DALTON
FULL PAPER

Synthesis, structure and redox properties of ferrocenylmethyl-nucleobases

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Received 28th June 1999, Accepted 28th July 1999

Ferrocenyl derivatives of thymine **1**, cytosine **2**, and uracil and of *N*2-acetylguanine and 2-amino-6-chloropurine have been prepared from reactions of [Fe(η^5-C_5H_5)(η^5-$C_5H_4CH_2N(CH_3)_3$)] I with the corresponding pyrimidine or purine base. The predominant site of alkylation for thymine and cytosine was N1 while for uracil N3 was preferred. Alkylation of the guanine precursor 2-amino-6-chloropurine yielded two products, the *N*2-monosubstituted, and the *N*2,*N*9-disubstituted, derivatives. Acetyl protection/deprotection of the N2 amino group allowed selective N9-alkylation to yield 2-amino-6-chloro-9-ferrocenylmethylpurine. With *N*2-acetylguanine alkylation occurred at either the N7 or N9 positions in a ≈3 : 1 ratio. The structures of eight compounds were determined by single crystal X-ray analysis. Electrochemical investigations by cyclic voltammetry revealed reversible redox processes for the compounds.

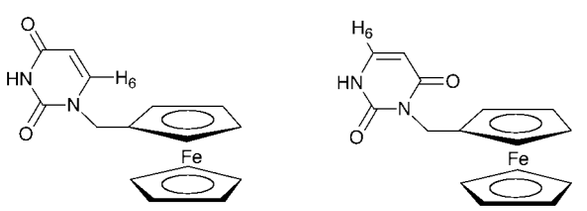
Organometallic compounds comprising nucleobases can be considered in three classes: (a) those involving M–C bonds derived from carbon atoms of the biomolecule, (b) organometallic fragments co-ordinated at N- and O-donor sites of the nucleobases, and (c) compounds with no direct interaction between the nucleobase and the metal ion. Examples for each of these classes have been reported, with class (a) featuring complexes of Hg^{II} and Pt^{II} uracil with M–C5 binding[1] and ruthenium(II) derivatives of adenine and guanine containing M–C8 binding;[2] class (b) includes the RhCp* derivatives of alkylguanine and the metallocene dichloride complexes of various nucleobases,[3,4] while for group (c) the substituted ferrocenyl derivatives are representative.[5,6] This last group of compounds is of interest for their potential co-ordination chemistry as they represent a novel class of redox-active ligands. Furthermore, these ferrocenylnucleobase derivatives represent a useful set of building blocks for supramolecular chemistry due to their capacity for base-pair hydrogen bonding allied with redox properties.

Previously,[6] we have reported some cationic and neutral ferrocenylnucleobase derivatives and their interactions with nucleic acids. Here we extend this work and report on the synthesis and electrochemistry of ferrocenylmethyl derivatives of thymine, uracil, and cytosine and purine derivatives including isomers of *N*2-acetyl-ferrocenylmethylguanine. The crystal and molecular structures of [Fe(η^5-C_5H_5){η^5-$C_5H_4CH_2$[NC(O)-NHC(O)CMeCH]}] **1**, [Fe(η^5-C_5H_5){η^5-$C_5H_4CH_2$[NC(O)NC-(NH_2)CHCH]}] **2**, three 2-amino-6-chloropurine derivatives and the N7 and N9 isomers of ferrocenylmethyl-*N*2-acetylguanine are also presented.

Results and discussion

Synthesis

Trimethylammoniomethylferrocene iodide is a useful source of the alkylating ferrocenylmethyl cation, liberating trimethylamine in the reactions described here. The compounds 1-ferrocenylmethylthymine, [Fe(η^5-C_5H_5){η^5-$C_5H_4CH_2$[NC(O)-NHC(O)CMeCH]}] **1**, 1-ferrocenylmethylcytosine, [Fe(η^5-C_5H_5){η^5-$C_5H_4CH_2$[NC(O)NC(NH_2)CHCH]}] **2**, and 3-ferrocenylmethyluracil, [Fe(η^5-C_5H_5){η^5-$C_5H_4CH_2$[NC(O)NHC(O)-CHCH]}] **3**, were all prepared by an analogous procedure, *i.e.* refluxing trimethylammoniomethylferrocene iodide in aqueous solution with the appropriate nucleobase. With thymine and uracil TLC and ^{1}H NMR revealed a mixture of products, presumably the N1 and N3 isomers. In the case of cytosine only a single product was formed identified as the N1 isomer. For the major product isolated from reactions with uracil, **3**, an NOE experiment exhibited no interactions between the H6 proton of the pyrimidine base and the methylene protons as was observed in the cases of ferrocenylmethylthymine **1** and ferrocenylmethylcytosine **2** indicating N3 as the site of alkylation.



