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Journal of Organometallic Chemistry 690 (2005) 33–47
Journal of Organometallic Chemistry
www.elsevier.com/locate/jorganchem

4-Silapiperidine and 4-silapiperidinium derivatives: syntheses and structural characterization

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Received 11 May 2004; accepted 8 August 2004
Available online 28 September 2004

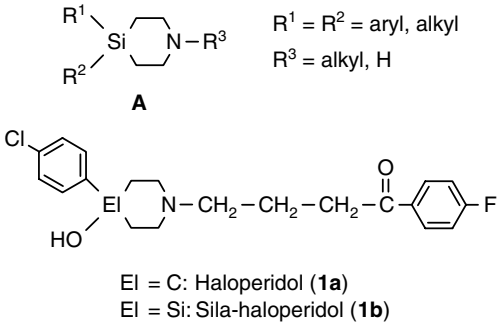
Abstract

A series of novel 4-silapiperidine and 4-silapiperidinium derivatives, with two silicon-bound aryl groups and various *N*-organyl groups, have been synthesized and structurally characterized (solution ^{1}H, ^{13}C, ^{19}F, and ^{29}Si NMR spectroscopy; eight crystal structure analyses). These synthetic and structural investigations provide the basis for the development of novel silicon-based drugs containing a 4-silapiperidine or 4-silapiperidinium skeleton.

Keywords: 4-Silapiperidine; 4-Silapiperidinium; Silicon; Silicon-based drugs

1. Introduction

Since the first 4-silapiperidines of the formula type **A** have been described in the literature in the 1980s [1–3], there have been only a few reports about further derivatives of this class of compound [4–6]. The majority of these compounds contain two phenyl ($R^1 = R^2 = Ph$) or two methyl groups ($R^1 = R^2 = Me$) attached to the silicon atom and various alkyl groups (R^3) bound to the nitrogen atom. Compounds of type **A** with $R^3 = H$ have also been mentioned in the literature [2,4], but there are no easily accessible publications describing their preparation. 4-Silapiperidines have been studied for their pharmacological activity [1,2,6] and have recently also gained interest in protecting group chemistry [5].



In context with our research program dealing with the development of silicon-based drugs [7,8], we have recently synthesized sila-haloperidol (**1b**), a silicon analogue of the neuroleptic haloperidol (**1a**). While the synthesis of sila-haloperidol (**1b**) itself has already been published [6], we here report on the synthesis and structural characterization of a series of further 4-silapiperidine and 4-silapiperidinium derivatives (compounds **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl) that have been prepared in synthetic studies at the beginning of the sila-haloperidol project.

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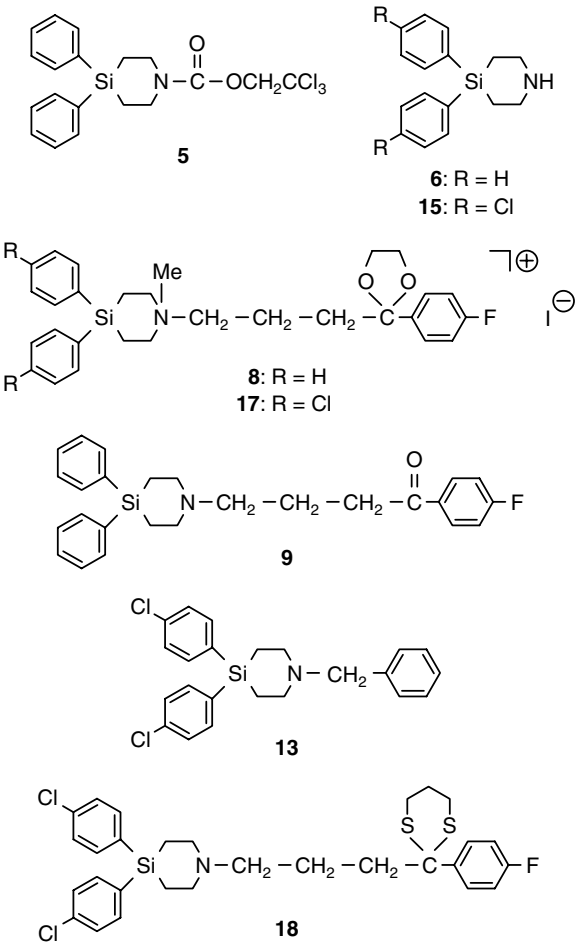
doi:10.1016/j.jorganchem.2004.08.023



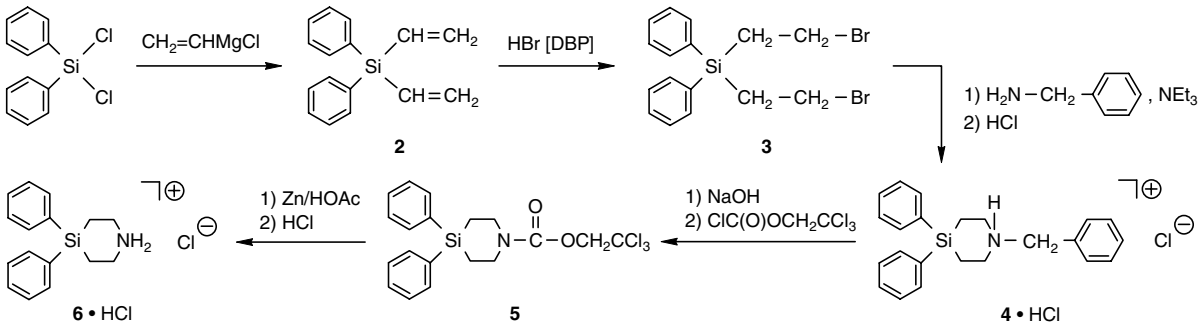
2. Results and discussion

2.1. Syntheses

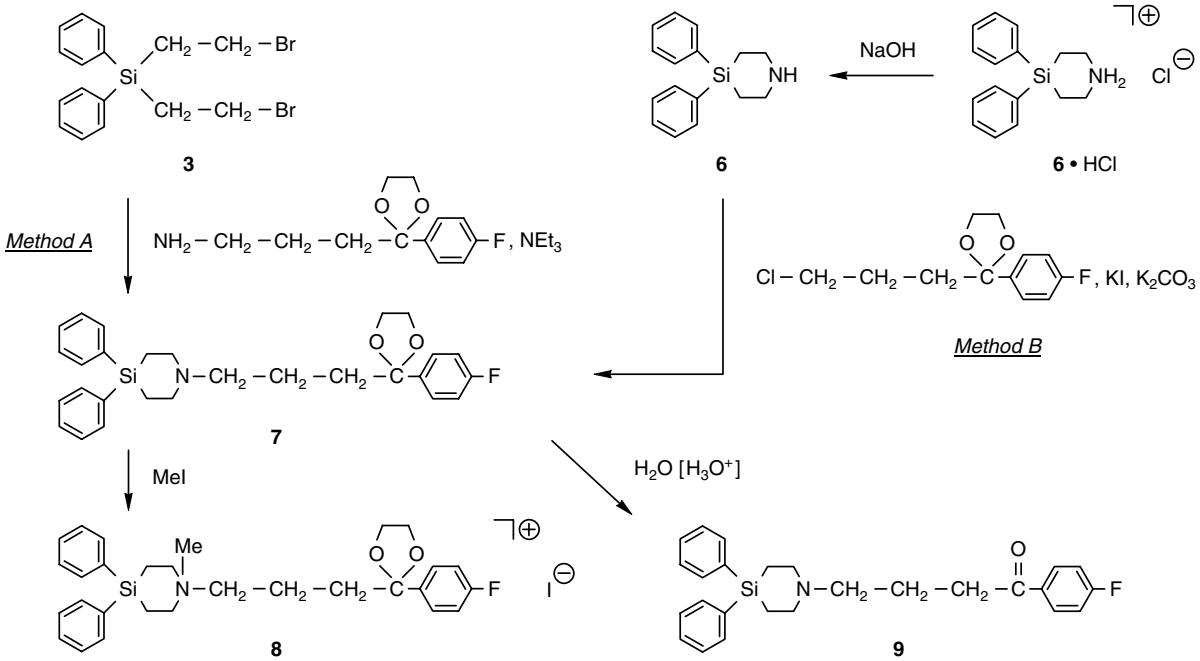
2,2,2-Trichloroethyl 4,4-diphenyl-4-silapiperidine-1-carboxylate (**5**) and 4,4-diphenyl-4-silapiperidinium chloride (**6** · HCl) were synthesized according to Scheme 1, starting from dichlorodiphenylsilane. Thus, treatment of Ph_2SiCl_2 with vinylmagnesium chloride yielded diphenyldivinylsilane (**2**) [9], which upon reaction with hydrogen bromide, catalyzed by dibenzoyl peroxide, gave bis(2-bromoethyl)diphenylsilane (**3**) [1]. Treatment of **3** with benzylamine, in the presence of triethylamine, followed by reaction with hydrogen chloride, afforded 1-benzyl-4,4-diphenyl-4-silapiperidinium chloride (**4** · HCl). Treatment of **4** · HCl with sodium hydroxide gave the amine **4**, which upon reaction with 2,2,2-trichloroethyl chloroformate [10] yielded **5**. This compound was then reacted successively with zinc/acetic acid and hydrogen chloride to give **6** · HCl [11].

1-{3-[2-(4-Fluorophenyl)-1,3-dioxolan-2-yl]propyl}-1-methyl-4,4-diphenyl-4-silapiperidinium iodide (**8**) and 1-[4-oxo-4-(4-fluorophenyl)butyl]-4,4-diphenyl-4-silapiperidine (**9**) were synthesized according to Scheme 2, starting from **3** or **6** · HCl. Thus, treatment of **3** with 3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propylamine [12], in the presence of triethylamine, yielded 1-{3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propyl}-4,4-diphenyl-4-silapiperidine (**7**) (*Method A*). Alternatively, **7** was prepared by treatment of **6** (obtained from **6** · HCl by reaction with sodium hydroxide) with 2-(3-chloropropyl)-2-(4-fluorophenyl)-1,3-dioxolane [13] in the presence of potassium iodide and potassium carbonate (*Method B*). Finally, reaction of **7** with methyl iodide afforded **8**, and hydrolysis of **7** with hydrochloric acid gave **9**.

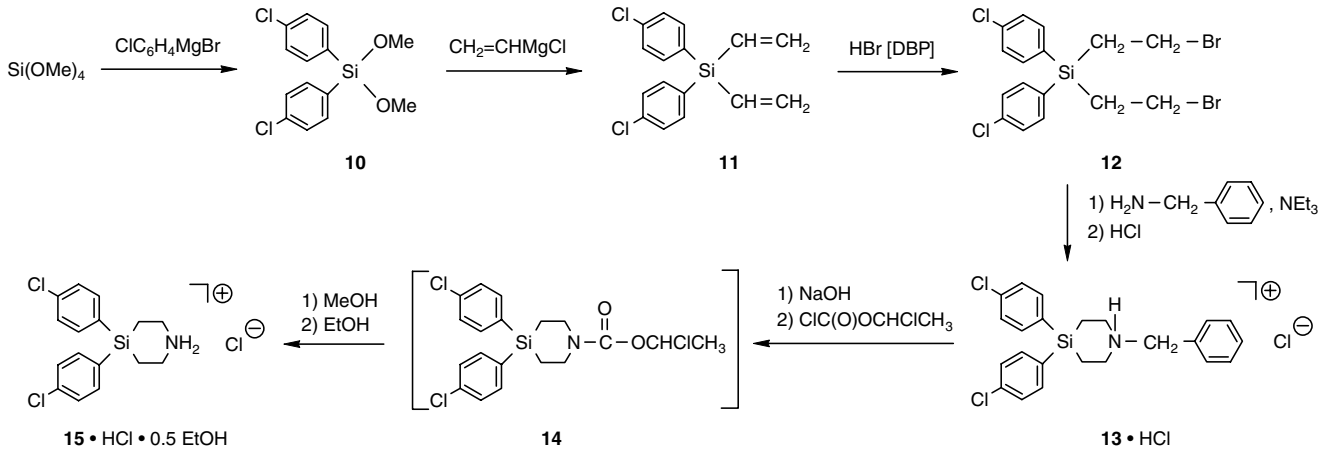
1-Benzyl-4,4-bis(4-chlorophenyl)-4-silapiperidinium chloride (**13** · HCl) and 4,4-bis(4-chlorophenyl)-1-silapiperidinium chloride (**15** · HCl; isolated as the hemiethanol solvate **15** · HCl · 0.5EtOH) were synthesized according to Scheme 3, starting from tetramethoxysilane. Thus, treatment of $Si(OMe)_4$ with (4-chlorophenyl)magnesium bromide gave bis(4-chlorophenyl)-dimethoxysilane (**10**), which upon reaction with vinylmagnesium chloride afforded bis(4-chlorophenyl)divi- nylsilane (**11**). Treatment of **11** with hydrogen bromide, in the presence of dibenzoyl peroxide, yielded bis(2-bromoethyl)bis(4-chlorophenyl)silane (**12**) [6]. Cyclization of **12** with benzylamine, in the presence of triethylamine, followed by reaction with hydrogen choride, gave **13** · HCl. Treatment of **13** · HCl with sodium hydroxide (formation of **13**) and subsequent reaction



Scheme 1.



