Organometallic Chemistry

Synthesis of biologically active compounds based on 2-ferrocenylmethylene-3-quinuclidone

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Biologically active nitrogen heterocycles (**1**—**7**) containing ferrocene and quinuclidine fragments were synthesized. 3-Methylene-2-ferrocenylmethylenequinuclidine forms adducts with *N*-phenylimides of azodicarboxylic (the structure was established by X-ray structural analysis) and maleic acids. 3-Methylene-2-ferrocenylmethylenequinuclidine also undergoes [4+2]-cyclodimerization when heated and adds salts of the 3-methyl-2-ferrocenylmethylene-1-azoniabicyclo[2.2.2]oct-3-yl cation at the terminal methylene group to form a linear addition product.

Key words: ferrocene, quinuclidine, pyrazoline, pyrimidine, ferrocenyl-1,3-diene, [4+2]cycloaddition, carbocations, alkylation, dimerization, X-ray structural analysis.

Compounds containing a ferrocenyl substituent often exhibit biological activity.[1] For example, ferrocenyl-substituted cyclopropanes,[2] cyclohexenes,[3] and tetrahydrophthalates[4] are characterized by antiphlogistic and analgesic activities. The biological activity of quinuclidine derivatives is also well known.[5] Therefore, it was of interest to synthesize compounds containing ferrocene and quinuclidine fragments and to study their biological activity.

The chemistry of many of the ferrocene derivatives of hetero- and carbocycles is based on the fact that the corresponding α,β-unsaturated carbonyl compounds containing ferrocenyl fragments are rather readily available. For example, the addition of hydrazines[6,7] and thiourea[8] to chalcones of the ferrocene series is characterized by selectivity, high yields, and ease of isolation of the products. Methods have been developed for the synthesis of conjugated dienes from ferrocenyl-substituted chalcones, and dimerization, cyclodimerization, and cycloaddition of conjugated dienes have been studied, thus substantially extending the possibilities for designing cyclic and fused polycyclic structures based on these compounds.[9—12]

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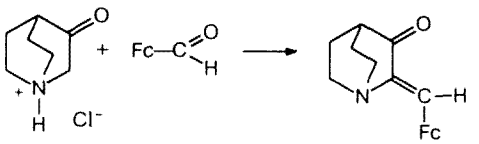
In this work, we studied various procedures for the synthesis of biologically active compounds containing ferrocene and quinuclidine fragments.

2-Ferrocenylmethylene-3-quinuclidone (**1**) was prepared by condensation of 3-quinuclidone hydrochloride with ferrocenecarbaldehyde in an aqueous-alcoholic solution of alkali:

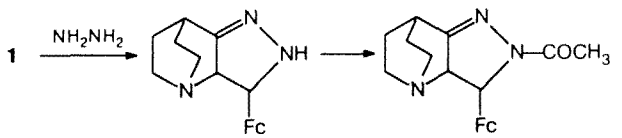


Fc = $C_5H_5FeC_5H_4$

1

Chalcone **1** formed in quantitative yield presumably as a pure *Z* isomer.[5]

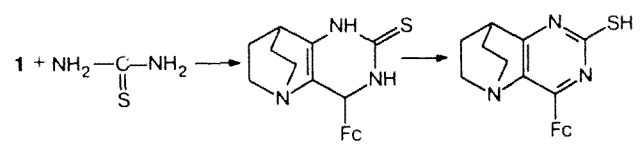
The reaction of **1** with hydrazine hydrate proceeds diastereoselectively to form 2-pyrazoline (**2**), which follows from the analysis of the ^{1}H NMR spectrum of the *N*-acetyl-substituted derivative (**3**) (Table 1):



2 **3**

The ^{1}H NMR spectrum of compound **3** has singlets for the protons of the C_5H_5 and Me groups that correspond to one diastereoisomer of 2-pyrazoline **2**. However, it cannot be concluded from the values of the spin-spin coupling constant ($^3J_{H(4)H(5)}$ = 8.25 Hz), whether the H(4) and H(5) protons of the pyrazoline ring are in *trans* or *cis* positions.

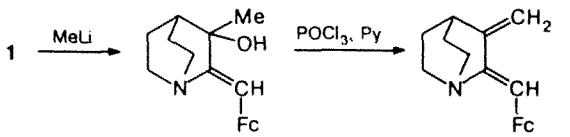
Chalcone **1** also reacts readily with thiourea to form tetrahydropyrimidinethione (**4**).[8] We found that compound **4** oxidizes readily with atmospheric oxygen to form aromatic pyrimidinethiol (**5**):



4 **5**

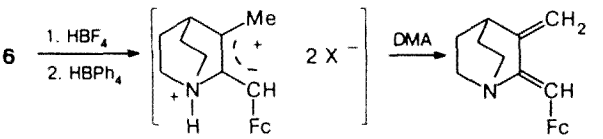
Analogous oxidation with atmospheric oxygen has been observed previously for carbocyclic adducts of *N*-arylmaleimides with ferrocenyl-1,3-butadienes.[13]

Treatment of quinuclidone **1** with methyllithium yielded quinuclidol **6**, which was then dehydrated by treating with $POCl_3$ in pyridine.[10]



6 **7**

In this case, stable dialkylenequinuclidine **7**, which remained unchanged in the crystalline state for a rather long period of time, was obtained. Compound **7** forms also under the action of bases on allyl carbonium-ammonium salts **8a,b**.

