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Polysiloxane cationic biocides with imidazolium salt (ImS) groups, synthesis and antibacterial properties

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ABSTRACT

Novel polysiloxanes with pendant biocidal *N,N′*-dialkylimidazolium salt (ImS) groups were synthesized and compared with polysiloxanes bearing conventional biocidal quaternary ammonium salt (QAS) groups. The bacteriostatic power of these polymers was tested and compared under the same conditions in aqueous solution against two common strains of Gram positive bacteria and three strains of Gram negative bacteria. These new ImS containing polymers exhibited high antibacterial potency against all bacteria studied, similar to those substituted with QAS groups. The advantage of the imidazolium substituted polysiloxane stems from its higher thermal stability, as compared with the quaternary alkylammonium functionalized polymer, as demonstrated by thermogravimetric studies.

1. Introduction

Interest in polymeric biocides is rapidly increasing for their potential use in human and animal health care as well as in the protection of materials against biocorrosion and surface fouling. There is a broad class of polymer biocides having biocidal groups permanently bonded to their chains. These can effectively inhibit the growth of bacteria and other microbes without releasing low molecular weight toxic products to the environment [1–4]. When covalently attached to the surfaces of a variety of materials they are able to kill bacteria on contact, and their antimicrobial activity is durable and sustainable [4–8]. With these polymers there is no problem of residual toxicity [4–8], by contrast to the group of antimicrobial polymers releasing the low MW biocides in a controlled way to their surroundings [1–4]. In addition, the common bacterial strains, *Escherichia coli* and *Staphylococcus aureus* do not appear to develop resistance against polymeric biocides [9]. Biocidal polymers of polycationic structure, in particular those having quaternary tetraalkylammonium (QAS) [5–18], tetraalkylphosphonium [19–21] and *N*-alkylpyridinium salt groups [5,10,22–26] pendant to the polymer chain have been developed. These polycations bearing considerable positive charge may destructively interact through electrostatic forces with the negatively charged bacteria walls and membranes leading to the death of the bacteria [2,27]. This destructive action is known to be strengthened by hydrophobic moieties (typically, C_8–C_{16} hydrocarbon chains) bonded to the nitrogen of the biocidal group. Amongst the polycationic antimicrobial agents organosilicon polymers, polysiloxanes [8,28–31] and polysilsesquioxanes [32] have been used. Polysiloxanes are particularly attractive as they show exceptionally high static and dynamic flexibility of their polymer chains, which gives them high solubility in many solvents, high permeability, and unusual surface properties [33]. All these features facilitate the contact of the biocidal polymer with the bacterial wall and its diffusion to cytoplasmic

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membranes. Polysiloxanes with pendant quaternary ammonium salt groups (QAS) show high biocidal potency [8,28,29]. Polysiloxane biocides bearing halamine groups were also synthesized [34–36]. These polymers are very effective in killing bacteria by direct contact with oxidative halogen chemically bonded to the polymer and find variety of uses such as in water disinfection.

In the search for new, active biocidal polymers we focused our attention on polysiloxanes with imidazolium salt (ImS) groups as some antibacterial effect of the uncharged imidazole ring attached to organic polymers has been observed recently [37,38].

This paper is devoted to the synthesis of polysiloxanes with the ImS groups pendant to polymer chain and to the comparison of their antibacterial activity and thermal stability with those of polysiloxanes bearing QAS groups. We designed these new polysiloxane biocides to be more thermally stable than the QAS substituted polysiloxanes in which the QAS groups readily undergo decomposition by the Hoffman elimination at elevated temperatures. To assure the reproducibility and reliability of the measured antibacterial activity–structure relationships, comparative studies were performed with aqueous solutions of biocidal polymers. The antibacterial potency of various polymeric biocides bonded to surfaces could not be adequately compared in this way because the antibacterial activity on a surface depends additionally on other factors.

2. Experimental

2.1. Chemicals

Reagent grade chemicals: 1-allylimidazole, Across Organics 97%; *N*,*N*-dimethyl-*N*-*n*-octylamine, Aldrich 95%; *n*-octyl chloride, Fluka, 98%; *n*-octyl bromide, Aldrich 99%; dimethyldichlorosilane, ABCR 98%; methyldichlorosilane, ABCR 99%; (3-chloropropyl)methyldichlorosilane, ABCR 97% were used without purification. *N*,*N*-Dimethylformamide (DMF), POCh pure, was dried over $MgSO_4$ for 1 day and distilled under reduced pressure. Toluene, POCh analytical grade, was shaken with concentrated H_2SO_4, washed with $NaHCO_3$ water solution and dried over $MgSO_4$ prior to distillation from sodium. 2-(3-*N*-imidazolopropyl)-2,4,4,6,6-pentamethyl-cyclotrisiloxane was synthesized and purified as described earlier [39]. Methyldiethoxysilane was obtained by the reaction of methyldichlorosilane with dried ethanol in a hexane solution in the presence of pyridine. (3-Imidazolopropyl)methyldichlorosilane hydrochloride and 1,1,3,3-tetramethyldisiloxane were synthesized as described elsewhere [39]. Their high purity was confirmed by ^{1}H NMR.