Scheme 2.

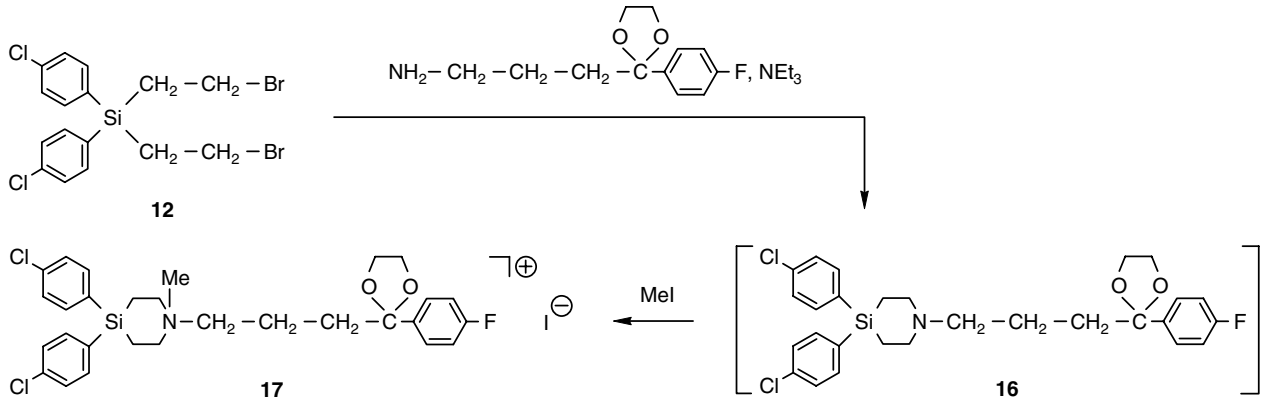


Scheme 3.

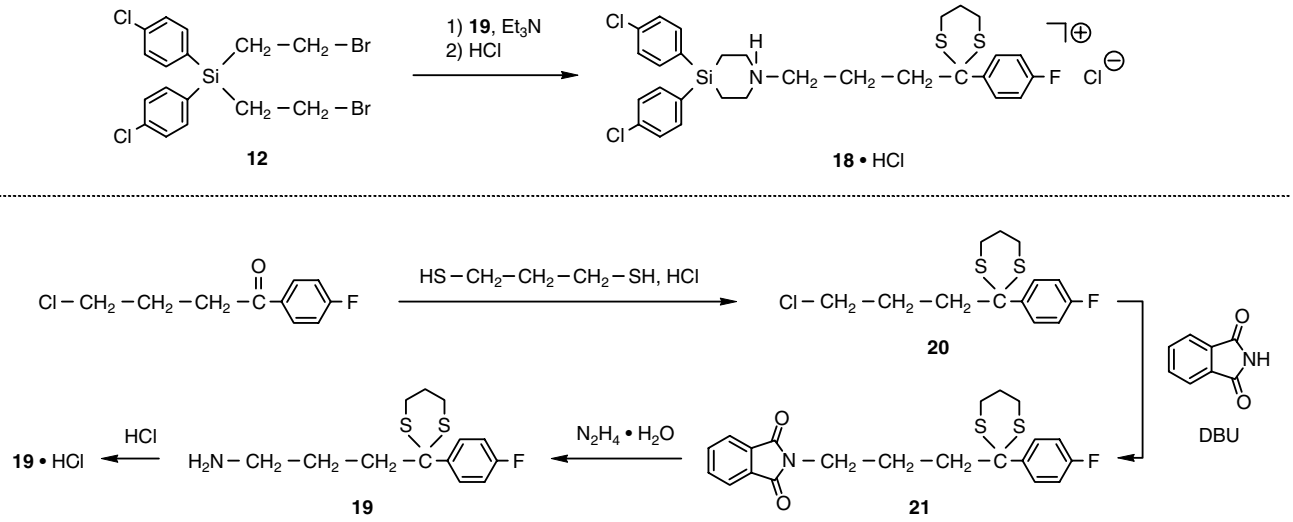
with 1-chloroethyl chloroformate [14] yielded 1-chloroethyl 4,4-bis(4-chlorophenyl)-4-silapiperidine-1-carboxylate (**14**; isolated as crude product, not purified and characterized), which upon reaction with methanol and recrystallization of the resulting product **15** · HCl from ethanol afforded **15** · HCl · 0.5EtOH.

4,4-Bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propyl}-1-methyl-4-silapiperidinium iodide (**17**) was synthesized according to Scheme 4, starting from **12**. Thus, cyclization of **12** with 3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propylamine [12], in the presence of triethylamine, gave 4,4-bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propyl}-4-silapiperidine (**16**; isolated as crude product, not purified and characterized), which upon treatment with methyl iodide afforded **17**. Crystallization of **17** from ethanol/ethyl acetate/water gave the hydrate **17** · H_2O.

4,4-Bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dithian-2-yl]propyl}-4-silapiperidinium chloride (**18** · HCl) was synthesized according to Scheme 5, starting from **12**. Thus, cyclization of **12** with 3-[2-(4-fluorophenyl)-1,3-dithian-2-yl]propylamine (**19**), in the presence of triethylamine, gave **18**, which upon treatment with hydrogen chloride afforded the hydrochloride **18** · HCl. Compound **19** was synthesized in three steps, starting from commercially available 4-chloro-1-(4-fluorophenyl)butan-1-one (Scheme 5). Thus, treatment of the ketone with propane-1,3-dithiol, in the presence of



Scheme 4.



Scheme 5.

hydrogen chloride, yielded 2-(3-chloropropyl)-2-(4-fluorophenyl)-1,3-dithiane (**20**), which upon reaction with phthalimide, in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), afforded 2-{3-[2-(4-fluorophenyl)-1,3-dithian-2-yl]propyl}phthalimide (**21**). Treatment of **21** with hydrazine hydrate finally gave **19**, which was converted to the hydrogen chloride **19** · HCl for analytical purposes.

Compounds **4** · HCl, **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17**, **17** · H_2O, **18** · HCl, **19** · HCl, **20**, and **21** were isolated as colorless solids, whereas **7** and **19** were obtained as highly viscous oils. The identities of all compounds were established by elemental analyses (C, H, N, S; except for **7** and **19**) and solution NMR studies (^{1}H, ^{13}C, ^{19}F, ^{29}Si). In addition, the crystal structures of **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl, **17** · H_2O, and **18** · HCl were determined.

2.2. Crystal structure analyses

Compounds **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl were structurally characterized by single-crystal X-ray diffraction. The crystal data and the experimental parameters used for the crystal structure analyses are summarized in Table 1; selected bond lengths and angles are given in Table 2. The molecular structures of the respective 4-silapiperidines and 4-silapiperidinium cations are depicted in Figs. 1–8.

As can be seen from Figs. 1–8, the 4-silapiperidine and 4-silapiperidinium skeletons of all compounds studied adopt a chair conformation, with very similar bond lengths and angles. The *N*-organyl groups of the 4-silapiperidine **9** and the 4-silapiperidinium derivatives **13** · HCl and **18** · HCl occupy the equatorial position. In the case of the 4-silapiperidinium derivatives **8** and **17** · H_2O, the *N*-methyl groups are found in the equatorial positions, whereas the axial sites are occupied by the larger *N*-organyl substituents. In the carbamate **5**, the nitrogen atom, the carbon atoms C14, C15, and C17, and the oxygen atoms O1 and O2 are localized in a plane (sum of angles at N, 359.9°; sum of angles at C17, 360.0°; maximum dihedral angle, 7.2° (C14–N–C17–O1)).

Table 1
Crystal data and experimental parameters for the crystal structure analyses of **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl

	5	**6** · HCl	**8**	**9**	**13** · HCl	**15** · HCl · 0.5EtOH	**17** · H_2O	**18** · HCl
Empirical formula	$C_{19}H_{20}Cl_3NO_2Si$	$C_{16}H_{20}ClNSi$	$C_{29}H_{35}FINO_2Si$	$C_{26}H_{28}FNOSi$	$C_{23}H_{24}Cl_3NSi$	$C_{17}H_{21}Cl_3NO_{0.5}Si$	$C_{29}H_{35}Cl_2FINO_3Si$	$C_{29}H_{33}Cl_3FNS_2Si$
Formula mass (g mol^{-1})	428.80	289.87	603.57	417.58	448.87	381.79	690.47	613.12
Collection T (K)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
λ (Mo Kα) (Å)	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073
Crystal system	Monoclinic	Orthorhombic	Monoclinic	Monoclinic	Orthorhombic	Triclinic	Triclinic	Orthorhombic
Space group (no.)	$P2_1c$ (14)	$Pna2_1$ (33)	$P2/n$ (13)	$P2_1c$ (14)	$P2_12_12_1$(19)	$P\bar{1}$ (2)	$P\bar{1}$ (2)	$Pbca$ (61)
a (Å)	8.6449(17)	9.3157(10)	12.9487(18)	19.065(4)	9.8970(7)	10.002(2)	8.4497(11)	13.2957(14)
b (Å)	11.318(2)	19.3055(17)	7.8525(8)	10.898(2)	11.0211(12)	11.169(2)	10.9075(19)	13.7808(11)
c (Å)	20.892(4)	8.8265(9)	27.881(4)	11.107(2)	20.4106(16)	18.382(4)	16.276(2)	31.808(2)
α (°)	90	90	90	90	90	93.87(3)	90.514(19)	90
β (°)	90.50(3)	90	95.032(17)	99.63(3)	90	99.96(3)	91.697(15)	90
γ (°)	90	90	90	90	90	112.85(3)	97.287(18)	90
V ($Å^3$)	2044.1(7)	1587.4(3)	2824.0(6)	2275.2(8)	2226.3(3)	1843.2(6)	1487.2(4)	5828.1(9)
Z	4	4	4	4	4	4	2	8
D_{calc} (g cm^{-3})	1.393	1.213	1.420	1.219	1.339	1.376	1.542	1.398
μ (mm^{-1})	0.520	0.303	1.208	0.128	0.475	0.562	1.334	0.526
$F(000)$	888	616	1232	888	936	796	700	2560
Crystal dimensions (mm)	$0.8 \times 0.7 \times 0.6$	$0.5 \times 0.5 \times 0.4$	$0.3 \times 0.2 \times 0.1$	$0.5 \times 0.3 \times 0.1$	$0.5 \times 0.5 \times 0.3$	$0.5 \times 0.5 \times 0.3$	$0.5 \times 0.3 \times 0.2$	$0.5 \times 0.2 \times 0.1$
2θ range (°)	4.72–56.10	4.86–53.96	3.60–49.92	4.32–49.42	4.20–51.92	4.52–49.42	4.50–53.54	4.44–52.78
Index ranges	$-11 \le h \le 11$, $-14 \le k \le 14$, $-27 \le l \le 25$	$-11 \le h \le 11$, $-23 \le k \le 24$, $-11 \le l \le 10$	$-15 \le h \le 15$, $-9 \le k \le 9$, $-33 \le l \le 32$	$-22 \le h \le 22$, $-12 \le k \le 12$, $-13 \le l \le 13$	$-12 \le h \le 11$, $-13 \le k \le 13$, $-25 \le l \le 25$	$-11 \le h \le 11$, $-13 \le k \le 13$, $-21 \le l \le 21$	$-10 \le h \le 9$, $-13 \le k \le 13$, $-20 \le l \le 20$	$-16 \le h \le 16$, $-17 \le k \le 17$, $-38 \le l \le 36$
Number of collected reflections	19801	10167	26127	16497	15552	17523	17144	38827
Number of independent reflections	4864	3127	4902	3857	4255	5911	5820	5888
R_{int}	0.0547	0.0412	0.0361	0.0353	0.0306	0.0493	0.0298	0.0747
Absorption correction	–	–	7 indexed faces	–	–	–	8 indexed faces	–
Maximum/minimum transmission	–	–	0.8389/0.5836	–	–	–	0.885/0.699	–
Number of reflections used	4864	3127	4902	3857	4255	5911	5820	5888
Number of restraints	–	1	–	–	–	–	–	–
Number of parameters	315	178	319	271	256	421	350	337
S[a]	1.042	1.032	1.031	1.033	1.030	1.015	1.070	1.020
Weight parameters a/b[b]	0.0562/0.5082	0.0549/0.0371	0.0419/0.8136	0.0523/0.2944	0.0319/0.5669	0.0742/0.0000	0.0477/1.0666	0.0755/0.1364
R_1[c] $[I > 2\sigma(I)]$	0.0371	0.0261	0.0251	0.0327	0.0225	0.0404	0.0296	0.0386
wR_2[d] (all data)	0.1022	0.0708	0.0680	0.0899	0.0596	0.1131	0.0830	0.1081
Absolute structure parameter	–	−0.04(5)	–	–	−0.04(4)	–	–	–
Maximum/minimum residual electron density (e $Å^{-3}$)	+0.494/−0.529	+0.255/−0.226	+0.389/−0.609	+0.246/−0.209	+0.256/−0.190	+0.525/−0.446	+0.743/−0.732	+0.466/−0.612