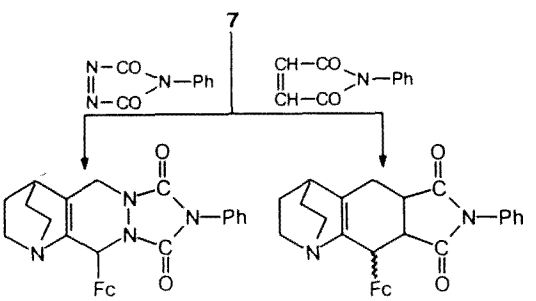


8a: X = BF_4
8b: X = BPh_4 **7**

DMA = *N,N*-dimethylaniline

Of all the salts of methylferrocenylallyl cations studied to date under analogous conditions,[9–13] only the 1,3,7,7-tetramethyl-2-ferrocenylmethylbicyclo-[2.2.1]hept-3-yl cation[14] deprotonates, while all other compounds give cyclodimers of the terpenoid type.

Diene **7** forms adducts **9** and **10** with *N*-phenylimides of azodicarboxylic and maleic acids, respectively.



9 **10a,b**

According to the ^{1}H NMR data (Table 1), compound **10** forms as a mixture of *endo*-**10a** and *exo*-**10b** isomers in the ratio of ~3:1. We attempted to assign *endo* and *exo* forms based on criteria found previously.[13–15] Although one of the isomers (**10a**) was isolated in the pure form, analysis of the ^{1}H NMR spectra of compounds **9**, **10a**, and **10b** is hampered because the signals of the CH_2 fragments overlap with each other and with the multiplets of the H(1), H(2), and H(3) atoms.

Compound **10a** was characterized as an *endo* isomer based on the fact that the signal from one of the protons

Table 1. ^{1}H NMR spectra of the compounds obtained (δ, *J*/Hz)

Compound	C_5H_5	C_5H_4	CH_2	CH	CH_3, OH, Ar, SH
1	4.096 s	4.39 (m, 2 H), 4.89 (m, 2 H)	1.93 (m, 4 H), 2.88 (m, 2 H), 3.05 (m, 2 H)	2.55 (m, 1 H), 6.94 (s, 1 H)	–
3	4.27 s	4.06 (m, 1 H), 4.18 (m, 2 H), 4.48 (m, 1 H)	1.97 (m, 4 H), 2.84 (m, 2 H), 3.10 (m, 2 H),	3.30 (m, 1 H), 4.37 (d, 1 H, *J* = 8.52) 4.86 (d, 1 H, *J* = 8.52)	2.29 (s, 3 H)
5	4.16 s	4.36 (m, 2 H), 5.39 (m, 2 H)	1.68 (m, 2 H), 1.96 (m, 2 H), 2.58 (m, 2 H), 3.12 (m, 2 H)	3.22 (m, 1 H)	3.83 (s, 1 H)
6	4.08 s	4.20 (m, 2 H), 4.68 (m, 1 H), 4.67 (m, 1 H)	1.65–2.10 (m, 4 H), 2.80–3.10 (m, 4 H)	2.74 (m, 1 H), 6.02 (s, 1 H)	1.48 (s, 3 H), 1.70 (s, 1 H)
7	4.09 s	4.20 (m, 2 H), 4.77 (m, 2 H)	1.67 (m, 4 H) 2.96 (m, 4 H), 4.72 (d, 1 H, *J* = 1.2) 5.18 (d, 1 H, *J* = 1.2)	2.51 (m, 1 H), 6.21 (s, 1 H)	–
9	4.24 s	4.16 (m, 4 H)	1.63 (m, 2 H), 1.84 (m, 2 H), 2.72 (m, 2 H), 3.28 (m, 2 H), 4.20 (d, 1 H, *J* = 16.5) 4.46 (d, 1 H, *J* = 16.5)	2.95 (m, 1 H), 5.63 (s, 1 H)	7.33–7.50 (m, 5 H)
10a	4.28 s	4.12 (m, 2 H), 4.01 (m, 2 H)	1.35–1.6 (m, 2 H), 2.40–2.6 (m, 4 H), 2.70–2.9 (m, 2 H), 3.35–3.45 (m, 2 H)	2.70 (m, 1 H), 3.10 (m, 1 H), 3.20 (m, 1 H), 3.74 (d, 1 H, *J* = 1.3)	6.90–7.50 (m, 5 H)
10b	4.21 s	4.30 (m, 4 H)	1.35–1.6 (m, 2 H), 2.40–2.6 (m, 4 H), 2.60–3.4 (m, 4 H)	2.58 (m, 1 H), 3.05 (m, 1 H), 3.20 (m, 1 H) 3.78 (d, 1 H, *J* = 1.25)	7.20–7.58 (m, 5 H)
11	4.3 s (Fc^1) 4.06 s (Fc^2)	3.20 (m, 1 H), 3.77 (m, 1 H), 4.09 (m, 1 H), 4.25 (m, 1 H) 4.12 (m, 2 H), 4.57 (m, 1 H), 4.61 (m, 1 H)	1.20–1.40 (m, 2 H), 1.50–1.85 (m, 8 H), 2.20–2.35 (m, 2 H), 2.60–3.18 (m, 8 H)	2.50 (m, 1 H), 2.65 (m, 1 H), 5.93 (s, 1 H)	–
13a	4.21 s, 4.205 s	4.24–4.023 m	1.20–1.70 (m, 8 H), 2.75–3.15 (m, 8 H)	2.36 (m, 1 H), 2.55 (m, 1 H), 4.79 (m, 1 H), 6.65 (m, 1 H), 7.86 (s, 1 H)	1.83 s
13b	4.11 s, 4.10 s	4.40–4.10 m	1.50 (m, 4 H), 1.70 (m, 2 H), 2.30 (m, 2 H), 2.80–3.10 (m, 8 H)	2.30 (m, 1 H), 2.60 (m, 1 H), 4.62 (m, 1 H), 6.58 (m, 1 H), 7.80 (s, 1 H)	1.95 s
15	4.04 (s, 5 H), 3.66 (s, 5 H)	4.74–3.90 (m, 8 H)	1.20–1.70 (m, 8 H), 2.60–2.80 (m, 8 H), 3.45 (m, 2 H)	2.50 (m, 1 H), 3.15 (m, 1 H), 5.10 (m, 1 H), 6.62 (s, 1 H)	2.17 (s, 3 H), 2.88 (s, 6 H), 7.28 (d, 2 H), 7.35 (d, 2 H, *J* = 8.2)

