Nucleobase Recognition by Artificial Receptors Possessing a Ferrocene Skeleton as a Novel Modular Unit for Hydrogen Bonding and Stacking Interactions

Masahiko Inouye,* Yutaka Hyodo, and Hiroyuki Nakazumi

PRESTO, Japan Science and Technology Corporation (JST), Department of Applied Materials Science, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan

Received October 23, 1998

Novel ferrocene-modified artificial nucleobase receptors were designed and synthesized. The nucleobase receptors possess hydrogen-bonding and π-stacking interaction sites that act simultaneously for binding to 1-butylthymine utilizing the pivot character of the ferrocene skeleton. Diamidopyridine was chosen for the hydrogen-bonding moiety, and various polynuclear aromatics were used for π-stacking one. The two components were tethered to the cyclopentadienyl rings via ethynediyl and oxymethylene spacers. The binding affinity of the receptors to 1-butylthymine was found to be dependent on the aromatic structures. Thus, the association constants for perylene-linked receptors were approximately doubled compared to those of aromatic-free ones, an energy difference of ~0.5 kcal/mol. Detailed comparisons between the 10 receptors clarified the value of the pivot character of the ferrocene for construction of the intermolecular interaction site.

Introduction

During the last two decades, artificial models developed in molecular recognition chemistry have illustrated the crucial role of complementarity in size, shape, and functional groups at the molecular level for selective host−guest binding. A key element in the design of such models is often inspired by naturally occurring biomolecules and biomolecular systems. Thus, in designing artificial receptors for nucleobases, much can be learned from the structures of DNA, in which hydrogen bonding and π-stacking interactions between adjacent and stacked base pairs stabilize the double-helical architecture.[1] Indeed, several model receptors utilizing both forces have been designed and synthesized.[2] In our successive model studies on molecular recognition,[3] our initial goal in this area was to develop the cooperative self-assembly of DNA-relevant molecules. Thus, we sought to construct novel nucleobase receptors, in which both of the interactions can operate simultaneously and in which the conformational flexibility of the receptors would be restricted so that the recognition mode is well-defined.[4] With this in mind, we report herein the results obtained for ferrocene-modified artificial nucleobase receptors, *ferroceptors* (ferrocene + receptors).

The serendipitous discovery of ferrocene has caused organometallic chemistry to progress explosively.[5] Ferrocene and its derivatives nowadays are also attracting much attention from the viewpoint of supramolecular chemistry such as redox-active ionophores and molecular receptors.[6] However, the "pivot" character of the ferrocene skeleton that aligns two substituents in a parallel manner up and down had been scarcely utilized in this field, except for ferrocene-containing liquid crystals.[7] Gokel et al. reported pioneer works for neutral molecule receptor systems using ferrocene's "atomic ball bearing" character. They pointed out that the binding to aromatic guest

* Fax: +81-722-54-9324. E-mail: inouye@chem.osakafu-u.ac.jp

(1) Saenger, W. *Principles of Nucleic Acid Structure*; Springer-Verlag: New York, 1984.

(2) For reviews: Rebek, J., Jr. *Science* **1987**, *235*, 1478−1484. Hamilton A. D.; Pant, N.; Muehldorf A. *Pure Appl. Chem*. **1988**, *60*, 533−538. Rebek, J., Jr. *Acc. Chem. Res*. **1990**, *23*, 399−404. Rebek, J., Jr. *Angew. Chem., Int. Ed. Engl*. **1990**, *29*, 245−255. Hamilton, A. D. In *Advances in Supramolecular Chemistry*; Gokel, G. W., Ed.; JAI: Greenwich, 1990; Vol. 1, pp 1−64. van Doorn, A. R.; Verboom, W.; Reinhoudt, D. N. In *Advances in Supramolecular Chemistry*; Gokel, G. W., Ed.; JAI: Greenwich, 1993; Vol. 3, pp 159−206. Schneider, H.-J.; Mohammad-Ali, A. K. In *Comprehensive Supramolecular Chemistry, Vol. 2*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vögtle, F., Eds.; Elsevier: Oxford, 1996; pp 91−95. Representative examples: (a) Rebek, J., Jr. *Science* **1987**, *235*, 1478−1484; Rebek, J., Jr.; Askew, B.; Ballester, P.; Buhr, C.; Jones, S.; Nemeth, D.; Williams, K. *J. Am. Chem. Soc.* **1987**, *109*, 5033−5035. Hamilton, A. D.; Engen, D. V. *J. Am. Chem. Soc.* **1987**, *109*, 5035−5036. Rebek, J., Jr.; Askew, B.; Ballester, P.; Buhr, C.; Costero, A.; Jones, S.; Williams, K. *J. Am. Chem. Soc.* **1987**, *109*, 6866−6867. (b) Muehldorf, A. V.; Engen, D. V.; Warner, J. C.; Hamilton, A. D. *J. Am. Chem. Soc.* **1988**, *110*, 6561−6562. Goswami, S.; Hamilton, A. D.; Engen, D. V. *J. Am. Chem. Soc.* **1989**, *111*, 3425−3426. (c) Tjivikua, T.; Deslongchamps, G.; Rebek, J. Jr. *J. Am. Chem. Soc.* **1990**, *112*, 8408−8414. (d) Zimmermman, S. C.; Wu, W.; Zeng, Z. *J. Am. Chem. Soc.* **1987**, *109*, 196−201. Zimmermman, S. C.; VanZyl, C. M. *J. Am. Chem. Soc.* **1987**, *109*, 7894−7896. Zimmermman, S. C.; Zeng, Z.; Wu, W.; Reichert, D. E. *J. Am. Chem. Soc.* **1991**, *113*, 183−196. (e) Breinlinger, E. C.; Rotello, V. M. *J. Am. Chem. Soc.* **1997**, *119*, 1165−1166.

(3) Inouye, M.; Ueno, M.; Kitao, T.; Tsuchiya, K. *J. Am. Chem. Soc.* **1990**, *112*, 8977−8979. Inouye, M.; Ueno, M.; Kitao, T. *J. Org. Chem*. **1992**, *57*, 1639−1641. Inouye, M.; Ueno, M.; Tsuchiya, K.; Nakayama, N.; Konishi, T.; Kitao, T. *J. Org. Chem*. **1992**, *57*, 5377−5383. Inouye, M.; Kim, K.; Kitao, T. *J. Am. Chem. Soc.* **1992**, *114*, 778−780. Inouye, M.; Noguchi, Y.; Isagawa, K. *Angew. Chem., Int. Ed. Engl*. **1994**, *33*, 1163−1166. Inouye, M.; Hashimoto, K.; Isagawa, K. *J. Am. Chem. Soc.* **1994**, *116*, 5517−5518. Inouye, M.; Miyake, T.; Furusyo, M.; Nakazumi, H. *J. Am. Chem. Soc.* **1995**, *117*, 12416−12425. Inouye, M. *Coord. Chem. Rev*. **1996**, *148*, 265−283. Inouye, M.; Akamatsu, K.; Nakazumi, H. *J. Am. Chem. Soc.* **1997**, *119*, 9160−9165. Inouye, M.; Takahashi, K.; Nakazumi, H. *J. Am. Chem. Soc.* **1999**, *121*, 341−345. Inouye, M.; Fujimoto, K.; Furusyo, M.; Nakazumi, H. *J. Am. Chem. Soc.* **1999**, *121*, 1452−1458.