2.2. Synthesis of (3-N-imidazolopropyl)methyldiethoxysilane

In a Schlenck reactor were placed: *N*-allylimidazole (6.8 g, 6.3×10^{-2} mol), toluene (10 ml) and Karstedt catalyst (0.0427 g of the solution in xylene containing 4.8×10^{-5} mol of Pt). The mixture was stirred at room temperature for 0.5 h. Then methyldiethoxysilane (14.0 g, 7.9×10^{-2} mol) was introduced. The mixture was stirred at 90 °C for 3 days. Distillation of the post-reaction mixture gave 9.18 g of the pure product identified as (3-*N*-imidazolopropyl)methyldiethoxysilane, yield 60% relatively to *N*-allylimidazole used, B.p. 95 °C/0.24 mmHg. Elemental analysis: C 53.1% (th 54.5%), H 9.32% (th 9.09%), N 12.12% (th 11.6%). ^{1}H NMR ($CDCl_3$) in ppm: 0.05 [s, Si**H$_3$**], 0.45–0.52 [m, Si**H$_2$**], 1.08–1.18 [t, OCH_2C**H$_3$**], !.71–1.87 [m, $SiCH_2$**H$_2$**], 3.63-3.75 [q, O**H$_2$**CH_3], 3.84–3.93 [t, CH_2**H$_2$**N], 6.86 [s, C**H**NCH_2], 6.98 [s, NC**H**CH], 7.44 [s, NC**H**N]. ^{29}Si NMR ($CDCl_3$) in ppm −7.23.

2.3. Synthesis of poly(3-N-imidazolopropyl)methylsiloxane

(3-*N*-Imidazolopropyl)methyldiethoxysilane (5.52 g, 2.28×10^{-2} mol), dioxane (15 ml) and 25% aqueous solution of ammonia (2 ml) were placed in a three neck round–bottomed flask equipped with a reflux condenser. The mixture was stirred at 50 °C for 2 days. Then volatile components were removed by evaporation. After washing with water and drying under vacuum, 3.5 g, yield 91%, of the crude polymer product was obtained. The polymer was dissolved in a methanol–water 1:3 vol/vol mixture (20 mL). The solution was placed in a tubular bag of a Spectrum Laboratories Inc. 6 Spectra/Por Dialysis Membrane, MWCO: 1000, wet in 0.1% sodium azide. The membrane bag filled with the polymer solution was placed in a 2 L beaker filled with distilled water and kept in an ambient temperature for 3 days. The polymer fraction remaining in the bag (polymer **1**), 3.2 g was isolated by evaporation of solvents and characterized by ^{1}H NMR (Fig. 1) and SEC: Mn = 1700 g/mol, Mw = 2200 g/mol.

2.4. Synthesis of poly[(3-N-imidazolopropyl)methylsiloxane-co-bisdimethylsiloxane]

In a reactor installed on a high vacuum line (hvl), purged with argon, 2[3(*N*-imidazolo)propyl]2,4,4,6,6-pentamethylcyclotrisiloxane (2.3 g, 7.3×10^{-3} mol) was placed. The reactor was evacuated and 3 ml of THF was distilled to it on hvl from a Na–K alloy. After the reactor was filled again with argon 2,6-di-*tert*-butylpyridine (0.17 g, 8.9×10^{-4} mol) and butyl lithium (0.050 mL of the 2.5 M solution in *n*-hexane containing 1.25×10^{-4} mol of *n*-BuLi) were introduced together with a known amount of *n*-dodecane as GC standard. The polymerization was carried out in ambient temperature and was monitored by GC. The reaction was quenched with an excess of Me_3SiCl at a monomer conversion of 93%. Volatile components of the post-reaction mixture were removed by distillation in vacuum and the polymer was heated in 60 °C under vacuum of 10^{-3} Torr for 8 h. 1.93 g of the product (polymer **2**) was obtained, yield 84%. The SEC analysis performed using DMF (70 °C) as eluent and polystyrene as standard gave Mn = 4700 g/mol, Mw/Mn = 1.50. ^{1}H NMR (solvent CD_3OD, in ppm): 0.02–1.2 (s, C**H$_3$**Si); 0.35–0.55 (b.s. C**H$_2$**Si); 1.67–1.90 (b.s. C**H$_2$**CH_2Si); 3.92–4.07 (b.s. C**H$_2$**N); 6.98, 7.10 (2 × s. C**H**CH); 6.50 (s. NC**H**N). ^{29}Si NMR (solvent CD_3OD, in ppm): –(20.3–21.9) (m. CH_2CH_3**Si**O); –(21.9–23.8) (m. $(CH_3)_2$**Si**O).