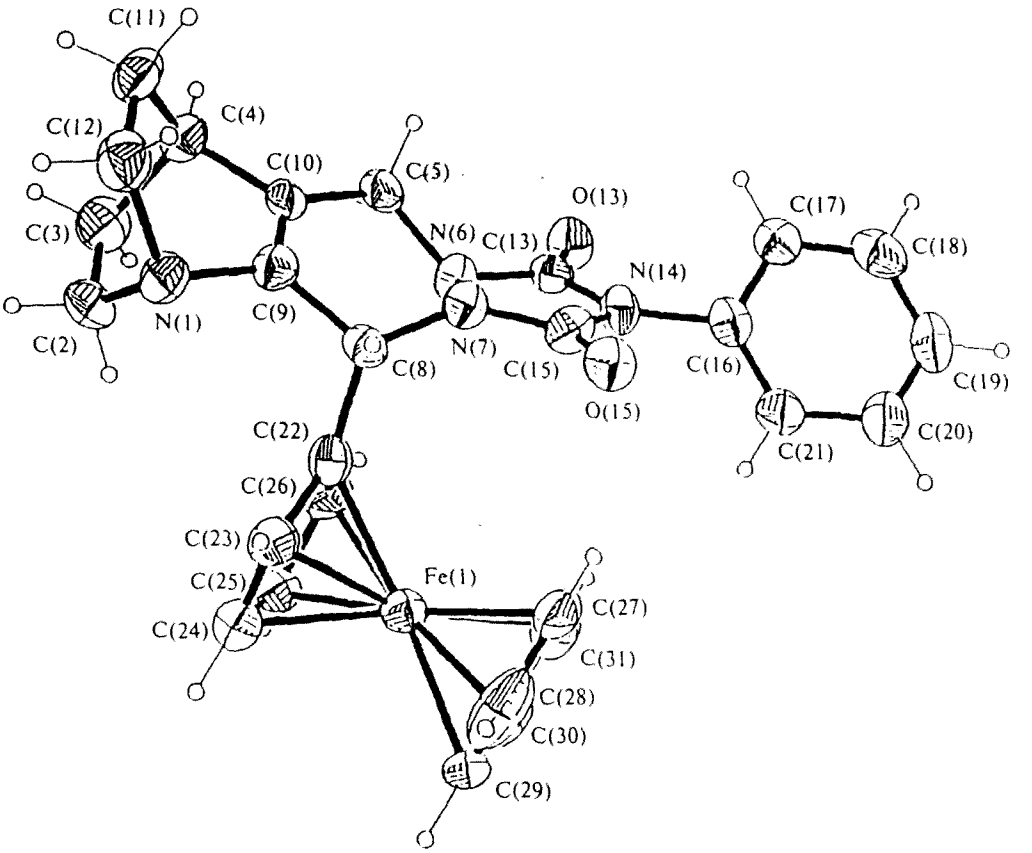


Fig. 1. Molecular structure of adduct **9**.