Alkylation reactions using trimethylammoniomethylferrocene iodide were also investigated for guanine, 2-amino-6-chloropurine, 2-acetamido-6-chloropurine and *N*2-acetylguanine. Direct alkylation of guanine did not provide a useful method for the preparation of ferrocenylmethylguanine due to the insolubility of guanine. Reactions with 2-amino-6-chloropurine gave two major products which were separated using column chromatography. These analysed as 6-chloro-2-ferrocenylmethylaminopurine **4**, and the disubstituted derivative 6-chloro-9-ferrocenylmethyl-2-ferrocenylmethylaminopurine **5**. Alkylation of the exocyclic amino groups of purines has been noted in the synthesis of 9-ferrocenylmethyladenine, with both mono- and di-substitution at N6 being observed as minor side-products.[5]

Protection of the N2-amino group *via* acetylation enabled the selective alkylation at N9 to yield 2-acetamido-6-chloro-9-ferrocenylmethylpurine which upon deprotection with base generated 2-amino-6-chloro-9-ferrocenylmethylpurine **6**. Reaction of **6** with HCl did not however provide a useful

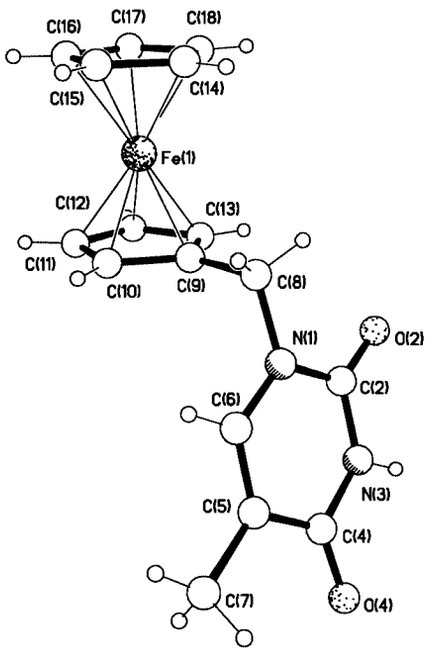


Fig. 1 Molecular structure of compound **1** showing the numbering scheme.

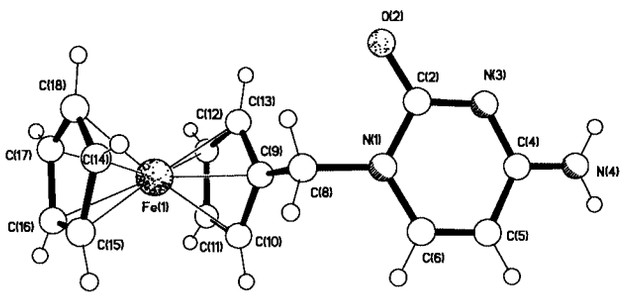


Fig. 2 Molecular structure of compound **2** showing the numbering scheme.

method of preparing 9-ferrocenylmethylguanine.[7] Ferrocenylmethylguanine derivatives were successfully prepared by alkylation of 2-acetylguanine. The initial reaction gave two products in an ≈3 : 1 ratio. These were isolated and identified as the *N*7 and *N*9 isomers by single crystal X-ray crystallography.

Crystal and molecular structures of compounds 1, 2, 4–8

Table 1 presents selected structural parameters for compounds **1**, **2**, **4**–**8** along with those for the previously reported 9-ferrocenylmethyladenine and 1-(3-ferrocenylmethyldimethylammoniopropyl)thymine.[6] Figures 1, 2, 4, 5, 6, 8 and 9 show the molecular structures and numbering schemes used in each case. All bond lengths and angles lie within the expected ranges by comparison with analogous compounds.[8]

In compound **1** the ferrocenylmethyl cation is bonded directly to N1 of thymine (Fig. 1). The Fe–C bond lengths range from 2.026 to 2.048(3) Å with the shortest being to $C(9)_{ipso}$. the C(8)–N(1) bond length for the $C_5H_4CH_2$–N linkage is 1.485(3) Å. The Fe–C_5H_5 perpendicular distance is 1.648 Å compared to 1.639 Å for the Fe–C_5H_4 distance. The interplanar angle between the cyclopentadienyl rings is 2.0°; that between the substituted Cp ring and nucleobase is 69.9°. The two cyclopentadienyl rings are eclipsed (mean torsional angle C–X1–X2–C 2.1° where X1 and X2 are the centres of the cyclopentadienyl rings).

Analysis of the molecular packing in compound **1** reveals short O(2)···N(3) hydrogen bonding (O···N distance 2.820 Å) generated by an inversion centre, to give dimeric units. Atom O(4) does not take part in hydrogen bonding interactions. Internucleobase hydrogen bonding of any type is absent in the previously reported ferrocenylthymine derivative. 1-(3-ferrocenylmethyldimethylammoniopropyl)thymine, due to interactions with the BF_4^- anion.[6] 1-Methylthymine, however, exhibits an analogous pattern of hydrogen bonding to that in **1** with sheets of centrosymmetric dimers related by translational symmetry, involving hydrogen bonding between O4 and N3H (O···N distance 2.840 Å).[9]

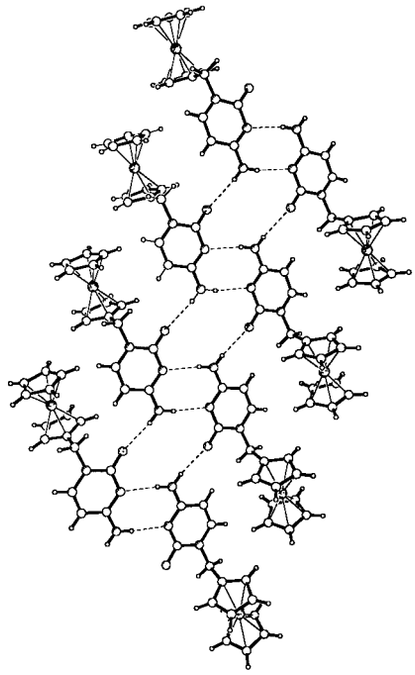


Fig. 3 Intermolecular hydrogen bonding in compound **2**.