(4) Inouye, M.; Konishi, T.; Isagawa, K. *J. Am. Chem. Soc.* **1993**, *115*, 8091−8095.

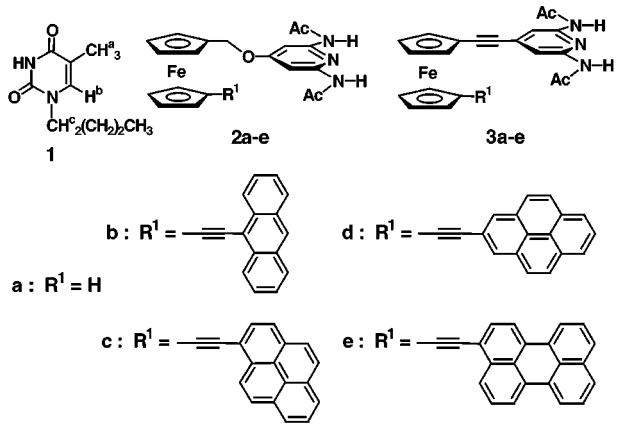
(5) For reviews: Deeming, A. J. In *Comprehensive Organometallic Chemistry, Vol. 4*; Wilkinson, G., Stone, F. G. A., Eds.; Pergamon: Oxford, 1982; pp 475−512. *Ferrocenes*; Togni, A., Hayashi, T., Eds.; VCH: New York, 1995.

(6) For recent reviews: Hall, C. D. In *Ferrocenes*; Togni, A., Hayashi, T., Eds.; VCH: New York, 1995; pp 279−316. Kaifer, A. E.; Mendoza, S. In *Comprehensive Supramolecular Chemistry, Vol. 1*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vögtle, F., Eds.; Elsevier: Oxford, 1996; pp 701−732.

(7) For a recent review: Deschenaux, R.; Goodby, J. W. In *Ferrocenes*; Togni, A., Hayashi, T., Eds.; VCH: New York, 1995; pp 471−495.

10.1021/jo982138u CCC: $18.00
Published on Web 03/26/1999

Scheme 1



molecules might be augmented by π-stacking.[8] No systematic studies on the potential of the receptors for π-stacking interaction, however, were carried out mainly because of the solubility of the receptors. Thus, the role of π-stacking in ferrocene's systems remains elusive as it does in many other examples.

Results and Discussion

Molecular Design. The inter-ring spacing in ferrocene is 0.33 nm, and two flat aromatic planes will interact with each other by π-stacking when both planes are connected to two cyclopentadienyl (Cp) rings of ferrocene. The design of the hydrogen-bonding moiety was based on the hydrogen-bonding complementarity between 1-butylthymine (**1**) and 2,6-diamidopyridine,[9] which was tethered to a Cp ring of ferrocene with oxymethylene or ethynediyl spacers. Polycyclic aromatic planes, the π-stacking units, were connected to another Cp ring of the ferrocene by an ethynediyl spacer. The sp-carbon spacers allow rotation only about the Cp−ethynediyl aromatic bonds, maintaining linearity along the Cp ring−polycyclic aromatics, which results in π-stacking interaction with the bound **1**. The oxymethylene spacers were selected to have the right balance of rigidity and flexibility (Scheme 1).

Synthesis. The ferroceptors **2b**−**e** bearing an oxymethylene linkage were synthesized from a key intermediate, 1-(hydroxymethyl)-1′-iodoferrocene (**10**), which was derived from 1′-(tri-*n*-butylstannyl)ferrocene-1-carboxaldehyde (**8**) by stepwise functionalizations.[10,11] Mitsunobu reaction[12] of **10** with 2,6-diacetamido-4-pyridone (**4**) gave **11**, which was ethynylated by Sonogashira reaction followed by deprotection of the acetylene terminal to afford **13**. Further Sonogashira reaction of **13** with various haloarenes **14**−**17** produced the ferroceptors **2b**−**e**. Ferroceptors **3b**−**e** possessing two acetylenic linkages were prepared from 1,1′-diiodoferrocene (**18**) by sequential Sonogashira reactions with 2,6-diacetamido-4-ethynylpyridine (**7**) and ethynylated aromatics **20**−**23**. Both of the ethynylated components were also synthesized by Sonogashira reaction from pyridyl triflate **5** and the corresponding haloarenes **14**−**17**, respectively, followed by deprotection of the acetylene terminal. In these syntheses, the reverse connection failed because deprotection of 1,1′-bis(trimethylsilylethynyl)ferrocene gave undesired product[11b] (Scheme 2).

Structural Feature of the Ferroceptors. In parent ferrocene, the barrier to internal rotation of the Cp rings with respect to each other is estimated to be only one-third of that in ethane.[5] This means that in the usual temperature range for NMR investigations the Cp ring rotates freely. Similar behavior is expected for our ferroceptors. Indeed, the ^{1}H NMR signals of the ferrocene skeleton (4.2−4.7 ppm) of ferroceptor **2e** (2.0 mM) in $CDCl_3$ revealed four sets of pseudo singlet at 298 K, which remained unchanged in the range to 223 K. The free rotation of the Cp rings of the ferroceptors was also corroborated on the basis of chemical shifts for methyl protons of the acetamide substituents. Thus, the methyl protons of **2a** lacking in π-planes appeared at 2.18 ppm, whereas those of **2b** possessing an anthracene ring were at 2.08 ppm. The upfield shift of 0.10 ppm might be attributed to the diamagnetic anisotropy of the anthracene ring. Further upfield shifts were observed in the cases of the ferroceptors possessing wider aromatic planes: **2c** (1.98 ppm), **2d** (1.98 ppm), and **2e** (2.04 ppm). The ferroceptors bearing two ethynediyl spacers **3a**−**e** showed a similar tendency. The upfield shifts could be due to the existence of the ferroceptor conformation in which the hydrogen-bonding moiety is located on the aromatic planes. The significant but rather small upfield shifts demonstrated the free rotation of the Cp rings even for the ferroceptors.

Binding Studies with 1-Butylthymine. The interactions of the ferroceptors **2** and **3** in $CDCl_3$ with 1-butylthymine (**1**) were investigated by ^{1}H NMR. Treatment of ferroceptors (2.0 mM) with **1** (2.0 mM) in $CDCl_3$ revealed the formation of triple-hydrogen-bonded complexes in the ^{1}H NMR spectra. The NH protons on both the ferroceptors and **1** were shifted downfield by 1.77−2.10 and 1.48−2.58 ppm, respectively. The 1:1 stoichiometry was confirmed by the continuous variation (Job) plots that contained a maximum at a mole ratio of 0.5 in each plot for the ferroceptors and **1**.[13] Association constants for the complexes were determined from ^{1}H NMR titration data by using Foster−Fife analysis[14] of the shifts in δ_{NH} for ferroceptors (under conditions of constant [ferroceptor] with varying [**1**]) and are collected in Table 1. The association constants were dependent on the polycyclic aromatic π-stacking units. Thus, the association constants for perylene-linked ferroceptors **2e** and **3e** to **1** were approximately doubled compared to those of aromatic-free ferroceptors **2a** and **3a**, suggesting that π-stacking interaction between the aromatic rings with

(8) Medina, J. C.; Gay, I.; Chen, Z.; Echegoyen, L.; Gokel, G. W. *J. Am. Chem. Soc.* **1991**, *113*, 365−366. Li, C.; Medina, J. C.; Maguire, G. E. M.; Abel, E.; Atwood, J. L.; Gokel, G. W. *J. Am. Chem. Soc.* **1997**, *119*, 1609−1618. Other ferrocene- and metallocene-based receptors: Carr, J. D.; Lambet, L.; Hibbs, D. E.; Hursthouse, M. B.; Adbul Malik, K. M.; Tucker, J. H. R. *J. Chem. Soc., Chem. Commun.* **1997**, 1649−1650. Grossel, M. C.; Hamilton, D. G.; Vine, T. A. *Tetrahedron Lett.* **1997**, *38*, 4639−4642. Beer, P. D. *Acc. Chem. Res.* **1998**, *31*, 71−80.

