Indole as a scaffold for anion recognition

Frederick M. Pfeffer,* Kieren F. Lim and Kathryn J. Sedgwick

Received 23rd February 2007, Accepted 24th April 2007
First published as an Advance Article on the web 8th May 2007
DOI: 10.1039/b702804k

Indole has an acidic N–H that can be used to form hydrogen bonds to anions and in this paper the synthesis of three new suitably functionalised indole based anion receptors is presented along with their evaluation using ^{1}H NMR titration techniques.

Introduction

In the rapidly maturing field of anion recognition and sensing[1] a range of functional groups containing N–H hydrogen bond donors (such as urea, thiourea, amide, and pyrrole) have been employed to bind a target anion.[2] Multiples (*e.g.* calixpyrroles) and combinations of these groups (*e.g.* amidopyrroles) have also been successfully used.[3] Nature, however, provides the best examples, such as the sulfate binding protein (SBP), that employs a total of seven H-bond donors to selectively and strongly coordinate the anion.[4]

Indeed, close examination of the bound SBP : SO_4^{2-} complex reveals that the N–H of a tryptophan side chain, *i.e.* indole, is employed as a H-bond donor.[4] Until very recently[5] this was the clearest evidence that the indole N–H could function as a H-bond donor to anions and indeed it seemed logical that if the closely related pyrrole could be employed as a synthetic framework for anion recognition[2b,3a] then so too could indole.

It has been demonstrated that multiple H-bond donors within a single host can cooperate in the binding of a single anion[6] and ideally any new hosts based on indole would also be capable of this feat. Therefore, included in the design was urea (or thiourea) and amide groups. The commercially available indole-2-carboxylic acid appeared attractive as there was a linkage point near to indole N–H and the 2-carboxy group has an inductive electron withdrawing effect on the indole. It was reasoned that a flexible carbon spacer linking the indole to a urea moiety would allow a degree of flexibility and hence allow these groups to cooperate in the binding of an anion. Thus indole derivatives **1**, **2** and **3** (Fig. 1) became synthetic targets and in this paper the construction and evaluation (using ^{1}H NMR titrations) of these new anion hosts is presented.

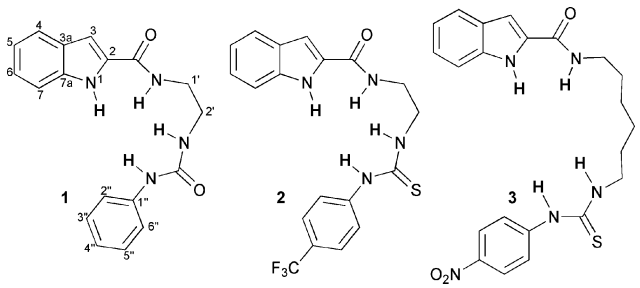


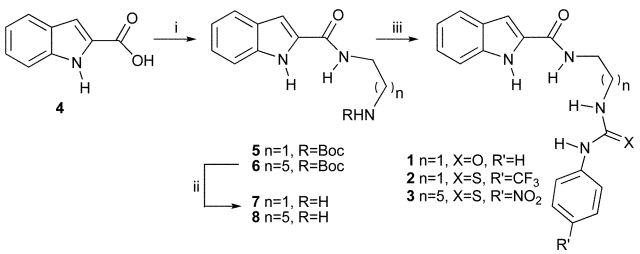
Fig. 1 New indole based anion hosts **1**, **2** and **3**.

School of Life and Environmental Sciences, Deakin University, Geelong, VIC, Australia. E-mail: thefef@deakin.edu.au; Fax: +61 3 5227 1040; Tel: +61 3 5227 1439

Results and discussion

Synthesis

The synthesis of **1** and **2** was accomplished in three steps by coupling indole-2-carboxylic acid **4** with monoboc diaminoethane[7] using 1-(3-(*N*,*N*-dimethylamino)propyl)-3-ethyl carbodiimide hydrochloride (EDCI) (Scheme 1). After recrystallisation, indole-amide **5** was isolated in 44% yield. The boc group was removed using dilute TFA then the resulting crude amine reacted directly with either phenylisocyanate to form **1** (83% yield), or *p*-trifluoromethylphenylisothiocyanate to form **2** (46% yield), after chromatographic purification. Host **3** was produced in low yield (8%) using identical methodology but employing monoboc diaminohexane[7] in the initial EDCI mediated coupling and *p*-nitrophenylisothiocyanate in the final step.