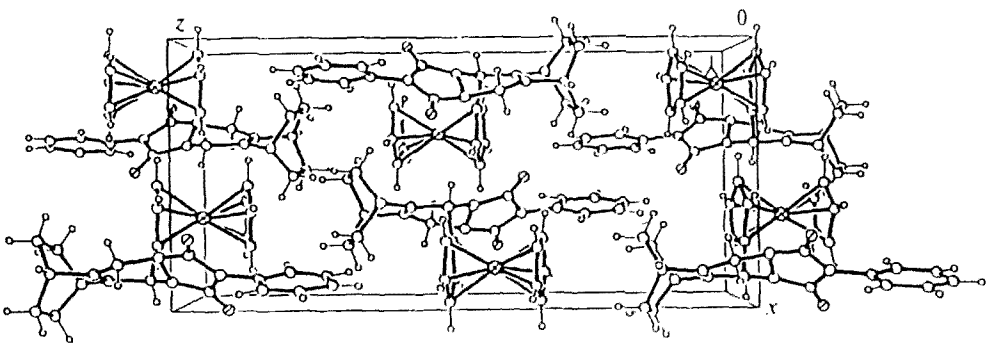
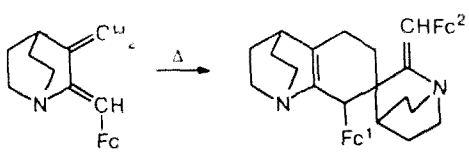


Fig. 2. Crystal structure of adduct **9**.

of the C_5H_4 group is observed at higher field than that of the second isomer.

The structure of adduct **9** was established by X-ray structural analysis. The overall view of molecule **9** is shown in Fig. 1. The crystal packing of the molecules is shown in Fig. 2. The positional parameters of the atoms and the corresponding thermal parameters are given in Table 2. The geometric parameters are listed in Tables 3 and 4.

When boiled, dialkylenequinuclidine **7** dimerizes regioselectively and stereospecifically according to the [4+2] cycloaddition mechanism. Spirane cyclodimer **11** forms exclusively as one (presumably, *endo*) form.



7 **11**

The structure of compound **11** was established based on the ^1H and ^{13}C NMR spectra (Tables 1 and 5). Dimer **11** was assigned to the *endo* type based on the fact that the signals from the protons of the C_5H_4 group of Fc^1 are observed at higher field than the singlet from the protons of the C_5H_5 group of Fc^1 (Table 1).

Table 2. Atomic coordinates ($\times 10^4$) and isotropic temperature factors for molecule **9** ($\times 10^3$, Å^2)

Atom	*x*	*y*	*z*	*U* (eq)
N(1)	3943(6)	4690(6)	−1464(3)	39(2)
C(2)	2684(8)	4606(7)	−1855(4)	44(3)
C(3)	2349(8)	3224(8)	−2048(4)	49(3)
C(4)	3448(8)	2348(7)	−1779(3)	38(2)
C(5)	3110(7)	1619(6)	−614(3)	35(2)
N(6)	2889(5)	2245(5)	−10(3)	32(2)
N(7)	3812(6)	3247(5)	127(2)	33(2)
C(8)	3789(7)	4362(6)	−293(3)	30(2)
C(9)	3767(6)	3809(7)	−949(3)	33(2)
C(10)	3492(7)	2621(6)	−1085(3)	31(2)
C(11)	4822(8)	2804(8)	−2051(3)	45(3)
C(12)	5061(8)	4183(8)	−1866(3)	48(3)
C(13)	2782(7)	1491(6)	519(3)	32(2)
O(13)	2227(5)	479(4)	560(2)	43(2)
N(14)	3506(6)	2138(5)	981(2)	34(2)
C(15)	4149(7)	3207(7)	741(3)	35(2)
O(15)	4879(4)	3963(5)	1016(2)	41(2)
C(16)	3650(7)	1714(7)	1630(3)	34(2)
C(17)	3942(7)	439(7)	1734(3)	38(2)
C(18)	4009(8)	2(7)	2346(4)	50(3)
C(19)	3824(8)	851(8)	2832(3)	50(3)
C(20)	3575(9)	2096(8)	2715(3)	50(3)
C(21)	3459(8)	2562(7)	2107(3)	40(2)
Fe(1)	1596(1)	6204(1)	480(1)	34(1)
C(22)	2559(8)	5250(7)	−233(3)	36(2)
C(23)	2579(9)	6580(6)	−335(3)	43(3)
C(24)	1227(9)	7045(9)	−364(3)	52(3)
C(25)	367(8)	5977(9)	−277(3)	50(3)
C(26)	1175(7)	4876(8)	−196(3)	42(2)
C(27)	2653(9)	6014(10)	1289(3)	60(3)
C(28)	2380(12)	7307(11)	1178(4)	70(4)
C(29)	1014(14)	7491(9)	1152(4)	72(4)
C(30)	413(9)	6339(12)	1250(4)	64(4)
C(31)	1392(13)	5417(8)	1335(4)	68(4)