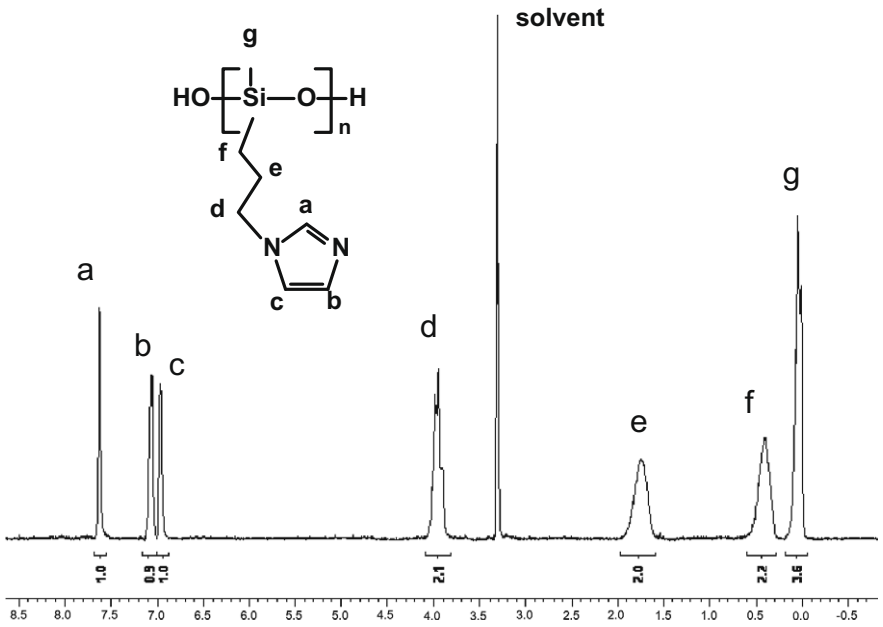


Fig. 1. ^{1}H NMR spectrum of poly[3-(*N*-imidazolo)propyl]methylsiloxane in the CD_3OD solution.

2.5. Synthesis of [N-3(N′-n-octylimidazolio)propyl]methyl siloxane halide polymers and copolymers

The 10 wt.% solution of an *N*-imidazolopropyl substituted polysiloxane in DMF and an excess of an alkyl halide were mixed in a glass reactor and kept for a period at 60 °C. The solvent and excess of alkyl halide were removed by evaporation in a vacuum to obtain a polymer which was subjected to analysis by ^{1}H NMR. Where the precursor polymer had been synthesized by polycondensation the cyclic and linear oligomers were separated from the ImS polymer product by dialysis. An example of the synthesis is given below while the conditions of reactions and characteristics of polymers are shown in Table 1.

Example: Polymer **1** (0.69 g, containing 4.08×10^{-3} mol of the imidazole group) and *n*-octyl bromide (2.40 g, 1.24×10^{-2} mol) in 5 mL of DMF were placed in a flask which was immersed in an oil bath set to 60 °C and kept for 72 h. DMF and the excess of *n*-octyl bromide were removed by evaporation in vacuum. The ^{1}H NMR analysis (Fig. 2) showed that the yield of the formation of the imidazolium bromide group was quantitative. The polymer was subjected to analysis. ^{29}Si NMR (solvent CD_3OD, in ppm): −14.4 (s. CH_2CH_3**Si**OD); −(21–24) (m. CH_2CH_3**Si**O-Si). SEC in DMF 70 °C: Mn 3000 g/mol, Mw/Mn 1.4 (Fig. 3a). A part of the ionic ImS polysiloxane, 0.28 g was dissolved in the 20 mL of water and the solution was placed in a tubular bag of a Spectrum Laboratories Inc. 6 Spectra/Por Dialysis Membrane, MWCO:1000 wet in 0.1 sodium azide. The bag was immersed in a 2 L beaker filled with distilled water. After 3 days of the dialysis process the bag was removed. The evaporation of water permitted us to regain the higher molar mass fraction which remained in the bag and a lower molar mass fraction which penetrated to beaker. The SEC analysis (in DMF 70 °C) gave Mn 3500 g/mol, Mw/Mn 1.21 and Mn 1500 g/mol, Mw/Mn 1.3 for the higher mass fraction and the lower mass fraction, respectively.

2.6. Synthesis of poly[(3-chloropropyl)methylsiloxane-co-dimethylsiloxane] and [3-N(N,N,N-octyldimethylammonio) propyl]methylsiloxane chloride polymers and its copolymers with dimethylsiloxane

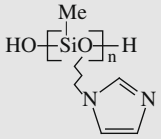
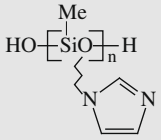
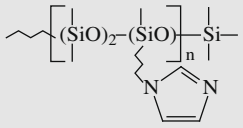
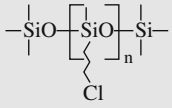
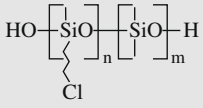
Synthetic procedure was similar to that described in Ref. [28]. The characteristics of the precursor polymer and parameters of the synthesis of biocidal polymers are placed in Table 1, while the characteristics of biocidal polymers are given in Table 2.

2.7. Analytical methods

^{1}H NMR measurements were performed using a Bruker AC-200 spectrometer while ^{29}Si NMR spectra were taken with a Bruker AC-500 operating at 500 MHz. Fully deuterated methanol was used as solvent. D_2SO_4 (30 μL) was added to the sample before the taking of the ^{1}H NMR spectrum of the imidazolium salt substituted polysiloxanes.