Scheme 1 Synthesis of new hosts **1**, **2** and **3**. *Reagents and conditions*: i. $NH_2(CH_2)_2NHBoc$ or $NH_2(CH_2)_6NHBoc$, EDCI, HOBt, NEt_3, DMF, 12 h, 44% for **5**, 89% for **6**; ii. $CHCl_3$, TFA, 4 h; iii. R′NCO or R′PhNCS, DIPEA, dioxane, 12 h, 83% for **1**, 46% for **2**, 8% for **3**.

The ^{1}H NMR spectra of the new compounds were insightful as the resonance assigned to the indole N–H was found furthest downfield (δ = 11.58, 11.60 and 11.54 ppm for **1**, **2** and **3** respectively in DMSO-d_6) suggesting it was electron poor and interacting with the polar aprotic solvent. Indeed for indole itself, the resonance assigned to the N–H was found at δ = 8.17 ppm in $CDCl_3$ and δ = 11.05 ppm in the more polar DMSO-d_6 which clearly indicated H-bonding.

Evaluation

In order to establish whether the indole N–H could interact with an anion, a series of anions (F^-, Br^-, Cl^-, AcO^- and $H_2PO_4^-$) as

their tetrabutylammonium salts were individually titrated against the new hosts **1**, **2** and **3**. To confirm whether the indole, amide and urea (or thiourea) protons were cooperating in the binding, the chemical shift changes in the ^{1}H NMR spectra of each of the four N–H groups (see Fig. 1) were recorded.

The first anions to be investigated were the spherical halides. When fluoride was titrated against **1** significant broadening of all N–H peaks was observed and indeed after the addition of 1.2 equivalents the resonances assigned to both the thiourea N–H joined to the phenyl ring, as well as the indole N–H, completely disappeared (Fig. 2). Deprotonation of the acidic groups was deemed responsible for the disappearances as when >2 eq. of anion had been added the telltale [FHF]$^-$ peak at ~16 ppm became evident.[8,9a] Nevertheless, a significant migration in the chemical shift of the indole N–H peak occurred ($\Delta\delta$ = 2.27 ppm) prior to its disappearance which indicated strong interaction with the anion prior to deprotonation.

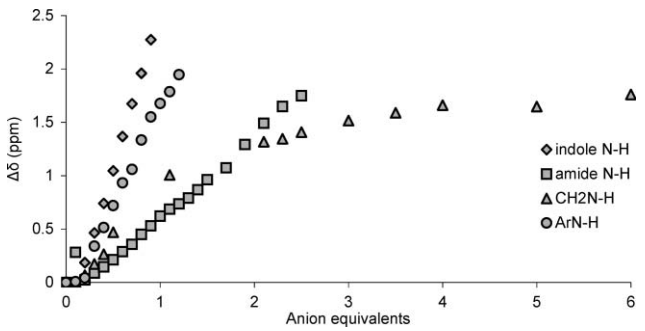


Fig. 2 ^{1}H NMR titration of F$^-$ against host **1**.

The F$^-$ titrations against hosts **2** and **3** provided similar results. Notably for **3** a colour change from clear to yellow-orange accompanied the addition of F$^-$, and this observation further confirms removal of the thiourea N–H, as colour changes associated with the deprotonation of electron withdrawn ureas and related systems with strongly basic anions have been well documented.[9]

When titrations using the larger chloride anion were performed a small change in the chemical shift of the thiourea N–H groups was noted (*e.g.* for **1**, $\Delta\delta$ = 0.39 and 0.34 ppm) but little change in the indole or the amide resonance was observed ($\Delta\delta$ < 0.1 for all hosts). For bromide even less change was noted ($\Delta\delta$ < 0.1 for all protons). It appeared that very little, if any, interaction was occurring between the indole N–H and either of these anions.

Next the trigonal planer acetate anion was investigated. For both **1** and **2** a strong change in the chemical shift of the urea (for **1**, R = H, $\Delta\delta$ = 2.26 and 2.23 ppm) and thiourea (for **2** (see Fig. 3), R = CF_3, $\Delta\delta$ = 3.06 and 2.89 ppm) protons was observed, the larger change for **2** due to the more electron withdrawn thiourea. Unfortunately for both of these hosts only a small change in the chemical shift of the indole or the amide proton was observed (for **1**, $\Delta\delta$ = 0.86 and 0.51 ppm and for **2**, $\Delta\delta$ = 0.61 and 0.46 ppm for the indole and amide protons respectively). These results indicated that little interaction of these H-bond donors and the anion was occurring and thus no cooperative binding had occurred. The binding isotherms were in excellent agreement with the 1 : 1 host : anion model when analysed using WinEQNMR[10] and binding constants of logβ = 3.1 ± 0.2 for **1** and logβ = 2.8 ± 0.4 for **2** were