(9) (a) Hamilton, A. D.; Engen, D. V. *J. Am. Chem. Soc.* **1987**, *109*, 5035−5036. (b) Feibush, B.; Figeroa, A.; Charls, R.; Onan, K. D.; Feibush, P.; Karger, B. L. *J. Am. Chem. Soc.* **1986**, *108*, 3310−3318.

(10) (a) Wright, M. E. *Organometallics* **1990**, *9*, 853−856. (b) Guillaneux, D.; Kagan, H. B. *J. Org. Chem.* **1995**, *60*, 2502−2505. (c) Broadhead, G. D.; Osgerby, J. M.; Pauson, P. L. *J. Chem. Soc.* **1958**, *58*, 650−656.

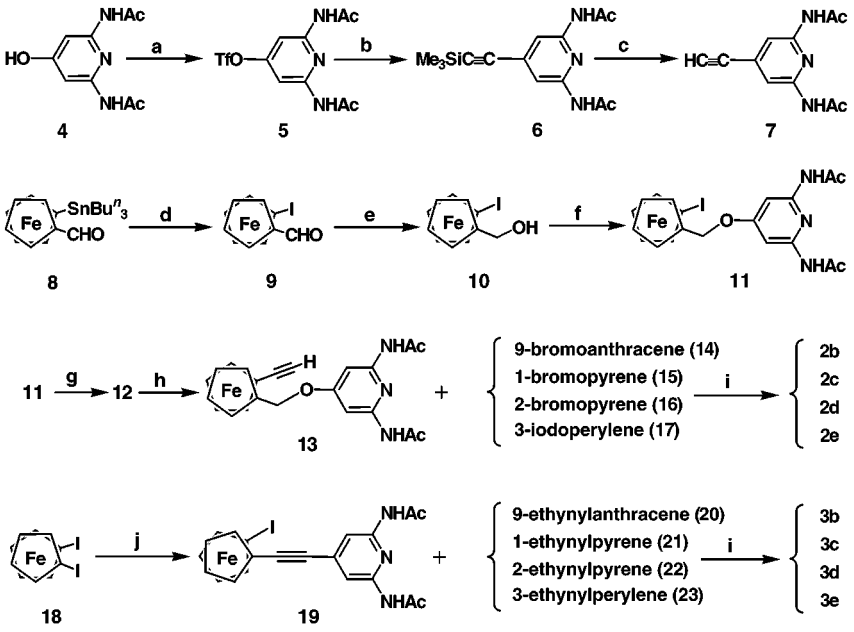
(11) (a) Kasahara, A.; Izumi, T.; Maemura, M. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 1021−1022. (b) Pudelski, J. K.; Callstrom, M. R. *Organometallics* **1992**, *11*, 2757−2759.

(12) (a) Mitsunobu, O. *Synthesis* **1981**, 1−28. (b) Manhas, M. S.; Hoffman, W. H.; Lal, B.; Bose, A. K. *J. Chem. Soc., Perkin Trans. 1* **1975**, 461−463.

(13) Job, A. *Ann. de Chim.* (*Paris*) **1928**, *9*, 113−203.

(14) Foster, R.; Fyfe, C. A. *Prog. Nucl. Magn. Reson. Spectrosc.* **1969**, *4*, 1−89.

Scheme 2[a]



[a] (a) Trifluoromethanesulfonic anhydride, pyridine; (b) $(Ph_3P)_2PdCl_2$, (trimethylsilyl)acethylene, Et_3N, DMF; (c) *n*-Bu_4NF, H_2O, THF; (d) I_2, CH_2Cl_2; (e) $NaBH_4$, EtOH; (f) **4**, DEAD, PPh_3, THF; (g) (trimethylsilyl)acethylene, $(Ph_3P)_2PdCl_2$, $Cu(OAc)_2 \cdot H_2O$, *i*-Pr_2NH; (h) KF, H_2O, DMSO; (i) $(Ph_3P)_2PdCl_2$, CuI, morpholine; (j) **7**, $Pd_2(dba)_3 \cdot CHCl_3$, $Cu(OAc)_2 \cdot H_2O$, PPh_3, THF, *i*-Pr_2NH.

Table 1. Association Constants and Thermodynamic Parameters Determined for the Binding of 1 to Ferroceptors in $CDCl_3$ at 25 °C[a]

		$\Delta\delta_{thy}$ (ppm)			ΔG	ΔH	$T\Delta S$
ferroceptor	K_a (M^{-1})	H^a	H^b	H^c	(kcal/mol)	(kcal/mol)	(kcal/mol)
2a	1140	0.018	0.043	0.043			
2b	1370	0.031	0.054	0.054			
2c	1470	0.020	0.041	0.041			
2d	1740	−0.009	−0.004	−0.004			
2e	2230	−0.086	−0.124	−0.124	−4.57	−8.09	−3.52
3a	960	0.020	0.043	0.043			
3b	1120	0.052	0.077	0.077			
3c	1020	0.036	0.052	0.052			
3d	1800	0.016	0.014	0.014			
3e	1820	−0.045	−0.059	−0.059	−4.45	−7.84	−3.39

[a] $\Delta\delta_{thy}$ values show shifts in ^1H NMR signals for **1** (2.0 mM) in the presence of ferroceptors (2.0 mM) in $CDCl_3$ at 25 °C. A positive sign for $\Delta\delta_{thy}$ indicates a downfield shift. See Scheme 1 for proton labeling.

bound **1** can be responsible for the increased K_a values.[15] In addition, the linkages between the hydrogen-bonding moiety and the Cp ring gave an interesting influence for the binding. The association constants of the flexible ferroceptors **2a**−**e** increased little by little with increasing an aromatic width, with the wider aromatics having the larger K_a values, while the rigid ferroceptors **3a**−**e** revealed "off (**3a**−**c**)/on (**3d**,**e**)" characteristics. The flexible oxymethylene linkage, to some extent, might cause the ferroceptors to adopt a favorable conformation for stacking to the bound **1**. The direction of an expanse of π-plane was also found to be important for the stacking. This was demonstrated in the cases of 1-ethynylpyrene-(**2c** and **3c**) and 2-ethynylpyrene-linked (**2d** and **3d**) ferroceptors. These results are satisfactorily explained by the increased probability of the close approach of the aromatic rings to the π-plane of **1**, depicted in Figure 1, in which locations for two substituents were estimated by CPK molecular modeling.