In compound **2** the ferrocenylmethyl cation is also attached to N1 of the pyrimidine moiety (Fig. 2). The Fe–C bond lengths range from 2.021 to 2.046(2) Å and Fe–Cp distances are 1.636 and 1.642 Å for the substituted and unsubstituted rings respectively. The interplanar angle between the Cp rings is 2.1° and the rings are essentially eclipsed (mean torsional angle C–X1–X2–C 8.0°). The substituted Cp ring and nucleobase are inclined at an angle of 71.7°. The C–N bond length for the $C_5H_4CH_2$–N linkage is 1.471(3) Å.

In contrast to compound **1**, the hydrogen bonding interactions in **2** form an extended network throughout the structure. Inversion centres generate dimers with an $N(4)H_{syn}\cdots$N(3) hydrogen bond distance of 3.019 Å. These pairs are linked into a tape motif through the interaction of the carbonyl oxygen and the amino proton on adjacent molecules related by lattice translation along the *b* axis (O(2)···H_{anti}N(4) 3.146 Å) (Fig. 3). Each cytosine group thus interacts with three other groups forming 8- and 12-membered rings, comprised of 2D : 2A and 4D : 4A, respectively. Such a motif is directly analogous to that of 1-methylcytosine,[10] where face-to-face dimers with an N3···HN4 distance of 3.038 Å are generated through inversion centres. These are then linked into chains through O2···HN4 interactions (2.882 Å).

In compound **4** the site of alkylation is the exocyclic amino group attached to C2. The Fe–C bond lengths lie in the range 2.023–2.071 Å and the Fe–Cp distances of 1.651 and 1.658 Å to the substituted and unsubstituted rings, respectively (Fig. 4). The angle between the cyclopentadienyl rings is 4.1° and these are eclipsed (mean torsional angle C–X1–X2–C 0.9°). The interplanar angle between the substituted Cp ring and purine moiety is 64.5°. Intermolecular hydrogen bonding involves N7···HN9 (N···N 2.831 Å) with molecules related by a screw axis forming a chain.

The crystal structure of compound **5** is substantially disordered in the nucleobase part of the molecule, effectively

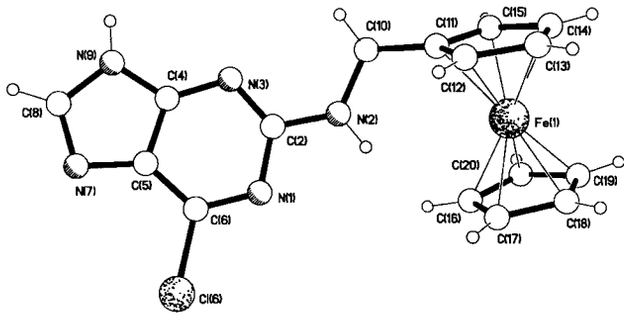


Fig. 4 Molecular structure of compound **4** showing the numbering scheme.

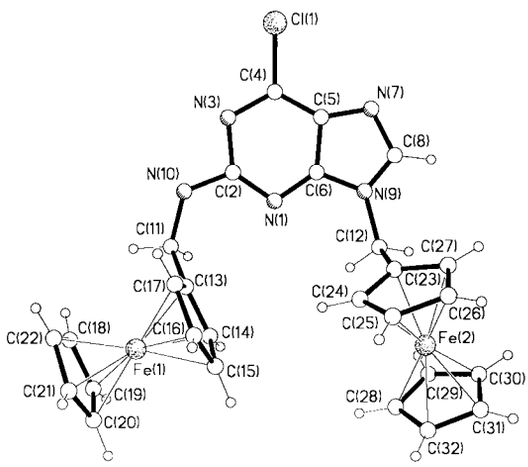


Fig. 5 Molecular structure of compound **5** showing the numbering scheme. Only one disorder component is shown. The other corresponds to a reflection across the N(1)–C(4)–Cl(1) line, exchanging the five-membered ring and the exocyclic nitrogen atom.

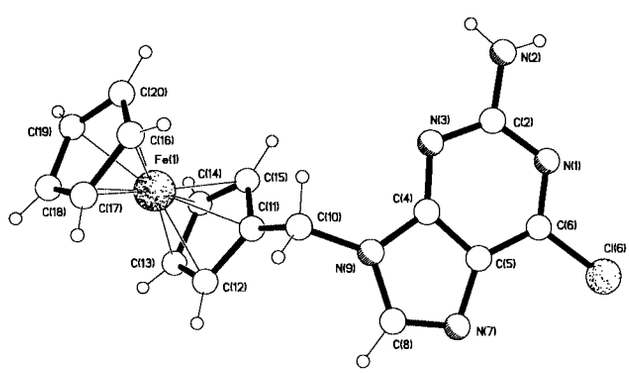


Fig. 6 Molecular structure of compound **6** showing the numbering scheme.

by 180° rotation about the line through Cl(1), C(4) and N(1), giving two alternative positions of the five-membered ring. This limits the discussion of the geometry (Fig. 5). However, it confirms the product to feature disubstitution of the purine moiety with ferrocenylmethyl groups attached at N9 and N2 [N(10) and N(9) in Fig. 5].