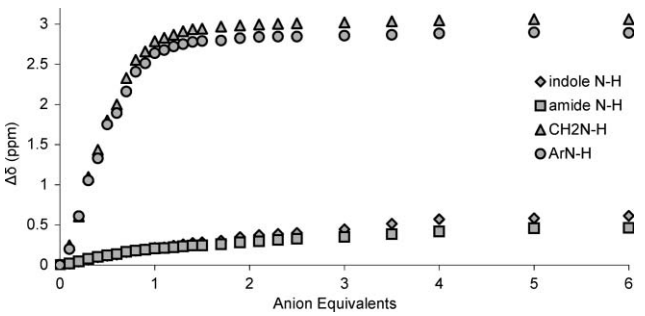


Fig. 3 ^{1}H NMR titration of AcO$^-$ against host **2**.

determined, typical of those for urea and thiourea based hosts.[3b,6] It is possible that the ethyl linker is too short in this instance to allow all 4 N–H bond donors to work together in the binding of acetate and the structurally complementary acetate : urea (or thiourea) binding arrangement dominated.

The situation for host **3** (Fig. 4) was somewhat more interesting; initially, like the results for hosts **1** and **2** a large change in the chemical shift of the thiourea protons was noted (for **3** R = NO_2, $\Delta\delta$ = 3.42 and 3.36 ppm) but after one eq. of AcO$^-$ had been added a more significant change in the chemical shift of the indole N–H was noted and after 6 eq. of anion had been added a total migration of $\Delta\delta$ = 1.30 and $\Delta\delta$ = 0.83 for the indole and the amide resonances respectively was observed. It is possible that the longer spacer length allowed the different motifs (thiourea *vs.* indole and amide) to act independently and that once the thiourea recognition motif had been saturated the indole and amide H-bond donors weakly bound a second equivalent of anion.

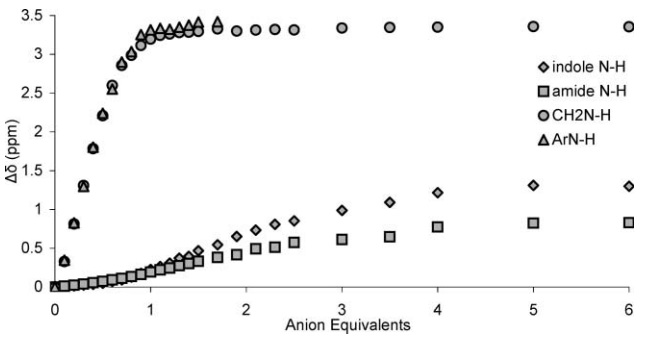


Fig. 4 ^{1}H NMR titration of AcO$^-$ against host **3**.

Finally the tetrahedral $H_2PO_4^-$ anion was titrated against the new hosts and it was immediately apparent that all N–H bond donors were interacting with this large, multi acceptor anion. For host **1** (Fig. 5) total changes in chemical shift ranged from δ = 1.22 (aliphatic thiourea N–H) to 1.79 ppm (amide N–H). Such an immediate and significant change in the chemical shift of all relevant protons indicated that they all cooperate in the binding of the $H_2PO_4^-$ anion and similar behaviour has been previously observed when investigating naphthalimide based systems with multiple H-bond donors.[6] Also similar to the naphthalimide system the new isotherms showed excellent agreement with a 1 : 1 host : anion binding model and from the curves a binding constant of logβ = 3.5 ± 0.3 was determined. It was noteworthy that the amide N–H showed the largest change in chemical shift ($\Delta\delta$ = 1.79 ppm); the indole N–H resonance also changed quickly

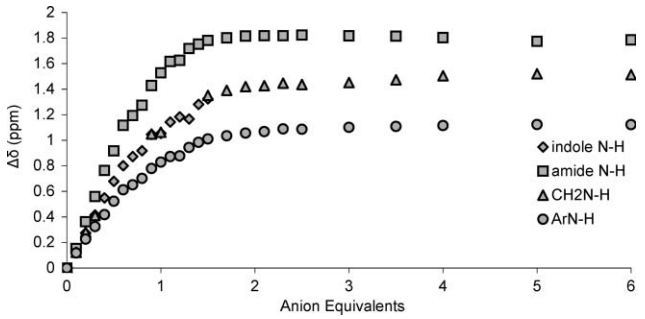


Fig. 5 ^{1}H NMR titration of $H_2PO_4^-$ against host **1**.†

($\Delta\delta = 1.33$ ppm after 1.5 eq.) but broadened such that it could not be monitored beyond this point.