The SEC analysis of the imidazole and imidazolium groups containing polysiloxanes was performed using a Knauer HPLC K-501 pump with a WYATT/OPTILAB 903 Interferometric RI detector using battery of two columns: PSS GRAM 100 Å, 8 × 300 mm, 10 m; PSS GRAM 3000 Å, 8 × 300 mm, 10 μm. *N*,*N*-Dimethylformamide containing LiBr (0.01 mol/L) was used as solvent. The flow rate was 0.8 mL/min and the solvent temperature was 70 °C. Polystyrene was used as standard. The SEC analysis of the 3-chloropropyl substituted polysiloxanes were performed

Table 1
Synthesis of biocidal polysiloxanes.

Polymer number	Reactants				Conditions of reaction			
	Low molar mass reactant	Precursor polymer	No	Mn, Mw/Mn (g/mol)	Reactants ratio[a)]	Temp. (°C)	Time (h)	Yield (%)
1a	*n*-OctCl		1	(1600, 1.31)	10	60	96	61
1b	*n*-OctCl				10	60	120	92
1c	*n*-OctBr				10	60	96	100
2a	*n*-OctBr		2	(3000, 1.28)	10	60	160	87
3a	*n*-OctBr		3	(4700, 1.50)	3	60	96	85
4a	*n*-OctMe$_2$N		4	(11800, 1.52)	1	80	140	97
5a	*n*-OctMe$_2$N		5	(14400, 1.50) n/nm = 0.23	1.5	60	450	88

[a] Molar ratio of the low molar mass reactant to the functional group in the precursor polymer.

using an LDC analytical Refracto-Monitor instrument with two Phenogel columns covering the molar mass range 10^2–10^5 g/mol and a refractive index detector. Toluene was used as eluent and polystyrene as standard.

Thermogravimetric analysis was performed with a Hires TGA 2950 thermal analyzer under atmosphere of nitrogen with the heating rate of 10 °C/min from 30 to 960 °C.

2.8. Antibacterial activity assessment

The antibacterial tests were performed against *Enterococcus hirae* (ATCC 10541), *S. aureus* (ATCC 6538), *E. coli* (ATCC 8739), *Proteus vulgaris* (NCTC 4635) and *Pseudomonas aeruginosa* (ATCC 9027). The minimum inhibitory concentrations (MIC) were determined in three independent measurements. The standard broth dilution technique [40] with inoculums of approximately 1×10^5 CFU mL^{-1} was used. The tested compounds were dissolved diluted in geometric progression, and dispensed into the wells of a microplate. Overnight bacterial culture was diluted with Mueller–Hilton broth to the proper density and dispensed into wells.

Microplates were incubated for 24–36 h at 37 °C and the growth of bacteria on the walls was examined. The MIC value was taken as the lowest concentration of polymers that inhibits visible growth of bacteria.

3. Results and discussions

3.1. Synthesis of biocidal polycationic polysiloxane with *N*,*N*′-dialkylimidazolium groups

Polysiloxanes with *N*,*N*′-dialkylimidazolium groups were synthesized via 3-*N*-imidazolopropyl substituted polysiloxanes. Homopolymers of a [3-*N*(*N*′-octylimidazolium halide)-propyl]methylsiloxane were obtained according to the Scheme 1.

The monomer used in the synthesis of the precursor polymer was 3[(*N*-imidazolo)propyl]methyldiethoxysilane obtained by the hydrosilylation of *N*-allylimidazole. Imida zole substituted olefins are not readily reactive in hydrosilylation as the nucleophilic imidazole ring deactivates catalyst by the formation of complexes with transition metals. In our previous work the hydrochloride complex of allylimidazole was used in the synthesis of 3[(*N*-imidazolo)propyl]methyldichlorosilane [39] to prevent this deactivation. This compound, synthesized by the hydrochloride complex method, was also exploited here for the generation of the copolymer of the imidazole substituted siloxane with dimethylsiloxane. However, we found that the direct hydrosilylation of allylimidazole by methyldiethoxysilane is possible in elevated temperatures and we successfully used this method to synthesize with a good yield the required monomer.