For compound **6** alkylation was confirmed to be at N9 of the 2-amino-6-chloropurine (Fig. 6). The Fe–C bond lengths lie in the range 2.026–2.061 Å with Fe–Cp distances of 1.648 and 1.653 Å to the substituted and unsubstituted rings, respectively. The angle between the cyclopentadienyl rings is 2.2° and these are almost eclipsed (mean torsional angle C–X1–X2–C 8.5°). The interplanar angle between the substituted Cp ring and purine moiety is 70.6°.

Within the crystal inversion centres relate pairs of molecules which are hydrogen bonded through N1 · · · HN2 (3.034 Å). Additional interactions generated by glide planes are seen

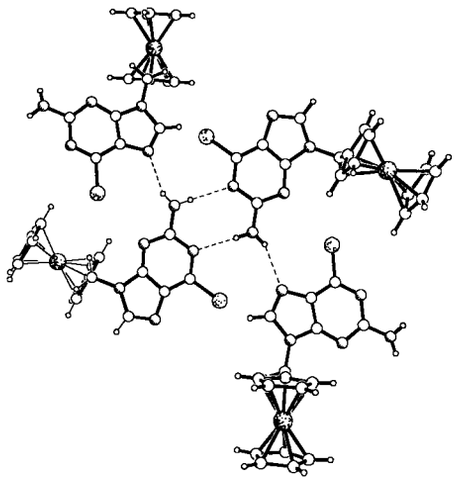


Fig. 7 Intermolecular hydrogen bonding seen in compound **6**.

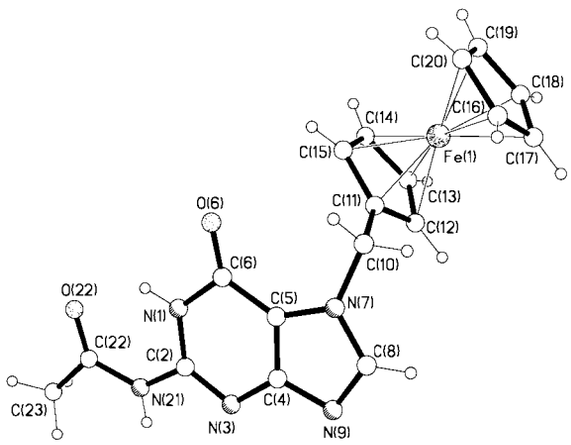


Fig. 8 Molecular structure of compound **7** showing the numbering scheme.

involving the second amino proton on N2 and N7 (N2 · · · N7 3.245 Å) to give tapes (Fig. 7).

Two products were isolated from the reaction of *N*2-acetylguanine with trimethylammoniomethylferrocene iodide. These were characterised as the N7 and N9 isomers, **7** and **8**, respectively. In **7** the Fe–C bond lengths range from 2.0213 to 2.0433(17) Å and the metal–ring plane distances are 1.638 and 1.644 for the substituted and unsubstituted rings respectively (Fig. 8). The two rings are parallel with regards one another (1.7°) and the purine moiety is inclined at an angle of 88.0° to the plane of the substituted cyclopentadienyl ring. Intramolecular hydrogen bonding is seen between the *N*2-acetyl group and the N(1)H proton (O(22) · · · N1 2.635 Å) and intermolecular interactions are seen *via* translational symmetry to link molecules (O6 · · · N2 distance 2.870 Å).

The N9-substituted isomer, **8**, has Fe–C bond lengths in the range 2.033–2.050(4) Å (Fig. 9). The iron–ring distances are 1.643 and 1.648 Å for the substituted and unsubstituted cyclopentadienyl rings and these lie parallel to one another (1.1°). The angle between the purine and the cyclopentadienyl group to which it is attached is 65.2°. Again, intramolecular hydrogen bonding is seen involving the acetyl group and the N1 proton (N1 · · · O22 2.633 Å). Occluded dimethylformamide is involved in hydrogen bonding to the amido proton at N21 (N21 · · · O_{dmf} 2.775 Å).

Electrochemistry

Table 2 summarises the formal electrode potentials of the compounds prepared. All the compounds exhibit reversible one-electron waves with formal potentials, E°, lying in the range

Table 1 Selected bond lengths (Å) and angles (°) for ferrocenyl-purine and -pyrimidine derivatives

	1	**2**	**4**	**5**	**5**	**6**	**7**	**8**	[a]	[b]
				N9–$CH_2C_5H_4$	N2–$CH_2C_5H_4$					
Fe–C (average)	2.039	2.030	2.046	2.035	2.036	2.045	2.038	2.040	2.037	2.042
Fe–C_5H_5	1.648	1.642	1.658	1.649	1.651	1.653	1.644	1.648	1.659	1.659
Fe–C_5H_4	1.639	1.636	1.651	1.639	1.646	1.648	1.638	1.643	1.640	1.640
Angle Cp–Cp eclipse	2.1	8.0	0.9	0.6	0.8	8.5	1.5	2.5	5.2	2.9
Angle Cp–Cp	2.0	2.1	4.1	3.1	1.0	2.2	1.7	1.1	0.9	5.1
Angle Cp_{sub}–Purine	69.9	71.7	64.5	65.4	85.7	70.6	88.0	65.2	64.9	38.0
C_{ipso}–C	1.491(4)	1.497(4)	1.498(10)	—	—	1.494(2)	1.502(2)	1.505(5)	1.498(5)	1.485(6)
$C_5H_4CH_2$–N	1.485(3)	1.471(3)	1.458(8)	—	—	1.470(2)	1.477(2)	1.473(4)	1.470(5)	1.552(5)

[a] $[Fe(\eta^5\text{-}C_5H_5)\{\eta^5\text{-}C_5H_4CH_2[C_5H_4N_5]\}]$ from ref. 6. [b] $[Fe(\eta^5\text{-}C_5H_5)\{\eta^5\text{-}C_5H_4CH_2NMe_2CH_2CH_2CH_2NC(O)NHC(O)CMeCH\}][BF_4]$ from ref. 6.