This trend was also true for host **2** where for the amide N–H $\Delta\delta = 2.47$ ppm after 2.1 eq. after which the peak became too broad to monitor. These results indicated that the bound arrangement of host : $H_2PO_4^-$ involved a particularly strong interaction to the amide N–H, and judging by the magnitude of $\Delta\delta$ the amide N–H to anion interaction was much stronger than that of the traditional thiourea functional group. Indeed for **2** $\Delta\delta$ for the amide N–H was more than 1 ppm greater than that for either of the thiourea N–H protons. Determination of a binding constant was difficult due to the extreme broadening of these peaks but an estimate of $\log\beta =$ 3.5 was made from the truncated isotherm.

For compound **3** the titration curve (Fig. 6) was more typical of thiourea based hosts and these N–H resonances showed the greatest change in chemical shift, the thiourea N–H joined to the aromatic ring changed by $\delta = 1.53$ ppm after 1.0 eq and the aliphatic thiourea proton moved $\delta = 1.79$ ppm after 4.0 eq. but again a large change in chemical shift was observed for all the H-bond donors. This suggests that all four H-bond donors were cooperating in the binding of the larger tetrahedral $H_2PO_4^-$ anion and again when determining binding constants close agreement with a theoretical 1 : 1 host : anion model was apparent for the thiourea and amide isotherms. The indole resonance could not be monitored after 1.7 eq had been added yet still shifted by 1.15 ppm indicating clear involvement in the binding. The amide was not as strongly involved ($\Delta\delta = 1.18$ ppm after 6 eq.), the additional length of the spacer likely to ensure a different geometry for the **3** : $H_2PO_4^-$ complex and thus a different extent to which all H-bond donors were involved.

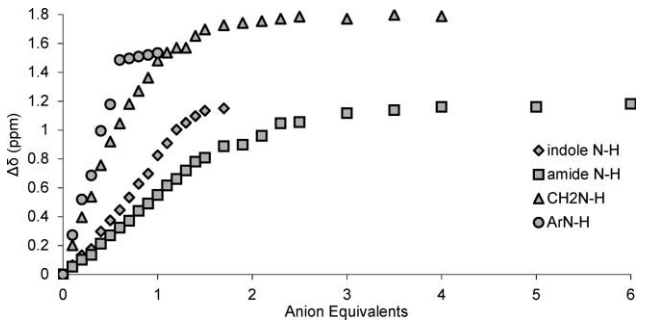


Fig. 6 ^{1}H NMR titration of $H_2PO_4^-$ against host **3**.

A summary of the binding constants determined from the titration isotherms using WinEQNMR is presented in Table 1 and from this a preference of the smaller hosts **1** and **2** for the tetrahedral $H_2PO_4^-$ anion can be seen. This preference is likely due to the cooperative nature of the multiple N–H bonds in the binding of a single anion. Indeed the preference of receptors containing multiple H-bond *donor* atoms (and an ability for cooperative binding) for anions with multiple *acceptor* atoms has been noted previously by our group and others.[6,11]

Table 1 Binding constants ($\log\beta$) for **1**, **2** and **3** against a selection of anions

	Anion		
Host	Cl^-	AcO^-	$H_2PO_4^-$
1	2.1[a]	3.1 ± 0.2	3.5 ± 0.3
2	2.2[a]	2.8 ± 0.4	3.5[a]
3	—	3.9 ± 0.7	3.4 ± 0.2

[a] Estimation only due to error $\geq$20%. Fluoride was omitted as no suitable titration curves could be obtained.

Conclusions

New compounds **1**, **2** and **3**, based on an indole framework, have been synthesised and shown using ^{1}H NMR titration techniques to interact with a series of anions. In particular the binding of the new hosts with $H_2PO_4^-$ shows clear interaction of all four N–H bond donors with the anion and thus they are cooperating in the binding of the anion. This successful demonstration cements indole in the arsenal of H-bond donors available for anion recognition; indeed, given the rich chemistry of indole, and its luminescent properties that were not pursued in this initial study, this framework has much to offer the field.

