Positive and negative allosteric effects of thiacalix[4]arene-based receptors having urea and crown-ether moieties

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Heteroditopic receptors (4a-e) based on a thiacalix[4]arene in the 1,3- alternate conformation, which have two urea moieties linking various phenyl groups substituted with either electron-donating or -withdrawing groups at their m-, or p-positions with a crown-ether moiety at the opposite side of the thiacalix[4]arene cavity, have been synthesized. The two examples with p-CH3 (4a) and p-NO2- substituted (4e) phenyl groups have been characterized by X-ray crystallography. The binding properties of receptor 4a were investigated by means of 1H NMR spectroscopic and absorption titration experiments in CHCl3-DMSO (10 : 1, v/v) solution in the presence of K+ ions and various anions. Interestingly, it was found that receptor 4e, which possesses two p-nitrophenyl ureido moieties, can complex most efficiently in the urea cavity or the crown-ether moiety; and the plausible allosteric effect of receptor 4e was also studied.

Introduction

The use of calix[n]arenes 1 as building blocks for receptors capable of the highly selective recognition of cations, anions or neutral molecules has received considerable attention in the field of supramolecular chemistry. Among the various kinds of calix[n]arenes available, thiacalix[4]arenes2-3 are proving to be competent scaffolds and are finding wide use, for example as chemosensors, as well as in catalysis because of their favourable conformational properties, easy functionalization and emerging metal coordination chemistry. Several kinds of systems based on thiacalix[4]arenes are suitable for allosteric regulation4 of host-guest interactions with metal cations, and these contribute greatly to organic processes in biological systems. Anions also play an important role in biological processes, and are closely related with biological systems such as DNA and enzyme substrates. The development and the investigation of anion selective sensors 5 have attracted considerable interest. However, it is more difficult to accomplish compared with metal cation sensors because anions can possess structures of different shapes,6 typically spherical (F-, Cl-, Br-, I-), Y-shaped (AcO-, PhCOO-) or tetrahedral (H2PO4 -). In recent years, anion receptors based on calix[n]arenes have become an active research topic. Calix[4]arene urea derivatives are efficient for anion recognition given the hydrogen-bonding interaction between anions and N-H protons which can occur.

Colorimetric chemosensors 7-8 have also attracted attention due to some desirable features such as easy detection by the naked eye, construction of simple, low-cost devices and so on. Many colorimetric anion receptors containing a variety of chromogenic signaling units such as indole, imidazolium, benzenediimide, 4-nitrophenylazo, diazo and anthraquinone groups have been developed. Furthermore, numerous colorimetric anion sensors utilizing a variety of structural scaffolds, which contain urea groups, have been investigated and proved to be efficient naked-eye detectors for various anions. However, there are a few reports on the development of colorimetric chemosensors based calix[4]arene type scaffolds.9-10

Lothak10 and co-workers have reported anion receptors based on either an upper rim substituted calix[4]arene or thiacalix[4]arene, which contains two p-nitrophenyl or p-tolyl ureido moieties.9a-c,d These anion receptors exhibited effective recognition abilities towards selected anions in common organic solvents. Moreover, Kumar10 and co-workers reported an anion receptor bearing a calix[4]arene in the 1,3- alternate conformation, which contains two p-nitrophenyl moieties.10e This compound exhibited strong binding and good selectivity for Cl- ion due to the formation of
strong hydrogen bonds between the Cl\textsuperscript{−} ion and N–H protons in common organic solvents. However, investigations concerning the appearance of an allosteric effect in analogues based on the interaction of thiacalix[4]arene and alkali metal cations and anions has not yet been reported.

Herein, we have independently designed a heterodimeric system\textsuperscript{11} based on a thiacalix[4]arene having two different side arms, viz two ureas moieties linking various phenyl groups bearing either electron-donating or -withdrawing groups at their m-, or p-positions. The calixarene also has a crown ether moiety at the opposite side of the thiacalix[4]arene cavity. We herein put forward the hypothesis (and then demonstrate) that the heterodimeric system, which is controlled by the complexation of the opposing side arms with anions and K\textsuperscript{+} ion, exhibits effective positive and negative allosteric effects.