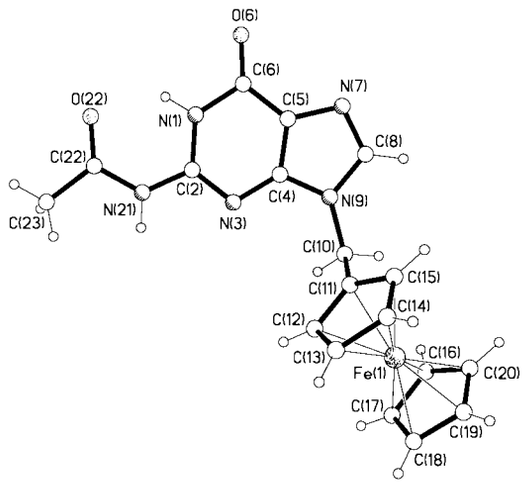


Fig. 9 Molecular structure of compound **8** showing the numbering scheme.

Table 2 Formal electrode potentials (*vs.* ferrocenium–ferrocene) for the ferrocenylnucleobases and related derivatives obtained from cyclic voltammetry (scan rate 500 mV s^{-1}) [a]

Complex	$E°$/V
9-Ferrocenylmethyladenine	+0.090
1 1-Ferrocenylmethylthymine	+0.087
2 1-Ferrocenylmethylcytosine [b]	+0.074
3 3-Ferrocenylmethyluracil	+0.135
4 6-Chloro-2-ferrocenylmethylaminopurine	−0.008
5 6-Chloro-9-ferrocenylmethyl-2-ferrocenylmethylaminopurine	+0.026 and +0.165
6 2-Amino-6-chloroferrocenylmethylpurine	+0.101
7 *N*2-Acetyl-7-ferrocenylmethylguanine	+0.130 [c]
8 *N*2-Acetyl-9-ferrocenylmethylguanine	+0.085 [c]

[a] The electrolyte was $[N(Bu^t)_4][PF_6]$ in acetonitrile in each case, using a 1 mm diameter gold working electrode, a tungsten counter electrode and a silver wire as a quasi-reference electrode. [b] Cyclic voltammogram run in acetonitrile with a few drops of DMF to aid dissolution. [c] Solvent $CHCl_3$, electrolyte $[N(Bu^t)_4][PF_6]$, scan rate 100 mV s^{-1}.

−0.008 to +0.165 V *vs.* ferrocenium–ferrocene with the exception of **5** which displayed two reversible one-electron waves, Fig. 10.

The formal electrode potential obtained for 9-ferrocenylmethyladenine showed a positive shift compared to ferrocene, +0.090 V, indicative of an increased difficulty in removing an electron. The ferrocenyl moiety is bridged through a methylene linkage to the N9 of the imidazole ring of adenine. The electron withdrawing effect of the nitrogen atom on the ferrocenylmethyl group would be expected to be further enhanced as it is part of an aromatic system, making oxidation of the ferrocene more difficult to achieve. A similar formal electrode potential of +0.101 V was obtained for 2-amino-6-chloro-9-ferrocenylmethylpurine **6**. As with 9-ferrocenylmethyladenine, the ferrocenylmethyl group is attached to N9 of the imidazole ring of the purine, resulting in a similar electron withdrawing effect from the ferrocene. The slight increase in difficulty of oxidising the ferrocene of 2-amino-6-chloro-9-ferrocenylmethylpurine may be attributed to the distant effect of the strongly electron withdrawing 6-chloro-substituent on the neighbouring aromatic heterocycle.

In contrast, the attachment of the ferrocenylmethyl group to a nitrogen atom bonded to, but not incorporated in, the heterocyclic ring, as in 6-chloro-2-ferrocenylmethylaminopurine, gave a formal electrode potential of −0.008 V, indicating that oxidation of the ferrocenyl unit is essentially unaffected compared to that of the ferrocene. The electronegativity of the nitrogen atom of the 2-amino group is presumably satisfied by the aromatic ring to which it is attached, resulting in minimum electron withdrawal from the ferrocenyl group. However, the presence of a second ferrocenylmethyl group at N9, as in **5**, appears to have an effect on the oxidation of the 2-ferrocenylmethylamino group. The disubstituted **5**, 6-chloro-9-ferro-

