted five times with dichloromethane. The organic phase was dried under Na_2SO_4 and the solvent evaporated. The final acrylic product was used without any further purification. (Yield: 82%).

3.1.3. Formation of the polymerizable hydrocarbon surfactants

1 mol of alkyl bromide or benzylbromide reacted with 1.5 mol of acrylic precursor, in solvent-free conditions, for 12 h, at a temperature of 50 °C and in the presence of 0.05% of hydroquinone. The crude gum obtained was purified by multiple trituration in cyclohexane. The quaternary ammonium compound was finally dried under vacuum for 72 h. Yields: from 88 to 96% depending with the length of the alkyl chains.

*3.1.3.1. Compound **1**.* ^{1}H NMR (200 MHz, MeOD, δ ppm, *J* Hz): 3.20 (6H, N^+CH_3, s), 3.86 (2H, $N^+CH_2CH_2OC(O)$, m), 4.74 (2H, $BzCH_2N^+$, s), 4.75 (2H, $N^+CH_2CH_2OC(O)$, m), 5.92 (1H, CH=CH_2 cis, $^3J = 10.28$, $^2J = 1.68$, dd), 6.15 (1H, CH=CH_2, dd, $^3J = 10.28$, $^3J = 17.18$, dd), 6.45 (1H, CH=CH_2 trans, $^3J = 17.18$, $^2J = 1.68$, dd), 7.61 (5H, Bz, m). ^{13}C NMR (200 MHz, MeOD, δ ppm): 52.2 ($N^+\mathbf{C}H_3$), 59.3 ($N^+\mathbf{C}H_2CH_2O$), 65.0 ($N^+CH_2\mathbf{C}H_2O$), 69.8 ($N^+\mathbf{C}H_2C_6H_5$), 128.6 ($OC(O)\mathbf{C}H{=}CH_2$), 129.2, 131.2, 132.4 ($\mathbf{C}H_{Ar}$), 132.9 ($OC(O)CH{=}\mathbf{C}H_2$), 135.4 ($\mathbf{C}_{Ar}$), 166.4 ($O\mathbf{C}(O)CH{=}CH_2$). MS, $[M\text{-}Br]^+$, *m*/*z*: 234.2; Anal. Calcd for $C_{14}H_{20}BrNO_2$: C 53.51, H 6.42, N 4.46; found: C 53.54, H 6.39, N 4.45.

*3.1.3.2. Compound **2**.* ^{1}H NMR (MeOD, δ ppm, *J* Hz): 0.85 (3H, CH_3CH_2, t), 1.26 (14H, $CH_3(CH_2)_7CH_2$, m), 1.76 (2H, $C_8H_{17}CH_2CH_2N^+$, m), 3.13 (6H, N^+CH_3, s), 3.37 (2H, $C_8H_{17}CH_2CH_2N^+$, m), 3.69 (2H, $N^+CH_2CH_2OC(O)$, m), 4.57 (2H, $N^+CH_2CH_2OC(O)$, m), 5.92 (1H, CH=CH_2 cis, $^3J = 10.28$, $^2J = 1.68$, dd), 6.15 (1H, CH=CH_2, dd, $^3J = 10.28$, $^3J = 17.18$, dd), 6.45 (1H, CH=CH_2 trans, $^3J = 17.18$, $^2J = 1.68$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.1 ($\mathbf{C}H_3CH_2CH_2$), 24.0 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 28–30.0 (5C, $CH_3CH_2CH_2(\mathbf{C}H_2)_5$), 33.5 ($CH_3CH_2\mathbf{C}H_2$), 52.2 ($N^+\mathbf{C}H_3$), 59.3 ($N^+CH_2\mathbf{C}H_2O$), 64.6 ($CH_2\mathbf{C}H_2N^+$), 65.0 ($N^+\mathbf{C}H_2CH_2O$), 128.6 ($OC(O)\mathbf{C}H{=}CH_2$), 132.9 ($OC(O)CH{=}\mathbf{C}H_2$), 166.4 ($O\mathbf{C}(O)CH{=}CH_2$). MS, $[M\text{-}Br]^+$, *m*/*z*: 284.3; Anal. Calcd for $C_{17}H_{34}BrNO_2$: C 56.04, H 9.41, N 3.84; found: C 56.04, H 9.51, N 3.83.