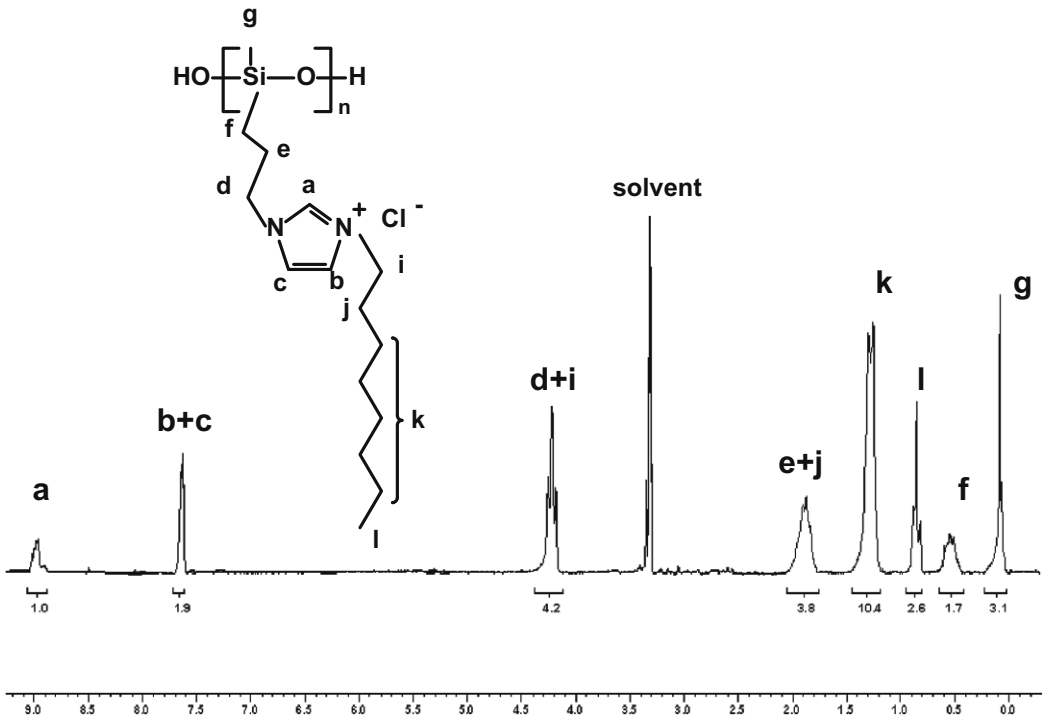


Fig. 2. ^{1}H NMR spectrum of Poly[3(*N*-octyl-*N*′-imidazolium)propyl chloride]methylsiloxane in the CD_3OD solution.

Hydrolytic polycondensation of 3[(*N*-imidazolo)propyl]methyldiethoxysilane in the presence of ammonia led to a polysiloxane with pendant 3-(*N*-imidazolo)propyl groups. The polymer was carefully purified by dialysis from water soluble low molar mass imidazole derivatives including lower hydroxyl-ended oligomers. The polymer generated by this way had on average about 10 imidazolo substituted siloxane units. It was characterized by ^{1}H NMR spectroscopy (Fig. 1) and SEC.

The polymer was subjected to a reaction with *n*-octyl bromide and *n*-octyl chloride in dimethylformamide (DMF). The progress of this reaction was monitored by the ^{1}H NMR spectroscopy. The spectrum of the fully imidazolium substituted polymer is presented in Fig. 2. The conditions of synthesis and characteristics of products are shown in Table 1. This polymer was also characterized by SEC, Fig. 3a. It had a bimodal molar mass distribution which pointed to a significant contribution from the fraction of cyclic polysiloxane. The dialysis in water of this polymer permitted us to separate cyclics as the lower molar mass fraction while the linear polymer constituted the higher molar mass fraction. The gel chromatograms of both these fractions are compared in Fig. 3b. The two step dialysis performed for precursor and biocidal polymer led to a narrow polydispersity of the former, Mw/Mn = 1.21.

The copolymer of [3(*N*-octyl-*N*′-imidazolium)propyl bromide]methylsiloxane with dimethylsiloxane was synthesized according to Scheme 2. The first step was the synthesis of 2-{[3(*N*-imidazolo)*N*′-propyl bromide)methyl-2,4,4,6,6-pentamethylcyclotrisiloxane which was subjected to anionic ring-opening polymerization. The synthesis was performed in an analogous way to that described earlier by us [39]. Since it is the polymerization of a mixed unit monomer it produces the copolymer composed of 3-imidazolopropyl substituted siloxane units and dimethylsiloxane units. This polymerization has the attributes of living polymerization thus imidazole groups should be evenly distributed along the polymer chain with one imidazole functionality in each repeat unit. However, this distribution was somewhat perturbed by chain transfer since the molar mass of polymer was lower and its polydispersity was higher than those expected for the polymerization with no chain transfer and no back biting. In the last step the pendant imidazole group was transformed to ionic imidazole bromide by the reaction with *n*-octyl bromide.

3.2. Synthesis of polysiloxanes bearing QAS groups

Polysiloxanes containing quaternary ammonium chloride groups were synthesized in a way similar to that described earlier [28,29] according to the Scheme 3. The precursor polysiloxanes having 3-chloropropyl groups pendant to siloxane chain were generated by hydrolytic polycondensation of (3-chloropropyl)methyldichlorosilane. This polymer was subjected to equilibration or coequilibration with octamethylcyclotrisiloxane (D_4) catalyzed by trifluoromethanesulfonic acid. A known amount of hexamethyldisiloxane was introduced to control molecular weight and to terminate the chain by trimethylsilyl groups. This procedure leads to statistical distribution of units in the case of copolymers [28]. Cyclic and linear oligomers were removed by careful manifold precipitation of polysiloxanes from their solution in methylene chloride