Complexation-Induced Shifts for Thymine Protons. Figure 1 points out that in the cases of perylene-linked ferroceptors **2e** and **3e** peripheral protons of **1** in addition to the NH will be subjected to the diamagnetic anisotropy of the perylene ring upon complexation. Indeed, when **1** (2.0 mM) was added to ca. 2.0 mM $CDCl_3$ solution of the ferroceptor **2e**, significant upfield shifts (0.09−0.12 ppm) of **1** were observed in H^a, H^b, and H^c (Figure 2). The upfield shifts of **1** were observed also with

(15) Many other discussions for π-stacking interaction have been reported: Chen, C.-T.; Siegel, J. S. *J. Am. Chem. Soc.* **1987**, *116*, 5959−5960. Newcomb, L. F.; Gellman, S. H. *J. Am. Chem. Soc.* **1994**, *116*, 4993−4994. Newcomb, L. F.; Haque, T. S.; Gellman, S. H. *J. Am. Chem. Soc.* **1995**, *117*, 6509−6519. Shetty, A. S.; Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 1019−1027. Lewis, F. D.; Yang, J.-Y.; Stern, C. L. *J. Am. Chem. Soc.* **1996**, *118*, 2772−2773. Guckian, K. M.; Schweitzer, B. A.; Ren, R. X.-F.; Sheils, C. J.; Paris, P. L.; Tahmassebi, D. C.; Kool, E. T. *J. Am. Chem. Soc.* **1996**, *118*, 8182−8183. Adams, H.; Carver, F. J.; Hunter, C. A.; Morales, J. C.; Seward, E. M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1542−1544. Breinlinger, E. C.; Rotello, V. M. *J. Am. Chem. Soc.* **1997**, *119*, 1165−1166. Gardner, R. R.; Christianson, L. A.; Gellman, S. H. *J. Am. Chem. Soc.* **1997**, *119*, 5041−5042. Reek, J. N. H.; Priem, A. H.; Engelkamp, H.; Rowan, A. E.; Elemans, J. A. A. W.; Nolte, R. J. M. *J. Am. Chem. Soc.* **1997**, *119*, 9956−9964. Deans, R.; Niemz, A.; Breinlinger, E. C.; Rotello, V. M. *J. Am. Chem. Soc.* **1997**, *119*, 10863−10864. Baudoin, O.; Teulade-Fichou, M.-P.; Vigneron, J.-P.; Lehn, J.-M. *J. Org. Chem.* **1997**, *62*, 5458−5470. Chen, Y.-S.; Kampf, J. W.; Lawton, R. G. *Tetrahedron Lett.* **1997**, *38*, 5781−5784. Schneider, H.-J. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1072−1073.

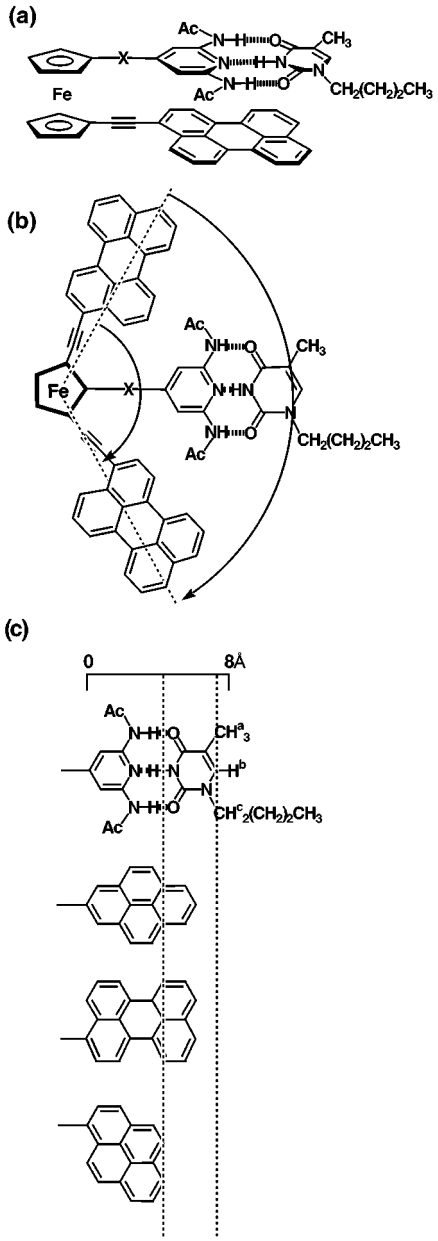


Figure 1. (a) Side view and (b) top view of a possible structure for the **1**·**2e** complex. (c) Estimated positions of the bound **1** and π-stacking moieties.

3e in place of **2e**, but little or none was seen with other ferroceptors. Without aromatic planes, small downfield shifts for these protons of **1** were observed because of the decrease in the electron density via hydrogen bonding to the diamidopyridine, as in the cases for **2a**−**c** (Table 1). Thus, there is a strong presumption that the through-space interactions, π-stacking and/or van der Waals interactions, may play a role in the increased affinity of the perylene-linked ferroceptors **2e** and **3e** for **1**.

Thermodynamic Parameters for the Binding. The more flexible oxymethylene linkages of **2a**−**e** were introduced to examine their influence on the binding compared to the ethynediyl linkage. Of course, introducing flexibility is introducing adjustability that results in simultaneous entropic disadvantages and enthalpic advantages for binding. Thermodynamic parameters were determined by VT-NMR (van't Hoff analysis) for the binding of the ferroceptors and **1** to shed light on this aspect (Table 1). Both the enthalpy and entropy changes

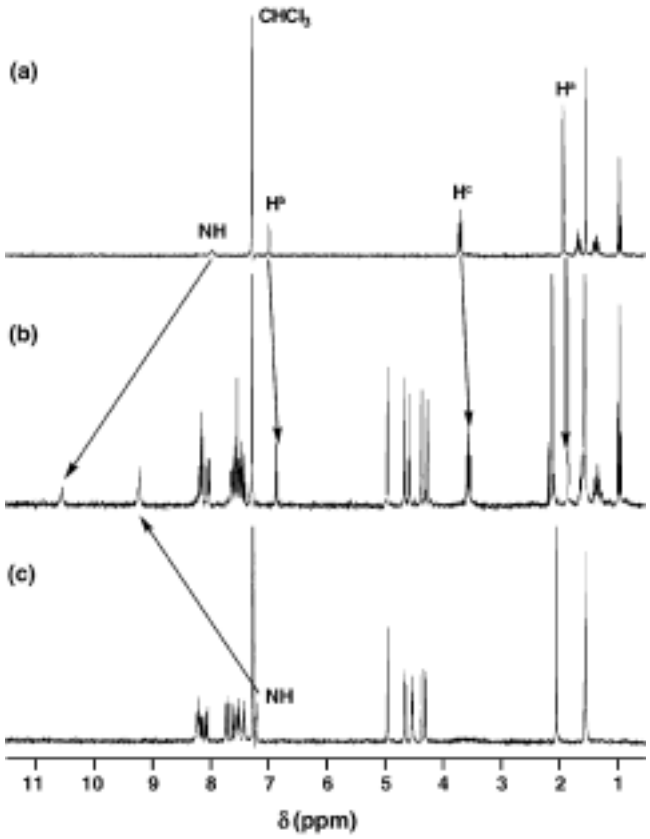


Figure 2. ^{1}H NMR spectra (500 MHz) of (a) **1**, (b) **1**·**2e**, and (c) **2e** in $CDCl_3$ at 25 °C.

for the binding of **1** by **2e**, however, were only slightly different from those for **3e**. This indicated that the oxymethylene spacer is still rigid and capable of maintaining pseudolinearity along the Cp−diamidopyridine axis. Indeed, the preliminary results of the molecular modeling suggested this assumption. From this study, we can use both of the linkages for further structural modifications of the ferroceptors, such as bifunctionalization and the introduction of second recognition sites.