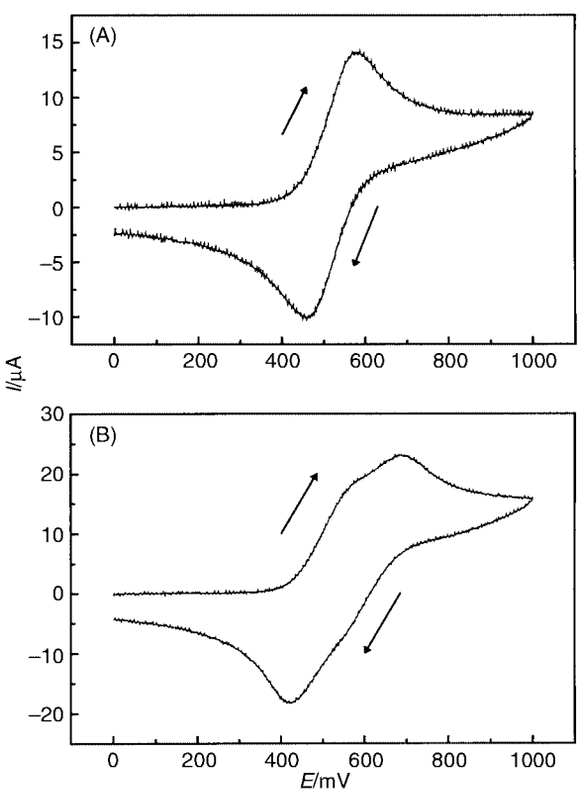


Fig. 10 Cyclic voltammogramms of (A) 1-ferrocenylmethylthymine **1**, and (B) 6-chloro-9-ferrocenylmethyl-2-ferrocenylmethylaminopurine **5**. The electrolyte was $[N(Bu^t)_4][PF_6]$ in acetonitrile, using a 1 mm diameter gold working electrode, a tungsten counter electrode and a silver wire as a quasi-reference electrode. The scan rate was 500 mV s^{-1}.

cenylmethyl-2-ferrocenylmethylaminopurine, gave two separate one-electron oxidations at +0.026 and +0.165 V, Fig. 10. These are assigned to the 2-ferrocenylmethylamino and 9-ferrocenylmethyl units respectively, by comparison with **4** and **6**. Two separate single-step processes are observed as expected on account of the distance separating the iron centres (Fe · · · Fe 7.131 Å in the solid state structure). Both the ferrocenyl units show a greater difficulty in their oxidation compared to the relevant monosubstituted derivatives, with the 9-ferrocenylmethyl unit showing the larger increase. This may be rationalised by the enhanced electron withdrawing effect of the initially oxidised 2-ferrocenylmethylamino group increasing the electrode potential of the 9-substituted metallocene.

The different substitution patterns of the isomers of *N*2 acetylguanine are revealed in the redox behaviour with the N7 isomer **7** undergoing oxidation at higher potential on account of the closer proximity of the C6 carbonyl group compared to the N9 isomer **8** (+0.130 *vs*. 0.085 V).

The formal electrode potentials obtained for the ferrocenylmethylpyrimidine derivatives indicate that oxidation of the ferrocenyl units is considerably more difficult than for ferrocene, with +0.074, +0.087 and +0.135 V found for 1-ferrocenylmethylcytosine **2**, 1-ferrocenylmethylthymine **1** and 3-ferrocenylmethyluracil **3**, respectively. The increased difficulty in oxidation can be interpreted in terms of the environment of the nitrogen to which the ferrocenylmethyl group is attached. For **1** and **2** the nitrogen atom (N1) in both cases is bonded to a carbonyl carbon (C2) and an alkene carbon (C6). The higher formal oxidation potential found for 3-ferrocenylmethyluracil **3** can be explained by the fact that N3 is adjacent to two carbonyl carbons (C2 and C4) which together possess a greater electron withdrawing effect than those groups attached to N1 for the other pyrimidines.

Conclusion

A series of ferrocenyl derivatives of purine and pyrimidine bases has been prepared using the ferrocenylmethyl cation generated from trimethylammoniomethylferrocene iodide as an alkylating agent. Among these are cytosine, thymine, uracil and guanine derivatives which, along with adenine,[5,6] complete the series of metallocene–nucleobase compounds. The applications of these compounds to supramolecular and co-ordination chemistry are currently being explored.

Experimental

Trimethylammoniomethylferrocene iodide was prepared from dimethylaminomethylferrocene (Lancaster) by reaction with MeI in methanol. Adenine, thymine, uracil, cytosine and 2-amino-6-chloropurine were obtained from Aldrich and used as supplied. *N*2-Acetylguanine was obtained from Sigma. Satisfactory elemental analysis was obtained.

Preparations

1-Ferrocenylmethylthymine 1. Thymine (0.5 g, 4.5 mmol) was combined with an aqueous solution (40 ml) of trimethylammoniomethylferrocene iodide (1.4 g, 4.5 mmol) and the mixture allowed to reflux overnight. The resulting precipitate was filtered off and washed with water, ethanol and finally diethyl ether. Purification of the crude solid by column chromatography on neutral alumina eluting with chloroform–methanol (9 : 1) yielded 1-ferrocenylmethylthymine as the major product, in 22% yield. Crystals suitable for X-ray crystallography were grown by slow cooling of a saturated DMF solution. ^{1}H NMR (500 MHz, DMSO): δ 3.44 (3 H, s, CH_3), 4.23 (2 H, t, β protons of C_5H_4), 4.29 (5 H, s, C_5H_5), 4.40 (2 H, t, α protons of C_5H_4), 4.64 (2 H, s, CH_2N), 7.67 (1 H, s, H6) and 11.3 (1 H, broad s, H3). MS: $[M]^+$ at *m*/*z* 324.