Results and discussions

Synthesis

The O-alkylation of distal-1 was carried out with 1.5 equivalents of tetraethyleneglycol ditosylate in the presence of an equivalent of K\textsubscript{2}CO\textsubscript{3} according to the reported procedure, and afforded the desired 1,3-alternate-2 in 83% yield.\textsuperscript{12} The hydrazinolysis of 1,3-alternate-2 was carried out with a large excess of hydrazine hydrate, and afforded the desired 1,3-alternate-3 in 86% yield. The condensation of 1,3-alternate-3 with 2.2 equivalents of the appropriate isocyanate in THF furnished the receptors 4\textsubscript{a–e} in good to excellent yields (Scheme 1). In general, the \textsuperscript{1}H NMR spectrum of receptors 4\textsubscript{a–e} in CDCl\textsubscript{3}–DMSO (10 : 1, v/v) exhibited the characteristics of a 1,3-alternate conformation such as two singlets (18H each) for the tert-butyl protons, one singlet (4H) for OCH\textsubscript{2}CO protons, two singlets (4H each) for aromatic protons and two singlets (2H each) for four urea NH protons.

The molecular structures of receptors 4\textsubscript{b} and 4\textsubscript{e} were also verified by X-ray crystallographic analysis (Fig. 1 and S15 and S16). Receptors 4\textsubscript{b} and 4\textsubscript{e} were recrystallized from a mixture of CHCl\textsubscript{3}–CH\textsubscript{3}CN (1 : 1, v/v) by slow evaporation. These results indicate that receptors 4\textsubscript{b} and 4\textsubscript{e} adopt the 1,3-alternate

Scheme 1 Synthesis of receptors 1,3-alternate-4\textsubscript{a–e}.

Fig. 1 X-ray crystal structure of receptor 4\textsubscript{e}. H-bonds shown as dashed lines. One of two similar molecules in the asymmetric unit is shown in two orientations rotated by approx. 90°. H atoms not involved in H-bonding, minor disorder components, and chloroform molecules of crystallization are omitted for clarity.
Table 1  Association constants of receptor 4_4–e with Cl⁻ ionsa,b

<table>
<thead>
<tr>
<th>Host</th>
<th>4_a</th>
<th>4_b</th>
<th>4_c</th>
<th>4_d</th>
<th>4_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>H</td>
<td>p-CH₃</td>
<td>p-CF₃</td>
<td>3,5-(CF₃)ᵢ</td>
<td>p-NO₂</td>
</tr>
<tr>
<td>K_a</td>
<td>6816 ± 545</td>
<td>3021 ± 242</td>
<td>12 813 ± 1025</td>
<td>6945 ± 625</td>
<td>34 411 ± 2400</td>
</tr>
</tbody>
</table>

a Measured in CDCl₃–DMSO (10 : 1, v/v) at 298 K by the ¹H NMR titration method using the chemical-shift change of the NH₄ proton (Fig. S17–S22); host concentration was 4.0 × 10⁻³ M. b Guests used: Bu₄NCl.

conformation in the solid state. There are two thiacalixarenes, one water molecule and three chloroform molecules in the asymmetric unit. Interestingly, it was found that two urea groups approach each other and are oriented in parallel due to the existence of dual intramolecular hydrogen bonding (in case of receptor 4_e, for the molecule shown: N(14)–H(14)⋯O(21) 2.37(2); N(15)–H(15)⋯O(21) 2.05(2) Å; for the second molecule: N(2)–H(2)⋯O(10) 2.37, N(3)–H(3)⋯O(10) 1.94(2) Å) (Fig. 1 and S16†). Moreover, the thiacalix[4]-arene-monocrown-5 has a three-dimensional cavity and is large enough to accommodate the metal cation. The association constants (K_a values) between the receptors 4_a–e and Cl⁻ ion were determined by ¹H NMR spectroscopic titration experiments (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1). These results suggest that the association constants depend on the electron-donating/withdrawing groups (Table 1).