[a] $S = \{\sum[w(F_o^2 - F_c^2)^2]/(n-p)\}^{0.5}$; n = number of reflections; p = number of parameters.
[b] $w^{-1} = \sigma^2(F_o^2) + (aP)^2 + bP$, with $P = [\max(F_o^2, 0) + 2F_c^2]/3$.
[c] $R_1 = \sum||F_o| - |F_c||/\sum|F_o|$.
[d] $wR_2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{0.5}$.

Table 2
Selected bond lengths (Å) and angles (°) for compounds **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl

	5	**6** · HCl	**8**	**9**	**13** · HCl	**15** · HCl · 0.5EtOH		**17** · H_2O	**18** · HCl
Si–C1	1.8724(17)	1.8708(14)	1.875(2)	1.8752(16)	1.8753(14)	1.870(3)	[1.868(3)]	1.881(3)	1.872(2)
Si–C7	1.8680(16)	1.8566(14)	1.875(2)	1.8726(16)	1.8639(14)	1.859(3)	[1.861(3)]	1.865(3)	1.870(2)
Si–C13	1.8794(15)	1.8797(16)	1.8811(19)	1.8607(15)	1.8774(14)	1.866(3)	[1.861(3)]	1.877(2)	1.871(2)
Si–C16	1.8721(17)	1.8685(15)	1.8759(19)	1.8667(15)	1.8734(14)	1.865(3)	[1.871(3)]	1.875(2)	1.8697(19)
N–C14	1.464(2)	1.495(2)	1.525(2)	1.4704(18)	1.5072(17)	1.492(4)	[1.493(4)]	1.520(3)	1.499(2)
N–C15	1.4678(19)	1.495(2)	1.522(2)	1.4679(19)	1.5100(19)	1.490(4)	[1.496(4)]	1.522(3)	1.507(2)
N–C17	1.3389(19)	–	1.514(2)	1.4749(18)	1.5114(18)	–	–	1.520(3)	1.508(2)
N–C29	–	–	1.506(2)	–	–	–	–	1.507(3)	–
C13–C14	1.534(2)	1.521(2)	1.520(3)	1.530(2)	1.5212(19)	1.518(4)	[1.526(4)]	1.526(3)	1.521(3)
C15–C16	1.533(2)	1.520(2)	1.522(3)	1.534(2)	1.529(2)	1.511(4)	[1.515(4)]	1.524(3)	1.532(3)
C1–Si–C7	108.91(7)	112.28(6)	109.60(8)	110.09(7)	111.46(6)	111.94(11)	[108.57(11)]	110.61(11)	109.83(9)
C1–Si–C13	109.96(7)	109.80(7)	112.03(9)	109.07(7)	109.97(7)	109.88(13)	[110.30(12)]	110.54(12)	110.63(9)
C1–Si–C16	109.45(7)	108.97(7)	111.74 (9)	110.79(7)	111.62(7)	108.89(12)	[110.94(11)]	108.66(11)	110.42(9)
C7–Si–C13	111.99(7)	113.06(7)	108.45(9)	112.06(7)	109.48(6)	110.73(12)	[112.21(11)]	113.21(11)	109.27(9)
C7–Si–C16	112.46(7)	110.81(6)	111.76 (8)	113.78(7)	111.32(7)	112.00(12)	[111.10(12)]	112.58(12)	114.51(9)
C13–Si–C16	103.98(7)	101.33(7)	103.10(8)	100.67(7)	102.64(6)	103.03(13)	[103.70(12)]	100.83(10)	101.94(9)
C14–N–C15	116.90(13)	116.54(12)	110.77(13)	112.58(11)	112.77(11)	115.2(2)	[115.5(2)]	112.54(17)	112.23(14)
C14–N–C17	119.37(13)	–	109.77(14)	109.50(11)	111.76(11)	–	–	113.36(18)	111.76(13)
C15–N–C17	123.65(13)	–	112.55(14)	109.03(12)	109.02(11)	–	–	108.43(19)	108.35(13)
Si–C13–C14	110.27(10)	110.48(11)	115.58(13)	110.52(10)	112.12(10)	112.74(19)	[110.31(16)]	111.11(16)	113.53(13)
Si–C16–C15	110.22(11)	110.54(10)	112.47(13)	109.88(10)	113.32(10)	110.48(19)	[111.65(18)]	110.51(17)	111.85(12)
N–C14–C13	111.71(13)	112.95(12)	114.56(15)	112.98(12)	112.30(12)	113.0(2)	[111.7(2)]	115.9(2)	112.29(15)
N–C15–C16	111.94(13)	112.32(13)	114.53(15)	114.38(12)	113.10(11)	112.6(2)	[112.2(2)]	115.14(18)	113.18(15)
C14–N–C29	–	–	105.81(14)	–	–	–	–	106.56(19)	–
C15–N–C29	–	–	108.35(14)	–	–	–	–	106.11(18)	–
C17–N–C29	–	–	109.33(13)	–	–	–	–	109.56(17)	–

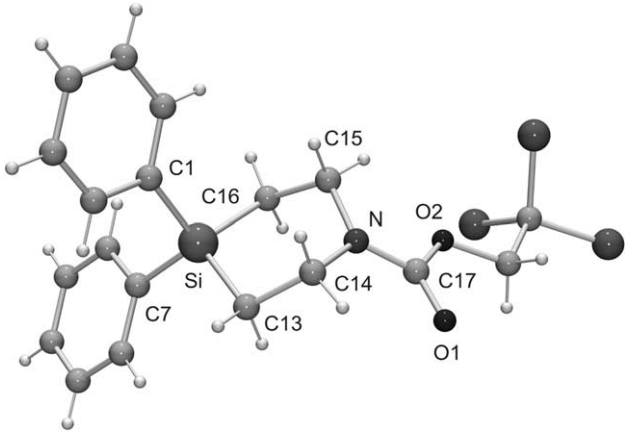


Fig. 1. Molecular structure of **5** in the crystal.

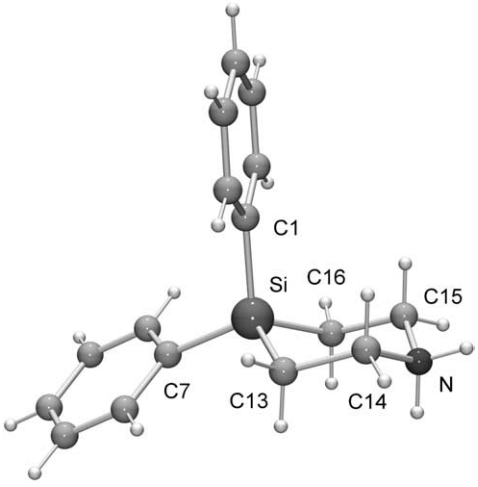


Fig. 2. Structure of the cation in the crystal of **6** · HCl.

The crystal structures of **6** · HCl, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl are governed by hydrogen bonds [15]. In the case of **6** · HCl, the cations and anions form intermolecular N–H···Cl hydrogen bonds, resulting in the formation of infinite chains along [1 0 0] (Fig. 9). Discrete ion pairs built up by N–H···Cl hydrogen bonds are found in case of **13** · HCl (N–H 0.933(18) Å, H···Cl 2.139(18) Å, N···Cl 3.0458(13) Å, N–H···Cl 163.8(16)°), whereas the crystal structure of **15** · HCl · 0.5EtOH is characterized by intermolecular N–H···Cl and O–H···Cl hydrogen bonds, resulting in the formation of centrosymmetric units consisting of two pairs of 4-silapiperidinium cations, four chloride anions, and two ethanol molecules (Fig. 10). For the hydrate **17** · H_2O, intermolecular O–H···O and O–H···I hydrogen bonds are found, by which the water molecule connects the 4-silapiperidinium cation and the iodide anion (Fig. 11). Compound **18** · HCl forms

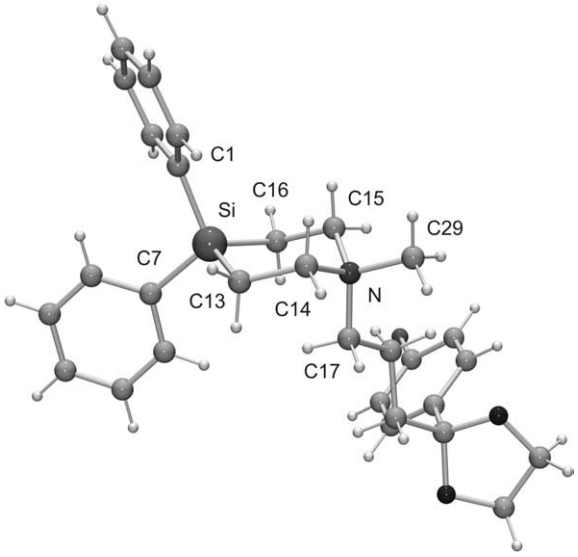


Fig. 3. Structure of the cation in the crystal of **8**.