1-Ferrocenylmethylcytosine 2. Cytosine (0.5 g, 4.5 mmol), was combined with trimethylammoniomethylferrocene iodide (1.413 g, 4.5 mmol) in 60 ml of water and allowed to reflux for 6 h. The resulting yellow precipitate was filtered off and washed with water, ethanol, ether and then allowed to dry, yield 73%. Crystals suitable for X-ray crystallography were grown by slow cooling of a saturated DMF solution. ^{1}H NMR (500 MHz, DMSO): δ 4.22 (2 H, t, β protons of C_5H_4), 4.28 (5 H, s, C_5H_5), 4.38 (2 H, t, α protons of C_5H_4), 4.65 (2 H, s, CH_2N), 5.69 (1 H, d, H5), 7.04 (2 H, broad s, NH_2) and 7.70 (1 H, d, H6). MS: $[M]^+$ at *m*/*z* 309.

3-Ferrocenylmethyluracil 3. Uracil (0.5 g, 4.46 mmol) was combined with an aqueous solution of trimethylammoniomethylferrocene iodide (1.4 g, 4.5 mmol). The mixture was allowed to reflux for 6 h during which time a yellow precipitate formed. This was filtered off, washed with water, ethanol and ether, then allowed to dry. The isolated solid was purified by column chromatography on neutral alumina in chloroform–methanol (98 : 2) to give a major product identified as 3-ferrocenylmethyluracil, yield 15%. ^{1}H NMR (500 MHz, DMSO): δ 4.16 (2 H, t, α protons of C_5H_4), 4.28 (5 H, s, C_5H_5), 4.35 (2 H, t, β protons of C_5H_4), 4.77 (2 H, s, CH_2N), 5.65 (2 H, d, H5 proton), 7.48 (2 H, d, H6) and 11.17 (broad s, 1 H, NH). MS: $[M]^+$ at *m*/*z* 310.

2-6-Chloroferrocenylmethylaminopurine 4 and 6-chloro-9-ferrocenylmethyl-2-ferrocenylmethylaminopurine 5. 2-Amino-6-chloropurine (0.25 g, 1.47 mmol) was combined with an aqueous solution of trimethylammoniomethylferrocene iodide (0.46 g, 1.47 mmol). The mixture was allowed to reflux overnight and the resulting yellow precipitate filtered off and washed successively with water, ethanol, ether and allowed to dry. The isolated crude solid was purified by column chromatography on silica eluting with chloroform–methanol (98 : 2). Two major products were isolated and identified as **4** (yield 5%) and **5** (yield 24%). Crystallisation of the pure compounds from chloroform yielded samples suitable for single crystal X-ray diffraction. Compound **4**: ^{1}H NMR (200 MHz, $CDCl_3$) δ. 4.08 (2 H, t, 2 protons of C_5H_4), 4.13 (5 H, s, C_5H_5), 4.16 (2 H, t, 2 protons of C_5H_4), 4.23 (2 H, d, CH_2), 5.38 (1 H, br s, NH9), 7.75 (1H, s, H8) and 9.46 (1H, br s, NH_2); MS $[M]^+$ at *m*/*z* 367. Compound **5**: ^{1}H NMR (200 MHz, $CDCl_3$) δ 4.04 (4 H, s, 4 equivalent protons of $2C_5H_4$), 4.12 (10 H, s, $2C_5H_5$), 4.23 (4 H, s, 4 equivalent protons of $2C_5H_4$), 4.47 (4 H, s, $2CH_2$), 7.7 (1 H, s, H8) and 9.4 (1 H, br s, NH_2); MS $[M]^+$ at *m*/*z* 565.

2-Amino-6-chloro-9-ferrocenylmethylpurine 6. Trimethylammoniomethylferrocene iodide (0.13 g, 0.34 mmol) and 2-acetamido-6-chloropurine[11] (0.072 g, 0.34 mmol) were heated to reflux in distilled water. After 2 h a yellow precipitate of 2-acetamido-6-chloro-9-ferrocenylmethylpurine formed and was filtered off, washed with cold water and allowed to dry (yield 91%). This was then treated with an aqueous solution of methanol (10 ml with 1 ml of water) containing 1 g of sodium hydroxide and allowed to reflux for 1 h. Once cool, the solution was reduced to dryness and the residue redissolved in water. A yellow precipitate formed on neutralisation with concentrated acetic acid. This was filtered off, washed with water and allowed to dry, yield 32%. Crystals of compound **6** suitable for single crystal X-ray diffraction studies were obtained from chloroform. 2-Acetamido-6-chloro-9-ferrocenylmethylpurine: ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.55 (3 H, s, CH_3), 4.2 (7 H, s, C_5H_5 + 2 protons of C_5H_4), 4.32 (2 H, t, 2 protons of C_5H_4), 5.1 (2 H, s, CH_2), 7.9 (1 H, s, CH_3) and 8.08 (2 H, s, NH_2). Compound **6**: ^{1}H NMR (200 MHz, $CDCl_3$) δ 4.2 (5 H, s, C_5H_5), 4.21 (2 H, t, 2 protons of C_5H_4), 4.28 (2 H, t, 2 protons of C_5H_4), 4.99 (2 H, s, CH_2), 5.13 (2 H, br s, NH_2) and 7.69 (1 H, s, H8).

