PERKIN 1

Synthesis of novel Hg^{2+} receptors based on *N*-benzyloxyamide derivatives and their application to anion-selective electrodes †

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Received (in Cambridge, UK) 8th November 2000, Accepted 10th April 2001
First published as an Advance Article on the web 23rd May 2001

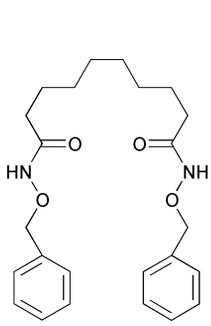
Novel Hg^{2+} receptors having two *N*-benzyloxyamide groups are synthesized, and their complexation ability toward metal cations is examined. The structure of the formed complexes was elucidated by ESI-MS and ^{1}H NMR spectroscopy. Deprotonation of the amide groups allows the receptors to form stable complexes with Hg^{2+}. As an application of this neutral Hg^{2+} complex, an anion-selective electrode combined with a cationic additive is prepared, and exhibits an anti-Hofmeister selectivity pattern with enhanced selectivity for the iodide anion. The overall selectivity pattern of the electrode is $I^- > ClO_4^- > SCN^- \approx Br^- >$ salicylate$^- > NO_2^- > Cl^- > NO_3^- \gg HCO_3^- > SO_4^{2-} > F^- > H_2PO_4^-$.

Introduction

The design and synthesis of new receptor molecules for the selective complexation of ions have attracted much attention because of their possible application to ion-selective electrodes (ISEs) or optodes.[1] So far, many synthetic receptors, mainly represented by crown ethers, have been developed for the purpose of recognizing biologically important cations such as alkali or alkaline earth metal ions,[2] and they have been used as ionophores for ISEs applied to clinical analysis. Receptors for transition metal ions, however, are relatively rare in spite of their importance for environmental monitoring.

In this respect, we recently reported that *N*-benzyloxyamide derivative **1** selectively forms complexes with Hg^{2+} and that it is a useful ionophore for ISEs to detect Hg^{2+} with good reproducibility.[3] Most ISEs based on heavy-metal ionophores developed to date generally demonstrate silver ion selectivity rather than that for other cations. However, the electrode based on ionophore **1** having two *N*-benzyloxyamide groups exhibited remarkably high selectivity for Hg^{2+}. In order to further investigate the nature of this functional group in detail, we synthesized the new *N*-benzyloxyamide derivatives **2a** and **2b** and examined the structures of their complexes using ESI-MS and ^{1}H NMR spectroscopy. As a result, it was found that **2a** and **2b** form stable complexes accompanied by deprotonation of the amide groups only when Hg^{2+} was added. This is one of the rare examples of a receptor which can form a neutral complex with a metal cation.

Transition metals are known to play an important role in the development of anion receptors;[4] therefore, we included anions in our complexation study aiming at a new type of halide ionophore. For example, chloride anion is one of the most important analytes in biological samples, and the development of chloride-selective electrodes is of current interest. Because traditional ISEs based on quaternary ammonium salts follow the well-known Hofmeister series (the order of the free energy of hydration of the analyte anions), several ionophores containing metals such as Mn,[5] Co,[6] Ag,[7] In,[8] or Hg[9,10] have been examined as halide-selective ionophores. Among them, the use of the Lewis acidity of the mercury atom is known to be effective for the detection of chloride anion, and organic mercury compounds[9] as well as inorganic mercury complexes[10] have been reported to be excellent halide ionophores. Thus, we decided to investigate the application of the stable Hg^{2+}–**2b** complex to an anion-selective electrode. It turned out that this electrode is promising as a chloride-selective electrode, because the response to major interfering anions like SCN^-, salicylate$^-$, or HCO_3^- was limited.



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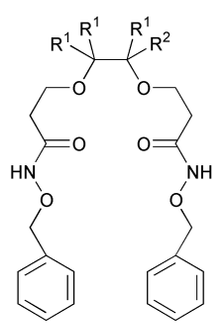

2a $R^1 = R^2 = CH_3$
2b $R^1 = H$, $R^2 = n\text{-}C_{14}H_{29}$

In this paper, we report that the mercury complexes of *N*-benzyloxyamide derivatives are not only interesting from a structual point of view but also are contributive to the development of new anion ionophores.

† Electronic supplementary information (ESI) available: MS of receptors **1** and **2a** with metal cations. See http://www.rsc.org/suppdata/p1/b0/b008978h/