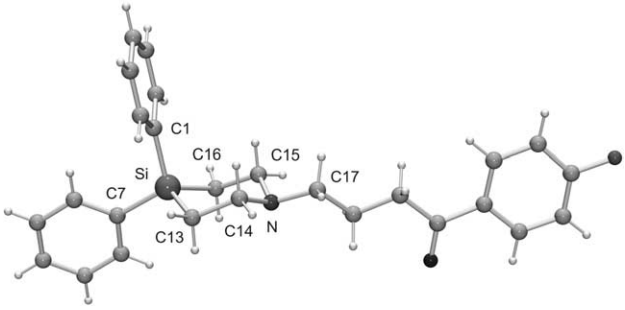


Fig. 4. Molecular structure of **9** in the crystal.

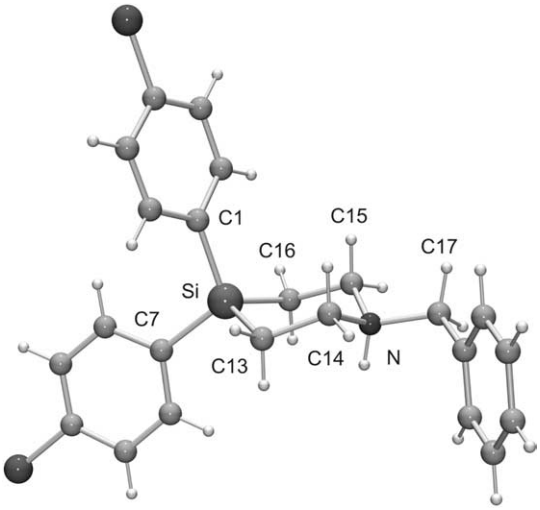


Fig. 5. Structure of the cation in the crystal of **13** · HCl.

discrete ion pairs, built by N–H···Cl hydrogen bonds (N–H 1.02(2) Å, H···Cl 2.01(2) Å, N···Cl 3.0236(16) Å, N–H···Cl 171.9(19)°).

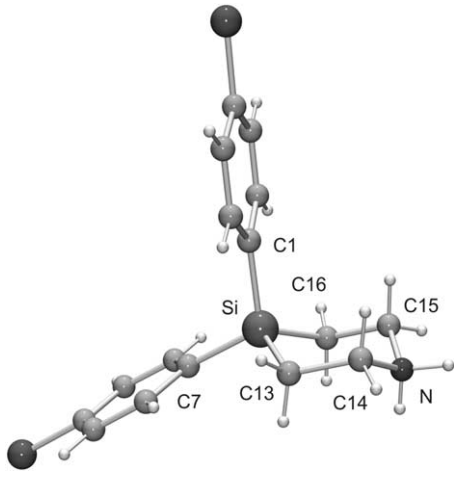


Fig. 6. Structure of one of the two cations in the asymmetric unit in the crystal of **15** · HCl · 0.5EtOH. The structure of the other cation (not depicted) is very similar.

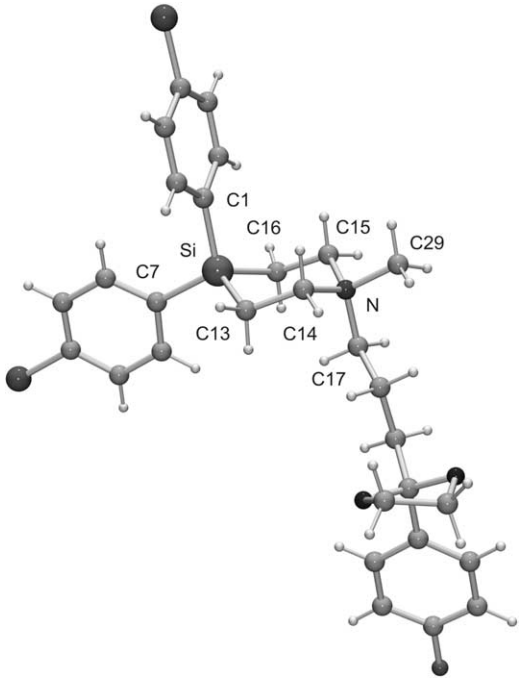


Fig. 7. Structure of the cation in the crystal of **17** · H_2O.

3. Conclusions

In this study, a series of 4-silapiperidine and 4-silapiperidinium derivatives, with two silicon-bound aryl groups and various *N*-organyl groups, were synthesized and structurally characterized by solution NMR spectroscopy and single-crystal X-ray diffraction. These investigations and the studies already reported in [6] provide the basis for the development of further silicon-based drugs containing a 4-silapiperidine or 4-silapiperidinium skeleton. As demonstrated in [6], the silicon-bound aryl groups can be removed with strong acids, such as

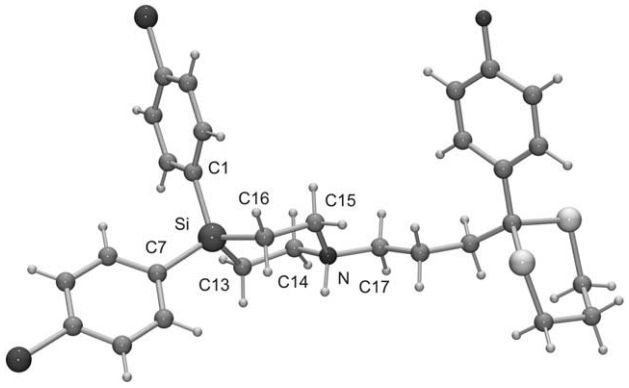


Fig. 8. Structure of the cation in the crystal of **18** · HCl.

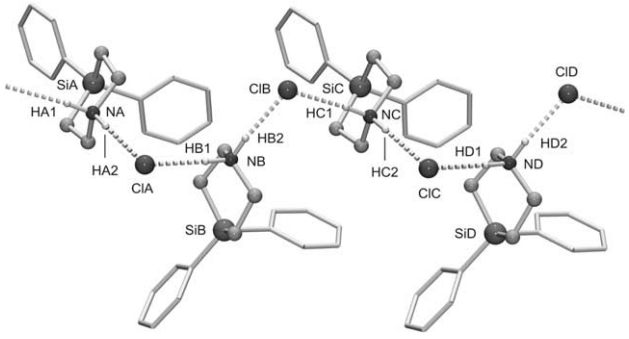


Fig. 9. Hydrogen-bonding system in the crystal of **6** · HCl. Selected distances (Å) and angles (°): NA–HA2 0.919(19), HA2···ClA 2.161(19), NA···ClA 3.0574(15), NA–HA2···ClA 164.54(16); NB–HB1 0.95(2), HB1···ClA 2.13(2), NB···ClA 3.0766(13), NB–HB1···ClA 175(2) [15]. The hydrogen atoms (except for N*H*) are omitted for clarity.

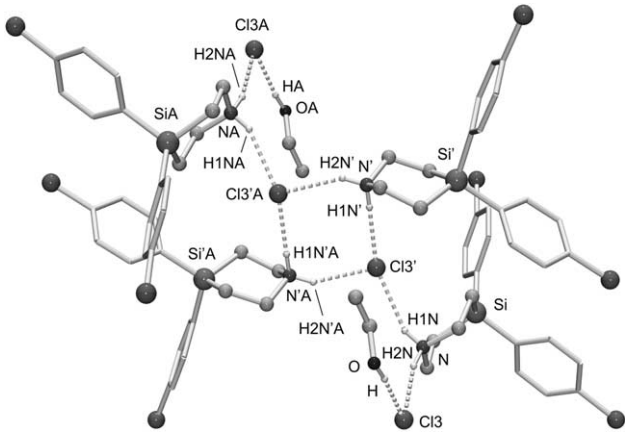


Fig. 10. Hydrogen-bonding system in the crystal of **15** · HCl · 0.5EtOH. Selected distances (Å) and angles (°): O–H 0.84, H···Cl3 2.24, O···Cl3 3.077(5), O–H···Cl3 173; N–H1N 0.85(4), H1N···Cl3′ 2.43(4), N···Cl3′ 3.208(2), N–H1N···Cl3′ 153(4); N–H2N 1.00(4), H2N···Cl3 2.12(4), N···Cl3 3.073(3), N–H2N···Cl3 161(3); N′–H1N′ 0.83(4), H1N′···Cl3′ 2.32(4), N′···Cl3′ 3.143(3), N′–H1N′···Cl3′ 179(5); N′–H2N′ 0.87(3), H2N′···Cl3′A 2.35(4), N′···Cl3′A 3.123(3), N′–H2N′···Cl3′A 149(3) [15]. The hydrogen atoms (except for N*H* and O*H*) are omitted for clarity.

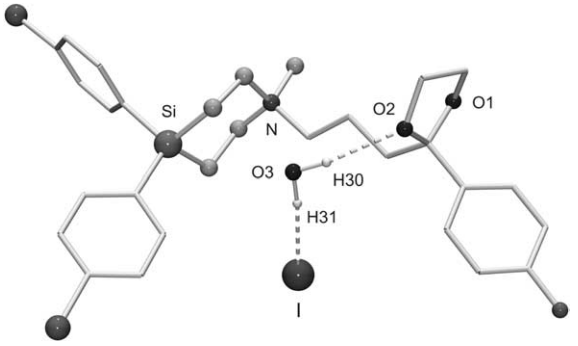


Fig. 11. Hydrogen-bonding system in the crystal of **17** · H_2O. Selected distances (Å) and angles (°): O3–H30 0.92(3), H30···O2 2.25(3), O3···O2 3.101(3), O3–H30···O2 154(3); O3–H31 0.97(4), H31···I 2.65(4), O3···I 3.600(2), O3–H31···I 169(3) [15]. The hydrogen atoms (except for O*H*) are omitted for clarity.

trifluoromethanesulfonic acid, to generate Si-functionalized 4-silapiperidine and 4-silapiperidinium derivatives.

4. Experimental

4.1. Syntheses

4.1.1. General procedures

All syntheses were carried out under dry nitrogen. Acetone, acetonitrile, benzylamine, dichloromethane, diethyl ether, dimethylformamide (DMF), ethanol, methanol, *n*-pentane, 2-propanol, tetrahydrofuran (THF), toluene, trichloromethane, and triethylamine were dried and purified according to standard procedures and stored under nitrogen. A Büchi GKR 50 apparatus was used for the bulb-to-bulb (Kugelrohr) distillations. Melting points were determined with a Büchi Melting Point B-540 apparatus using samples in open glass capillaries. ^{1}H, ^{13}C, ^{19}F, and ^{29}Si NMR spectra were recorded at 22 °C on a Bruker DRX-300 NMR spectrometer (^{1}H, 300.1 MHz; ^{13}C, 75.5 MHz; ^{19}F, 282.4 MHz; ^{29}Si, 59.6 MHz) or a Bruker AMX-400 NMR spectrometer (^{1}H, 400.1 MHz; ^{13}C, 100.6 MHz) using $CDCl_3$, [D_6]DMSO, or C_6D_6 as the solvent. Chemical shifts (ppm) were determined relative to internal $CHCl_3$ (^{1}H, δ 7.24; $CDCl_3$), internal [D_5]DMSO (^{1}H, δ 2.49; [D_6]DMSO), internal C_6D_5H (^{1}H, δ 7.28; C_6D_6), internal $CDCl_3$ (^{13}C, δ 77.0; $CDCl_3$), internal [D_6]DMSO (^{13}C, δ 39.5; [D_6]DMSO), internal C_6D_6 (^{13}C, δ 128.0; C_6D_6), external $CFCl_3$ (^{19}F, δ 0), or external TMS (^{29}Si, δ 0). Analysis and assignment of the ^{1}H NMR data were supported by ^{1}H,^{1}H COSY and ^{29}Si,^{1}H COSY experiments. Assignment of the ^{13}C NMR data was supported by DEPT 135, ^{13}C,^{1}H HMQC, and ^{13}C,^{1}H HMBC experiments.

*4.1.2. Diphenyldivinylsilane (**2**)*

This compound was synthesized from commercially available dichlorodiphenylsilane according to [9].

*4.1.3. Bis(2-bromoethyl)diphenylsilane (**3**)*

This compound was synthesized from **2** according to [1].