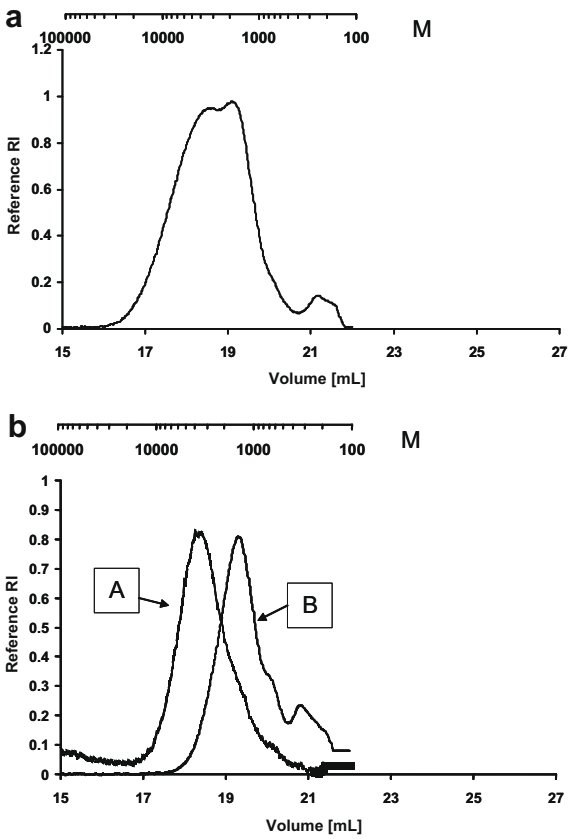


Fig. 3. SEC of poly[3-(*N*-imidazolo)propyl]methylsiloxane, (a) before dialysis, (b) fractions after dialysis – B – low molecular weight fraction, mostly cyclic oligomers, trimer M = 1083 g/mol, tetramer M = 1444 g/mol, pentamer M = 1500 g/mol. A- high molecular weight fraction, mostly linear polymer.

with a limited amount of methanol. Polysiloxanes had polydispersity indexes of 1.5. The characteristics of the precursors are shown in Table 1.

The reaction of precursors with *n*-octylamine was carried out in dimethylformamide (DMF) at elevated temperature and usually using a large excess of the amine. The progress of the reaction was monitored by ^{1}H NMR spectroscopy. Excess of amine and solvent were carefully removed. The conditions of quaternization and characteristics of the QAS substituted polysiloxanes are given in Table 2.

3.3. Thermal properties of the polycationic polysiloxanes

The thermogravimetric studies, presented in Fig. 4, revealed that the polysiloxane having imidazolium groups undergo thermal decomposition at temperatures substantially higher than the polymers bearing QAS groups. The onset of the decomposition of the homopolymer substituted with QAS and its copolymer with dimethylsiloxane are 203 and 179 °C, respectively. A slow decomposition of these polymers also takes place at lower temperatures. This feature of the QAS substituted polysiloxanes reduces the possibility of their application as additives to silicone coatings or elastomers as some of them need to be able to withstand elevated temperatures. On the other hand, the onset of the decomposition of the imidazolium substituted polysiloxane appears at 260 °C, which is significantly higher. The higher thermal stability of this polymer gives a greater possibility for using it as an additive to silicone materials to protect them against infections and biological corrosion.

It should be also mentioned that shapes of thermogravimetric traces in Fig. 4 are different for the QAS and imidazolium substituted homopolymers. The former (curve B) undergoes a three step decomposition losing in the first step, up to 270 °C, about 40% of its initial weight, which corresponds to the loss of the octyl group bonded to nitrogen from the expected Hoffman elimination. In the second step, 270–400 °C, the remaining approximately 17% of the functional group is cleaved, while in the third step, 400–600 °C depolymerization occurs and only 4% of residue remains. By contrast, the imidazolium substituted polymer loses all the functionalized organic group at silicon in the first step, up to 380 °C, where above 60% of its initial mass is lost. After depolymerization at 380–600 °C about 8% of residue remains.

3.4. Studies of antibacterial properties and discussion of results

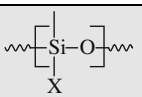
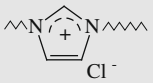
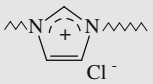
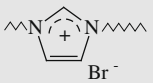
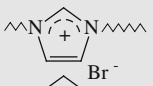
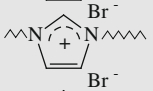
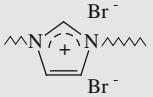
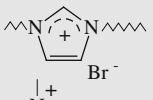
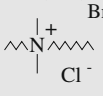
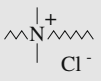
All of the polycationic polysiloxanes synthesized in this study are soluble in water. The antibacterial properties of these materials were studied in aqueous solutions using the broth dilution method. The biocidal powers of the various structures were compared by determining their MIC (minimum inhibitory concentration) values. Studies were performed for two Gram positive bacterial strains, *E. hirae* and *S. aureus* as well as for three Gram negative bacterial strains, *E. coli*, *P. vulgaris* and *P. aeruginosa*. The MIC values against these bacteria for various biocidal polysiloxanes are presented in Table 2.

For each of the bacteria strain–biocide pair the MIC was evaluated at least three times in independent measurements and a good agreement between results of these measurements was attained (the mean deviation from the average value is 12%).