Table 3. Principal bond lengths for molecule **9**

Bond	*d*/Å	Bond	*d*/Å
N(1)—C(2)	1.504 (10)	N(1)—C(9)	1.444 (9)
N(1)—C(12)	1.498 (10)	C(4)—C(10)	1.510 (9)
C(5)—N(6)	1.465 (8)	C(5)—C(10)	1.500 (9)
N(6)—N(7)	1.419(8)	N(6)—C(13)	1.381 (9)
N(7)—C(8)	1.469 (8)	N(7)—C(15)	1.355 (9)
C(8)—C(9)	1.517 (9)	C(8)—C(22)	1.537 (10)
C(9)—C(10)	1.303 (10)	C(13)—O(13)	1.195 (8)
C(13)—N(14)	1.395 (9)	N(14)—C(15)	1.384 (9)
N(14)—C(16)	1.463 (8)	C(15)—O(15)	1.221 (9)

Table 4. Principal bond angles for molecule **9**

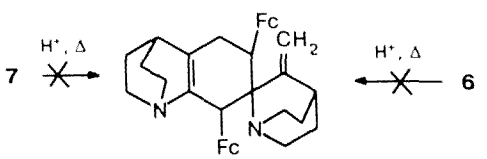
Angle	ω/deg	Angle	ω/deg
N(6)—C(5)—C(10)	108.6 (5)	C(5)—N(6)—N(7)	114.4 (5)
C(5)—N(6)—C(13)	118.6 (5)	N(7)—N(6)—C(13)	107.6 (5)
N(6)—N(7)—C(8)	116.7 (5)	N(6)—N(7)—C(15)	109.6 (5)
C(8)—N(7)—C(15)	128.3 (6)	N(7)—C(8)—C(9)	105.3 (5)
N(7)—C(8)—C(22)	116.2 (5)	C(9)—C(8)—C(22)	107.2 (5)
N(1)—C(9)—C(8)	117.5 (6)	N(1)—C(9)—C(10)	117.5 (6)
C(8)—C(9)—C(10)	124.8 (6)	C(4)—C(10)—C(5)	121.3 (6)
C(4)—C(10)—C(9)	113.8 (6)	C(5)—C(10)—C(9)	124.6 (6)
N(1)—C(12)—C(11)	111.7 (6)	N(6)—C(13)—O(13)	126.9 (6)
N(6)—C(13)—N(14)	105.3 (5)	O(13)—C(13)—N(14)	127.7 (6)
C(13)—N(14)—C(15)	111.3 (5)	C(13)—N(14)—C(16)	125.2 (6)
C(15)—N(14)—C(16)	123.4 (6)	N(7)—C(15)—N(14)	105.7 (6)
N(7)—C(15)—O(15)	126.3 (7)	N(14)—C(15)—O(15)	128.0 (6)
N(14)—C(16)—C(17)	117.6 (6)	N(14)—C(16)—C(21)	119.9 (6)
C(8)—C(22)—C(23)	124.9 (7)	C(8)—C(22)—Fe(1)	136.3 (5)

Unlike s-*trans*-/s-*cis*-ferrocenylbutadienes and 1-ferrocenylbuten-3-ols, which undergo cyclodimerization in acidic media to form 1,3,4,5-tetrasubstituted cyclohexenes,[9,10] diene **7** with an s-*cis* arrangement of double bonds and the corresponding allyl alcohol **6** do not form product **12** (as would be expected according to the proton cyclodimerization mechanism) even when boiled in acetic acid.

Table 5. Data of the ^{13}C NMR spectra of compounds **11** and **13b**

Group	**11**	**13b**
C_5H_5	69.43, 68.83	69.27, 68.61
C_5H_4	70.52, 69.61, 69.11, 68.38, 68.04, 67.86, 66.22, 65.57	69.40—68.25
C_5Fc[a]	89.76, 82.21	88.02, 83.16
CH=	116.01	118.19, 117.54
C	152.20, 145.47, 139.55, 44.44	153.41, 151.23, 148.19, 146.11
CHFc	47.06	63.12
CH_3	—	21.67
CH_2	50.79, 49.57, 48.01, 46.69, 29.76, 28.17, 25.54, 24.53, 23.78	50.63, 48.97, 47.35, 45.28, 30.12, 29.81, 28.18, 26.63
CH	31.70, 30.83	32.83, 31.25

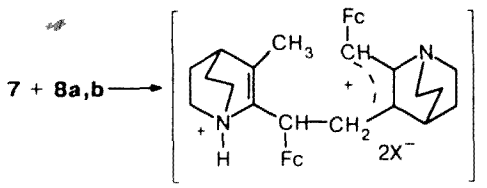
[a] Tertiary carbon atoms of the cyclopentadienyl ring of ferrocene.



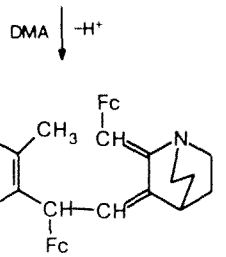
12

We obtained linear dimer **13** by the reaction of diene **7** with tetrafluoroborate **8a** or tetraphenylborate **8b**. The reaction with **8a** yielded a mixture of two isomers **13a** and **13b** in the ratio of ~2.5:1 (according to the data

of NMR spectra, Table 1), while the reaction with **8b** produced pure isomer **13b**, which corresponds to the data obtained previously.[11] However, the configurations of these isomers (*Z* or *E*) were not established.