with the electron-withdrawing CF₃ group at the p-position was greater than that of receptor 4_d with the electron-withdrawing CF₃ group at the m-position. This result indicates that electron-withdrawing groups located at the p-position can significantly influence the acidity of the urea protons by conjugating with the phenyl groups. From the above, it is clear that receptor 4_e with the electron-withdrawing NO₂ group at the p-position has the most effective recognition ability toward selected anions. Given this, further complexation studies of receptor 4_e (2.5 μM) exhibits an absorption band at 310 nm in the UV spectrum in the absence of anions. Upon addition of Cl⁻ ion (0–50 μM) to the solution of receptor 4_e, Fig. 2 reveals a gradual decrease in the absorption of the band at 310 nm with a simultaneous increase in the absorption at 340 nm. Meanwhile, a clear isosbestic point was observed at 322 nm for the receptor 4_e. A Job’s plot binding between the receptor 4_e and Cl⁻ ion reveals a 1 : 1 stoichiometry (Fig. S25†), whilst the association constant (K_a value) for the complexation with Cl⁻ ion by receptor 4_e was determined to be 34 152 M⁻¹ by UV-vis titration experiments in CHCl₃–DMSO (10 : 1, v/v) (Fig. S24, S27–S31†). Moreover, the concentration dependence of the ¹H NMR chemical shifts of the ureido protons in receptor 4_e was not observed (Fig. S23†). This result suggests that receptor 4_e has a strong intramolecular hydrogen bond between the two ureas linking the p-nitrophenyl moieties. These results strongly suggested that Cl⁻ ion recognition by receptor 4_e was via a hydrogen-bonding interaction between the Cl⁻ ion and N–H protons as
shown in Fig. 3. Similarly, the UV-vis titration experiments of receptor 4e with other various anions besides Cl$^-$ ion were carried out, and the $K_a$ values are summarized in Table 2. As a result, it was found that receptor 4e exhibited high selectivity towards F$^-$ ion amongst all of the anions tested, and was capable of complexing with all of the anions tested, irrespective of their shape. Interestingly, the color of the receptor 4e solution changed from colorless to dark yellow upon addition of F$^-$ ion (5 equivalents), and this could be easily observed by the naked eye. Upon the addition of F$^-$ ions (0–50 μM) to the solution of the receptor 4e, the absorption peak at 342 nm gradually moved to a longer wavelength, finally reaching a maximum value at 360 nm (Fig. 4 and S26†). This result suggests that the quinoid structure was formed by the deprotonation of urea NH groups in the p-nitrophenyl ureido moiety. Moreover, the addition of F$^-$, AcO$^-$, PhCOO$^-$ or H$_2$PO$_4^-$ (1 equivalent) to solutions of receptor 4e in CHCl$_3$–DMSO (10 : 1, v/v) during the $^1$H NMR titration experiments resulted in the disappearance of the urea proton signals, NH$_a$ and NH$_b$ (Fig. 5). These results indicate that strong interactions between these anions and the urea NH groups in the receptor 4e occur and that the kinetics of these anion exchanges is on the NMR time scale. On the other hand, $^1$H NMR spectroscopic and UV-vis titration experiments of receptor 4e with K$^+$ ion at the crown-ether moiety were also carried out (Fig. S32 and S33†). When only K$^+$ ion (1 equivalent) were added, not only the downfield shi of the crown-ether bridge protons was observed, but also all the NH protons in $^1$H NMR titration experiments (Fig. 6b and 7b). It was found that a Job’s plot binding between

![Graph](image_url)

**Fig. 4** UV-vis absorption spectra of receptor 4e (2.5 μM) upon the addition of Bu$_4$NF (0–50 μM) in CH$_2$Cl$_2$–DMSO (10 : 1, v/v).