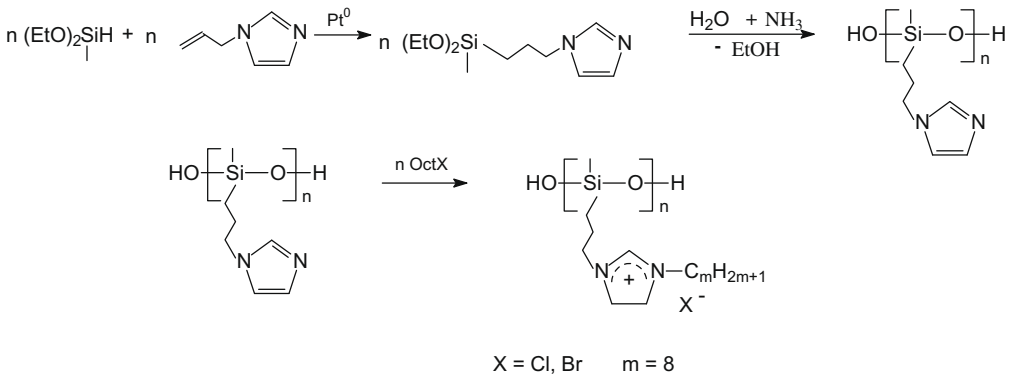
For some MIC additional observations were performed showing that all bacteria over the MIC were dead which means that the MIC values corresponded to the MBC values (minimum bacteriocidal concentration).

Polysiloxanes having pendant ImS functions proved to be powerful bacteriocides against a broad spectrum of bacteria strains. Their antibacterial activity is comparable to polysiloxanes bearing antibacterial QAS functions. Although the biocidal behavior of these two classes of biocides is similar some differences are observed in their action against bacteria species and in the structure-activity relationships. The density of the biocidal functions along the chain is not so crucial for the QAS polysiloxane as it is for the ImS derivative. With the exception of *E. coli* the QAS copolymer with dimethylsiloxane shows more or less similar activity as the QAS homopolymer (compare entries 8 and 9 in Table 2) in spite of the lower density of active groups on the copolymer. This behavior could be explained

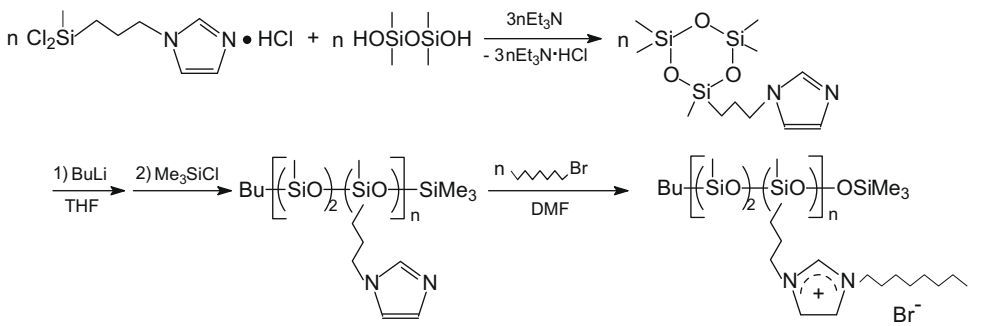
Table 2
Bacteriostatic activities of the ImS and QAS substituted polysiloxanes.

No	Polymer number	Biocidal polysiloxane 				MIC [μg/mL][a]				
		Active group X	Contribution from active units X/Si	Mn (g/mol)	Mw/Mn	Gram positive		Gram-negative		
						Enterococcus hirae	*Staphylococcus aureus*	*Escherichia coli*	*Proteus vulgaris*	*Pseudomonas aeruginosa*
1	1a		0.61	2460[b]	1.31[b]	62	31	31	160	40
2	1b		0.92	2900[b]	1.31[b]	5	3	10	20	20
3	1c		1.0	3950[b] 3000[c]	1.31[b] 1.37[c]	4	4	8	40	40
4	1c-1[d]		1.0	3500[c]	1.21[c]	5	5	10	40	40
5	1c-2[e]		1.0	1500[c]	1.3[c]	20	5	10	80	20
6	2a		0.9	6100[b]	1.3[b]	2.5	5	10	40	20
7	3a[f]		0.28	7600[b]	1.50[b]	160	80	210	–	510
8	4		0.97	22,000[b]	1.52[b]	<7.5	4	10	80	80
9	5a[f]		0.23	19,900[b]	1.50[b]	<5	<5	80	80	80

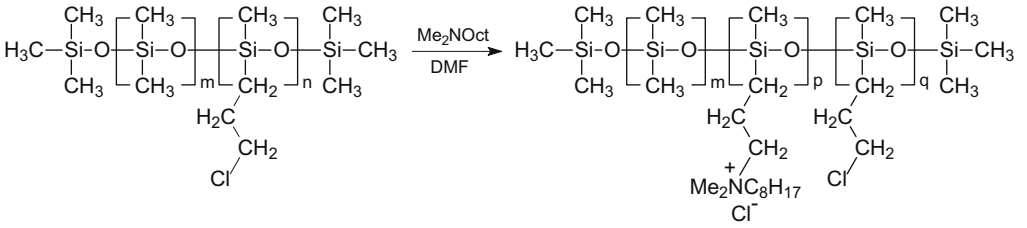
[a] Since MIC is the lowest concentration inhibiting the growth of bacteria in the series of the dilution in geometrical progression of polymer biocide the real value of MIC is between this measured and the highest concentration allowing bacteria to survive. The statistical error calculated as mean deviation from the average value in series of repeated experiments was ±12%.
[b] Calculated from molecular mass and polydispersity of precursor and ^{1}H NMR of the biocidal polymer.
[c] Directly measured by SEC using polystyrene as standard.
[d] Fraction obtained by dialysis of polymer given in entry 3.
[e] Fraction of cyclics separated by dialysis.
[f] Copolymer with dimethylsiloxane.