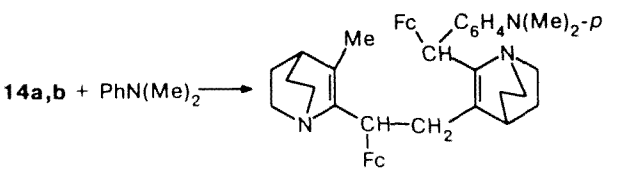
14a,b



13a,b

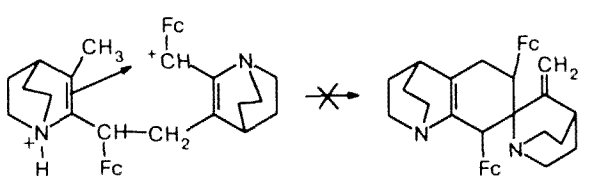
$X^- = BF_4^-$(**a**); BPh_4^-(**b**)

Apparently, linear dimer **13** forms as a result of deprotonation of the intermediate salts of the allyl carbocation (**14a,b**), which is a product of the addition of cation **8** at the secondary carbocation center to the methylene group of diene **7**. In this case, deprotonation competes with alkylation of *N,N*-dimethylaniline at the *para* position by allyl cation **14**, which, apparently, results from the carbonium-ammonium nature of cation **14**. We succeeded for the first time in determining and isolating the product of the alkylation of *N,N*-dimethylaniline by the intermediate dimeric allyl carbocation (compound **15**).



15

The processes under consideration are preferable to intramolecular alkylation, which yields cycloaddition product **12**.



14 **12**

These peculiarities of the behavior of dialkylenequinuclidine **7** under the conditions of proton cyclodimerization and cation cycloaddition of ferrocenylbutadienes is due largely to steric effects in the quinuclidine fragment and to the enhanced stability of ferrocenylcarbocations. The combination of these factors made it possible to observe an intermediate stage in the addition of methylferrocenylallyl cation **8** to diene **7**.

According to the preliminary biological tests, compounds **1**, **3**, **4**, **6**, **7**, and **11** exhibit rather high antiviral activity.

Experimental

The ^1H and ^{13}C spectra were recorded on a Bruker CXP-200 spectrometer (200 and 50 MHz) for solutions in $CDCl_3$; TMS was used as the internal standard (Tables 1 and 5). The data of elemental analysis are given in Table 6.

2-Ferrocenylmethylene-3-quinuclidone (1) was prepared using the standard procedure[16] from ferrocenylaldehyde and quinuclidone hydrochloride in an aqueous-alcoholic solution of alkali. The yield was 85 %, dark-red crystals, m.p. 122—123 °C.

Table 6. Results of elemental analysis of the compounds

Compound	Found / Calculated (%)				Molecular formula
	C	H	Fe	N	
1	67.56 / 67.30	6.19 / 5.98	17.53 / 17.39	4.20 / 4.36	$C_{18}H_{19}FeNO$
2	64.31 / 64.50	6.58 / 6.31	16.91 / 16.66	12.34 / 12.53	$C_{18}H_{21}FeN_3$
3	63.82 / 63.67	5.96 / 6.15	14.63 / 14.81	11.04 / 11.13	$C_{20}H_{23}FeN_3O$
5	60.57 / 60.50	5.23 / 5.08	14.98 / 14.81	11.21 / 11.13	$C_{19}H_{19}FeN_3S$
6	67.54 / 67.66	6.65 / 6.87	16.67 / 16.56	4.03 / 4.15	$C_{19}H_{23}FeNO$
7	71.68 / 71.49	6.51 / 6.63	17.53 / 17.50	4.52 / 4.38	$C_{19}H_{21}FeN$
9	65.38 / 65.60	5.47 / 5.30	11.38 / 11.30	11.09 / 11.33	$C_{27}H_{26}FeN_4O_2$
10a,b	70.91 / 70.74	5.64 / 5.73	11.28 / 11.34	5.83 / 5.69	$C_{29}H_{28}FeN_2O_2$
10b	70.52 / 70.74	5.83 / 5.73	11.44 / 11.34	5.42 / 5.69	$C_{29}H_{28}FeN_2O_2$
11	71.54 / 71.49	6.51 / 6.63	17.63 / 17.50	4.25 / 4.38	$C_{38}H_{42}Fe_2N_2$
13a,b	71.24 / 71.49	6.69 / 6.63	17.24 / 17.50	4.18 / 4.38	$C_{38}H_{42}Fe_2N_2$
15	73.01 / 72.73	7.25 / 7.03	14.63 / 14.71	5.41 / 5.53	$C_{46}H_{53}Fe_2N_3$

2-Ferrocenyl-2,4,5-triazatricyclo[5.2.2.0^{2,6}]undec-5-ene (2). Hydrazine hydrate (5 mL) was added to a solution of chalcone **1** (1.07 g, 3.3 mmol) in ethanol (40 mL), and the reaction mixture was stirred for 3 h with heating. The yellow crystals that formed after cooling were filtered off, washed with aqueous alcohol, and dried over P_2O_5. The yield was 0.80 g (72%), m.p. 263—265 °C.