**Fig. 5** Partial $^1$H NMR spectra of receptor 4e/guest (H/G = 1 : 1); free receptor 4e and in the presence of 1 equiv. of Bu$_4$NX (X = F, Cl, Br, I, AcO, PhCOO, H$_2$PO$_4$). Host concentration was 2.5 μM. Solvent: CDCl$_3$–DMSO (10 : 1, v/v). 300 MHz at 298 K. *Denotes the solvent peak.

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### Table 2 Association constants of receptor 4e with various anions$^{a,b}$

<table>
<thead>
<tr>
<th>Anion</th>
<th>F$^-$</th>
<th>Cl$^-$</th>
<th>Br$^-$</th>
<th>I$^-$</th>
<th>AcO$^-$</th>
<th>PhCOO$^-$</th>
<th>H$_2$PO$_4^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Spherical</td>
<td>Spherical</td>
<td>Spherical</td>
<td>Y-shape</td>
<td>Y-shape</td>
<td>Tetrahedral</td>
<td></td>
</tr>
<tr>
<td>$K_a$ [M$^{-1}$]</td>
<td>128 775 $\pm$ 10 302</td>
<td>34 152 $\pm$ 27 32</td>
<td>7 396 $\pm$ 58 4</td>
<td>4 540 $\pm$ 36 3</td>
<td>1 07 298 $\pm$ 8 58 4</td>
<td>1 06 743 $\pm$ 8 53 9</td>
<td>108 687 $\pm$ 8 69 5</td>
</tr>
</tbody>
</table>

*a* Measured in CH$_3$Cl$_2$–DMSO (10 : 1, v/v) at 298 K by UV-vis titration method (Fig. 2, 4, S24 and S27–S31); host concentration was 2.5 μM. *b* Guests used: tetrabutylammonium salt.
receptor $4_e$ and K$^+$ ion exhibited a 1 : 1 stoichiometry and that the $K$ value for the complexation with K$^+$ ion was determined to be 28.536 ($\pm$1998) M$^{-1}$ by UV-vis titration experiments in CH$_2$Cl$_2$-DMSO (10 : 1, v/v) [Fig. S34 and S35]. These results suggest that the crown-5 ring of receptor $4_e$ binds K$^+$ ion. To seek more detailed information about the presence of an effective positive or negative allosteric effect between receptor $4_e$, K$^+$ and Br$^-$ or Cl$^-$ ions, $^1$H NMR spectroscopic and UV-vis titration experiments in CHCl$_3$-DMSO (10 : 1, v/v) [Fig. S36] were carried. Fig. 6 reveals that when Br$^-$ ion were added to the solution of $[4_e\supset$KSO$_2$CF$_3$] (Fig. 6c), the addition induces a downfield shift of 0.42 ppm ($\delta$ = 9.09 to 9.51 ppm) for the NH$_4$ protons, and upfield shifts of 0.85 ppm ($\delta$ = 8.95 to 8.10 ppm) for the NH$_3$ protons and of 0.29 ppm ($\delta$ = 8.10 to 7.81 ppm) for the NH$_4$ protons, while the chemical shifts for the crown-ether bridge protons did not change. These results suggested the formation of a heteroditopic dinuclear complex of the type Br$^-\subset[4_e\supset$K$^+$] (Fig. 6c), and we propose a positive allosteric effect of receptor $4_e$ towards Br$^-$ ions in the presence of K$^+$ ion by an ion-pair electrostatic interaction and a conformational change of the flexible thiacalix[4]arene cavity. This induces the decomplexation of the K$^+$ ion from the crown-5 ring of receptor $4_e$ because the Cl$^-$ ion has a smaller ionic radius and therefore an increase in basicity in comparison with the Br$^-$ ion, and a negative allosteric effect of receptor $4_e$ to Cl$^-$ ion in the presence of K$^+$ ion as shown in Fig. 7 is proposed.