*3.1.3.3. Compound **3**.* ^{1}H NMR (200 MHz, MeOD, δ ppm, *J* Hz): 0.84 (3H, CH_3CH_2, t), 1.24 (18H, $CH_3(CH_2)_9CH_2$ CH_2, m), 1,74 (2H, $C_{10}H_{21}CH_2CH_2N^+$, m), 3.15 (6H, N^+CH_3, s), 3.38 (2H, $C_{10}H_{21}CH_2CH_2N^+$, m), 3.70 (2H, $N^+CH_2CH_2OC(O)$, m), 4.56 (2H, $N^+CH_2CH_2OC(O)$, m), 5.89 (1H, CH=CH_2 cis, $^3J = 10.32$, $^2J = 1.59$, dd), 6.13 (1H, CH=CH_2, dd, $^3J = 10.32$, $^3J = 17.35$, dd), 6.46 (1H, CH=CH_2 trans, $^3J = 17.35$, $^2J = 1.59$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.1 ($\mathbf{C}H_3CH_2CH_2$), 24.0 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 28–30.0 (7C, $CH_3CH_2CH_2(\mathbf{C}H_2)_7$), 28–30.0 (7C, $CH_3CH_2CH_2(\mathbf{C}H_2)_7$), 33.5 ($CH_3CH_2\mathbf{C}H_2$), 52.2 ($N^+\mathbf{C}H_3$), 59.3 ($N^+CH_2\mathbf{C}H_2O$), 64.6 ($CH_2\mathbf{C}H_2N^+$), 65.0 ($N^+\mathbf{C}H_2CH_2O$), 128.6 ($OC(O)\mathbf{C}H{=}CH_2$), 132.9 ($OC(O)CH{=}\mathbf{C}H_2$), 166.4 ($O\mathbf{C}(O)CH{=}CH_2$). MS, $[M\text{-}Br]^+$, *m*/*z*: 312.3; Anal. Calcd for $C_{19}H_{38}BrNO_2$: C 58.15, H 9.76, N 3.57; found: C 58.12, H 9.79, N 3.51.

*3.1.3.4. Compound **4**.* ^{1}H NMR (MeOD, δ ppm, *J* Hz): 0.92 (3H, CH_3CH_2, t), 1.23 (22H, $CH_3(CH_2)_{11}CH_2CH_2$, m), 1.71 (2H, $C_{12}H_{25}CH_2CH_2N^+$, m), 3.11 (6H, N^+CH_3, s), 3.35 (2H, $C_{12}H_{25}CH_2CH_2N^+$, m), 3.67 (2H, $N^+CH_2CH_2OC(O)$, m), 4.61 (2H, $N^+CH_2CH_2OC(O)$, m), 5.93 (1H, CH=CH_2 cis, $^3J = 10.25$, $^2J = 1.65$, dd), 6.16 (1H, CH=CH_2, dd, $^3J = 10.25$, $^3J = 16.98$, dd), 6.49 (1H, CH=CH_2 trans, $^3J = 16.98$, $^2J = 1.65$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.3 ($\mathbf{C}H_3CH_2CH_2$), 24.2 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 28.1–30.0 (9C, $CH_3CH_2CH_2(\mathbf{C}H_2)_9$), 33.6 ($CH_3CH_2\mathbf{C}H_2$), 52.3 ($N^+\mathbf{C}H_3$), 59.2 ($N^+CH_2\mathbf{C}H_2O$), 64.5 ($CH_2\mathbf{C}H_2N^+$), 65.2 ($N^+\mathbf{C}H_2CH_2O$), 128.8 ($OC(O)\mathbf{C}H{=}CH_2$), 132.7 ($OC(O)CH{=}\mathbf{C}H_2$), 166.1 ($O\mathbf{C}(O)CH{=}CH_2$). MS, $[M\text{-}Br]^+$, *m*/*z*: 340.3; Anal. Calcd for $C_{21}H_{42}BrNO_2$: C 59.99, H 10.07, N 3.33; found: C 60.02, H 10.16, N 3.36.