Conclusion

We developed novel ferrocene-modified hydrogen-bonding structures as rationally designed new artificial nucleobase receptors. Additional intermolecular interactions utilizing ferrocene's pivot character were exploited in the receptors. Although the stacking interaction in the present system is not remarkably high (an energy of ~0.5 kcal/mol) because of the free rotation of the ferrocene skeleton, the driving force for the binding to 1-butylthymine was found to be governed not only by hydrogen bondings but also by aromatic π-stacking and/or van der Waals interactions and could be regulated by changing the aromatic rings. We are currently investigating the introduction of a second recognition site in the ferrocene skeleton to add allosteric behavior to the ferroceptors. In the future, bifunctionalization of both the allosteric ferroceptors and the substrates will create cooperative self-assembly of more than one biologically relevant species.

Experimental Section

Instrumentation. ^{1}H and ^{13}C NMR spectra were recorded at 270 and 67.8 MHz, respectively, unless otherwise noted.

EI mass spectra were measured at 70 eV. For FAB mass experiments, Xe was used as the atom beam accelerated to 8 keV. Melting points are uncorrected.

Materials. Iodoferrocene,[10b] (hydroxymethyl)ferrocene,[10c] 3-aminoperylene,[16] 1-*n*-butylthymine[17] (**1**), 2,6-diacetamido-4-pyridone[4] (**4**), 1′-(tri-*n*-butylstannyl)ferrocene-1-carboxaldehyde[10a] (**8**), 2-bromopyrene[18] (**16**), 1,1′-diiodoferrocene[10b] (**18**), and 9-ethynylanthracene[19] (**20**) were prepared according to literature procedures. Other starting materials were all commercially available.

Methods for the Evaluation of Stoichiometry and Association Constants. Job's plot of [complex] vs mole fraction of the receptor for the complexation of the receptor and **1** was obtained by ^{1}H NMR in $CDCl_3$ at 25 °C under conditions where [receptor] + [**1**] is maintained at 5.0 mM.[13] The relative concentration of a complex [complex (rel)] in $CDCl_3$ was evaluated from $\Delta\delta_{obsd}$ for the receptor-NH, according to the equation [complex (rel)] = $\Delta\delta_{obsd}$[receptor]$_t$ (t = total; obsd = observed; sat = saturated).

Determination of binding constants (K_a) was carried out under Benesi−Hildebrand conditions at 25 °C in $CDCl_3$.[14] The concentrations of the receptor and **1** were 0.075 and 0.75−1.5 mM, respectively. The chemical shifts of the receptor-NH protons were monitored as a function of concentration of **1**. In every case, the double reciprocal plots according to the equation $1/\Delta\delta_{obsd} = 1/\Delta\delta_{sat} + 1/\Delta\delta_{sat}K_a[\mathbf{1}]_t$ gave good linearity with a correlation coefficient $r \geq 0.98$ and a standard deviation of $\sigma \leq 60$ M^{-1} for K_a. For every K_a, at least a 40−80% complexation was covered.

Determination of Thermodynamic Parameters. Van't Hoff plots were employed for evaluating the thermodynamics of complexation. Several K_a values were measured in the temperature range from 259 to 303 K as described above. Plotting R ln K_a versus $1/T$ gave a straight line and resulted in ΔH and then $T\Delta S$.

4-(2,6-Diacetamidopyridyl) Trifluoromethanesulfonate (5). To a pyridine (15 mL) solution of 2,6-diacetamido-4-pyridone[4] (**4**) (1.01 g, 4.82 mmol) was added trifluoromethanesulfonic anhydride (1.76 g, 6.23 mmol) dropwise at 0 °C over a 10 min period. The reaction mixture was stirred at room temperature for 12 h. After removal of the solvent, the residue was subjected to chromatography (silica gel; eluent, $CHCl_3$/MeOH 20:1) to give **5**: yield 72% (1.19 g); mp 207−209 °C (dec); IR (KBr) 1700, 1676, 1553, 1426, 1298, 1243, 1213, 1141, 861, 831 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.93 (s, 2 H), 7.79 (br s, 2 H), 2.21 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 169.13, 158.58, 150.01, 102.08, 24.67; MS *m/e* (rel intensity) 341 (M$^+$, 14%).

2,6-Diacetamido-4-[(trimethylsilyl)ethynyl]pyridine (6). To a DMF (5 mL) solution of **5** (340 mg, 1.0 mmol), $(Ph_3P)_2$-$PdCl_2$ (28 mg, 0.04 mmol), and Et_3N (2 mL) was added (trimethylsilyl)acetylene (310 mg, 3.0 mmol) at room temperature. The reaction mixture was stirred at 70 °C for 8 h. After removal of the solvent, the residue was poured into water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, AcOEt/hexane 1:5) to give **6**: yield 78% (220 mg); mp 149−151 °C (dec); IR (KBr) 1676, 1556, 1524, 1417, 1274, 845 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.92 (br s, 2 H), 7.55 (br s, 2 H), 2.18 (s, 6 H), 0.24 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 168.74, 149.54, 135.61, 111.84, 102.30, 99.83, 24.61; MS *m/e* (rel intensity) 289 (M$^+$, 35%).

2,6-Diacetamido-4-ethynylpyridine (7). To a THF (10 mL) solution of **6** (290 mg, 1.0 mmol) was added tetra-*n*-butylammonium fluoride (320 mg, 1.2 mmol) and a few drops of water. The reaction mixture was stirred at room temperature for 2 h. After removal of the solvent, the residue was poured into water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, CH_2Cl_2/MeOH 20:1) to give **7**: yield 74% (160 mg); mp 217−219 °C (dec); IR (KBr) 3250, 2115, 1715, 1669, 1562, 1415 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.98 (br s, 2 H), 7.67 (br s, 2 H), 3.25 (s, 1 H), 2.19 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.44, 149.52, 134.82, 112.06, 81.62, 24.79; MS *m/e* (rel intensity) 217 (M$^+$, 19%).

2,6-Diacetamido-4-(ferrocenylmethoxy)pyridine (2a). To a THF (15 mL) suspension of (hydroxymethyl)ferrocene[10c] (100 mg, 0.46 mmol), **4** (100 mg, 0.46 mmol), and Ph_3P (120 mg, 0.46 mmol) was added diethyl azodicarboxylate (81 mg, 0.46 mmol) at room temperature. The reaction mixture was stirred for 18 h at the same temperature. After removal of the solvent, the residue was dissolved in water and extracted with CH_2Cl_2. The CH_2Cl_2 extract was evaporated and chromatographed (silica gel; eluent, $CHCl_3$/AcOEt 1:1) to give **2a**: yield 11% (20 mg); mp 85−87 °C; IR (KBr) 1677, 1583, 1439 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.57 (br s, 2 H), 7.56 (br s, 2 H), 4.91 (s, 2 H), 4.37 (t, J = 1.8 Hz, 2 H), 4.21 (t, J = 1.8 Hz, 2 H), 4.19 (s, 5 H), 2.18 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.54, 150.45, 96.42, 81.30, 69.41, 68.84, 68.68, 66.97, 24.84; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 407 (M$^+$, 100%).

