Organometallic Nucleoside Analogues with Ferroceny1 Linker Groups: Synthesis and Cancer Cell Line Studies.

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ferrcne, nucleoside analogues, anticancer, bioorganometallic, DNA

ABSTRACT: Examples of organometallic compounds as nucleoside analogues are rare within the field of medicinal bioorganometallic chemistry. We report on the synthesis and properties of two chiral ferrocene derivatives containing both a nucleobase and a hydroxylalkyl group. These so-called ferronucleosides show promising anticancer activity, with cytostatic studies on five different cancer cell lines indicating that both functional groups are required for optimal activity.

Nucleoside analogues have long been established as an effective class of compound that exhibits antiviral or anticancer activity. 1 Two common structural features are a nucleobase moiety and a hydroxymethyl group (Figure 1), which together allow them to act as substrates that adversely affect processes associated with nucleic acid synthesis. These two components are typically connected by an organic linker group that is a modification or a replacement of the sugar ring, which can either be cyclic (e.g. AZT) or acyclic (e.g. acyclovir). 2 Due to their structural similarities to natural nucleosides, which can lead to resistance and side-effects, there is a continuing need for a diverse range of analogues with different structural features. Ferrocene has attracted active interest in recent years within the field of medicinal and bioorganometallic chemistry, 3 with organometallic analogues and derivatives of the antimalarial drug chloroquine (ferroquine) and the breast cancer drug tamoxifen (the ferrocifen family) being the most widely known. 4 At the same time there has been a number of examples of other ferrocene containing compounds that have shown anticancer, 5 antibacterial and antifungal properties. 6 However although there are also some recent examples of ferrocene-conjugated nucleobases 7 and hydroxylalkyl ferrocenes 8 that exhibit anticancer activity, as far as we are aware, nucleoside analogues of the type shown in Figure 1 that are bridged solely by an organometallic linker group and show biological activity have not been reported. 9

As part of our programme to develop novel metal-containing analogues of DNA and its components, 10 we recently reported an organometallic nucleic acid oligomer designated as Ferrocene Nucleic Acid (FeNA). 10b The monomeric components of the reported form of FeNA consist of a tetra-substituted ferrocene unit containing two alkyl hydroxyl groups to allow connectivity via phosphodiesters, and two thymine nucleobases. We noticed that these monomeric compounds have the required features for a novel nucleoside analogue, where the 5-membered sugar ring is substituted for a 5-membered cyclopentadienyl ring of a ferrocene unit. Accordingly we now report bis-substituted ferroces 1 and 2 (so-called ferronucleosides), that contain both a nucleobase (thymine or adenine) and a hydroxyl group, along with various control compounds (Fig. 2). The cell line studies reported here demonstrate the promise of these ferrocenyl derivatives as a novel class of nucleoside analogue that show anticancer activity.

Figure 1. Schematic representation of the structural relationship between thymidine and a nucleoside analogue that contains a variable linker group connecting a hydroxymethyl group with a nucleobase, with AZT (azidothymidine) as a specific example.
It was decided to first synthesize nucleoside analogues with a 1,2-disubstituted arrangement on one Cp ring, with the other Cp ring unfunctionalized. This would enable us to utilize the synthetic chemistry already developed within the group for FcNA monomer synthesis. For the same reason, the compounds would have a three-carbon hydroxyl linker (with a methyl group on the alpha carbon to direct ortho-lithiation) and a two-carbon linker to the nucleobase. The synthetic route taken to make the ferronucleoside targets 1 and 2 is outlined in Scheme 1. The chirally pure Ugi amine 7 was treated with n-BuLi and quenched with iodine to introduce the required planar 1,2-disubstitution pattern. Subsequent functional group inter-conversion gave compound 11, to provide the chain extension giving a three carbon linker. Treatment of 11 with silyl enol ether, catalyzed by the Lewis acid boron trifluoride, gave compound 12 in good yield. Reduction of the ester, followed by TBDPS protection gave compound 14. Conversion to aldehyde 15 (via n-BuLi halogen exchange and quenching with DMF) enabled a Wittig reaction to be performed to from alkene 16, with subsequent hydroboration-oxidation giving the mono-protected bis-alcohol 17 in high chiral purity (as checked by chiral HPLC analysis, overall 97% ee). The conversion of 17 to the target compounds 1 and 2 proceeded via a Mitsunobu reaction with the appropriate protected nucleobase, followed by deprotection of the protecting groups. The family of compounds was also extended by making the control compounds 3-6 (Fig. 2), to assess the role of the alcohol and nucleobase groups, noting that compound 6 had previously been shown to display antineoplastic activity against cervix carcinoma (HeLa) tumor cells.