*3.1.3.5. Compound **5**.* ^{1}H NMR (MeOD, δ ppm, *J* Hz): 0.84 (3H, CH_3CH_2 t), 1.22 (26H, $CH_3(CH_2)_{13}CH_2CH_2$, m), 1.73 (2H, $C_{14}H_{29}CH_2CH_2N^+$, m), 3.11 (6H, N^+CH_3, s), 3.34 (2H, $C_{14}H_{29}CH_2CH_2N^+$, m), 3.73 (2H, $N^+CH_2CH_2OC(O)$, m), 4.45 (2H, $N^+CH_2CH_2OC(O)$, m), 5.91 (1H, CH=CH_2 cis, $^3J = 10.23$, $^2J = 1.72$, dd), 6.11 (1H, CH=CH_2, dd, $^3J = 10.23$, $^3J = 17.21$, dd), 6.47 (1H, CH=CH_2 trans, $^3J = 17.21$, $^2J = 1.72$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.0 ($\mathbf{C}H_3CH_2CH_2$), 24.2 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 28–30.0 (11C, $CH_3CH_2CH_2(\mathbf{C}H_2)_{11}$), 33.3 ($CH_3CH_2\mathbf{C}H_2$), 52.1 ($N^+\mathbf{C}H_3$), 59.4 ($N^+CH_2\mathbf{C}H_2O$), 64.8 ($CH_2\mathbf{C}H_2N^+$), 65.2 ($N^+\mathbf{C}H_2CH_2O$), 128.1 ($OC(O)\mathbf{C}H{=}CH_2$), 132.2 ($OC(O)CH{=}\mathbf{C}H_2$), 166.1 ($O\mathbf{C}(O)CH{=}CH_2$). MS, $[M\text{-}Br]^+$, *m*/*z*: 368.4; Anal. Calcd for $C_{23}H_{46}BrNO_2$: C 61.59, H 10.34, N 3.12, found: C 61.59, H 10.29, N 3.13.

3.1.3.6. Compound ***6***. ^{1}H NMR (MeOD, δ ppm, J Hz): 1.30 (14H, $CH_2CH_2(CH_2)_7CH_2CH_2$, m), 1.62 (2H, $N^+CH_2CH_2CH_2$, m), 1.84 (2H, $CH_2CH_2OC(O)$, m), 2.99 (8H, N^+CH_3 and $N^+CH_2CH_2$, m), 4.09 (2H, $CH_2OC(O)$, m), 4.51 (2H, $BzCH_2N^+$, s), 5.92 (1H, CH=CH_2 cis, $^3J = 10.28$, $^2J = 1.68$, dd), 6.15 (1H, CH=CH_2, dd, $^3J = 10.28$, $^3J = 17.18$, dd), 6.45 (1H, CH=CH_2 trans, $^3J = 17.18$, $^2J = 1.68$, dd), 7.50 (5H, Bz, m). ^{13}C NMR (200 MHz, MeOD, δ ppm): 22.8 ($N^+CH_2\mathbf{C}H_2(CH_2)_8CH_2OC(O)$), 25.5–30.0 (8C, $N^+CH_2CH_2(\mathbf{C}H_2)_8CH_2OC(O)$), 52.2 ($N^+\mathbf{C}H_3$), 62.9 ($N^+\mathbf{C}H_2CH_2(CH_2)_8CH_2OC(O)$), 64.5 ($N^+CH_2CH_2(CH_2)_8\mathbf{C}H_2OC(O)$), 69.7 ($N^+\mathbf{C}H_2C_6H_5$), 128.4 (OC(O)$\mathbf{C}$H=$CH_2$) 129.2, 131.2, 132.4 ($\mathbf{C}H_{Ar}$), 130.4 (OC(O)CH=$\mathbf{C}H_2$), 135.4 ($\mathbf{C}_{Ar}$), 166.3 (O$\mathbf{C}$(O)CH=$CH_2$). MS, $[M\text{-}Br]^+$, m/z: 360.3; Anal. Calcd for $C_{23}H_{38}BrNO_2$: C 61.72, H 8.70, N 3.18; found: C 62.23, H 8.95, N 3.11.