1′-Iodoferrocene-1-carboxaldehyde (9). To a CH_2Cl_2 (100 mL) solution of 1′-(tri-*n*-butylstannyl)ferrocene-1-carboxaldehyde[10a] (**8**) (2.35 g, 4.68 mmol) was added a CH_2Cl_2 (100 mL) solution of iodine (1.78 g, 7.02 mmol) at room temperature. The reaction mixture was stirred at this temperature for 2 h. The CH_2Cl_2 mixture was washed with aqueous $NaHSO_3$ solution and water. After removal of the solvent, the residue was dissolved in saturated aqueous KF solution and extracted with ether. The ether solution was washed with water. The ether layer was evaporated and chromatographed (silica gel; eluent, $CHCl_3$) to give **9**: yield 95% (1.51 g); mp 34−35 °C; IR (KBr) 1677 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 9.99 (s, 1 H), 4.75 (t, J = 1.8 Hz, 2 H), 4.57 (t, J = 1.2 Hz, 2 H), 4.48 (t, J = 1.8 Hz, 2 H), 4.23 (t, J = 1.2 Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 193.30, 76.27, 76.12, 72.21, 70.42; MS *m/e* (rel intensity) 340 (M$^+$, 43%).

1-(Hydroxymethyl)-1′-iodoferrocene (10). To an EtOH (180 mL) solution of **9** (1.46 g, 4.31 mmol) was added $NaBH_4$ (100 mg, 2.6 mmol) at room temperature. The reaction mixture was stirred for 1.5 h at the same temperature. After removal of the solvent, the residue was dissolved in water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, $CHCl_3$) to give **10**: yield 93% (1.37 g); mp 88−89 °C; IR (KBr) 3232, 1398, 1342, 1232, 1174, 1136, 1045 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.45−4.39 (m, 5 H), 4.19 (s, 2 H), 4.17−4.15 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ 89.40, 74.87, 71.27, 70.78, 69.17, 60.17, 39.98; MS *m/e* (rel intensity) 342 (M$^+$, 49%).

2,6-Diacetamido-4-[(1′-iodoferrocenyl)methoxy]pyridine (11). To a THF (15 mL) suspension of **10** (170 mg, 0.50 mmol), **4** (110 mg, 0.50 mmol), and Ph_3P (130 mg, 0.50 mmol) was added diethyl azodicarboxylate (87 mg, 0.50 mmol) at room temperature. The suspension was stirred for 12 h at the same temperature. After removal of the solvent, the residue was dissolved in water and extracted with CH_2Cl_2. The CH_2-Cl_2 extract was evaporated and chromatographed (silica gel; eluent, $CHCl_3$/AcOEt 1:1) to give **11**: yield 37% (100 mg); mp 86−87 °C; IR (KBr) 1680, 1616, 1581, 1442, 1240, 1155 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.60 (br s, 2 H), 7.53 (br s, 2 H), 4.91 (s, 2 H), 4.41 (t, J = 1.8 Hz, 2 H), 4.32 (t, J = 1.8 Hz, 2 H), 4.22 (t, J = 1.8 Hz, 2 H), 4.18 (t, J = 1.8 Hz, 2 H), 2.18 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.42, 82.67, 75.25, 71.86, 69.57, 66.21, 40.08, 24.73; MS *m/e* (rel intensity) 533 (M$^+$, 22%).

2,6-Diacetamido-4-{[(1′-trimethylsilylethynyl)ferrocenyl]methoxy}pyridine (12). To an *i*-Pr_2NH suspension of **11** (266 mg, 0.50 mmol), $(Ph_3P)_2PdCl_2$ (20.8 mg, 0.03 mmol), and $Cu(OAc)_2 \cdot H_2O$ (6.0 mg, 0.03 mmol) was added (trimethylsilyl)acetylene (245 mg, 2.5 mmol). The reaction mixture was refluxed for 8 h. After removal of the solvent, the residue was chromatographed (silica gel; eluent, AcOEt) to give **12**: yield 84% (210 mg); IR (KBr) 2146, 1681, 1616, 1583, 1439, 1247, 1155, 1041 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.57 (br s, 2 H), 7.52 (br s, 2 H), 4.95 (s, 2 H), 4.45 (t, J = 1.2 Hz, 2 H), 4.39 (t, J = 1.2 Hz, 2 H), 4.24−4.20 (m, 4 H), 2.17 (s, 6 H); ^{13}C NMR ($CDCl_3$)

(16) Dewar, M. J. S.; Mole, T. *J. Chem. Soc.* **1956**, 1441−1443.
(17) Browne, D. T. In *Synthetic Procedures in Nucleic Acid Chemistry*; Zorbach, W. W., Tipson, R. S., Eds.; Interscience: New York, 1968.
(18) Musa, A.; Sridharan, B.; Lee, H.; Mattern, D. L. *J. Org. Chem.* **1996**, *61*, 5481−5484. Kreyenschmidt, M.; Baumgarten, M.; Tyutyulkov, N.; Müllen, K. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1957−1959.
(19) House, H. O.; Ghali, N. I.; Haack, J. L.; VanDerveer, D. *J. Org. Chem.* **1980**, *45*, 1807−1817.

δ 168.50, 81.72, 72.36, 71.19, 70.99, 69.49, 66.32, 65.70, 24.80; MS *m/e* (rel intensity) 503 (M^+, 15%).

2,6-Diacetamido-4-[(1′-ethynylferrocenyl)methoxy]pyridine (13). To a DMSO (10 mL) solution of **12** (100 mg, 0.20 mmol) was added saturated aqueous KF solution (0.5 mL). The reaction mixture was stirred for 1 h, poured into water, and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, AcOEt) to give **13**: yield 93% (80 mg); mp 85−87 °C; IR (KBr) 3249, 2100, 1683, 1583, 1438, 1240, 1155, 1041 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.59 (br s, 2 H), 7.51 (br s, 2 H), 4.94 (s, 2 H), 4.78 (t, J = 1.8 Hz, 2 H), 4.42 (t, J = 1.8 Hz, 2 H), 4.27−4.24 (m, 4 H), 3.06 (s, 1 H), 2.17 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.66, 150.53, 96.42, 81.74, 80.61, 75.39, 72.30, 70.99, 70.56, 69.43, 69.33, 68.65, 66.76, 65.97, 24.75; MS *m/e* (rel intensity) 431 (M^+, 22%).

3-Iodoperylene (17). To a 27% aqueous H_2SO_4 solution (137 mL) of 3-aminoperylene[16] (100 mg, 0.37 mmol) was added an aqueous solution (30 mL) of $NaNO_2$ (7.0 g, 100 mmol) at 0 °C. Immediately to the reaction mixture was added a cold (ca. 0 °C) aqueous solution (30 mL) of KI (15 g, 90 mmol), and the reaction mixture was stirred at 0 °C for 1 h. The reaction mixture was allowed to warm to room temperature and was stirred at the same temperature for an additional 12 h. The reaction mixture was poured into aqueous $NaHSO_3$ solution and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, hexane/CH_2Cl_2 5:1) to afford crude **17**: yield 11% (17 mg, 90% purity). This compound was identified on the basis of mass spectrum and was used for the next reaction without further purification.