*4.1.4. 1-Benzyl-4,4-diphenyl-4-silapiperidinium chloride (**4** · HCl)*

Following the procedure given in [1], a mixture of **3** (30.0 g, 75.3 mmol), benzylamine (80.0 g, 747 mmol), triethylamine (23.0 g, 227 mmol), and trichloromethane (700 ml) was heated under reflux for 16 h. After the mixture was cooled to 20 °C, water (500 ml) was added. The organic phase was separated, the aqueous layer was extracted with trichloromethane (2 × 300 ml), the combined organic extracts were dried over anhydrous sodium sulfate, the solvent and the excess benzylamine and triethylamine were removed under reduced pressure, and the highly viscous residue was dissolved in acetone (60 ml). A 2.0 M ethereal hydrogen chloride solution (40.0 ml, 80.0 mmol of HCl) was added dropwise at 20 °C, and the mixture was stirred at this temperature for 24 h. The resulting precipitate was isolated by filtration and recrystallized from 2-propanol (slow cooling of a saturated boiling solution to 20 °C) to give **4** · HCl in 75% yield as a colorless crystalline solid (21.5 g, 56.6 mmol); m.p. 210 °C. ^{1}H NMR (300.1 MHz, [D$_6$]DMSO): δ 1.55–1.70 (m, 2H, SiCH_AH$_B$CH$_2$N), 1.81–1.98 (m, 2H, SiCH$_A$$H_BCH_2$N), 2.90–3.08 (m, 2H, SiCH$_2$CH_AH$_B$N), 3.53–3.67 (m, 2H, SiCH$_2$CH$_A$$H_B$N), 4.31 (d, $^{2}J_{HH}$ = 5.2 Hz, 2H, NCH_2C$_6$H$_5$), 7.32–7.54 and 7.65–7.73 (m, 15H, SiC$_6$$H_5$, CH$_2C_6$$H_5$), 11.4 (br s, 1H, N$H$). ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ 7.7 (SiC_2CH$_2$N), 51.2 (SiCH$_2$$CH_2$N), 58.8 (NCH$_2C_6H_5$), 128.1 (*C*-3/*C*-5, SiC$_6$H$_5$), 128.4 (*C*-3′/*C*-5′, SiC$_6$H$_5$), 128.7 (*C*-2/*C*-6, CH$_2$C$_6$H$_5$), 129.3 (*C*-4, CH$_2$C$_6$H$_5$), 130.0 (*C*-4, SiC$_6$H$_5$), 130.2 (*C*-4′, SiC$_6$H$_5$), 130.4 (*C*-1, CH$_2$C$_6$H$_5$), 131.4 (*C*-3/*C*-5, CH$_2$C$_6$H$_5$), 131.5 (*C*-1, SiC$_6$H$_5$), 133.8 (*C*-1′, SiC$_6$H$_5$), 134.3 (*C*-2/*C*-6, SiC$_6$H$_5$), 134.7 (*C*-2′/*C*-6′, SiC$_6$H$_5$). ^{29}Si NMR ([D$_6$]DMSO): δ −17.4. Anal. Found: C, 72.1; H, 6.9; N, 3.7. Calc. for C$_{23}$H$_{26}$ClNSi: C, 72.70; H, 6.90; N, 3.69%.

*4.1.5. 2,2,2-Trichloroethyl 4,4-diphenyl-4-silapiperidine-1-carboxylate (**5**)*

Compound **4** · HCl (16.5 g, 43.4 mmol) was added at 20 °C to a mixture of a 2 M aqueous sodium hydroxide solution (60 ml) and diethyl ether (80 ml), and the resulting mixture was stirred at 20 °C for 30 min. The organic phase was separated, the aqueous layer was extracted with diethyl ether (2 × 100 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was then subjected to a Kugelrohr distillation (220 °C/0.01 mbar) to give **4** in 92% yield as an oily liquid (13.7 g, 39.9 mmol). A solution of **4** and 2,2,2-trichloroethyl chloroformate (10.0 g, 47.2 mmol) in THF (100 ml) was then heated under reflux for 48 h. After the mixture was cooled to 20 °C, the volatile components were removed by distillation in vacuo, and the oily residue was dissolved in boiling 2-propanol. Slow cooling of this solution to 20 °C gave **5** in 78% yield as a colorless crystalline solid (14.5 g, 33.8 mmol); m.p. 121 °C. ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 1.35–1.48 (m, 4H, SiCH_2CH$_2$N), 3.70–3.86 (m, 4H, SiCH$_2$CH_2N), 4.78 (s, 2H, OCH_2C), 7.31–7.48 (m, 6H, *H*-3/*H*-4/*H*-5, SiC$_6$H$_5$), 7.49–7.58 (m, 4H, *H*-2/*H*-6, SiC$_6$H$_5$). ^{13}C NMR (75.5 MHz, CDCl$_3$): δ 11.4 and 12.0 (SiCH$_2$CH$_2$N), 44.1 and 44.5 (SiCH$_2$$CH_2$N), 75.0 (OCH$_2$C), 95.9 (C$C$ Cl$_3$), 128.2 (*C*-3/*C*-5, SiC$_6$H$_5$), 129.9 (*C*-4, SiC$_6$H$_5$), 134.46 (*C*-1, SiC$_6$H$_5$), 134.55 (*C*-2/*C*-6, SiC$_6$H$_5$), 153.8 (*C*O). ^{29}Si NMR (CDCl$_3$): δ −14.4. Anal. Found: C, 53.2; H, 4.6; N, 2.9. Calc. for C$_{19}$H$_{20}$Cl$_3$NO$_2$Si: C, 53.22; H, 4.70; N, 3.27%.

*4.1.6. 4,4-Diphenyl-4-silapiperidinium chloride (**6** · HCl)*

A mixture of **5** (13.2 g, 30.8 mmol), zinc powder (10.0 g, 153 mmol), and acetic acid (100 ml) was stirred at 20 °C for 48 h. The solid components were removed by filtration, and the filtrate was concentrated under reduced pressure to a volume of ca. 25 ml, followed by the addition of a 6 M aqueous sodium hydroxide solution (200 ml). The mixture was stirred at 20 °C for 10 min and was then extracted with diethyl ether (3 × 150 ml). The combined organic extracts were dried over anhydrous sodium sulfate, half of the solvent was removed under reduced pressure, and a 2 M ethereal hydrogen chloride solution (20.0 ml, 40.0 mmol of HCl) was added to the stirred mixture at 20 °C. The resulting precipitate was isolated by filtration and recrystallized from ethanol (slow cooling of a saturated boiling solution to 20 °C) to give **6** · HCl in 84% yield as a colorless crystalline solid (7.50 g, 25.9 mmol); m.p. 223–224 °C. ^{1}H NMR (300.1 MHz, CDCl$_3$): δ 1.65–1.81 (m, 4H, SiCH_2CH$_2$N), 3.33–3.50 (m, 4H, SiCH$_2$CH_2N), 7.33–7.47 (m, 6H, *H*-3/*H*-4/*H*-5, SiC$_6$H$_5$), 7.50–7.58 (m, 4H, *H*-2/*H*-6, SiC$_6$H$_5$), 9.6 (br s, 2H, NH_2). ^{13}C NMR (75.5 MHz, CDCl$_3$): δ 9.0 (SiCH$_2$CH$_2$N), 44.1 (SiCH$_2$$CH_2$N), 128.4 (*C*-3/*C*-5, SiC$_6$H$_5$), 130.4 (*C*-4, SiC$_6$H$_5$), 131.8 (*C*-1, SiC$_6$H$_5$), 134.6 (*C*-2/*C*-6, SiC$_6$H$_5$). ^{29}Si NMR (CDCl$_3$): δ −16.6. Anal. Found: C, 66.2; H, 6.8; N, 4.8. Calc. for C$_{16}$H$_{20}$ClNSi: C, 66.30; H, 6.95; N, 4.83%.

*4.1.7. 1-{3-[2-(4-Fluorophenyl)-1,3-dioxolan-2-yl]propyl}-4,4-diphenyl-4-silapiperidine (**7**)*

Method A: A mixture of **3** (5.00 g, 12.6 mmol), 3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propylamine [12] (3.40 g, 15.1 mmol), triethylamine (3.00 g, 29.6 mmol), acetonitrile (30 ml), and toluene (30 ml) was heated in

a 250-ml autoclave at 90 °C for 16 h. After the mixture was cooled to 20 °C, the precipitate was removed by filtration, and water (60 ml) was added to the filtrate. The organic phase was separated, the aqueous layer was extracted with toluene (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was then subjected to a Kugelrohr distillation (250 °C/0.01 mbar) to give **8** in 67% yield as a highly viscous liquid (3.90 g, 8.45 mmol). ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 1.25–1.40 (m, 4H, $SiCH_2CH_2N$), 1.47–1.62 (m, 2H, $NCH_2CH_2CH_2C$), 1.80–1.92 (m, 2H, $NCH_2CH_2CH_2C$), 2.36–2.47 (m, 2H, $NCH_2CH_2CH_2C$), 2.73–2.86 (m, 4H, $SiCH_2CH_2N$), 3.68–3.80 and 3.93–4.06 (m, 4H, OCH_2CH_2O), 6.95–7.05 (m, 2H, *H*-3/*H*-5, CC_6H_4F), 7.30–7.47 (m, 8H, *H*-3/*H*-4/*H*-5, SiC_6H_5, *H*-2/*H*-6, CC_6H_4F), 7.48–7.56 (m, 4H, *H*-2/*H*-6, SiC_6H_5). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 11.0 ($SiCH_2CH_2N$), 21.2 ($NCH_2CH_2CH_2C$), 38.5 ($NCH_2CH_2CH_2C$), 52.1 ($SiCH_2CH_2N$), 57.9 ($NCH_2CH_2CH_2C$), 64.5 (OCH_2CH_2O), 110.1 (C_2CO_2), 114.9 (d, $^{2}J_{CF}$ = 21.4 Hz, *C*-3/*C*-5, CC_6H_4F), 127.5 (d, $^{3}J_{CF}$ = 8.4 Hz, *C*-2/C-6, CC_6H_4F), 127.9 (*C*-3/*C*-5, SiC_6H_5), 129.4 (*C*-4, SiC_6H_5), 134.7 (*C*-2/*C*-6, SiC_6H_5), 135.6 (*C*-1, SiC_6H_5), 138.5 (d, $^{4}J_{CF}$ = 2.9 Hz, *C*-1, CC_6H_4F), 162.4 (d, $^{1}J_{CF}$ = 245.6 Hz, *C*-4, CC_6H_4F). ^{19}F NMR ($CDCl_3$): δ −115.5. ^{29}Si NMR ($CDCl_3$): δ −15.3. $C_{28}H_{32}FNO_2Si$. An elemental analysis was not performed because of the high viscosity of the product; instead, the methylammonium iodide **8** was analyzed (see below).

Method B: Compound **6** · HCl (4.00 g, 13.8 mmol) was added at 20 °C to a mixture of a 2 M aqueous sodium hydroxide solution (30 ml) and diethyl ether (40 ml), and the resulting mixture was stirred at 20 °C for 30 min. The organic phase was separated, the aqueous layer was extracted with diethyl ether (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was then subjected to a Kugelrohr distillation (180°C/0.01 mbar) to give **6** in 95% yield as an oily liquid (3.29 g, 13.1 mmol). A mixture of **6**, 2-(3-chloropropyl)-2-(4-fluorophenyl)-1,3-dioxolane (3.20 g, 13.1 mmol), potassium iodide (500 mg, 3.01 mmol), potassium carbonate (2.50 g, 18.1 mmol), and acetonitrile (60 ml) was heated in a 250-ml autoclave at 100 °C for 18 h. After the mixture was cooled to 20 °C, the precipitate was separated by filtration, and the solvent of the filtrate was removed under reduced pressure, followed by the addition of a 0.1 M aqueous sodium hydroxide solution (60 ml) and diethyl ether (100 ml). The organic phase was separated, the aqueous layer was extracted with diethyl ether (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was then subjected to a Kugelrohr distillation (250 °C/0.01 mbar) to give **7** in 42% yield as a highly viscous liquid (2.70 g, 5.85 mmol). $C_{28}H_{32}FNO_2Si$. The NMR-spectroscopic data of the product were identical with those obtained for the product synthesized according to *Method A*. An elemental analysis was not performed because of the high viscosity of the product; instead, the methylammonium iodide **8** was analyzed (see below).