The cytostatic activity of six ferrocene compounds was evaluated in comparison to the established anticancer drugs cisplatin and 5-fluorouracil (5-FU) using a proliferation assay carried out on three tumor cell lines: murine leukemia cells (L1210), HeLa, and human T-lymphocyte cells (CEM). The data indicate that the concomitant presence of both the hydroxyl and nucleobase components are of crucial importance to give the highest cytostatic activity, with 1 and 2 exhibiting low to sub micromolar antiproliferative activity comparable with cisplatin (Table 1). In addition, 1 and 2 were almost equally as active as 5-FU in L1210 cell cultures, 2- to 5-fold less active in HeLa cell cultures, but 20-to 50-fold more active in CEM cell cultures. Compounds 1 and 2 proved poorly toxic to non-tumorigenic human embryonic lung (HEL) fibroblast cell cultures (minimal cytotoxic concentration: >50 µM).

Table 1. Cytostatic activity of compounds 1-4.

<table>
<thead>
<tr>
<th>Compound</th>
<th>IC_{50} (µM) (^*)</th>
</tr>
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<tbody>
<tr>
<td>L1210</td>
<td>CEM</td>
</tr>
<tr>
<td>1</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
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<tr>
<td>3</td>
<td>12</td>
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<tr>
<td>4</td>
<td>417</td>
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<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>Cisplatin</td>
<td>1</td>
</tr>
<tr>
<td>5-FU</td>
<td>0.33 ± 0.17</td>
</tr>
</tbody>
</table>

\(^*\)IC_{50} inhibitory concentration, or compound concentration required to inhibit tumor cell proliferation by 50%. Data are the mean of at least two independent experiments.

Cell growth studies carried out on an oesophageal cancer cell line revealed that compound 1 inhibited growth at
concentrations of 6.25 µM, whereas control compounds 3 and 4 (Figure 3 and supplementary data respectively) had much less or no effect, even up to higher concentrations of 25 µM. The same trend was observed for the adenine compound 2 and its control 5 (see supplementary data). Once again the data indicates that both functional groups (the hydroxyl in addition to the nucleobase) are required for the best cytostatic activities, which is comparable to cisplatin under these conditions.

Assays of cellular viability (MTT assay) and cell proliferation (BrdU assay) were then performed on colorectal cancer cell lines. The results after 48 hr exposure (Figure 4) revealed that compounds 1 and 2 had anti-neoplastic activities approaching that of 5-FU, whereas the other compounds were less effective. Encouragingly, an AMES assay to investigate the potential mutagenicity of these ferrocenyl derivatives revealed that the compounds were inactive.

In conclusion, novel ferrocenyl nucleoside analogues 1 and 2 appear to exhibit cytostatic activities that are comparable under the conditions used to commercially established anticancer drugs such as cisplatin and 5-FU. Control studies indicate that the presence of both a hydroxyl and a nucleobase group are required for optimal activity. This suggests a mechanistic role for these novel bioregulatory compounds involving an adverse affect on nucleic acid synthesis, as is the case for nucleobase analogue drugs containing organic linker groups. We are currently planning to carry out further studies to reveal the mode of action of these ferrocenonucleosides and to highlight stereochemical and structure activity relationships for improving biological activity and specificity.

**EXPERIMENTAL SECTION**

**General Information:** Unless stated otherwise, all reactions were performed under an Ar atmosphere. Compound 6 was prepared as described previously. All tested compounds had a purity of ≥95%, as shown by HPLC (see supplementary information for data and conditions used).

(R,S)-1-(α-N,N-Dimethylaminoethyl)-2-idoferrocene (8). The Ugi amine 7 (4.00 g, 15.56 mmol) was dissolved in EtO (50 ml) at room temperature, n-BuLi (12 ml, 30 mmol) was added and the mixture stirred overnight. The reaction mixture was cooled to -78°C and iodine (9.52 g, 37.51 mmol), dissolved in THF (60 ml), was added over 10 min. The reaction mixture was stirred at -78°C for 90 min before being warmed to room temperature, at which point it was stirred for an additional 90 min before being quenched with 0°C with sodium thiosulfate (50 ml, 25% w/v). After dilution with EtO (30 ml), the layers were separated and the aqueous layer further extracted with EtO (3 x 50 ml). The combined organic fractions were dried over MgSO₄, the solvent removed **in vacuo** before purification via flash column chromatography (5% MeOH, 5% TEA in DCM) to yield product (3.18 g, 55%).