Ferroceptor 2e. A morpholine (5 mL) solution of **13** (90 mg, 0.21 mmol), **17** (210 mg, 0.55 mmol), $(Ph_3P)_2PdCl_2$ (6 mg, 0.022 mmol), and CuI (1.6 mg, 0.022 mmol) was stirred at 70 °C for 12 h. After removal of the solvent, the residue was poured into water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, AcOEt) to give crude **2e** (61.4 mg). The crude product was recrystallized from CH_2Cl_2/*i*-Pr_2O to afford **2e**: yield 10% (15 mg); mp 160−165 °C (dec); IR (KBr) 2200, 1706, 1676, 1619, 1583, 1441 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.19−8.07 (m, 5 H), 7.68 (d, J = 7.9 Hz, 2 H), 7.58 (d, J = 7.9 Hz, 1 H), 7.52−7.48 (m, 3 H), 7.41 (br s, 2 H), 7.22 (br s, 2 H), 4.94 (s, 2 H), 4.64 (t, J = 1.8 Hz, 2 H), 4.51 (t, J = 1.8 Hz, 2 H), 4.34 (t, J = 1.8 Hz, 2 H), 4.28 (t, J = 1.8 Hz, 2 H), 2.04 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.38, 150.06, 130.52, 128.13, 127.97, 127.02, 126.74, 126.66, 126.39, 120.57, 120.51, 120.37, 119.72, 96.31, 93.99, 85.30, 83.28, 72.16, 70.12, 69.89, 69.71, 65.69, 24.75; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 681 (M^+, 7%).

Other oxymethylene-linked ferroceptors **2b**−**d** were prepared from **13** and **14**−**16**, respectively, in a manner similar to that described for **2e**.

2b: yield 20%; mp 107−109 °C (dec); IR (KBr) 2200, 1682, 1617, 1583, 1439, 1239, 1156 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.51 (d, J = 8.6 Hz, 2 H), 8.38 (s, 1 H), 7.99 (d, J = 8.6 Hz, 2 H), 7.63−7.45 (m, 4 H), 7.40 (br s, 2 H), 7.17 (br s, 2 H), 4.98 (s, 2 H), 4.74 (t, J = 1.8 Hz, 2 H), 4.55 (t, J = 1.8 Hz, 2 H), 4.41 (t, J = 1.8 Hz, 2 H), 4.35 (t, J = 1.8 Hz, 2 H), 2.08 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.30, 150.11, 132.30, 131.23, 128.72, 128.48, 128.13, 126.90, 126.76, 126.66, 126.37, 125.59, 118.09, 99.35, 96.27, 83.83, 83.11, 72.20, 70.52, 70.22, 69.83, 66.70, 65.96, 24.73; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 607 (M^+, 100%).

2c: yield 15%; mp 115−118 °C (dec); IR (KBr) 2208, 1696, 1678, 1620, 1585, 1440, 1238, 1155 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.48 (d, J = 8.6 Hz, 1 H), 8.19 (d, J = 8.6 Hz, 2 H), 8.14−8.01 (m, 6 H), 7.36 (br s, 2 H), 7.00 (br s, 2 H), 4.98 (s, 2 H), 4.70 (s, 2 H), 4.55 (s, 2 H), 4.38 (s, 2 H), 4.32 (s, 2 H), 1.98 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.34, 168.10, 149.92, 131.34, 129.41, 127.99, 127.73, 127.30, 126.13, 125.75, 125.35, 125.27, 124.39, 96.25, 72.20, 70.14, 69.87, 69.69, 24.67; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 631 (M^+, 75%).

2d: yield 10%; mp 177−179 °C (dec); IR (KBr) 2200, 1696, 1580, 1544, 1444, 1248, 1155 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.20−7.95 (m, 9 H), 7.48 (br s, 2 H), 7,21 (br s, 2 H), 5.00 (s, 2 H), 4.63 (s, 2 H), 4.53 (s, 2 H), 4.34 (s, 2 H), 4.30 (s, 2 H), 1.98 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.38, 150.06, 130.52, 128.13, 127.97, 127.02, 126.74, 126.66, 126.39, 120.57, 120.51, 120.37, 119.72, 96.31, 93.99, 85.30, 83.28, 72.16, 70.12, 69.89, 69.71, 65.69, 24.75; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 632 (MH^+, 74%).

Ferroceptor 3a. An Et_2NH solution of iodoferrocene[10b] (31 mg, 0.10 mmol), **7** (28 mg, 0.12 mmol), $(PPh_3)_2PdCl_2$ (2.5 mg, 3.6 μmol), and CuI (1.3 mg, 7.2 μmol) was stirred at 70 °C for 12 h. After removal of the solvent, the residue was poured into water and extracted with CH_2Cl_2. The CH_2Cl_2 extract was evaporated and subjected to preparative thin-layer chromatography (silica gel; eluent, CH_2Cl_2/MeOH 15:1) to give **3a**: yield 10% (4 mg); mp 103−106 °C (dec); IR (KBr) 2211, 1677, 1612, 1550, 1413 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.98 (br s, 2 H), 7.58 (br s, 2 H), 4.55 (t, J = 1.7 Hz, 2 H), 4.29 (t, J = 1.7 Hz, 2 H), 4.25 (s, 5 H), 2.21 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.45, 149.44, 136.59, 132.07, 128.64, 111.25, 92.94, 85.28, 76.42, 74.36, 72.80, 71.17, 70.14, 65.95, 41.01, 24.85; MS *m/e* (rel intensity) 401 (M^+, 100%).

2,6-Diacetamido-4-[(1′-iodoferrocenyl)ethynyl]pyridine (19). To an *i*-Pr_2NH solution of 1,1′-diiodoferrocene[10b] (**18**) (1.05 g, 2.40 mmol), $Pd_2(dba)_3$·$CHCl_3$ (12.4 mg, 0.072 mmol), $Cu(OAc)_2$·H_2O (4.8 mg, 0.14 mmol), and PPh_3 (6.3 mg, 0.28 mmol) was added a THF/*i*-Pr_2NH (1:1, 2 mL) mixed solution of **7** (87 mg, 0.40 mmol) dropwise at 70 °C over a 2 h period. The reaction mixture was stirred at this temperature for 12 h. After removal of the solvent, the residue was poured into water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, CH_2Cl_2/MeOH 20:1) to afford crude **19**. The crude product was washed with CH_2Cl_2/Et_2O/hexane mixed solvent to give **19**: yield 50% (107 mg); mp 84−86 °C; IR (KBr) 2212, 1677, 1612, 1367, 1274, 1232 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.02 (br s, 2 H), 7.53 (br s, 2 H), 4.53 (t, J = 1.8 Hz, 2 H), 4.47 (t, J = 1.8 Hz, 2 H), 4.30 (t, J = 1.8 Hz, 2 H), 4.25 (t, J = 1.8 Hz, 2 H), 2.21 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 168.64, 149.50, 136.48, 111.25, 92.84, 85.30, 76.40, 74.34, 72.78, 71.17, 24.83; MS *m/e* (rel intensity) 527 (M^+, 100%).