Experimental

All melting points were obtained using a Stuart Scientific SMP3 melting point apparatus. All ^{1}H, ^{13}C and ^{19}F spectra were recorded on a Jeol JNM-EX 270 MHz FT-NMR or a Varian 300 MHz Unity Plus NMR spectrometer as indicated. Samples were dissolved in $CDCl_3$ or anhydrous DMSO-d_6 as indicated and spectra referenced against TMS. Coupling constants are reported in Hz. Low resolution mass spectra were recorded on a VG Platform Fisions Instrument, using acetonitrile as the mobile phase. High resolution mass spectrometry (HRMS) was performed on an Agilent 6210 LC/MSDTOF instrument using acetonitrile as the mobile phase. Thin layer chromatography was performed on aluminium backed Kieselgel 60 (230–400 mesh) plates and compounds visualised using a $KMnO_4$ oxidising dip. Column chromatography was performed using silica gel, Kieselgel 60 (70–230 mesh), or aluminium oxide as indicated. All solvents used were AR grade. All reagents were purchased from Aldrich and used as supplied.

2-[2′-(*tert*-Butoxycarbonylamino)ethylamido]indole 5

To a solution of indole-2-carboxylic acid (1.50 g, 9.33 mmol) in dry DMF (55 mL), monoboc diaminoethane[7] (2.194 g, 13.7 mmol), EDCI (1.912 g, 9.97 mmol), triethylamine (0.962 g, 9.51 mmol) and hydroxybenzotriazole (HOBt; 25 mg, 1.9×10^{-4} mmol) were added. The reaction was stirred at room temperature, under an atmosphere of nitrogen overnight whereupon TLC (3 : 1 EtOAc

: petroleum ether) indicated a new product had formed. The reaction mixture was filtered and the filtrate concentrated to dryness under reduced pressure. The resulting brown oil was crystallised from DCM, to yield cream crystals which were collected using a Hirsch Funnel (1.253 g, 44%); mp 178.7–180.3 °C; δ_H(270 MHz; DMSO-d_6, TMS) 1.38 (9H, s, $C(CH_3)_3$), 3.13 (2H, s, H2′), 3.35 (2H, s, H1′), 6.94 (1H, s, H3), 7.05 (1H, t, $J = 5.2$, H5), 7.09 (1H, s, OC(O)NH), 7.15 (1H, t, $J = 5.4$, H6), 7.41 (1H, d, $J = 5.7$, H7), 7.61 (1H, d, $J = 5.4$, H4), 8.50 (1H, s, C(O)NH), 11.58 (1H, s, H1); δ_C(270 MHz; DMSO-d_6, TMS) 28.79, 39.62, 40.37, 78.27, 102.97, 112.83, 120.21, 121.98, 123.75, 127.62, 132.28, 136.94, 156.27, 161.83; *m/z* (HRMS) 607.32259 ($[M_2 + H]^+$. $C_{32}H_{43}N_6O_6$ requires 607.32386)

2-[(2′-Amino)ethylamido]indole 7

To a solution of protected indole **5** (1.253 g, 4.14 mmol) in chloroform (60 mL), trifluoroacetic acid (15 mL) was added slowly. The reaction was stirred under an atmosphere of nitrogen for 4 hours. The reaction was monitored by TLC (75 : 25 EtOAc : petroleum ether) until no starting material remained. The solvent was removed under reduced pressure, the resulting crude solid taken up in chloroform and solvent removed again to leave a pink-brown solid that was used without further purification in the following two reactions.

2-[2′-(Phenylureido)ethylamido]indole 1

To a solution of crude indole amine **7** (0.250 g, 1.23 mmol) in 1,4-dioxane (40 mL), phenylisocyanate (2.0 mL of 10% in 1,4-dioxane, 1.85 mmol) and sodium hydroxide (3 drops of 10%) were added dropwise. The reaction was stirred under an atmosphere of nitrogen for 2 hours whereupon the solvent was removed under reduced pressure. The resulting crude product was purified by column chromatography (50 : 50 EtOAc : petroleum ether, silica), the desired fractions combined and the solvent removed under reduced pressure to afford a cream solid (0.248 g, 83%); mp 202.7–204.2 °C; δ_H(270 MHz; DMSO-d_6, TMS) 3.5* (2H, s, H2′), 3.7* (2H, s, H1′), 6.30 (1H, brt, $J = 3.9$, C(O)N*H*CH_2), 6.89 (1H, t, $J = 4.9$, H4″), 7.03 (1H, t, $J = 5.2$, H5), 7.12 (1H, s, H3), 7.17 (1H, t, $J = 5.4$, H6), 7.23 (2H, d, $J = 5.2$, H2″ and 5″), 7.39 (2H, d, $J = 5.1$, H12″ and 6″), 7.44 (1H, d, $J = 6.1$, H7), 7.61 (1H, d, $J = 5.3$, H3), 8.56 (1H, s, C(O)NHAr), 8.58 (1H, s, amide NH), 11.58 (1H, s, H1); δ_C(270 MHz; DMSO-d_6, TMS) 38.5*, 44.1*, 102.96, 112.85, 118.23, 120.24, 121.59, 122.00, 123.77, 127.64, 129.18, 132.30, 136.95, 141.04, 155.96, 161.88; *m/z*(ES): 357.3 ($M + Cl^-$. $C_{18}H_{18}N_4O_2$ + Cl requires 357.1), (HRMS) 645.29246 ($[M_2 + H]^+$. $C_{36}H_{37}N_8O_4$ requires 645.29322). [* ^{1}H NMR peaks 3.5 and 3.7 and ^{13}C NMR peaks 38.5 and 44.1 were obscured by DMSO, and assigned by analogy to other molecules in the series.]