1H NMR (400 MHz, CDCl₃) δ 4.46 (dd, J = 2.4, 1.4 Hz, 1H), 4.24 (t, J = 2.6 Hz, 1H), 4.15 (dd, J = 2.7, 1.3 Hz, 1H), 4.12 (s, 5H), 3.62 (q, J = 6.8 Hz, 1H), 2.15 (s, 6H), 1.50 (d, J = 6.8 Hz, 3H). 13C NMR (101 MHz, CDCl₃) δ 90.21 (ips Cp), 74.32 (Fc), 71.67 (Fc), 68.19 (Fc), 65.59 (Fc), 57.59 (CH*), 45.49 (ips Cp), 41.22 (CH*), 16.01 (CH*). MS (ES) (m/z) calcd for C₁₄H₁₈N₆Fel 382.9833, found 382.9820. IR (cm⁻¹): 3078 (=C=O), 2972 (CH=CH), 2878 (CH₂), 1601 (CH*), 1371 (CH₂), 1243, 1087, 821 (CH=CH), 732 (CH Ar). Mp: 58°C-60°C.

(R,S)-1-(α-Acetoxyethyl)-2-ido-ferrocene (9). Compound 8 (3.26 g, 8.51 mmol) and acetic anhydride (25.68 ml, 272.17 mmol) were heated at 50°C for 2 hrs. The acetic anhydride was removed under high vacuum (0.1 mmHg) and the residue purified via flash column chromatography (10% EtOAc in hexane) to yield the yellow-brown oily product (2.94 g, 87%). 1H NMR (400 MHz, CDCl₃) δ 5.89 (q, J = 6.4 Hz, 1H), 4.51 (dd, J = 2.6, 1.4 Hz, 1H), 4.33 (dd, J = 2.8, 1.4 Hz, 1H), 4.28 (t, J = 2.6 Hz, 1H), 4.15 (s, 5H), 2.01 (s, 3H), 1.66 (d, J = 6.5 Hz, 3H). 13C NMR (101 MHz, CDCl₃) δ 170.30 (C=O), 87.54 (ips Cp), 75.63 (Fc), 71.76 (Fc), 69.71 (Fc), 68.94 (Fc), 65.80 (CH*), 44.03 (ips Cp), 21.16 (CH₂), 18.66 (CH*). IR (cm⁻¹): 3095 (=C=H), 2972
(CH3), 2928 (CH2), 2866 (CH3), 1729 (C=O), 1445 (CH3), 1371 (CH3), 1085, 820 (CH=CH), 703 (CH Ar).

\( R_{S_2} \)-1-(\( \alpha \)-Hydroxyethyl)-2-iodo-ferocene (10). Compound 9 (2.937 g, 7.37 mmol) was dissolved in EtOH (35 ml). NaOH (30 ml, 10% w/v) was added and the reaction was heated at 95°C for 15 min. After cooling to room temperature, the organic layer was extracted with EtOAc (2 x 40 ml). The organic layers were dried over NaSO4, the solvent removed \textit{in vacuo} and the residue purified via flash column chromatography (25% EtOAc in hexane) to yield the yellow oily product (2.43 g, 92%). 1H NMR (400 MHz, CDCl3) \( \delta \) 4.85 (qd, \( J = 6.5, 2.8 \) Hz, 1H), 4.46 (dd, \( J = 2.5, 1.4 \) Hz, 1H), 4.29 (dd, \( J = 2.7, 1.3 \) Hz, 1H), 4.25 (t, \( J = 2.6 \) Hz, 1H), 4.14 (s, 5H), 1.88 (d, \( J = 3.6 \) Hz, 1H), 1.62 (d, \( J = 6.5 \) Hz, 3H). 13C NMR (101 MHz, CDCl3) \( \delta \) 91.61 (ipso Cp), 75.01 (Fc), 71.59 (Fc), 68.72 (Fc), 66.51 (Fc), 64.98 (CH*), 43.62 (ipso Cp), 21.31 (CH3). MS (ES) (m/z) cals for \( C_{16}H_{38}O_{2}^{56}Fe \) 355.9361, found 355.9352. IR (cm\(^{-1}\)) : 3255 (OH), 3093 (C-H), 2967 (CH2), 2920 (CH3), 1445 (CH3), 1369 (CH3), 1099 (C-OH), 816 (CH=CH), 684 (CH=CH).