4-Acetyl-3-ferrocenyl-2,4,5-triazatricyclo[5.2.2.0^{2,6}]undec-5-ene (3). Compound **2** (1.12 g, 3.3 mmol) was dissolved in $(CH_3CO)_2O$ (2 mL). Then the mixture was treated with a 5% Na_2CO_3 solution. The yellow crystals that formed were filtered off, washed with aqueous alcohol, and dried over P_2O_5. The yield was 0.89 g (71%), m.p. 200—201 °C (from alcohol).

3-Ferrocenyl-2,4,6-triazatricyclo[6.2.2.0^{2,7}]dodec-2(7)-ene-5-thione (4). Chalcone **1** (1.07 g) and thiourea (1.0 g) were added simultaneously to a solution of sodium metal (1.0 g) in isopropanol (50 mL). The mixture was boiled until the deep color of chalcone disappeared. Then the mixture was poured rapidly into ice water (100 mL). The yellow crystals that formed were filtered off and dried *in vacuo* over P_2O_5. The yield was 0.92 g (73%), m.p. 238—239 °C. (Published data:[8] m.p. 240 °C.)

3-Ferrocenyl-2,4,6-triazatricyclo[6.2.2.0^{2,7}]dodeca-2(7),3,5-triene-5-thiol (5). Dry air was passed through a solution of pyrimidinethione **4** (0.63 g, 1.65 mmol) in $CHCl_3$ for 4 h. The solvent was evaporated, and the residue was chromatographed on Al_2O_3 (Brockmann III) (benzene was used as the eluent). Yellow crystals were obtained (0.41 g, 65%), m.p. 104—105 °C.

3-Hydroxy-3-methyl-2-ferrocenylmethylenequinuclidine (6). A suspension of chalcone **1** (3.1 g, 10 mmol) in dry benzene (50 mL) was added with stirring to an ether solution of methyllithium (30 mmol). The mixture was stirred for 1 h and then treated with a 5% NaOH solution. The organic layer was separated, washed with water, and dried over Na_2SO_4. After the solvent was distilled *in vacuo*, the residue was recrystallized from alcohol. Carbinol **6** was obtained in a yield of 2.6 g (77%) as orange crystals, m.p. 161—162 °C.

3-Methyl-2-ferrocenylmethylene-1-azoniabicyclo[2.2.2]oct-3-yl tetrafluoroborate (8a) was synthesized from alcohol **6** in absolute ether by adding HBF_4 etherate. **Tetraphenylborate 8b** was prepared from alcohol **6** in glacial acetic acid in the presence of $NaBPh_4$ using the standard procedure.[9,11] All operations with solid salts **8a** and **8b** were carried out under an atmosphere of dry argon.

3-Methylene-2-ferrocenylmethylenequinuclidine (7) a. $POCl_3$ (2 mL) was added dropwise to a solution of carbinol **6** (1.12 g, 3.3 mmol) in dry pyridine (50 mL). The reaction mixture was stirred at 20°C for 3 h and diluted with water. The diene was extracted with benzene. After distillation of the solvent *in vacuo*, the residue was purified by chromatography on Al_2O_3 (Brockmann III) using hexane as the eluent. Diene **7** was obtained in a yield of 0.75 g (70%) as orange crystals, m.p. 92—93 °C.

b. Freshly distilled *N,N*-dimethylaniline (2 mL) was added dropwise with stirring to a solution of tetrafluoroborate **8a** (1.65 g, 3.3 mmol) in CH_2Cl_2 (20 mL). Then the mixture was washed with water, a 1% HCl solution, and again with water. The solvent was disltilled off. Chromatography yielded diene **7** in a yield of 0.69 g (65%), m.p. 92—93 °C.

c. Diene **7** was obtained analogously from compound **8b** (3.20 g, 3.3 mmol) after chromatography in a yield of 0.71 g (67%).

d. Carbinol **6** (1.12 g, 3.3 mmol) was dissolved in a mixture of dry benzene (50 mL) and acetic acid (10 mL). The mixture was stirred at 20 °C for 6 h. Then the acid was washed with water repeatedly. The solvent was distilled *in vacuo*. Chromatography yielded diene **7** in a yield of 0.85 g (80%).

e. Carbinol **6** (1.12 g, 3.3 mmol) was dissolved in a mixture of acetic acid (30 mL) and several drops of acetyl chloride. The mixture was boiled for 3 h. Then benzene (50 mL) was added, and the acid was washed off with water. Chromatography yielded diene **7** in a yield of 0.64 g (60%).