2-[2′-(*p*-Trifluoromethylphenylthioureido)ethylamido]indole 2

To a solution of crude indole amine **7** (0.600 g, 2.96 mmol) in dry DMF (20 mL), *p*-trifluoromethylphenylisothiocyanate (0.750 g, 3.69 mmol) and DIPEA (0.805 g, 6.22 mmol) were added. The reaction was stirred overnight, at room temperature under a nitrogen atmosphere, whereupon TLC (75 : 25 EtOAc : petroleum ether) indicated the formation of a new product. The solvent was removed under reduced pressure, and the crude product purified by column chromatography (75 : 25 EtOAc : petroleum ether, silica). The desired fractions were combined and the solvent removed under reduced pressure, to afford a yellow solid (0.369 g, 46%); mp 182.1–184.5 °C; δ_H(270 MHz; DMSO-d_6, TMS) 3.54 (1H, s, H1′), 3.72 (1H, s, H2′), 7.05 (1H, t, $J = 4.8$, H5), 7.14 (1H, s, H3), 7.18 (1H, t, $J = 4.9$, H6), 7.42 (1H, d, $J = 5.5$, H4), 7.62 (2H, d, $J = 2.6$, H2″ and 6″), 7.64 (1H, d, $J = 3.4$, H7), 7.71 (2H, d, $J = 5.7$, H3″ and 5″), 8.20 (1H, s, C(O)N*H*CH_2), 8.63 (1H, s, amide NH), 9.97 (1H, s, C(O)NHAr), 11.60 (1H, s, H1); δ_C(270 MHz; DMSO-d_6, TMS) 38.66, 44.01, 103.13, 112.86, 120.27, 122.02, 122.55, 123.60, 123.84, 126.29, 127.63, 132.20, 136.98, 143.75, 162.03, 181.15;); δ_F (270 MHz; DMSO-d_6, TMS) −59.96, *m/z* (HRMS) 407.11305 ($[M + H]^+$. $C_{19}H_{18}N_4OF_3S$ requires 407.11479).

2-[6′-(*tert*-Butoxycarbonylamino)hexylamido]indole 6

To a solution of indole-2-carboxylic acid (0.545 g, 3.39 mmol) in dry DMF (20 mL), monoboc diaminohexane[7] (1.094 g, 5.06 mmol), EDCI (0.751 g, 3.92 mmol), triethylamine (0.350 g, 3.47 mmol) and hydroxybenzotriazole (8.2 mg, 6.1×10^{-5} mmol) were added. The reaction was stirred overnight, at room temperature, under an atmosphere of nitrogen whereupon TLC (75 : 25 EtOAc : petroleum ether) indicated the disappearance of the starting material. The reaction mixture was filtered, and the filtrate was concentrated to dryness. The resulting crude brown oil was purified by column chromatography (75 : 25 EtOAc : petroleum ether, silica gel 60 mesh). The desired fractions were combined and the solvent removed under reduced pressure, yielding a yellow solid (1.080 g, 89%); mp 113.1–115.4 °C; δ_H(270 MHz; DMSO-d_6, TMS) 1.3* (4H, H3′ and 4′), 1.5* (4H, H2′ and 5′), 1.99 (9H, s, $C(CH_3)_3$), 2.89 (2H, brq, $J = 6.4$, H6′), 3.26 (2H, brq, $J = 6.4$, H1′), 6.79 (1H, s, amide NH), 7.02 (1H, t, $J = 7.4$, H5) 7.09 (1H, s, H3), 7.16 (1H, t, $J = 7.2$, H6), 7.43 (1H, d, $J = 8.2$, H7), 7.61 (1H, d, $J = 7.9$, H4), 8.43 (1H, brt, $J = 5.7$, OC(O)NH), 11.53 (1H, s, H1); δ_C(270 MHz; DMSO-d_6, TMS) 26.53, 26.76, 28.82, 29.81, 39.24, 40*, 77.82, 102.70, 112.80, 120.16, 121.93, 123.64, 127.65, 132.48, 136.88, 156.11, 161.51. [* obscured by DMSO peak.]