\( R_{S_2} \)-1-(\( \alpha \)-Methoxyethyl)-2-iodo-ferocene (11). Compound 10 (2.43 g, 6.83 mmol) was dissolved in a MeOH/AcOH (20 ml, 9:1) mixture and the solution was stirred at room temperature for 48 hrs. The reaction was quenched with water (10 ml) and extracted with DCM (2\times20 ml). The combined organic fractions were dried over MgSO4, the solvent removed \textit{in vacuo} and the residue purified via flash column chromatography (25% EtOAc in hexane) to yield the yellow oily product (2.37 g, 94%). 1H NMR (400 MHz, CDCl3) \( \delta \) 4.49 (dd, \( J = 2.4, 1.4 \) Hz, 1H), 4.34 (q, \( J = 6.5 \) Hz, 1H), 4.29 – 4.25 (m, 2H), 4.13 (s, 5H), 3.26 (s, 3H), 1.64 (d, \( J = 6.5 \) Hz, 3H). 13C NMR (101 MHz, CDCl3) \( \delta \) 89.78 (ipso Cp), 74.78 (Fc), 74.22 (Fc), 71.66 (Fc), 68.86 (Fc), 65.38 (CH*), 56.00 (Fc), 39.48 (ipso Cp), 19.63 (CH3). MS (ES) (m/z) cals for \( C_{16}H_{38}O_{2}^{56}Fe \) 369.9517, found 369.9513. IR (cm\(^{-1}\)) : 3094 (C=C), 2974 (CH3), 2926 (CH3), 2871 (CH3), 2815 (CH3), 1448 (CH3), 1371 (CH3), 1085 (C-O-C), 820 (CH=CH).

\( S_{S_2} \)-1-(\( \alpha \)-Methyl-2-ethoxypropionate)-2-iodo-ferocene (12). Compound 11 (2.37 g, 6.42 mmol) and 1-ethoxyvinylvinyltrimethylsilane (8.234 g, 51.37 mmol) were dissolved in DCM (30 ml). The mixture was cooled to 78°C and BF3\( \cdot \)OEt2 (1.77 ml, 14.12 mmol) was then added dropwise. The reaction mixture was stirred for 15 min at 78°C before being warmed to room temperature and quenched with saturated NaHCO3 (40 ml). The organic layer was separated and the aqueous layer was further extracted with DCM (40 ml). The combined organic fractions were dried over MgSO4, the solvent removed \textit{in vacuo} and the residue purified via flash column chromatography (10% EtOAc in hexane) to yield a yellow oily product (2 g, 95%). 1H NMR (400 MHz, CDCl3) \( \delta \) 7.70 – 7.65 (m, 4H), 7.43 – 7.32 (m, 6H), 4.38 (dd, \( J = 2.4, 1.3 \) Hz, 1H), 4.10 (s, 5H+H), 4.00 (dd, \( J = 2.7, 1.3 \) Hz, 1H), 3.70 – 3.65 (m, 2H), 2.77 – 2.68 (m, 1H), 1.88 – 1.80 (m, 1H), 1.43 – 1.34 (m, 1H), 1.31 (d, \( J = 6.9 \) Hz, 3H), 1.05 (s, 9H). 13C NMR (101 MHz, CDCl3) \( \delta \) 135.63 (Ph), 134.10 (ipso Ph), 134.05 (ipso Ph), 129.47 (Ph), 127.58 (Ph), 96.25 (ipso Cp), 73.81 (Fc), 71.38 (Fc), 66.61 (Fc), 64.27 (Fc), 62.10 (CH3), 44.45 (ipso Cp), 41.60 (CH3), 30.03 (CH*), 26.94 (tBu), 19.24 (ipso tBu), 18.91 (CH3). MS (ES) (m/z) cals for \( C_{16}H_{38}O_{2}^{56}FeSiNa \) 622.0851, found 622.0846. IR (cm\(^{-1}\)) : 3071 (C=C), 2958 (CH3), 2929 (CH3), 2856 (CH3), 1472 (CH3), 1387 (CH3), 1361, 1106, 1085, 821 (CH Ar TDBPS), 700 (C=C).