Reaction of diene 7 with azodicarboxylic acid *N*-phenylimide. Azodicarboxylic acid *N*-phenylimide (0.6 g) was added portionwise (as the color of the solution disappeared) to a solution of diene **7** (1.06 g, 3.3 mmol) in hexane (70 mL). The temperature of the mixture was held to within 0—5 °C. The mixture was stirred for 1 h. Then the solvent was evaporated *in vacuo*. The crystals that formed were purified by recrystallization from benzene. 3-Ferrocenyl-1,4,5-triazatricyclo[6.2.2.0^{2,7}]dodec-2(7)-ene-4,5-dicarboxylic acid *N*-phenylimide (adduct **9**) was obtained in a yield of 1.4 g (85%) as yellow crystals, m.p. 228 °C.

X-ray structural study of adduct 9. Crystals of $C_{27}H_{26}FeN_4O_2$ are orthorhombic, a = 9.910(2), b = 10.437 (2), c = 21.372(4) Å, V = 2210.5(11) Å^3, Z = 4, space group $P2_12_12_1$ using 1621 reflections (1521 reflections with $F > 4.0\sigma(F)$).

The unit cell parameters and intensities of reflections were measured on a Simens P3/F diffractometer at ~20 °C (Cu-Kα radiation, λ = 1.54178 Å, highly-oriented graphite crystal) using the ω-scanning technique ($3° < 2\theta < 110°$). The structure was solved by the direct method and refined by the full-matrix least-squares method with anisotropic thermal parameters for nonhydrogen atoms. All hydrogen atoms were placed in calculated positions and refined isotropically except for the atoms bonded to cyclopentadienyl rings, whose positional and thermal parameters were fixed. R = 0.0418 and R_w = 0.0573. The following weighting scheme was used: $W^{-1} = \sigma^2(F) + 0.0008F^2$.

Reaction of diene 7 with *N*-phenylmaleimide. A mixture of diene **7** (1.06 g, 3.3 mmol) and *N*-phenylmaleimide (0.6 g) in dry toluene (50 mL) was boiled for 8 h. After the removal of the solvent and chromatography of the residue on Al_2O_3 (Brockmann III) using benzene as the eluent, 3-ferrocenyl-1-azatricyclo[6.2.2.0^{2,7}]dodec-2(7)-ene-4,5-dicarboxylic acid *N*-phenylimide was obtained in a yield of 1.3 g (80%) as a ~3:1 mixture of diastereoisomers **10a,b**, m.p. 167—168 °C. After repeated recrystallization from benzene, pure isomer **10a** was isolated, m.p. 203—204 °C.

Thermal cyclodimerization of 3-methylene-2-ferrocenylmethylenequinuclidine (7). A solution of diene **7** (1.06 g) in dry toluene (50 mL) was boiled for 8 h. Then the solvent was distilled *in vacuo*. The residue was chromatographed on Al_2O_3 (Brockmann III). Initial diene **7** (0.3 g, 28%, hexane was used as the eluent) and 3-ferrocenyl-2'-ferrocenylmethylene-spiro(1-azatricyclo[6.2.2.0^{2,7}]dodecane-4,3'-quinuclidine) (cyclodimer **11**) (0.64 g, 60%, a 1:1 hexane—benzene mixture was used as the eluent) were obtained, orange crystals, m.p. 287—288 °C.

Reaction of diene 7 with tetrafluoroborate (8a). A solution of diene **7** (0.53 g, 1.65 mmol) in CH_2Cl_2 (20 mL) was added with stirring to a solution of salt **8a** (0.83 g, 1.65 mmol) in CH_2Cl_2 (30 mL). After 15 min, *N,N*-dimethylaniline (2 mL) was added dropwise. Then the reaction mixture was stirred for 30 min, benzene (50 mL) was added, and the mixture was washed with water, a 1% HCl solution, and again with water. After the removal of the solvent, the residue was chromatographed on SiO_2 (a 1:1:1 hexane—benzene—ether mixture). A ~2.5:1 mixture of *Z* and *E* isomers of 3-[2-ferrocenyl-2-(3-me-

thyl-Δ^2-dehydroquinuclid-2-yl)ethylidene-2-ferrocenylmethylene]quinuclidine (**13a,b**) (0.43 g, 40%, R_f = 0.52, orange crystals, m.p. 143—145 °C) and 2[(*p*-dimethylaminophenyl)(ferrocenylmethyl)]-3-[2-ferrocenyl-2-(3-methyl-Δ^2-dehydroquinuclid-2-yl)ethyl]-Δ^2-dehydroquinuclidine (**15**) (0.29 g, 23%, R_f = 0.32, orange crystals, m.p. 165—166 °C) were obtained.

Reaction of diene 7 with tetraphenylborate 8b. Analogously, linear dimer **13b** (0.41 g, 38%, R_f = 0.52, orange crystals, m.p. 173—174 °C) and compound **15** (0.31 g, 25%, R_f = 0.32) were obtained from salt **8b** (1.59 g, 1.65 mmol) and diene **7** (0.53 g) after the treatment and chromatographic separation.

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