2-[(6-Amino)hexylamido]indole 8

To a solution protected indole **6** (549 mg, 1.53 mmol) in chloroform (30 mL), trifluoroacetic acid (7.5 mL) was added slowly. The reaction was stirred under an atmosphere of nitrogen for 4 hours. The reaction was monitored by TLC (75 : 25 EtOAc : petroleum ether) until no starting material remained. The solvent was removed under reduced pressure, the resulting crude solid washed in chloroform and solvent removed again to leave a pink-brown solid (crude 437 mg) that was used directly in the following step.

2-[2′-(*p*-nitrophenylthioureido)hexylamido]indole 3

To a solution of crude indole amine **8** (0.594 g, 1.53 mmol) in dry DMF (20 mL) *p*-nitrophenylisothiocyanate (0.463 g, 2.56 mmol) and DIPEA (0.826 g, 6.39 mmol) were added. The reaction was stirred overnight, at room temperature under a nitrogen atmosphere, whereupon TLC (75 : 25 EtOAc : petroleum ether) analysis indicated a new product had formed. The solvent was removed under reduced pressure and the resulting crude orange oil was purified by column chromatography (3 : 1 EtOAc : EtOH, Al_2O_3). The desired fractions were combined and the solvent

removed under reduced pressure to afford a yellow solid (78 mg, 8.0%); mp 83.6–85.4 °C; (Found: C, 60.07; H, 5.80; N, 15.89. $C_{22}H_{25}N_5O_3S$ requires C, 60.12; H, 5.73; N, 15.93%); δ_H(270 MHz; DMSO-d_6, TMS) 1.37 (4H, s, H3′ and 4′), 1.58 (4H, brq, $J = 4.5$, H2′ and 5′), 3.29 (2H, brq, $J = 4.7$, H6′) 3.49 (2H, brq, $J = 3.5$, H1′) 7.02 (1H, t, $J = 4.7$, H5), 7.10 (1H, s, H3), 7.17 (1H, t, $J = 4.7$, H6), 7.43 (1H, d, $J = 6.0$, H7), 7.61 (1H, d, $J = 5.4$, H4), 7.83 (2H, d, $J = 6.2$, H2″ and 6″), 8.18 (2H, d, $J = 6.2$, H3″ and 5″), 8.31 (1H, s, C(O)N*H*CH_2), 8.46 (1H, brt, $J = 4.0$, amide NH), 10.09 (1H, s, C(O)NHAr), 11.54 (1H, s, H1); δ_C(270 MHz; DMSO-d_6, TMS) 26.73, 28.56, 29.73, 40*, 44.35, 102.64, 112.73, 120.10, 120.70, 121.86, 123.59, 125.02, 127.57, 132.39, 136.79, 142.11, 146.94, 161.45, 180.35. [* obscured by DMSO peak.]

Notes and references

1 A. Bianchi, K. Bowman-James and E. Garcia-España, *Supramolecular Chemistry of Anions*, Wiley-VCH, New York, 1997; F. P. Schmidtchen and M. Berger, *Chem. Rev.*, 1997, **97**, 1609; P. D. Beer and P. A. Gale, *Angew. Chem., Int. Ed.*, 2001, **40**, 487; F. P. Schmidtchen and M. Berger, *Chem. Rev.*, 1997, **97**, 1609; see also special issues of *Coord. Chem. Rev.*, 2003, **240**(1–2) and *Coord. Chem. Rev.*, 2006, **250**(23–24).

2 (*a*) C. R. Bondy and S. J. Loeb, *Coord. Chem. Rev.*, 2003, **240**, 77; M. J. Chmielewski and J. Jurczak, *Chem.–Eur. J.*, 2005, **11**, 6080; (*b*) J. L. Sessler, S. Camiolo and P. A. Gale, *Coord. Chem. Rev.*, 2003, **240**, 17; (*c*) S. O. Kang, J. M. Llinares, D. Powell, D. VanderVelde and K. Bowman-James, *J. Am. Chem. Soc.*, 2003, **125**, 10152; P. Buhlmann, S. Nishizawa, K. P. Xiao and Y. Umezawa, *Tetrahedron*, 1997, **53**, 1647; P. D. Beer and S. E. Stokes, *Polyhedron*, 1995, **14**, 873; P. Gale, in *Encyclopedia of Supramolecular Chemistry*, ed. J. Atwood and J. Steed, Marcel Dekker, New York, 2004, p. 31.