\( S_{S_2} \)-1-(\( \alpha \)-Methyl-3-(tert-butylideneislyloxy)propyl)-2-formyl-ferrocene (15). Compound 14 (2.182 g, 3.51 mmol) was dissolved in Et2O (30 ml), the mixture was cooled to -78°C and n-BuLi (2.32 ml, 7.01 mmol) was added. After 30 min, DMP (0.68 ml, 8.76 mmol) was added and the mixture was stirred at -78°C for another 30 min before being allowed to warm to room temperature before quenching with water (20 ml). The phases were separated and the aqueous layer was extracted...
with Et\textsubscript{2}O (2 x 20 ml). The combined ethereal fractions were dried over Na\textsubscript{2}SO\textsubscript{4}, the solvent removed in vacuo and the residue purified via flash column chromatography (10% EtOAc in hexane) to yield the red oily product (1.686 g, 92%).

\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \(\delta\) 10.11 (s, 1H), 7.68 – 7.59 (m, 4H), 7.42 – 7.33 (m, 6H), 4.75 (dd, \(J = 2.7, 1.4\) Hz, 1H), 4.48 (t, \(J = 2.6\) Hz, 1H), 4.43 (dd, \(J = 2.6, 1.4\) Hz, 1H), 4.21 (s, 5H), 3.61 (t, \(J = 7.1, 2.1\) Hz), 3.21 – 3.10 (m, 1H), 1.73 – 1.50 (m, 2H), 1.34 (d, \(J = 6.9\) Hz, 3H), 1.04 (s, 9H).

\textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}) \(\delta\) 133.95 (ipso Ph), 133.80 (ipso Ph), 129.55 (Ph), 127.61 (CH\textsubscript{N}), 127.50 (CH\textsubscript{N}), 99.14 (CH\textsubscript{C}), 87.83 (CH\textsubscript{C}), 76.31 (ipso Cp), 75.01 (ipso Cp), 72.98 (ipso Cp), 56.32 (ipso Cp), 56.18 (ipso Cp), 43.38 (ipso Cp), 30.93 (CH\textsubscript{C}), 27.51 (CH\textsubscript{C}), 26.91 (tBu), 19.37 (CH\textsubscript{C}), 19.22 (ipso tBu). MS (ES) (m/z) calcd for C\textsubscript{56}H\textsubscript{38}O\textsubscript{8}FeSiNa 563.2045, found 563.2039. IR (\textit{cm}\textsuperscript{-1}): 3378 br (OH), 3072 (=CH Fc), 2930 (CH\textsubscript{C}), 1917 (CH\textsubscript{C}).

(\textit{S,R})-1-[\textit{N-Methyl-(3-(tertbutilphenoxy)propyl)]-2-vinyl-ferrocene (16). Triphenylmethylphosphonium bromide (1.722 g, 4.82 mmol), potassium tert-butoxide (0.541 g, 4.82 mmol) and a catalytic amount of dibenzo-18-crown-6-ether were dissolved in THF (20 ml). The mixture was stirred for 30 min and then 15 (1.686 g, 3.21 mmol), dissolved in THF (30 ml), was added to the mixture. The reaction mixture was stirred overnight at room temperature, before quenching with water (10 ml) and extracting with Et\textsubscript{2}O (2 x 20 ml). The combined ethereal fractions were dried over Na\textsubscript{2}SO\textsubscript{4}, solvent removed in vacuo and purified via flash column chromatography (5% EtOAc in hexane) to yield the product as a yellow oil (1.497 g, 89%).

\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \(\delta\) 7.69 – 7.63 (m, 4H), 7.44 – 7.33 (m, 6H), 6.62 (dd, \(J = 17.4, 10.1\) Hz, 1H), 5.34 (dd, \(J = 17.5, 1.8\) Hz, 1H), 5.01 (dd, \(J = 10.8, 1.7\) Hz, 1H), 4.43 (dd, \(J = 2.5, 1.4\) Hz, 1H), 4.12 (t, \(J = 2.6\) Hz, 4.06 (dd, \(J = 2.5, 1.4\) Hz, 1H), 4.03 (s, 5H), 3.62 (dd, \(J = 7.2, 5.4\) Hz, 2H), 2.94 – 2.86 (m, 1H), 1.72 – 1.61 (m, 1H), 1.45 – 1.37 (m, 1H), 1.30 (d, \(J = 6.8\) Hz, 3H), 1.06 (s, 9H).

\textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}) \(\delta\) 135.59 (Ph), 134.08 (ipso Ph), 134.02 (ipso Ph), 133.50 (CH\textsubscript{N} vinyl), 129.49 (Ph), 127.56 (Ph), 110.96 (CH\textsubscript{vinyl}, 94.84 (ipso Cp), 81.37 (ipso Cp), 69.66 (Fc), 66.55 (Fc), 66.27 (Fc), 64.08 (Fc), 61.89 (CH\textsubscript{vinyl}, 42.80 (CH\textsubscript{vinyl}, 27.65 (CH\textsubscript{vinyl}), 26.89 (tBu), 19.23 (ipso tBu), 18.92 (CH\textsubscript{vinyl}). MS (ES) (m/z) calcd for C\textsubscript{56}H\textsubscript{38}O\textsubscript{8}FeSi 522.2024, found 522.2055. IR (\textit{cm}\textsuperscript{-1}): 3072 (=CH Fc), 2958 (CH\textsubscript{c}), 2930 (CH\textsubscript{c}), 2857 (CH\textsubscript{c}), 1625 (Ar Ph), 1589, 1427 (CH\textsubscript{c}), 1388 (CH\textsubscript{c}), 1105 (Si-OR), 1086 (Si-OR), 821 (CH Ar Ph), 699 (vinyl)/C=C).
DIAD (0.24 ml, 1.09 mmol) was added at room temperature before the mixture was warmed up to 65°C for 2 hrs. The reaction mixture was evaporated, extracted with EtOAc (30 ml), washed with brine (20 ml) followed by water (20 ml) and dried over Na2SO4. The solvent was removed in vacuo and the residue purified via flash column chromatography (30% EtOAc in hexane) to give the protected product (0.343 g, 72%). Deprotection was achieved firstly by stirring the compound in TBAF (5 ml, 1M) for 2 hr. The solvent was then removed and the residue redissolved in methylene (33 wt. % in ethanol, 2 ml) and stirred at room temperature for an additional 30 min. The methylene was then evaporated and the crude mixture purified via flash column chromatography to give the product as a yellow solid (170 mg, 73%). 1H NMR (400 MHz, DMSO-d6) δ 8.19 (s, 1H), 8.17 (s, 1H), 7.21 (s, 2H), 4.41 – 4.33 (m, 2H+1H (OH)), 4.11 (s, 5H), 4.02 (d, J = 2.4 Hz, 2H), 3.99 (t, J = 2.4 Hz, 1H), 3.42 – 3.28 (m, 2H), 2.97 – 2.75 (m, 2H), 2.75 – 2.67 (m, 1H), 1.53 – 1.45 (m, 1H), 1.32 (d, J = 6.8 Hz, 3H+1H). 13C NMR (101 MHz, DMSO-d6) δ 155.95 (ipso adenine), 152.43 (CH adenine), 149.39 (ipso adenine), 140.71 (CH adenine), 118.75 (ipso adenine), 94.43 (ipso Cp), 81.89 (ipso Cp), 68.80 (Cp), 66.46 (Cp), 64.92 (Cp), 64.74 (Cp), 58.66 (CH3), 43.10 (CH3), 42.43 (CH2), 27.98 (CH3), 27.10 (CH*), 19.38 (CH3). MS (ES) (m/z) calcd for C14H25N5O6Fe 420.1487, found 420.1484. IR (cm⁻¹): 3348 (br OH), 3270 (NH2), 3240 (NH2), 3089 (=CH Fe), 2955 (CH3), 2926 (CH3), 2871 (CH3), 1674 (C=N), 1604 (NH2), 1574 (NH2), 1305 (OH), 1076 (C-O), 814 (CH Ar). Mp: 90°C-92°C.