3.1.3.7. Compound ***7***. ^{1}H NMR (MeOD, δ ppm, J Hz): 0.85 (3H, CH_3CH_2, t), 1.29 (28H, $CH_3(CH_2)_7CH_2$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 1.69 (6H, $C_8H_{17}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$ and $CH_2CH_2OC(O)$, 3.03 (6H, N^+CH_3, s), 3.26 (4H, $C_8H_{17}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m)), 4.08 (2H, $CH_2OC(O)$, m), 5.93 (1H, CH=CH_2 cis, $^3J = 10.25$, $^2J = 1.71$, dd), 6.17 (1H, CH=CH_2, dd, $^3J = 10.25$, $^3J = 17.21$, dd), 6.42 (1H, CH=CH_2 trans, $^3J = 17.21$, $^2J = 1.71$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.1 ($\mathbf{C}H_3CH_2CH_2$), 22.8 ($N^+CH_2\mathbf{C}H_2(CH_2)_8CH_2OC(O)$), 24.0 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 25.5–30.0 (13C, $N^+CH_2CH_2(\mathbf{C}H_2)_8CH_2OC(O)$ and $CH_3CH_2CH_2(\mathbf{C}H_2)_5$), 33.5 ($CH_3CH_2\mathbf{C}H_2$), 52.2 ($N^+\mathbf{C}H_3$), 63.0 ($\mathbf{C}H_2N^+\mathbf{C}H_2$), 64.5 ($N^+CH_2CH_2(CH_2)_8\mathbf{C}H_2OC(O)$), 128.4 (OC(O)$\mathbf{C}$H=$CH_2$), 130.4 (OC(O)CH=$\mathbf{C}H_2$), 166.3 (O$\mathbf{C}$(O)CH=$CH_2$). MS, $[M\text{-}Br]^+$, m/z: 410.4; Anal. Calcd for $C_{26}H_{52}BrNO_2$: C 63.65, H 10.68, N 2.86; found: C 63.61, H 10.72, N 2.81.

3.1.3.8. Compound ***8***. ^{1}H NMR (MeOD, δ ppm, J Hz): 0.84 (3H, CH_3CH_2, t), 1.23 (32H, $CH_3(CH_2)_9CH_2$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 1.68 (6H, $C_{10}H_{21}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$), 3.00 (6H, N^+CH_3, s), 3.24 (4H, $C_{10}H_{21}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 4.09 (2H, $CH_2OC(O)$, m), 6.15 (1H, CH=CH_2, dd, $^3J = 10.27$, $^3J = 17.19$, dd), 5.92 (1H, CH=CH_2 cis, $^3J = 10.27$, $^2J = 1.65$, dd), 6.45 (1H, CH=CH_2 trans, $^3J = 17.19$, $^2J = 1.65$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.5 ($\mathbf{C}H_3CH_2CH_2$), 22.7 ($N^+CH_2\mathbf{C}H_2(CH_2)_8CH_2OC(O)$), 24.2 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 25.5–30.0 (15C, $N^+CH_2CH_2(\mathbf{C}H_2)_8CH_2OC(O)$ and $CH_3CH_2CH_2(\mathbf{C}H_2)_7$), 32.9 ($CH_3CH_2\mathbf{C}H_2$), 51.8 ($N^+\mathbf{C}H_3$), 63.1 ($\mathbf{C}H_2N^+\mathbf{C}H_2$), 63.9 ($N^+CH_2CH_2(CH_2)_8\mathbf{C}H_2OC(O)$), 127.9 (OC(O)$\mathbf{C}$H=$CH_2$), 130.7 (OC(O)CH=$\mathbf{C}H_2$), 166.7 (O$\mathbf{C}$(O)CH=$CH_2$). MS, $[M\text{-}Br]^+$, m/z: 438.4; Anal. Calcd for $C_{28}H_{56}BrNO_2$: C 64.84, H 10.88, N 2.70; found: C 64.89, H 10.92, N 2.73.