3 (*a*) S. J. Brooks, P. A. Gale and M. E. Light, *Chem. Commun.*, 2006, 4344; P. A. Gale, *Chem. Commun.*, 2005, 3761; (*b*) F. M. Pfeffer, T. Gunnlaugsson, P. Jensen and P. E. Kruger, *Org. Lett.*, 2005, **7**, 5357; T. Gunnlaugsson, A. P. Davis, G. M. Hussey, J. Tierney and M. Glynn, *Org. Biomol. Chem.*, 2004, **2**, 1856; (*c*) A. J. Ayling, M. N. Pérez-Payán and A. P. Davis, *J. Am. Chem. Soc.*, 2001, **123**, 12716; J. L. Sessler, P. Anzenbacher, K. Jursikova, H. Miyaji, J. W. Genge, N. A. Tvermoes, W. E. Allen, J. A. Shriver, P. A. Gale and V. Kral, *Pure Appl. Chem.*, 1998, **70**, 2401.

4 B. Jacobson and F. Quiocho, *J. Mol. Biol.*, 1988, **204**, 783; J. W. Pflugrath and F. A. Quiocho, *J. Mol. Biol.*, 1988, **200**, 163.

5 Sessler *et al.* have recently reported the anion-binding properties of a simple synthetic diindolylquinoxaline anion receptor: J. Sessler, D. Cho and V. Lynch, *J. Am. Chem. Soc.*, 2006, **128**, 16518.

6 F. M. Pfeffer, M. Seter, N. Lewcenko and N. W. Barnett, *Tetrahedron Lett.*, 2006, **47**, 5241; T. Gunnlaugsson, M. Glynn, G. M. Tocci, P. E. Kruger and F. M. Pfeffer, *Coord. Chem. Rev.*, 2006, **250**, 3094; F. M. Pfeffer, A. M. Buschgens, N. W. Barnett, T. Gunnlaugsson and P. E. Kruger, *Tetrahedron Lett.*, 2005, **46**, 6579.

7 Both monoboc diamines were prepared according to: O. Buchardt, J. B. Hansen, M. C. Nielsen and U. Ehrbar, *Synthesis*, 1982, 404.

8 I. G. Shenderovich, P. M. Tolstoy, N. S. Golubev, S. N. Smirnov, G. S. Denisov and H. H. Limbach, *J. Am. Chem. Soc.*, 2003, **125**, 11710; S. O. Kang, D. Powell, V. W. Day and K. Bowman-James, *Angew. Chem., Int. Ed.*, 2006, **45**, 1921.

9 (*a*) T. Gunnlaugsson, P. E. Kruger, P. Jensen, F. M. Pfeffer and G. M. Hussey, *Tetrahedron Lett.*, 2003, **44**, 8909; (*b*) T. Gunnlaugsson, H. D. P. Ali, M. Glynn, P. E. Kruger, G. M. Hussey, F. M. Pfeffer, C. M. G. dos Santos and J. Tierney, *J. Fluoresc.*, 2005, **15**, 287; E. Quinlan, S. E. Matthews and T. Gunnlaugsson, *Tetrahedron Lett.*, 2006, **47**, 9333; M. Boiocchi, L. Del Boca, D. Esteban-Gomez, L. Fabbrizzi, M. Licchelli and E. Monzani, *Chem.–Eur. J.*, 2005, **11**, 3097; S. Camiolo, P. Gale, M. B. Hursthouse and M. E. Light, *Org. Biomol. Chem.*, 2003, **1**, 741–744; D. E. Gómez, L. Fabbrizzi, M. Licchelli and E. Monzani, *Org. Biomol. Chem.*, 2005, **3**, 1495–1500; T. Gunnlaugsson, P. E. Kruger, P. Jensen, J. Tierney, H. D. Paduka-Ali and G. M. Hussey, *J. Org. Chem.*, 2005, **70**, 10875; L. S. Evans, P. A. Gale, M. E. Light and R. Quesada, *Chem. Commun.*, 2006, 965.

10 M. J. Hynes, *J. Chem. Soc., Dalton Trans.*, 1993, 311.

11 E. A. Katayev, Y. A. Ustynyuk and J. L. Sessler, *Coord. Chem. Rev.*, 2006, **250**, 3004.