*4.1.8. 1-{3-[2-(4-Fluorophenyl)-1,3-dioxolan-2-yl]propyl}-1-methyl-4,4-diphenyl-4-silapiperidinium iodide (**8**)*

Methyl iodide (1.54 g, 10.8 mmol) was added at 20 °C to a solution of **7** (1.00 g, 2.17 mmol) in acetone (20 ml), and the resulting mixture was stirred at 20 °C for 24 h. The solvent and the excess methyl iodide were removed under reduced pressure, and the solid residue was dried in vacuo and then recrystallized from ethanol/ethyl acetate (2:1 (v/v)) (slow cooling of a saturated boiling solution to 0 °C) to give **8** in 88% yield as a colorless crystalline solid (1.15 g, 1.91 mmol); m.p. 186–187 °C. ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 1.51–1.75 (m, 4H, $SiCH_2CH_2N$), 1.78–2.03 (m, 4H, $NCH_2CH_2CH_2C$, $NCH_2CH_2CH_2C$), 3.34 (s, 3H, NCH_3), 3.57–4.04 (m, 10H, OCH_2CH_2O, $SiCH_2CH_2N$, $NCH_2CH_2CH_2C$), 6.89–6.98 (m, 2H, *H*-3/*H*-5, CC_6H_4F), 7.27–7.55 (m, 12H, SiC_6H_5, *H*-2/*H*-6, CC_6H_4F). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 6.7 ($SiCH_2CH_2N$), 16.5 ($NCH_2CH_2CH_2C$), 36.0 ($NCH_2CH_2CH_2C$), 50.1 (NCH_3), 60.7 (NCH_2CH_2-CH_2C), 61.1 ($SiCH_2CH_2N$), 64.4 (OCH_2CH_2O), 109.0 (C_2CO_2), 115.1 (d, $^{2}J_{CF}$ = 21.4 Hz, *C*-3/*C*-5, CC_6H_4F), 127.3 (d, $^{3}J_{CF}$ = 8.4 Hz, *C*-2/*C*-6, CC_6H_4F), 128.6 (*C*-3/*C*-5, SiC_6H_5), 128.7 (*C*-3′/*C*-5′, SiC_6H_5), 130.6 (*C*-1, SiC_6H_5), 130.78 (*C*-4, SiC_6H_5), 130.80 (*C*-4′, SiC_6H_5), 131.2 (*C*-1′, SiC_6H_5), 134.2 (*C*-2/*C*-6, SiC_6H_5), 134.4 (*C*-2′/*C*-6′, SiC_6H_5), 137.5 (d, $^{4}J_{CF}$ = 2.9 Hz, *C*-1, CC_6H_4F), 162.5 (d, $^{1}J_{CF}$ = 246.7 Hz, *C*-4, CC_6H_4F). ^{19}F NMR ($CDCl_3$): δ −114.5. ^{29}Si NMR ($CDCl_3$): δ −22.1. Anal. Found: C, 57.5; H, 5.8; N, 2.4. Calc. for $C_{29}H_{35}FINO_2Si$: C, 57.71; H, 5.84; N, 2.32%.

*4.1.9. 1-[4-Oxo-4-(4-fluorophenyl)butyl]-4,4-diphenyl-4-silapiperidine (**9**)*

2 M hydrochloric acid (2 ml) was added to a solution of **7** (1.50 g, 3.25 mmol) in acetone (20 ml), and the mixture was then heated at 60 °C for 2 h. After the mixture was cooled to 20 °C, a 6 M aqueous sodium hydroxide solution (6 ml) and toluene (40 ml) were added. The organic phase was separated, the aqueous layer was extracted with toluene (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, the residue was dissolved in 2-propanol (7 ml), and the resulting solution was then kept undisturbed at −20 °C for three days to give **9** in

88% yield as a colorless crystalline solid (1.20 g, 2.87 mmol); m.p. 82 °C. ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 1.27–1.45 (m, 4H, $SiCH_2CH_2N$), 1.90–2.06 (m, 2H, $NCH_2CH_2CH_2C$), 2.50–2.63 (m, 2H, $NCH_2CH_2CH_2C$), 2.80–2.97 (m, 4H, $SiCH_2CH_2N$), 2.98 (t, $^{3}J_{HH}$ = 6.9 Hz, 2H, $NCH_2CH_2CH_2C$), 7.06–7.14 (m, 2H, *H*-3/*H*-5, CC_6H_4F), 7.31–7.42 (m, 6H, *H*-3/*H*-4/*H*-5, SiC_6H_5), 7.47–7.53 (m, 4H, *H*-2/*H*-6, SiC_6H_5), 7.95–8.03 (m, 2H, *H*-2/*H*-6, CC_6H_4F). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 10.7 ($SiCH_2CH_2N$), 21.7 ($NCH_2CH_2CH_2C$), 36.2 ($NCH_2CH_2CH_2C$), 52.3 ($SiCH_2CH_2N$), 57.0 ($NCH_2CH_2CH_2C$), 115.6 (d, $^{2}J_{CF}$ = 21.8 Hz, *C*-3/*C*-5, CC_6H_4F), 130.7 (d, $^{3}J_{CF}$ = 9.1 Hz, *C*-2/*C*-6, CC_6H_4F), 128.0 (*C*-3/*C*-5, SiC_6H_5), 129.6 (*C*-4, SiC_6H_5), 133.6 (d, $^{4}J_{CF}$ = 3.3 Hz, *C*-1, CC_6H_4F), 134.7 (*C*-1/*C*-2/*C*-6, SiC_6H_5), 165.7 (d, $^{1}J_{CF}$ = 254.3 Hz, *C*-4, CC_6H_4F), 198.4 (*CO*). ^{19}F NMR ($CDCl_3$): δ −106.1. ^{29}Si NMR ($CDCl_3$): δ −15.6. Anal. Found: C, 74.6; H, 6.8; N, 3.1. Calc. for $C_{26}H_{28}FNOSi$: C, 74.78, H, 6.76; N, 3.35%.

4.1.10. Bis(4-chlorophenyl)dimethoxysilane (10)

This compound was prepared from tetramethoxysilane according to [6].

4.1.11. Bis(4-chlorophenyl)divinylsilane (11)

This compound was prepared from **10** according to [6].

4.1.12. Bis(2-bromoethyl)bis(4-chlorophenyl)silane (12)

This compound was prepared from **11** according to [6].

4.1.13. 1-Benzyl-4,4-bis(4-chlorophenyl)-4-silapiperidinium chloride (13 · HCl)

A mixture of **12** (5.00 g, 10.7 mmol), benzylamine (14.9 g, 139 mmol), triethylamine (3.00 g, 29.6 mmol), and trichloromethane (100 ml) was heated under reflux for 16 h. After the mixture was cooled to 20 °C, water (100 ml) was added. The organic phase was separated, the aqueous layer was extracted with trichloromethane (2 × 50 ml), the combined organic extracts were dried over anhydrous sodium sulfate, the solvent and the excess benzylamine and triethylamine were removed under reduced pressure, and the highly viscous residue was dissolved in acetone (5 ml). A 2.0 M ethereal hydrogen chloride solution (6.0 ml, 12.0 mmol of HCl) was added dropwise at 20 °C, and the mixture was stirred at this temperature for 24 h. The resulting precipitate was isolated by filtration and recrystallized from 2-propanol by slow evaporation of the solvent at 20 °C to give **13** · HCl in 65% yield as a colorless crystalline solid (3.10 g, 6.91 mmol); m.p. 220–221 °C (dec.). ^{1}H NMR (300.1 MHz, [D$_6$]DMSO): δ 1.57–1.73 (m, 2H, $SiCH_AH_BCH_2N$), 1.82–2.00 (m, 2H, $SiCH_AH_BCH_2N$), 2.90–3.08 (m, 2H, $SiCH_2CH_AH_BN$), 3.52–3.67 (m, 2H, $SiCH_2CH_AH_BN$), 4.30 (d, $^{3}J_{HH}$ = 5.2 Hz, 2H, $NCH_2C_6H_5$), 7.37–7.58 and 7.62–7.78 (m, 13H, SiC_6H_4Cl, CC_6H_5), 11.5 (br s, 1H, N*H*). ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ 7.6 ($SiCH_2CH_2N$), 51.0 ($SiCH_2CH_2N$), 58.9 ($NCH_2CH_2CH_2C$), 128.2 (*C*-3/*C*-5, SiC_6H_4Cl), 128.5 (*C*-3′/*C*-5′, SiC_6H_4Cl), 128.7 (*C*-2/*C*-6, CC_6H_5), 129.3 (*C*-4, CC_6H_5), 130.1 (*C*-1, SiC_6H_4Cl), 130.4 (*C*-1, CC_6H_5), 131.4 (*C*-3/*C*-5, CC_6H_5), 132.4 (*C*-1′, SiC_6H_4Cl), 135.5 (*C*-4, SiC_6H_4Cl), 135.7 (*C*-4′, SiC_6H_4Cl), 136.2 (*C*-2/*C*-6, SiC_6H_4Cl), 136.7 (C-2′/C-6′, SiC_6H_4Cl). ^{29}Si NMR ([D$_6$]DMSO): δ −16.3. Anal. Found: C, 61.2; H, 5.5; N, 3.1. Calc. for $C_{23}H_{24}Cl_3NSi$: C, 61.54; H, 5.39; N, 3.12%.

4.1.14. 4,4-Bis(4-chlorophenyl)-4-silapiperidinium chloride–semiethanol (15 · HCl · 0.5EtOH)

Compound **13** · HCl (2.50 g, 5.57 mmol) was added at 20 °C to a mixture of a 2 M aqueous sodium hydroxide solution (25 ml) and diethyl ether (50 ml), and the resulting mixture was stirred at 20 °C for 30 min. The organic phase was separated, the aqueous layer was extracted with diethyl ether (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was then subjected to a Kugelrohr distillation (220 °C/0.002 mbar) to give **13** in 91% yield as an oily liquid (2.10 g, 5.09 mmol). 1-Chloroethyl chloroformate (750 mg, 5.25 mmol) was added dropwise within 5 s at 0 °C to a stirred solution of **13** in trichloromethane (30 ml). The mixture was stirred at 0 °C for 10 min and then at 65 °C for a further 50 min. After the mixture was cooled to 20 °C, the solvent was removed under reduced pressure, and the residue (1-chloroethyl-4,4-bis(4-chlorophenyl)-4-silapiperidine-1-carboxylate (**14**; crude product, not purified)) was dissolved in methanol (20 ml), and the resulting solution was stirred under reflux for 60 min (formation of a precipitate). Approximately 10 ml of the methanol were distilled off, and the mixture was then kept undisturbed at −20 °C for 24 h. The precipitate was isolated by filtration and recrystallized from ethanol (slow cooling of a saturated boiling solution to 20 °C) to give **15** · HCl · 0.5EtOH in 68% yield as a colorless crystalline solid (1.45 g, 3.80 mmol); m.p. 261–262 °C (dec.). ^{1}H NMR (400.1 MHz, $CDCl_3$): δ 1.44 (t, $^{3}J_{HH}$ = 7.0 Hz, 1.5H, CH_3CH_2OH), 1.90–2.00 (m, 4H, $SiCH_2CH_2N$), 2.8 (br s, 0.5H, CH_3CH_2OH), 3.57–3.69 (m, 4H, $SiCH_2CH_2N$), 3.92 (q, $^{3}J_{HH}$ = 7.0 Hz, 1H, CH_3CH_2OH), 7.58–7.63 and 7.66–7.71 (m, 8H, SiC_6H_4Cl), 9.9 (br s, 2H, NH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ 8.8 ($SiCH_2CH_2N$), 18.3 (CH_3CH_2OH), 44.1 ($SiCH_2CH_2N$), 58.3 (CH_3CH_2OH) 128.9 (*C*-3/*C*-5, SiC_6H_4Cl), 129.7 (*C*-1, SiC_6H_4Cl), 135.9 (*C*-2/*C*-6, SiC_6H_4Cl), 137.2 (*C*-4, SiC_6H_4Cl). ^{29}Si NMR

($CDCl_3$): δ −16.0. Anal. Found: C, 53.3; H, 5.5; N, 3.7. Calc. for $C_{17}H_{21}Cl_3NO_{0.5}Si$: C, 53.48; H, 5.54; N, 3.67%.