Scheme 1.



Scheme 2.



Scheme 3.

by a larger conformational freedom of the copolymer rich in dimethylsiloxane units. Such a copolymer may easily adopt a conformation favourable for the interaction with the bacterial wall which compensates for the lower number of active groups. However, in the case of the ImS substituted polysiloxanes the antibacterial power clearly decreases with the decrease in the number of the ImS group along the polymer chain. The homopolymers are more active than copolymers (compare entries 2 with 1 and 5 with 7 in Table 2).

The antibacterial power of the QAS and ImS substituted polysiloxanes is stronger against Gram positive bacteria than that against Gram negative ones which is related to the difference in the structure of their cell walls. It is generally accepted that the mechanism of the bacteriocidal action of the polycationic biocides involves their destructive interaction with the cell wall and/or cytoplasmic membranes [1,20,21]. Macromolecules may interact more effectively with the cell of Gram positive bacteria as their polyglycane outer layer is sufficiently loosely packed to facilitate deep penetration of the polymer chain inside the cell to interact with the cytoplasmic membrane. On the other hand, a Gram negative bacteria cell has an additional membrane with a bilayer phospholipid structure which protects the inner cytoplasmic membrane to a greater degree against the adverse action of the polymeric biocide. Nevertheless, the ImS substituted polysiloxane shows high activity also against Gram negative bacterial strains. It is possible that the action against outer membrane plays a larger role than previously reported.

Results of the studies of the interaction with bacteria of polysiloxanes with *N*-*n*-octylimidazolio-*N*′-propyl chloride and bromide (entries 2 and 3, Table 2) indicate that the structure of the counterion has little influence on the antibacterial power of the ImS substituted polysiloxane. This observation cannot be generalized since contradictory observations for the behavior of various polycationic biocide series have been reported in the literature. Although no different effects in a halide series were observed by Ikeda et al. [18], Salt and Wisman found that a QAS cation with Br^- counteranions is more potent than that with Cl^- [41].

A serious problem in the synthesis of polymeric biocides is the separation of linear polymers from cyclic oligomers as intramolecular cyclization often accompanies the linear growth of macromolecule. The question arises how the oligomer fraction affects the antibacterial activity of

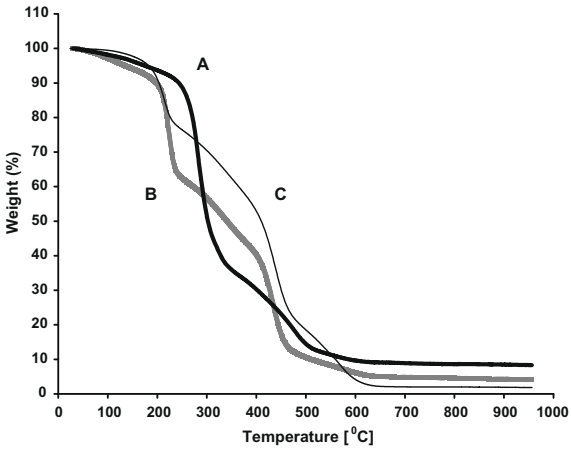


Fig. 4. Thermogravimetric traces of (A) poly{*N*-[3-(*N*′-octylimidazolio)]propyl chloride}methylsiloxane, (B) poly {*N*-[3-(N,*N*-dimethyl-*N*-*n*-octylammonio)]propyl chloride}methylsiloxane, (C) poly{*N*[[3-(*N*,*N*-dimethyl-*N*-*n*-octylammonio)]propyl chloride]methylsiloxane-co-dimethylsiloxane}.

the polymer. In order to address this problem the comparison of the bacteriostatic activity of fractions separated by dialysis were performed (Table 2, entries 4 and 5). The high molar mass fraction, in which cyclic components are mostly removed, is at least as active as the low molar mass fraction containing cyclic and linear oligomers. So these data do not point to any significant difference between antibacterial potency of cyclic oligomers and polymers.

4. Conclusions

New biocidal polymers synthesized here, polysiloxanes with *N*,*N*′-dialkylimidazolium halide groups pendant to the polymer chain are very potent bacteriocides for a broad spectrum of bacteria. They show particularly high bacteriocidal activity against Gram positive bacteria, and they are also very efficient against Gram negative bacteria. Polymers of this new class of polymeric biocides shows a superior thermal resistance to commonly studied quaternary ammonium salt substituted polymers.

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