3.1.3.9. Compound ***9***. ^{1}H NMR (MeOD, δ ppm, J Hz): 0.85 (3H, CH_3CH_2, t), 1.24 (36H, $CH_3(CH_2)_{11}CH_2$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 1.66 (6H, $C_{12}H_{25}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, 3.03 (6H, N^+CH_3, s), 3.26 (4H, $C_{12}H_{25}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 4.10 (2H, $CH_2OC(O)$, m)), 5.92 (1H, CH=CH_2 cis, $^3J = 10.31$, $^2J = 1.72$, dd), 6.15 (1H, CH = CH_2, dd, $^3J = 10.31$, $^3J = 17.21$, dd), 6.45 (1H, CH = CH_2 trans, $^3J = 17.21$, $^2J = 1.72$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.2 ($\mathbf{C}H_3CH_2CH_2$), 22.8 ($N^+CH_2\mathbf{C}H_2(CH_2)_8CH_2OC(O)$), 24.1 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 25.5–30.0 (17C, $N^+CH_2CH_2(\mathbf{C}H_2)_8CH_2OC(O)$ and $CH_3CH_2CH_2(\mathbf{C}H_2)_9$), 33.5 ($CH_3CH_2\mathbf{C}H_2$), 52.2 ($N^+\mathbf{C}H_3$), 63.0 ($\mathbf{C}H_2N^+\mathbf{C}H_2$), 64.5 ($N^+CH_2CH_2(CH_2)_8\mathbf{C}H_2OC(O)$), 128.4 (OC(O)$\mathbf{C}$H=$CH_2$), 130.4 (OC(O)CH=$\mathbf{C}H_2$), 166.3 (O$\mathbf{C}$(O)CH=$CH_2$). MS, $[M\text{-}Br]^+$, m/z: 466.5, Anal. Calcd for $C_{30}H_{60}BrNO_2$: C 65.91, H 11.06, N 2.56; found: C 65.93, H 11.13, N 2.57.

3.1.3.10. Compound ***10***. ^{1}H NMR (MeOD, δ ppm, J Hz): 0.84 (3H, CH_3CH_2, t), 1.23 (40H, $CH_3(CH_2)_{13}CH_2$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 1.67 (6H, $C_{14}H_{29}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$), 3.00 (6H, N^+CH_3, s), 3.24 (4H, $C_{14}H_{29}CH_2CH_2N^+$ and $N^+CH_2CH_2(CH_2)_7CH_2CH_2OC(O)$, m), 4.08 (2H, $CH_2OC(O)$, m), 5.92 (1H, CH=CH_2 cis, $^3J = 10.25$, $^2J = 1.58$, dd), 6.15 (1H, CH=CH_2, dd, $^3J = 10.25$, $^3J = 17.04$, dd), 6.45 (1H, CH=CH_2 trans, $^3J = 17.04$, $^2J = 1.58$, dd). ^{13}C NMR (200 MHz, MeOD, δ ppm): 15.1 ($\mathbf{C}H_3CH_2CH_2$), 22.8 ($N^+CH_2\mathbf{C}H_2(CH_2)_8CH_2OC(O)$), 23.9 ($CH_3\mathbf{C}H_2CH_2$ and $\mathbf{C}H_2CH_2N^+$), 25.5–30.0 (19C, $N^+CH_2CH_2(\mathbf{C}H_2)_8CH_2OC(O)$ and $CH_3CH_2CH_2(\mathbf{C}H_2)_{11}$), 33.5 ($CH_3CH_2\mathbf{C}H_2$), 52.2 ($N^+\mathbf{C}H_3$), 63.0 ($\mathbf{C}H_2N^+\mathbf{C}H_2$), 64.5 ($N^+CH_2CH_2(CH_2)_8\mathbf{C}H_2OC(O)$), 128.4 (OC(O)$\mathbf{C}$H=$CH_2$), 130.4 (OC(O)CH=$\mathbf{C}H_2$), 166.3 (O$\mathbf{C}$(O)CH=$CH_2$). MS, $[M\text{-}Br]^+$, m/z: 494.5; Anal. Calcd for $C_{32}H_{64}BrNO_2$: C 66.87, H 11.22, N 2.44; found: C 66.91, H 11.14, N 2.41.

3.2. Surfactant properties evaluation

The critical micelle concentrations (CMC) were determined from conductimetry measurements [38,39] at 25 °C using a conductimeter apparatus Consort C831.

3.3. Antimicrobial assays

Antibacterial and antifungal activities were evaluated using measurement of the Minimal Inhibitory Concentration (MIC) and Minimum Lethal Concentration (MLC). Four microorganisms were used: *P. aeruginosa* (ATCC 9027), *S. aureus* (ATCC 6538), *A. niger* (ATCC 6275) and *C. albicans* (ATCC 10231).

3.3.1. MIC determination

The MIC (Minimum Inhibitory Concentration) is defined as the lowest concentration of an antimicrobial agent that will inhibit the growth of a microorganism after incubation.

The MIC values were determined using the turbidometric method. In a typical experiment, a Biomek® 1000 (Beckman®) automat was used, performing automatically series of dilutions of the tested antimicrobial agents solutions before microbial inoculation, in 96 well micro-titration plates. The MIC was taken, after 24 h of incubation at 30 °C for bacteria and after 72 h of incubation at 25 °C for fungi, as the first concentration where no turbidity was observed.