1-[a-Methyl-(3-hydroxypropyl)]ferrocene (3). 3-3-Ethoxy-1-methyl-3-oxopropylferrocene15 (220 mg, 0.733 mmol) was dissolved in diethyl ether (10 ml). LiAlH4 (56 mg, 1.466 mmol) was added carefully and the resulting suspension was left to stir for 1 hr. The reaction was quenched with saturated sodium potassium tartrate (10 ml), extracted with diethyl ether (2 x 20 ml), dried over MgSO4 and the solvent removed in vacuo. The residue was purified via flash column chromatography to give the product as a yellow oil (100 mg, 58%). 1H NMR (300 MHz, CDCl3) δ 4.13 (s, 5H), 4.09 – 4.04 (m, 4H), 3.67 (q, J = 6.2 Hz, 2H), 2.74 – 2.53 (m, 1H), 1.85 – 1.61 (m, 2H), 1.27 (d, J = 6.9 Hz, 3H). 13C NMR (101 MHz, CDCl3) δ 95.41 (ipso Cp), 68.51 (CH Cp), 67.22 (CH Cp), 67.12 (CH Cp), 67.07 (CH Cp), 65.70 (CH Cp), 61.12 (CH2), 41.47 (CH2), 29.62 (CH2), 20.64 (CH3). MS (ES) (m/z) calcd for C14H25N5O6Fe 258.0707, found 258.0708. IR (cm⁻¹): 3512-3146 br (OH), 2933 (CH3), 1052 (C-O).

1-(Thyminyl)-ethyl-ferrocene (4). Triphenylphosphine (348 mg, 1.30 mmol), N-3-benzoylthymine15 (223 mg, 1.04 mmol), and 2-ferroceny lethanol16 (200 mg, 0.87 mmol) were dissolved in THF (10 ml) and stirred for 10 min at room temperature. The flask was then covered with foil and DIAD (0.28 ml, 1.30 mmol) was added at room temperature before the mixture was heated at 65°C for 2 hrs. The solvent was then evaporated and the residue extracted with EtOAc (30 ml), washed with brine (20 ml) and water (20 ml) and dried over Na2SO4 before the solvent was removed in vacuo. Deprotection was achieved by treating the crude mixture with methylene solution (33 wt. % in ethanol, 5 ml) for 30 min. The solvent was then evaporated in vacuo and the residue purified via flash column chromatography (40% EtOAc in hexane) to give the product (176 mg, 60%). 1H NMR (300 MHz, CDCl3) δ 8.29 (s, 1H), 6.70 (d, J = 1.2 Hz, 1H), 4.15 (s, 5H), 4.13 – 4.09 (m, 2H), 4.04 (t, J = 1.8 Hz, 2H), 3.79 (t, J = 7.1 Hz, 2H), 2.73 (t, J = 7.1 Hz, 2H), 1.85 (d, J = 1.2 Hz, 3H). 13C NMR (101 MHz, CDCl3, trace of MeOD) δ 216.94 (ipso thymine), 193.73 (C=O), 181.71 (C=O), 141.17 (CH-thymine), 83.57 (ipso-Cp), 68.63(CH-Cp), 68.37(CH-Cp), 67.94 (CH-Cp), 50.20 (CH2), 29.17 (CH), 11.98 (CH3). MS (ES) (m/z) calcd for C14H19N5O6Fe 338.0718, found 338.0720. Mp: degraded at 235°C. IR (cm⁻¹): 3146 (NH), 2999 (CH), 1683 (C=O), 1644 (NH bending).

ASSOCIATED CONTENT

Supporting Information. 1H NMR spectra and 13C NMR spectra for compounds 1-5 and 8-17. HPLC data for compounds 1-6 and 17. Cell study procedures, cell growth data for 2, 4 and 5 on an oesophageal cancer cell line. This material is available free of charge via the Internet at http://pubs.acs.org.

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ABBREVIATIONS

DCM, dichloromethane; DIAD, diisopropyl azodicarboxylate; DMSO, dimethyl sulfoxide; TEA, triethyamine; DMAP, 4-dimethylamino pyridine; n-BuLi, n-butyllithium; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; BrdU, bromodeoxyuridine; THF, tetrahydrofuran

REFERENCES


(9) A ferrocene derivative containing a nucleobase and a hydroxyl group (but not bridged solely by a ferrocene group) was reported previously, which did not show apoptosis-inducing activity against tumor cells (see Reference 7d).


(12) Initial cell line studies indicate that compound 1 also displays antiviral activity (Patent application - GB1322752.5). Further studies are underway to establish mechanistic pathways (e.g. phosphorylation).


(15) Locke, A. J.; Richards, C. J. Asymmetric synthesis of [3](1,1’)- and [3](1’1’)[3](3,3’)-ferrochenophanes. Organometallics. 1999, 18, 3750-3759.