4.1.15. 4,4-Bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propyl}-1-methyl-4-silapiperidinium iodide (17) and hydrate 17 · H_2O

A mixture of **12** (5.00 g, 10.7 mmol), 3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propylamine [12] (2.50 g, 11.1 mmol), triethylamine (3.00 g, 29.6 mmol), acetonitrile (30 ml), and toluene (30 ml) was heated in a 250-ml autoclave at 90 °C for 16 h. After the mixture was cooled to 20 °C, the precipitate was removed by filtration, and water (60 ml) was added to the filtrate. The organic phase was separated, the aqueous layer was extracted with toluene (2 × 50 ml), and the combined organic extracts were dried over anhydrous sodium sulfate. The solvent and the excess triethylamine were removed under reduced pressure, and the residue (4,4-bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dioxolan-2-yl]propyl}-4-silapiperidine (**16**; crude product, not purified)) was dissolved in acetone (30 ml), followed by the addition of methyl iodide (3.60 g, 25.4 mmol). The resulting mixture was stirred at 20 °C for 24 h, the solvent and the excess methyl iodide were removed under reduced pressure, and the solid residue was dried in vacuo and then recrystallized from ethanol (slow cooling of a saturated boiling solution to 20 °C) to give **17** in 62% yield as a colorless crystalline solid (4.45 g, 6.62 mmol); m.p. 168–169 °C. ^{1}H NMR (300.1 MHz, [D$_6$]DMSO): δ 1.52–1.78 (m, 6H, SiCH_2CH$_2$N, NCH$_2$CH_2CH$_2$C), 1.84–1.95 (m, 2H, NCH$_2$CH$_2$CH_2C), 3.00 (s, 3H, NCH_3), 3.30–3.63 (m, 6H, SiCH$_2$CH_2N, NCH_2CH$_2$CH$_2$C), 3.62–3.74 and 3.91–4.06 (m, 4H, OCH_2CH_2O), 7.12–7.23 (m, 2H, *H*-3/*H*-5, CC$_6$H$_4$F), 7.38–7.47 (m, 2H, *H*-2/*H*-6, CC$_6$H$_4$F), 7.47–7.55 (m, 4H, *H*-3/*H*-5, SiC$_6$H$_4$Cl), 7.57–7.73 (m, 4H, *H*-2/*H*-6, SiC$_6$H$_4$Cl). ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ 5.3 (Si*C*H$_2$CH$_2$N), 16.0 (NCH$_2$*C*H$_2$CH$_2$C), 36.1 (NCH$_2$ CH$_2$*C*H$_2$C), 48.6 (N*C*H$_3$), 59.4 (N*C*H$_2$CH$_2$CH$_2$C), 59.4 (SiCH$_2$*C*H$_2$N), 64.3 (O*C*H$_2$*C*H$_2$O), 108.8 (C$_2$*C*O$_2$), 115.0 (d, $^2J_{CF}$ = 21.4 Hz, *C*-3/*C*-5, CC$_6$H$_4$F), 127.5 (d, $^3J_{CF}$ = 8.0 Hz, *C*-2/*C*-6, CC$_6$H$_4$F), 128.3 (*C*-3/*C*-5, SiC$_6$H$_4$Cl), 128.4 (*C*-3′/*C*-5′, SiC$_6$H$_4$Cl), 130.7 (*C*-1, SiC$_6$H$_4$Cl), 131.2 (*C*-1′, SiC$_6$H$_4$Cl), 135.6 (*C*-4, SiC$_6$H$_4$Cl), 135.7 (*C*-4′, SiC$_6$H$_4$Cl), 136.4 (*C*-2/*C*-6, SiC$_6$H$_4$Cl), 136.5 (*C*-2′/*C*-6′, SiC$_6$H$_4$Cl), 138.4 (d, $^4J_{CF}$ = 2.9 Hz, *C*-1, CC$_6$H$_4$F), 161.8 (d, $^1J_{CF}$ = 243.8 Hz, *C*-4, CC$_6$H$_4$F). ^{19}F NMR ([D$_6$]DMSO): δ −115.1. ^{29}Si NMR ([D$_6$]DMSO): δ −19.1. Anal. Found: C, 51.7; H, 5.0; N, 2.1%. Calc. for $C_{29}H_{33}Cl_2FINO_2Si$ (M_r = 672.47): C, 51.80; H, 4.95; N, 2.08%. Crystallization of the product (1.00 g, 1.49 mmol) from ethanol/ethyl acetate/water (2:1:0.1 (v/v/v)) by slow evaporation of the solvent at 20 °C gave the hydrate **17** · H_2O in 85% yield as a colorless crystalline solid (870 mg, 1.26 mmol); m.p. 172–174 °C. Anal. Found: C, 50.7; H, 4.9; N, 2.0. Calc. for $C_{29}H_{35}Cl_2FINO_3Si$: C, 50.44; H, 5.11; N, 2.03%.

4.1.16. 4,4-Bis(4-chlorophenyl)-1-{3-[2-(4-fluorophenyl)-1,3-dithian-2-yl]propyl}-4-silapiperidinium chloride (18 · HCl)

A mixture of **12** (7.20 g, 15.4 mmol), **19** (4.20 g, 15.5 mmol), triethylamine (4.50 g, 44.5 mmol), acetonitrile (50 ml), and toluene (50 ml) was heated in a 250-ml autoclave at 90 °C for 40 h. After the mixture was cooled to −20 °C, the precipitate was removed by filtration, and water (60 ml) was added to the filtrate. The organic phase was separated, the aqueous layer was extracted with toluene (2 × 50 ml), the combined organic extracts were dried over anhydrous sodium sulfate, and the solvent was removed under reduced pressure. The residue was dissolved in diethyl ether (40 ml), and the solution was cooled to −20 °C, followed by dropwise addition of a 2.0 M ethereal hydrogen chloride solution (10 ml, 20.0 mmol of HCl). The mixture was stirred at −20 °C for 10 min, and the precipitate was isolated by filtration, washed with diethyl ether (2 20 ml), and recrystallized from methanol (slow cooling of a saturated boiling solution to 20 °C) to give **18** · HCl in 71% yield as a colorless crystalline solid (6.70 g, 10.9 mmol); m.p. 233–234 °C (dec.). ^{1}H NMR (300.1 MHz, [D$_6$]DMSO): δ 1.50–1.71 and 1.72–1.97 (m, 8H, SiCH_2CH$_2$N, NCH$_2$CH_2CH$_2$C, SCH$_2$CH_2CH$_2$S), 2.05–2.25 (m, 2H, NCH$_2$CH$_2$CH_2C), 2.48–2.68 (m, 2H, SCH_AH$_B$CH$_2$CH_AH$_B$S), 2.80–3.15 (m, 6H, SCH$_A$H$_B$CH$_2$CH$_A$H$_B$S, SiCH$_2$CH_AH$_B$N, NCH_2CH$_2$ CH$_2$C), 3.35–3.60 (m, 2H, SiCH$_2$CH$_A$H$_B$N), 7.15–7.30 (m, 2H, *H*-3/*H*-5, CC$_6$H$_4$F), 7.40–7.60 and 7.63–7.85 (m, 10H, *H*-2/*H*-3/*H*-5/*H*-6, SiC$_6$H$_4$Cl, *H*-2/*H*-6, CC$_6$H$_4$F), 10.9 (br s, 1H, N*H*). ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ 7.3 (Si*C*H$_2$CH$_2$N), 19.3 (NCH$_2$*C*H$_2$ CH$_2$C), 24.3 (SCH$_2$*C*H$_2$CH$_2$S), 26.8 (S*C*$_2$CH$_2$*C*H$_2$S), 39.3 (NCH$_2$CH$_2$*C*H$_2$C), 51.3 (SiCH$_2$*C*H$_2$N), 54.7 (N*C*$_2$CH$_2$CH$_2$C), 56.5 (C$_2$*C*S$_2$), 115.3 (d, $^2J_{CF}$ = 21.4 Hz, *C*-3/*C*-5, CC$_6$H$_4$F), 128.2 (*C*-3/*C*-5, SiC$_6$H$_4$Cl), 128.4 (*C*-3′/*C*-5′, SiC$_6$H$_4$Cl), 130.1 (d, $^3J_{CF}$ = 8.0 Hz, *C*-2/*C*-6, CC$_6$H$_4$F), 130.3 (*C*-1, SiC$_6$H$_4$Cl), 132.2 (*C*-1′, SiC$_6$H$_4$Cl), 135.5 (*C*-4, SiC$_6$H$_4$Cl), 135.6 (*C*-4′, SiC$_6$H$_4$Cl), 136.2 (*C*-2/*C*-6, SiC$_6$H$_4$Cl), 136.6 (*C*-2′/*C*-6′, SiC$_6$H$_4$Cl), 137.5 (d, $^4J_{CF}$ = 2.9 Hz, *C*-1, CC$_6$H$_4$F), 161.1 (d, $^1J_{CF}$ = 244.9 Hz, *C*-4, CC$_6$H$_4$F). ^{19}F NMR ([D$_6$]DMSO): δ −115.9. ^{29}Si NMR ([D$_6$]DMSO): δ −16.6. Anal. Found: C, 56.4; H, 5.4; N, 2.3; S 10.4. Calc. for $C_{29}H_{33}Cl_3FNS_2Si$: C, 56.81; H, 5.42; N, 2.28; S, 10.46%.

4.1.17. 3-[2-(4-Fluorophenyl)-1,3-dithian-2-yl]propylamine (19)

A mixture of **21** (7.50 g, 18.7 mmol), hydrazine hydrate (10.0 g, 200 mmol), and ethanol (500 ml) was

heated under reflux for 3 h. After the mixture was cooled to 20 °C, the precipitate was filtered off and discarded, and the solvent of the filtrate was removed under reduced pressure. Diethyl ether (150 ml) and a half-saturated aqueous sodium carbonate solution (10 ml) were added to the solid residue, and the mixture was stirred at 20 °C for 10 min. The organic phase was separated, the aqueous layer was extracted with diethyl ether (2 × 100 ml), the combined organic extracts were dried over anhydrous sodium sulfate, and the solvent was removed under reduced pressure to give **19** in 78% yield as a yellowish, highly viscous oily liquid (3.95 g, 14.6 mmol). (This product was used for the synthesis of **18** · HCl without further purification.) ^{1}H NMR (400.1 MHz, C_6D_6): δ 0.9 (br s, 2H, NH_2), 1.42–1.55 (m, 3H, NCH$_2$CH_2CH$_2$C, SCH$_2$CH_AH$_B$CH$_2$S), 1.71–1.85 (m, 1H, SCH$_2$CH$_A$$H_BCH_2$S), 2.10–2.19 (m, 2H, NCH$_2$CH$_2$CH_2C), 2.28–2.50 (m, 6H, SCH_2CH$_2$CH_2S, NCH_2CH$_2$CH$_2$C), 6.96–7.04 (m, 2H, *H*-3/*H*-5, CC$_6$H$_4$F), 7.94–8.01 (m, *H*-2/*H*-6, CC$_6$H$_4$F). ^{13}C NMR (100.6 MHz, C_6D_6): δ 25.4 (SCH$_2$*C*H$_2$CH$_2$S), 27.6 (S*C*H$_2$CH$_2$*C*H$_2$S), 28.4 (NCH$_2$*C*H$_2$CH$_2$C), 42.2 (N*C*H$_2$CH$_2$CH$_2$C), 43.1 (NCH$_2$CH$_2$*C*H$_2$C), 58.7 (C$_2$*C*S$_2$), 115.3 (d, $^2J_{CF}$ = 21.0 Hz, *C*-3/*C*-5, CC$_6$H$_4$F), 131.2 (d, $^3J_{CF}$ = 8.1 Hz, *C*-2/*C*-6, CC$_6$H$_4$F), 138.5 (d, $^4J_{CF}$ = 2.9 Hz, *C*-1, CC$_6$H$_4$F), 162.0 (d, $^1J_{CF}$ = 246.5 Hz, *C*-4, CC$_6$H$_4$F). ^{19}F NMR (C_6D_6): δ −116.2. $C_{13}H_{18}FNS_2$. An elemental analysis was not performed because of the high viscosity of the product. Instead, the hydrochloride **19** · HCl was analyzed (see below).