3-Ethynylperylene (23). To a morpholine (10 mL) solution of **17** (230 mg, 0.63 mmol), $(Ph_3P)_2PdCl_2$ (25 mg, 0.035 mmol), and CuI (6.7 mg, 0.35 mmol) was added 3-methyl-1-butyne-3-ol (150 mg, 1.8 mmol) at room temperature. The reaction mixture was stirred at 100 °C for 4 h. To the mixture was added additional 3-methyl-1-butyne-3-ol (250 mg, 3.0 mmol) at the same temperature, and the mixture was stirred at 110 °C for 6 h. After removal of the solvent, the residue was dissolved in water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and chromatographed (silica gel; eluent, $CHCl_3$) to give 3-(3-hydroxy-3-methyl-1-butynyl)-perylene: yield 18% (38 mg); mp 162−165 °C (dec); IR (KBr) no diagnostic peaks; ^1H NMR ($CDCl_3$) δ 8.25−8.10 (m, 4 H), 7.72−7.40 (m, 6 H), 7.33−7.28 (m, 1 H), 1.75 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 128.44, 128.28, 128.13, 126.72, 126.64, 120.94, 31.73; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 334 (M^+, 60%). To NaH (9 mg, 0.22 mmol; commercial 60% dispersion was washed thoroughly with hexane prior to use) was added a toluene solution (4 mL) of 3-(3-hydroxy-3-methyl-1-butynyl)-perylene (70 mg, 0.21 mmol). The reaction mixture was heated to 110 °C immediately and stirred for 10 min at that temperature. The reaction mixture was poured into water and extracted with AcOEt. The AcOEt extract was evaporated and chromatographed (silica gel; eluent, $CHCl_3$) to give **23**: yield 30% (17 mg); mp 178−180 °C (dec); IR (KBr) no diagnostic peaks; ^1H NMR ($CDCl_3$) δ 8.25−8.06 (m, 5 H), 7.74−7.45 (m, 6 H), 3.55 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 134.84, 131.33, 128.88, 127.91, 126.60, 120.27.

Ethynylarenes **21** and **22** were synthesized from **15** and **16**, respectively, via corresponding (3-hydroxy-3-methyl-1-butynyl)arenes in a manner similar to that described for **23**.

1-(3-Hydroxy-3-methyl-1-butynyl)pyrene: yield 60%; mp 104−105 °C (dec); IR (KBr) no diagnostic peaks; ^1H NMR ($CDCl_3$) δ 8.38 (d, J = 9.2 Hz, 1 H), 8.03−7.78 (m, 8 H), 2.73 (s, 1 H), 1.78 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 131.75, 131.02, 130.82, 129.47, 128.15, 127.91, 127.00, 126.01, 125.42, 125.38,

125.13, 124.23, 124.05, 117.05, 99.47, 81.25, 66.01, 31.75; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 284 (M^+, 100%).

1-Ethynylpyrene (21): yield 85%; mp 115−117 °C (dec); IR (KBr) 3294 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.58 (d, J = 9.2 Hz, 1 H), 8.28−7.98 (m, 8 H), 3.63 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 132.50, 131.59, 131.17, 130.99, 130.17, 128.56, 128.40, 127.18, 126.64, 126.29, 125.73, 125.69, 125.32, 124.37, 82.79, 82.63; MS *m/e* (rel intensity) 226 (M^+, 100%).

2-(3-Hydroxy-3-methyl-1-butynyl)pyrene: yield 63%; mp 108−110 °C (dec); IR (KBr) no diagnostic peaks; ^1H NMR ($CDCl_3$) δ 8.20−7.93 (m, 9 H), 1.72 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 131.22, 131.02, 129.65, 128.05, 127.79, 126.86, 126.31, 125.36, 124.41, 124.35, 120.09, 94.19, 82.81, 65.83, 31.63; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 284 (M^+, 100%).

2-Ethynylpyrene (22): yield 50%; mp 110−112 °C (dec); IR (KBr) 3295 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.28 (s, 2 H), 8.22−7.98 (m, 7 H), 3.24 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 131.31, 131.06, 128.23, 128.19, 126.88, 126.49, 125.46; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 226 (M^+, 100%).

Ferroceptor 3e. A morpholine (1.5 mL) solution of **19** (26 mg 0.05 mmol), **23** (30 mg, 0.11 mmol), $(Ph_3P)_2PdCl_2$ (2.1 mg, 3 μmol), and CuI (0.6 mg, 3 μmol) was stirred at 90 °C for 10 h. After removal of the solvent, the residue was poured into water and extracted with $CHCl_3$. The $CHCl_3$ extract was evaporated and subjected to preparative thin-layer chromatography (silica gel; eluent, CH_2Cl_2/MeOH 20:1) to give **3e**: yield 20% (7 mg); mp 200−202 °C (dec); IR (KBr) 2208, 1701, 1680, 1553, 1414, 1261 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.22−8.08 (m, 4 H), 7.91 (d, J = 7.9 Hz, 1 H), 7.72 (d, J = 7.9 Hz, 2 H), 7.55−7.47 (m, 4 H), 7.34 (br s, 2 H), 6.88 (br s, 2 H), 4.69 (t, J = 1.8 Hz, 2 H), 4.65 (t, J = 1.8 Hz, 2 H), 4.39 (t, J = 1.8 Hz, 4 H), 1.99 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 130.39, 128.57, 127.99, 127.90, 126.86, 126.75, 126.61, 120.40, 119.89, 119.69, 110.58, 86.52, 81.24, 73.00, 72.46, 70.41, 70.19, 24.69; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 675 (M^+, 100%).

Other ethynediyl-linked ferroceptors **3b**−**d** were prepared from **19** and **20**−**22**, respectively, in a manner similar to that described for **3e**.

3b: yield 20%; mp 230−233 °C (dec); IR (KBr) 2202, 1682, 1550, 1416 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.49 (d, J = 8.5 Hz, 2 H), 8.28 (s, 1 H), 7.92 (d, J = 8.5 Hz, 2 H), 7.57−7.43 (m, 6 H), 7.18 (br s, 2 H), 4.76 (t, J = 1.8 Hz, 2 H), 4.68 (t, J = 1.8 Hz, 2 H), 4.43 (t, J = 1.8 Hz, 4 H), 2.10 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 148.53, 132.26, 131.16, 128.25, 127.08, 126.33, 125.54, 110.71, 73.23, 72.78, 71.29, 70.99, 66.50, 24.81; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 601 (M^+, 43%).

3c: yield 20%; mp 146−147 °C (dec); IR (KBr) 2208, 1679, 1612, 1552, 1414 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.44 (d, J = 9.2 Hz, 1 H), 8.23−7.86 (m, 10 H), 6.52 (br s, 2 H), 4.73 (t, J = 1.8 Hz, 2 H), 4.67 (t, J = 1.8 Hz, 2 H), 4.39 (t, J = 1.8 Hz, 4 H), 1.92 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 147.86, 129.55, 127.75, 127.46, 127.22, 126.11, 125.91, 125.02, 124.88, 124.27, 119.18, 110.46, 87.06, 73.07, 72.58, 70.54, 70.26, 69.17, 24.61; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 625 (M^+, 77%).

3d: yield 20%; mp 126−128 °C (dec); IR (KBr) 2209, 1731, 1688, 1552, 1414, 1262, 1095, 1027, 803 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.20−7.86 (m, 9 H), 7.48 (br s, 2 H), 6.63 (br s, 2 H), 4.65 (s, 2 H), 4.63 (s, 2 H), 4.39 (s, 2 H), 4.36 (s, 2 H), 1.94 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 149.95, 132.52, 131.20, 130.92, 130.60, 127.79, 127.36, 127.08, 110.65, 83.30, 72.56, 70.60, 70.20, 68.20; FABMS (in 3-nitrobenzyl alcohol) *m/e* (rel intensity) 625 (M^+, 100%).

Supporting Information Available: Copies of ^1H NMR spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

JO982138U