Table 3 Crystallographic data for compounds **1**, **2**, **4**–**8**

	1	**2**	**4**	**5**	**6**	**7**	**8**
Formula	$C_{16}H_{16}FeN_2O_2$	$C_{15}H_{15}FeN_3O$	$C_{16}H_{14}ClFeN_5$	$C_{27}H_{24}ClFe_2N_5P$	$C_{16}H_{14}ClFeN_5$	$C_{18}H_{17}FeN_5O_2$	$C_{21}H_{24}FeN_6O_3$
M	324.2	309.2	367.62	565.7	367.6	391.2	464.3
Crystal system	Monoclinic	Monoclinic	Monoclinic	Triclinic	Monoclinic	Monoclinic	Orthorhombic
Space group	$P2_1/n$	$P2_1/c$	$I2/a$	$P\bar{1}$	$P2_1/n$	$P2_1/c$	*Pbca*
a/Å	5.8871(12)	17.0466(19)	7.912(3)	7.4437(7)	10.6304(10)	10.2282(9)	22.443(3)
b/Å	11.597(2)	7.3337(8)	9.803(3)	11.2087(10)	11.3735(10)	7.1859(6)	7.6933(11)
c/Å	20.262(4)	10.6368(12)	38.355(14)	14.7197(14)	13.3561(12)	22.3765(19)	23.913(3)
α/°				101.704(2)			
β/°	91.02(3)	105.972(3)	92.622(8)	95.290(2)	107.155(2)	102.597(2)	
γ/°				96.077(3)			
U/Å^3	1383.2(5)	1278.4(2)	2970.3(17)	1187.7(2)	1543.0(2)	1605.1(2)	4128.8(10)
Z	4	4	8	2	4	4	8
D_c/g cm^{-3}	1.557	1.606	1.644	1.582	1.583	1.619	1.494
μ/mm^{-1}	1.10	1.18	1.20	1.36	1.16	0.97	0.77
T/K	160	160	160	160	160	160	160
R(*F*) ('observed' data)	0.0422	0.0409	0.0769	0.0719	0.0274	0.0301	0.0441
R′ (F^2) (all data)	0.0933	0.0950	0.1806	0.1694	0.0694	0.0743	0.1033
Data, parameters	3172, 195	2864, 190	2593, 209	5235, 334	3627, 215	3884, 237	3636, 284

***N*2-Acetyl-7-ferrocenylmethylguanine 7 and *N*2-acetyl-9-ferrocenylmethylguanine 8.** *N*2-acetylguanine (0.50 g, 2.59 mmol) and trimethylammoniomethylferrocene iodide (1.0 g, 2.59 mmol) were added to water (20 ml). The reaction mixture was heated to reflux and heating continued for 6 h. The reaction was cooled to r.t. and the solid filtered off, washed with water and dried. The two components of the solid were separated by column chromatography on alumina (10 cm depth, 2.5 cm diameter), eluting initially with 2.5% MeOH in CH_2Cl_2 followed by 10% MeOH in CH_2Cl: **7**, 46%; **8**, 14%, respectively. Both were recrystallised from DMF for crystal structure analysis. This determined that **7** is the N7 isomer and **8** the N9 isomer. Compound **7**: ^{1}H NMR (d_6-DMSO, 200 MHz) δ 12.2 and 11.7 (both br s, 1 H, D_2O exchange, NH, OH), 8.4 (s, 1 H, H8), 5.4 (s, 2 H, NCH_2), 4.5 (m, 2 H, Cp), 4.4 (s, 5 H, Cp), 4.25 (m, 2 H, Cp) and 2.2 (s, 3 H, CH_3CO); MS $[M]^+$ at *m*/*z* 391. Compound **8**: ^{1}H NMR (d_6-DMSO, 200 MHz) δ 12.0 (br s, 2 H, D_2O exchange, NH, OH), 8.15 (s, 1 H, H8), 5.1 (s, 2 H, NCH_2), 4.5 (m, 2 H, Cp), 4.3–4.2 (m, 7 H, Cp) and 2.3 (s, 3 H, CH_3CO); MS $[M]^+$ at *m*/*z* 391.

Crystallography

Crystal data for compounds **1**, **2**, **4**–**8** are in Table 3. All measurements were made on a Bruker AXS SMART CCD diffractometer with Mo-Kα radiation ($\lambda = 0.71073$ Å). Data were corrected semiempirically for absorption. Programs were the manufacturer's standard control and integration software and SHELXTL.[12]

CCDC reference number 186/1599.

See http://www.rsc.org/suppdata/dt/1999/3229/ for crystallographic files in .cif format.

Electrochemistry

A conventional two-compartment glass cell was used with a 1 mm diameter platinum disc working electrode. A silver wire was used as a quasi-reference electrode and the potential scale was established by measuring a cyclic voltammogram of ferrocene. The electrolyte was $[N(Bu^t)_4][PF_6]$ in acetonitrile. The potentiostat was an EG&G model 263A.

Acknowledgements

The EPSRC is thanked for a studentship (to C. J. I.), an Advanced Research Fellowship (to A. H.) and a diffractometer (W. C.). The MS Service Centre, University of Wales, Swansea is also acknowledged.

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Paper 9/05168F