3.3.2. MLC determination

The MLC (Minimum Lethal Concentration) is defined as the lowest concentration of antimicrobial agent that will kill microorganisms and consequently will prevent growth after subculture onto antibiotic-free media.

The MLC values were determined from the MIC microtiter plates (after 5 days incubation for bacteria or 7 days for fungi) by inoculating three trypticase soy agar (TSA) or sabouraud dextrose agar (SDA) plates with 100 μL of the three concentration above the MIC. Plates were incubated as described below and the first concentration where no growth was observed was taken as the MLC.

3.3.3. Cultivation

Antimicrobial experiments were taken using the third generation of bacteria or fungi. Bacteria and fungi samples were taken during their exponential phase. Bacteria were grown overnight on a TSA culture tubes and inoculated into 20 mL of M9G (pH 7.0) culture medium and incubated overnight at 30 °C. The optical density of the bacterial suspension was then measured (660 nm) and additional M9G medium was added to adjust the optical density at 660 nm to 0.05 corresponding approximately to between $5\cdot10^6$ and $5\cdot10^7$ cfu mL^{-1}. Real concentration of microorganisms was deduced by counting on petri dishes. Fungi were incubated on SDA culture tubes for 5 days at 25 °C. Each fungal strain was cultivated during 5–7 days on SDA at 25 °C ± 2 °C. The fungal

spores were then collected by adding 5 mL of M9G (pH 5.0) to the SDA slant, which were then gently scraped to suspend the microorganisms. The fungal solution was then filtered with sterile gauze under aseptic conditions to eliminate the residual mycelium. The suspension was adjusted using a counting cell under microscope, to $5\cdot10^6$–$5\cdot10^7$ spores per mL by adding M9G. Initial solution concentration of each antimicrobial agent was prepared in sterile deionised water.

4. Conclusion

The variation of the surface active properties and the biological activities of ten quaternary ammonium acrylic surfactants, differing in the nature of the hydrocarbon side chain ($C_{10}H_{21}$, $C_{12}H_{25}$, $C_{14}H_{29}$, $C_{16}H_{33}$ or C_6H_5–CH_2) and the spacer linking the ammonium head to the acrylic moiety (ethyl or undecenyl) were measured. The structure/activity study has shown that the length of the hydrocarbon spacer plays an important role in the biological activity because of its influence on the general hydrophobicity of the compounds. The MICs of undecylenic spacer (more hydrophobic) surfmers were systematically lower than the values recorded for surfactants with ethylenic spacers (less hydrophobic), whatever the nature of the hydrocarbon side chain ($C_{10}H_{21}$, $C_{12}H_{25}$, $C_{14}H_{29}$, $C_{16}H_{33}$ or C_6H_5–CH_2).

Moreover, all the synthesized quaternary ammoniums showed important antimicrobial activities which could be exploitable in the development of a wide range of bactericidal materials.

Acknowledgment

The authors wish to thank Catherine Piccini from Rohm and Haas for her valuable collaboration. LC thanks French government for MENRT grant.