**Conclusion**

In summary, a new family of heteroditopic receptors ($4_a$–$e$) based on a thiacalix[4]arene in the 1,3-alternate conformation, which has two urea moieties bearing various phenyl groups substituted with either electron-donating or -withdrawing groups at their $m$-, or $p$-positions, as well as a crown-ether moiety at the opposite side of thiacalix[4]arene cavity, has been synthesized. By using $^1$H NMR spectroscopic and UV-vis titration experiments, receptor $4_e$ possessing an electron-withdrawing NO$_2$ group at the $p$-position has the most effective recognition ability towards the selected anions. The binding of K$^+$ ions and various anions at the crown-5 ring moiety and the two urea NH groups in two p-nitrophenyl ureido moieties, respectively, was investigated. The results indicated the complexation mode, and it was found that receptor $4_e$ was able to bind all of the anions tested, irrespective of their shape. Receptor $4_e$ exhibited highest selectivity towards F$^-$ ion amongst all of the anions tested and indicated that this receptor might be a promising candidate as a colorimetric chemosensor. The appearance of positive and negative allosteric effects in receptor $4_e$ was also investigated by $^1$H NMR and UV-vis titration experiments. Interestingly, the formation of a heteroditopic dinuclear complex of receptor $4_e$ with Br$^-$ and K$^+$ ions by a positive allosteric effect could be observed. On the other hand, the fact that two urea NH groups in two p-nitrophenyl ureido moieties of receptor $4_e$ bind the Cl$^-$ ion, which then induces the decomplexation of the K$^+$ ion from the crown-5 ring, is indicative of a negative allosteric effect.

**Experimental section**

**General**

All melting points were determined with Yanagimoto MP-S1. $^1$H-NMR spectra were determined at 300 MHz with a Nippon Denshi JEOL FT-300 NMR spectrometer with SiMe$_4$ as an internal reference; $J$-values are given in Hz. UV spectra were measured by a Shimadzu 240 spectrophotometer. Mass spectra were obtained on a Nippon Denshi JMS-01SG-2 mass spectrometer at an ionization energy of 70 eV using a direct inlet system through GLC. Elemental analyses were performed by Yanaco MT-5.

**Materials**

Unless otherwise stated, all other reagents used were purchased from commercial sources and used without further purification.
Compounds 1\textsuperscript{a} and 2\textsuperscript{a} were prepared following the reported procedures.

**Synthesis of compound 3**

Compound 2 (1.0 g, 0.95 mmol) was put into a round-bottom flask and ethanol (120 mL), THF (120 mL) and hydrazine hydrate (14 mL, large excess) were added and refluxed for 48 h. After cooling, the solvents and excess hydrazine were removed under reduced pressure to give the crude product as a white solid. The residue was triturated sequentially with water and methanol and the product collected by filtration. Compound 3 was obtained 0.84 g (86%) as a white solid. M.p. 216–218 °C. IR: \( \nu_{\text{max}} \) (KBr)/cm\(^{-1}\): 3421, 2961, 1670, 1438, 1263, 1091, 1019 and 801. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \( \delta \) = 1.25 (18H, s, tBu \times 2), 1.37 (18H, s, tBu \times 2), 3.00 (4H, \( tJ = 9.1\) Hz, OCH\(_2\times 2\)), 3.40 (4H, br, OCH\(_2\times 2\)), 3.48 (4H, br, NH\(_2\times 2\)), 3.60 (4H, broad s, OCH\(_2\times 2\)), 3.96 (4H, \( tJ = 9.1\) Hz, OCH\(_2\times 2\)), 4.55 (4H, s, OCH\(_2\)CO\(_2\)), 7.35 (4H, s, Ar-H \times 2), 7.41 (4H, s, Ar-H \times 2) and 7.54 (2H, s, NH \times 2) ppm. \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \( \delta \) = 30.5 (CH\(_3\)), 33.5 (C(CH\(_3\))\(_3\)), 64.9 (OCH\(_3\)), 67.4 (OCH\(_2\)), 69.2 (OCH\(_2\)), 70.5 (OCH\(_2\)), 72.6 (OCH\(_2\)), 126.2 (ArC), 126.4 (ArC), 126.5 (ArC), 126.7 (ArC), 145.6 (ArC), 146.7 (ArC), 153.6 (ArC), 154.4 (ArC) and 167.6 (CO) ppm. FABMS: \( m/z \): 1023.28 (M\(^+\)). C\(_{68}\)H\(_{78}\)F\(_6\)N\(_6\)O\(_{11}\)S\(_4\) (1289.69): calculated C 62.53, H 6.56, N 6.25.