4.1.18. 3-[2-(4-Fluorophenyl)-1,3-dithian-2-yl]propylammonium chloride (**19** · HCl)

A 2.0 M ethereal hydrogen chloride solution (1 ml, 2.00 mmol of HCl) was added dropwise to a stirred cooled solution (–20 °C) of **6** (500 mg, 1.84 mmol) in diethyl ether (10 ml). The mixture was stirred at −20 °C for 10 min, and the precipitate was isolated by filtration to give **19** · HCl in 96% yield as a colorless crystalline solid (545 mg, 1.77 mmol); m.p. 168–169 °C. ^{1}H NMR (300.1 MHz, [D$_6$]DMSO): δ 1.38–1.54 (m, 2H, NCH$_2$CH_2CH$_2$C), 1.75–1.93 (m, 2H, SCH$_2$CH_2CH$_2$S), 2.06–2.22 (m, 2H, NCH$_2$CH$_2$CH_2C), 2.50–2.77 and 2.80–2.95 (m, 6H, SCH_2CH$_2$CH_2S, NCH_2CH$_2$CH$_2$C), 7.17–7.28 (m, 2H, *H*-3/*H*-5, CC$_6$H$_4$F), 7.72–7.83 (m, *H*-2/*H*-6, CC$_6$H$_4$F), 8.0 (br s, 3H, NH_3). ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ 22.5 (NCH$_2$*C*H$_2$CH$_2$C), 24.5 (SCH$_2$*C*H$_2$CH$_2$S), 26.8 (S*C*H$_2$CH$_2$*C*H$_2$S), 38.3 (N*C*H$_2$CH$_2$CH$_2$C), 39.6 (NCH$_2$CH$_2$*C*H$_2$C), 56.6 (C$_2$*C*S$_2$), 115.3 (d, $^2J_{CF}$ = 21.4 Hz, *C*-3/*C*-5, CC$_6$H$_4$F), 130.2 (d, $^3J_{CF}$ = 8.4 Hz, *C*-2/*C*-6, CC$_6$H$_4$F), 137.6 (d, $^4J_{CF}$ = 3.3 Hz, *C*-1, CC$_6$H$_4$F), 161.1 (d, $^1J_{CF}$ = 244.9 Hz, *C*-4, CC$_6$H$_4$F). ^{19}F NMR ([D$_6$]DMSO): δ −116.2. Anal. Found: C, 50.8; H, 6.1; N, 4.6; S, 20.6. Calc. for $C_{13}H_{19}ClFNS_2$: C, 50.71; H, 6.22; N, 4.55; S, 20.83%.

4.1.19. 2-(3-Chloropropyl)-2-(4-fluorophenyl)-1,3-dithiane (**20**)

A mixture of 4-chloro-1-(4-fluorophenyl)butan-1-one (15.0 g, 74.8 mmol), propane-1,3-dithiol (10.0 g, 92.4 mmol), and a 2.0 M ethereal hydrogen chloride solution (90 ml, 180 mmol of HCl) was stirred at 20 °C for three days and then cooled to 0 °C, followed by the addition of water (100 ml). The organic phase was separated, washed with water (2 × 100 ml), and dried over anhydrous sodium sulfate. The solvent and the excess propane-1,3-dithiol were removed under reduced pressure (crystallization of the residue upon standing at 20 °C), and the resulting solid was washed with methanol (50 ml) and then recrystallized from *n*-pentane (slow cooling of a saturated boiling solution to 20 °C) to give **20** in 82% yield as a colorless crystalline solid (17.8 g, 61.2 mmol); m.p. 53–54 °C. ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 1.66–1.78 (m, 2H, ClCH$_2$CH_2CH$_2$C), 1.84–2.02 (m, 2H, SCH$_2$CH_2CH$_2$S), 2.08–2.18 (m, 2H, NCH$_2$CH$_2$CH_2C), 2.60–2.74 (m, 4H, SCH_2CH$_2$CH_2S), 3.39 (t, $^3J_{HH}$ = 6.4 Hz, 2H, ClCH_2CH$_2$CH$_2$C), 6.98–7.09 (m, 2H, *H*-3/*H*-5, CC$_6$H$_4$F), 7.80–7.90 (m, 2H, *H*-2/*H*-6, CC$_6$H$_4$F). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 25.0 (SCH$_2$*C*H$_2$CH$_2$S), 27.2 (ClCH$_2$*C*H$_2$CH$_2$C), 27.5 (S*C*H$_2$CH$_2$*C*H$_2$S), 42.3 (NCH$_2$CH$_2$*C*H$_2$C), 44.7 (Cl*C*H$_2$CH$_2$CH$_2$C), 57.6 (C$_2$*C*S$_2$), 115.3 (d, $^2J_{CF}$ = 21.1 Hz, *C*-3/*C*-5, CC$_6$H$_4$F), 130.5 (d, $^3J_{CF}$ = 8.0 Hz, *C*-2/*C*-6, CC$_6$H$_4$F), 137.2 (d, $^4J_{CF}$ = 3.3 Hz, *C*-1, CC$_6$H$_4$F), 161.7 ($^1J_{CF}$ = 247.1 Hz, *C*-4, CC$_6$H$_4$F). ^{19}F NMR ($CDCl_3$): δ −115.8. Anal. Found: C, 53.9; H, 5.5; S, 22.0. Calc. for $C_{13}H_{16}ClFS_2$: C, 53.68; H, 5.54; S, 22.05%.

4.1.20. 2-{3-[2-(4-Fluorophenyl)-1,3-dithian-2-yl]propyl}phthalimide (**21**)

A mixture of **20** (11.0 g, 37.8 mmol), phthalimide (6.00 g, 40.8 mmol), 1,8-diazabicyclo[5.4.0]undec-7-ene (5.80 g, 38.1 mmol), and DMF (80 ml) was stirred at 45 °C for three days. The mixture was then cooled to 20 °C, and water (100 ml), dichloromethane (150 ml), and 0.1 M hydrochloric acid (20 ml) were added. The organic phase was separated, the aqueous layer was extracted with dichloromethane (2 × 100 ml), and the combined organic extracts were washed with water (100 ml) and then dried over anhydrous sodium sulfate. The solvent was removed under reduced pressure, and the residue was redissolved in diisopropyl ether (40 ml) (formation of a precipitate at 20 °C within 2 h). The product was isolated by filtration and recrystallized from ethyl acetate (slow cooling of a saturated boiling solution to 20 °C) to give **21** in 72% yield as a colorless solid (10.9 g, 27.1 mmol); m.p. 128–129 °C. ^{1}H NMR (300.1 MHz, $CDCl_3$): δ 1.56–1.74 (m, 2H, NCH$_2$CH_2CH$_2$C), 1.78–1.97 (m, 2H, SCH$_2$CH_2CH$_2$S), 1.97–2.10 (m, 2H,

$NCH_2CH_2CH_2C$), 2.56–2.65 (m, 4H, $SCH_2CH_2CH_2S$), 3.53 (t, $^3J_{HH} = 7.0$ Hz, 2H, $NCH_2CH_2CH_2C$), 6.90–7.05 (m, 2H, *H*-3/*H*-5, CC_6H_4F), 7.62–7.73 (m, 2H, *H*-4/*H*-5, $C(O)C_6H_4C(O)$), 7.74–7.90 (m, 4H, *H*-3/*H*-6, $C(O)C_6H_4C(O)$, *H*-2/*H*-6, CC_6H_4F). ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 23.2 ($NCH_2CH_2CH_2C$), 25.0 ($SCH_2CH_2CH_2S$), 27.5 ($SCH_2CH_2CH_2S$), 37.6 (N- $CH_2CH_2CH_2C$), 42.1 ($NCH_2CH_2CH_2C$), 57.8 (C_2CS_2), 115.2 (d, $^2J_{CF} = 21.1$ Hz, *C*-3/*C*-5, CC_6H_4F), 123.1 (*C*-3/*C*-6, $C(O)C_6H_4C(O)$), 130.6 (d, $^3J_{CF} = 8.0$ Hz, *C*-2/*C*-6, CC_6H_4F), 132.0 (*C*-1/*C*-2, $C(O)C_6H_4C(O)$), 133.8 (*C*-4/*C*-5, $C(O)C_6H_4C(O)$), 137.0 (d, $^4J_{CF} = 2.9$ Hz, *C*-1, CC_6H_4F), 161.6 ($^1J_{CF} = 247.0$ Hz, *C*-4, CC_6H_4F), 168.1 (*C*O). ^{19}F NMR ($CDCl_3$): δ −115.9. Anal. Found: C, 62.9; H, 5.0; N, 3.5; S, 15.8. Calc. for $C_{21}H_{20}FNO_2S_2$: C, 62.82; H, 5.02; N, 3.49; S, 15.97%.

4.2. Crystal structure analyses

Suitable single crystals of **5**, **6** · HCl, **8**, **9**, **13** · HCl, **15** · HCl · 0.5EtOH, **17** · H_2O, and **18** · HCl were obtained by crystallization from 2-propanol (**5**, **9**, **13** · HCl, **18** · HCl), ethanol (**6** · HCl, **15** · HCl · 0.5EtOH), ethanol/ethyl acetate (2:1 (v/v)) (**8**), or ethanol/ethyl acetate/water (2:1:0.1 (v/v/v)) (**17** · H_2O) at 20 °C. The crystals were mounted in inert oil (perfluoroalkyl ether, ABCR) on a glass fiber and then transferred to the cold nitrogen gas stream of the diffractometer (Stoe IPDS; graphite-monochromated Mo Kα radiation ($\lambda = 0.71073$ Å)). The structures were solved by direct methods [16,17]. All non-hydrogen atoms were refined anisotropically [18]. Except for compound **5**, a riding model was employed in the refinement of the C*H* hydrogen atoms. The N*H* and O*H* hydrogen atoms were localized in difference Fourier syntheses and refined freely, except for the O*H* hydrogen atom of the solvent molecule in **15** · HCl · 0.5EtOH (riding model).

Acknowledgement

This work was supported by the Fonds der Chemischen Industrie.

Appendix A. Supplementary material

Crystallographic data (excluding structure factors) for the crystal structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC-237706 (**5**), CCDC-237707 (**6** · HCl), CCDC-237708 (**8**), CCDC-237709 (**9**), CCDC-237710 (**13** · HCl), CCDC-237711 (**15** · HCl · 0.5EtOH), CCDC-237712 (**17** · H_2O), and CCDC-237713 (**18** · HCl). Copies of the data may be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk). Supplementary data associated with this article can be found, in the online version at doi:10.1016/j.jorganchem.2004.08.023.

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