References

[1] A.P. Fraise, J. Antimicrob. Chemother. 49 (2002) 11–12;
A.P. Fraise, J. Appl. Microbiol. 92 (2002) 158S–162S;
A.D. Russell, J. Appl. Microbiol. 92 (2002) 1S–3S;
A.D. Russell, J. Appl. Microbiol. 92 (2002) 121S–135S;
S.E. Walsh, J.Y. Maillard, A.D. Russell, C.E. Catrenich, D.L. Charbonneau, R.G. Bartolo, J. Hosp. Infect. 55 (2003) 98–107.
[2] J.M. Ascenzi, Handbook of Disinfectants and Antiseptics, Marcel Dekker Inc., New York, 1996.
[3] G. Domagk, Dtsh. Med. Wochenschr. 61 (1935) 829–832.
[4] F. Kopecky, Pharmazie 3 (1996) 135–144.
[5] J.J. Merianos, in: S.S. Block (Ed.), Disinfection, Sterilization and Preservation, fourth ed. Lea and Febiger, Philadelphia, 1992, pp. 225–255.
[6] M. Summers, J. Eastoe, Langmuir 19 (2003) 6357–6362.
[7] K. Owusu-Adom, C.A. Guymon, Polymer 49 (2008) 2636–2643.
[8] N. Cao, X. Wang, L. Song, Z.C. Zhang, J. Polym. Sci. Polym. Chem. 45 (2007) 5800–5810.
[9] B. Jönsson, Surfactants and Polymers in Aqueous Solution, Wiley, Chichester, 1998, (Chapter 16).
[10] F.C. De Schryver, G. Voortmans, A. Verbeeck, C. Jackers, Macromolecules 21 (1988) 1977–1980.
[11] S. Abele, A. Zicmanis, C. Graillat, C. Monnet, A. Guyot, Langmuir 15 (1999) 1033–1044.
[12] A. Guyot, Curr. Opin. Colloid Interface Sci. 1 (1996) 580–586.
[13] D.L. Gin, S.A. Miller, J.H. Ding, Curr. Opin. Colloid Interface Sci. 4 (1999) 338–347.
[14] D. Joynes, D.C. Sherrington, Polymer 38 (1997) 1427–1438.
[15] B.A. Pindzola, J. Jin, D.L. Gin, J. Am. Chem. Soc. 125 (2003) 2940–2949.
[16] J. Jin, V. Nguyen, W. Gu, X. Lu, B.J. Elliott, D.L. Gin, Chem. Mater. 17 (2005) 224–226.
[17] M.T. Ercan, S.A. Tuncel, B.E. Caner, E.J. Piskin, J. Microencapsul. 10 (1993) 67–76.
[18] S. Gibanel, V. Heroguez, Y. Gnanou, E. Aramendia, A. Bucsi, J. Forcada, Polym. Adv. Technol. 12 (2001) 494–499.
[19] E.J. Kim, S.H. Cho, S.H. Yuk, Biomaterials 22 (2001) 2495–2499.
[20] A.V. Kabanov, Pharm. Sci. Technol. Today 2 (1999) 365–372.
[21] U. Rungsardthong, T. Ehtezazi, L. Bailey, S.P. Armes, M.C. Garnett, S. Stolnik, Biomacromolecules 4 (2003) 683–690.
[22] S.M. Hamid, D.C. Sherrington, Polymer 28 (1987) 325–331.
[23] S.M. Hamid, D.C. Sherrington, Polymer 28 (1987) 332–339.
[24] E. Kissa, Fluorinated Surfactants, Synthesis, Properties, Applications, vol. 50, Marcel Dekker, New York, 1994, pp. 191.
[25] D. Myers, Surfaces, Interfaces, and Colloids: Principles and Applications, second ed. Wiley-VCH, Weinheim, 1999, pp. 358–96.
[26] K. Shinoda, T. Nakagawa, B. Tamamushi, T. Isemura, Colloidal Surfactants, Academic Press, New York, 1963.
[27] R. Zana, Langmuir 12 (1996) 1208–1211.
[28] H.C. Evans, J. Chem. Soc. (1956) 579–586.
[29] J. Frahm, S. Diekmann, A. Haase, Berichte der Bunsen-Gesellschaft 84 (1980) 566–571.
[30] P.A.R. Pires, O.A. El Seoud, J. Colloid Interface Sci. 304 (2006) 474–485.
[31] S. Shimizu, P.A. Pires, O.A. El Seoud, Langmuir 20 (2004) 9551–9559.
[32] A. Samakande, P.C. Hartmann, R.D. Sanderson, J. Colloid Interface Sci. 296 (2006) 316–323.
[33] F. Devinsky, I. Lacko, T. Imam, J. Colloid Interface Sci. 143 (1991) 336–342.
[34] F. Devinsky, I. Lacko, D. Mlynarcik, V. Racansky, L. Krasnec, Tenside Detergents 22 (1985) 10–15.
[35] R.J.W. Lambert, J. Pearson, J. Appl. Microbiol. 88 (2000) 784–790.
[36] E. Tomlinson, M.R.W. Brown, S.S. Davis, J. Med. Chem. 20 (1977) 1277–1282.
[37] P. Balgavy, F. Devinsky, Adv. Colloid Interface Sci. 66 (1996) 23–63.
[38] K. Staehler, J. Selb, P. Barthelemy, B. Pucci, F. Candau, Langmuir 14 (1998) 4765–4775.
[39] G. Tuin, F. Candau, R. Zana, Colloid Surf. A-Physicochem. Eng. Asp. 131 (1998) 303–313.