**Synthesis of receptor 4\textsubscript{a}**

To compound 3 (150 mg, 0.147 mmol) in THF (10 mL), was added phenyl isocyanate (38 mg, 0.320 mmol) and the mixture was stirred at room temperature for 24 h. The resulting precipitate was collected by filtration, washed with hexane to give receptor 4\textsubscript{a} as a white solid. Recrystallization from CHCl\(_3\)-CH\(_2\)CN (2:1) gave receptor 4\textsubscript{d} (163 mg, 86%) as white solid. m.p. 205–207 °C. IR: \( \nu_{\text{max}} \) (KBr)/cm\(^{-1}\): 3283, 2959, 1678, 1547, 1444, 1266, 1207, 1151, 1089, 999 and 815. \(^1\)H NMR (300 MHz, CDCl\(_3\)-DMSO, 10:1): \( \delta \) = 1.27 (18H, s, tBu \times 2), 1.39 (18H, s, tBu \times 2), 2.28 (6H, s, CH\(_2\times 2\)), 2.97 (4H, \( tJ = 9.1\) Hz, OCH\(_2\times 2\)), 3.40 (4H, br, OCH\(_2\times 2\)), 3.63 (4H, s, OCH\(_2\))\(_2\)), 3.85 (4H, \( tJ = 9.1\) Hz, OCH\(_2\times 2\)), 4.58 (4H, s, OCH\(_2\)CO\(_2\)), 6.96 (4H, \( dJ = 7.7\), phenyl-H \times 4), 7.16 (4H, \( dJ = 7.7\), phenyl-H \times 4), 7.35 (4H, s, Ar-H \times 4), 7.48 (4H, s, Ar-H \times 4), 7.51 (2H, s, NH \times 2), 8.10 (2H, s, NH \times 2), 8.22 (2H, s, NH \times 2) ppm. \(^{13}\)C NMR (100 MHz, CDCl\(_3\)-DMSO, 10:1): \( \delta \) = 20.7 (CH\(_3\)), 30.9 (CH\(_3\)), 31.4 (CH\(_3\)), 34.4 (C(CH\(_3\))\(_3\)), 34.5 (C(CH\(_3\))\(_2\)), 65.9 (OCH\(_3\)), 68.6 (OCH\(_2\)), 70.0 (OCH\(_2\)), 71.6 (OCH\(_3\)), 73.6 (OCH\(_3\)), 119.4 (ArC), 126.6 (ArC), 127.0 (ArC), 127.3 (ArC), 128.2 (ArC), 129.0 (ArC), 129.5 (ArC), 131.9 (ArC), 135.7 (ArC), 136.1 (ArC), 147.4 (ArC), 148.5 (ArC), 154.4 (ArC), 154.8 (ArC), 155.1 (CO), 155.5 (ArC) and 168.5 (CO) ppm. FABMS: \( m/z \): 1289.46 (M\(^+\)). C\(_{68}\)H\(_{64}\)N\(_6\)O\(_{11}\)S\(_4\) (1289.69): calculated C 63.33, H 6.56, N 6.52.

**Synthesis of receptor 4\textsubscript{b}**

To compound 3 (150 mg, 0.147 mmol) in THF (10 mL), was added p-trifluoromethylphenyl isocyanate (59 mg, 0.320 mmol) and the mixture was stirred for at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with EtOH to give receptor 4\textsubscript{b} as a white solid. Recrystallization from CHCl\(_3\)-CH\(_2\)CN (1:1) gave receptor 4\textsubscript{d} (187 mg, 83%) as white solid. M.p. 208–210 °C. IR: \( \nu_{\text{max}} \) (KBr)/cm\(^{-1}\): 3315, 2963, 1677, 1577, 1443, 1215, 1136, 1092, 1019 and 880. \(^1\)H NMR (300 MHz, CDCl\(_3\)-DMSO, 10:1): \( \delta \) = 1.32.
The association constants were determined by using 1H NMR spectroscopic titration experiments in a constant concentration of 4a. The 1H NMR spectra were recorded after addition of the reactants and the temperature of the NMR probe was kept constant at 27 °C. The 1H NMR spectroscopic data of representative complexes are given below:

**Receptor 4a ⊙ Cl**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 2.97 (4H, br, OCH2O × 2), 3.40 (4H, br, OCH2O × 2), 3.63 (4H, br, OCH2O × 2), 3.85 (4H, br, OCH2O × 2), 4.59 (4H, s, OCH2O × 2), 7.89 (2H, br, NH2 × 2), 8.10 (2H, br, NH2 × 2) and 8.95 (2H, br, NH2 × 2) ppm.

**Receptor 4b ⊙ Cl**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 2.97 (4H, br, OCH2O × 2), 3.40 (4H, br, OCH2O × 2), 3.63 (4H, br, OCH2O × 2), 3.85 (4H, br, OCH2O × 2), 4.68 (4H, s, OCH2O × 2), 7.80 (2H, br, NH2 × 2), 8.09 (2H, br, NH2 × 2) and 8.63 (2H, br, NH2 × 2) ppm.

**Receptor 4c ⊙ Cl**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 2.97 (4H, br, OCH2O × 2), 3.40 (4H, br, OCH2O × 2), 3.63 (4H, br, OCH2O × 2), 3.85 (4H, br, OCH2O × 2), 4.60 (4H, s, OCH2O × 2), 8.10 (2H, br, NH2 × 2), 8.18 (2H, br, NH2 × 2) and 10.8 (2H, br, NH2 × 2) ppm.

**Receptor 4d ⊙ K**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 3.11 (4H, br, OCH2O × 2), 3.36–3.58 (4H, m, OCH2O × 2), 3.64–3.90 (4H, m, OCH2O × 2), 4.08 (4H, br, OCH2O × 2), 4.30–4.61 (4H, m, OCH2O × 2), 8.10 (2H, s, NH2 × 2), 8.95 (2H, broad s, NH2 × 2) ppm.

**Cl ⊙ [receptor 4e ⊙ K]**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 2.97 (4H, br, OCH2O × 2), 3.40 (4H, br, OCH2O × 2), 3.63 (4H, br, OCH2O × 2), 3.85 (4H, br, OCH2O × 2), 4.60 (4H, s, OCH2O × 2), 8.14 (2H, br, NH2 × 2), 8.58 (2H, br, NH2 × 2) and 10.2 (2H, br, NH2 × 2) ppm.

**Receptor 4e ⊙ Br**. 1H NMR (300 MHz, CHCl3–DMSO–D2O, 10 : 1, v/v): δ = 3.11 (4H, br, OCH2O × 2), 3.36–3.58 (4H, m, OCH2O × 2), 3.64–3.90 (4H, m, OCH2O × 2), 4.08 (4H, br, OCH2O × 2), 4.30–4.61 (4H, m, OCH2O × 2), 7.81 (2H, br, NH2 × 2), 8.10 (2H, br, NH2 × 2) and 9.51 (2H, br, NH2 × 2) ppm.

**Crystallographic analysis of receptors 4d and 4e**

Crystal data for 4e, $\text{Cs}_8\text{H}_{18}\text{N}_3\text{O}_{15}\text{S}_4\cdot\frac{1}{2}(\text{H}_2\text{O})\cdot\frac{1}{2}(\text{CHCl})$, $M_r = 1477.71$. Monoclinic, $P2_1/n$; a = 18.8935 (13), b = 23.9302 (16), c = 33.589 (2) Å; $\beta = 91.5063 (12)°$; $V = 15181.2 (17)$ Å$^3$; $Z = 8$; $D_x = 1.293$ Mg m$^{-3}$; $F(000) = 6224$; $T = 210(2)$ K; $\mu (\text{Mo-Kx}) = 0.34$ mm$^{-1}$; $\lambda = 0.71073$ Å, crystal size 0.71 × 0.54 × 0.32 mm$^3$.

Crystals were colorless blocks. Diffraction data were measured on a Bruker APEX 2 CCD diffractometer equipped with graphite monochromated Mo Kα radiation.
monochromated MoKα radiation by thin-slice ω-scans.13 134 900 measured reflections, 31 218 independent reflections (Rint = 0.049) to θmax = 26.5°; 19 539 reflections with I > 2σ(I).

The structure was determined by direct methods using the SHELX program and refined by the full-matrix least-squares method, on F2, in SHELXL-2013/14.14,15 The non-hydrogen atoms were refined with anisotropic thermal parameters. Hydrogen atoms on C and some N atoms were included in idealized positions and their Uiso values were set to ride on the Ueq values of the parent atoms. H atoms on N were freely refined. At the conclusion of the refinement, wR2 = 0.173 (all data) and R1 = 0.056 (observed data), 1903 parameters, Δmax = 0.56 e Å⁻³; 465 restraints, Δmin = −0.43 e Å⁻³. The platon squeeze procedure was used to model two of the three unique CHCl3 molecules due to severe disorder.16 Two-fold disorder was modelled in some tBu groups, in parts of one of the crown ether chains and the other CHCl3 molecule. H atoms on water molecule O(23) could not be located in difference maps, so were not included in the model.† Crystal data for 4c. C42H46N6O15S2·½(CHCl3)·3(MeCN), Mr = 1534.44. Monoclinic, P21/c, a = 17.7980 (10), b = 26.7870 (16), c = 32.552 (2) Å; β = 96.384 (4)°; V = 15 423.1 (16) Å³; Z = 8; Dc = 1.322 Mg m⁻³; F(000) = 6472; T = 100 (2) K; μ(Mo-Kα) = 0.31 mm⁻¹; λ = 0.7749 Å, crystal size 0.25 × 0.25 × 0.02 mm². Crystals were colorless plates. Diffraction data were measured on a Bruker APEX 2 CCD diffractometer at station 11.3.1 of the ALS using synchrotron radiation by thin-slice ω-scans.15 155 885 measured reflections, 50 956 independent reflections (Rint = 0.052) to θmax = 34.8°; 35 702 reflections with I > 2σ(I). Structure solution with SHELXT and refinement as above.16,17 Hydrogen atoms on C and some N atoms were included in idealized positions and their Uiso values were set to ride on the Ueq values of the parent atoms. H atoms on the remaining N atoms were freely refined. At the conclusion of the refinement, wR2 = 0.294 (all data) and R1 = 0.086 (observed data), 2055 parameters, Δmax = 2.44 e Å⁻³; 656 restraints, Δmin = −1.86 e Å⁻³. The platon squeeze procedure was used to model four of the six unique MeCN molecules due to severe disorder.18 Two-fold disorder was modelled in some tBu groups and in parts of one the crown ether chains and one HN-p-C6H4NO2 group.†

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Notes and references