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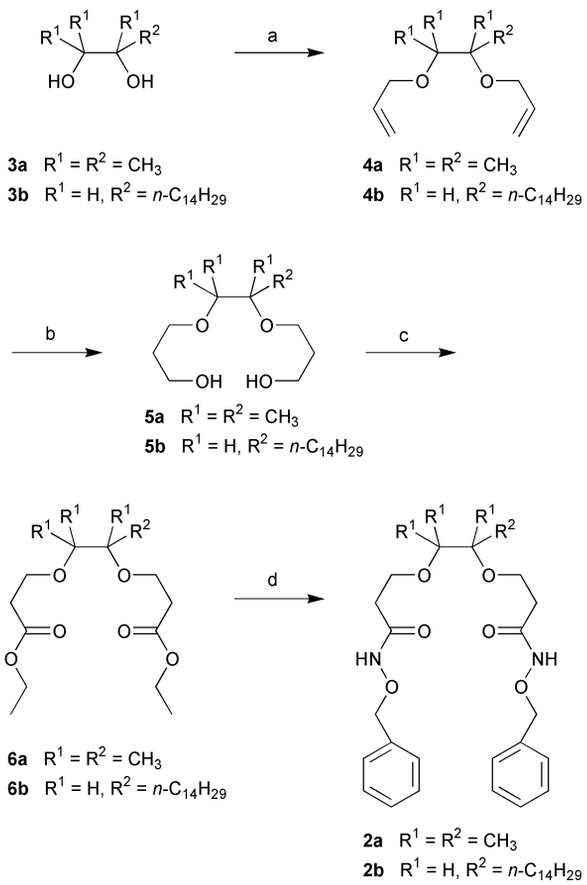
 DOI: 10.1039/b008978h

Results and discussion

Synthesis of receptors 2a and 2b

N-Benzyloxyamide derivatives **2a** and **2b**, which have additional oxygen atoms and alkyl groups compared with receptor **1**, were prepared from pinacol **3a** and hexadecane-1,2-diol **3b**, respectively (Scheme 1). The Williamson reaction between **3a** and



Scheme 1 *Reagents and conditions*: (a) NaH, allyl bromide, THF, reflux (**4a**: 89%; **4b**: 82%); (b) (i) $NaBH_4$, $BF_3{\cdot}Et_2O$, THF, 0 °C; (ii) 3 mol dm^{-3} aq. NaOH, 30% H_2O_2, rt (**5a**: 47%; **5b**: 24%); (c) (i) $NaIO_4$, $RuCl_3{\cdot}H_2O$, CCl_4–CH_3CN–water, rt; (ii) TsOH, molecular sieves 3 Å, benzene–EtOH, reflux (**6a**: 50%; **6b**: 52%); (d) (i) KOH, EtOH–water, rt; (ii) $SOCl_2$, CH_2Cl_2, rt; (iii) *O*-benzylhydroxylamine, pyridine, rt (**2a**: 24%; **2b**: 57%).

allyl bromide gave diene **4a**, which was converted to diol **5a** by hydroboration in 42% yield. Oxidation of **5a** to the corresponding dicarboxylic acid followed by esterification for purification gave diester **6a** in 50% yield. Hydrolysis of **6a** and subsequent treatment with thionyl dichloride gave an acid chloride, which was treated with *O*-benzylhydroxylamine to give receptor **2a** in 24% yield. Using essentially the same procedure, receptor **2b** was synthesized from **3b** *via* diene **4b**, diol **5b**, and diester **6b** in 6% overall yield in seven steps.

Complexation ability of receptor 2a with Hg^{2+}

In order to confirm the complexation ability of receptor **2a** with metal cations, ESI-MS measurements were undertaken for a mixture of **2a** in Pr^iOH and several cation salts in MeOH. Fig. 1 shows the spectrum of the mixture of **2a** and $AgNO_3$. In this case, the molecular-ion peak of the complex between **2a** and Ag^+, namely $[M + Ag]^+$, was observed at $m/z = 579$ together with the sodium complex peak $[M + Na]^+$ ($m/z = 495$). When the spectra of **2a** were measured in the presence of $Ca(NO_3)_2{\cdot}4H_2O$ or $Ca(AcO)_2{\cdot}H_2O$, both $[M + Ca]^{2+}$ ($m/z = 256$) and $[M + Na]^+$ peaks were observed (data not shown). On

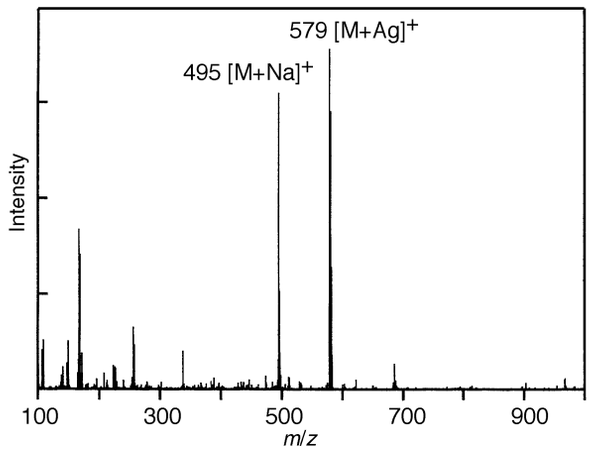


Fig. 1 MS spectrum of receptor **2a** with Ag^+. The sample solution is a mixture of **2a** (2.7 mmol dm^{-3}) in Pr^iOH and $AgNO_3$ (2.7 mmol dm^{-3}) in MeOH in the volumetric ratio of 1 : 2.

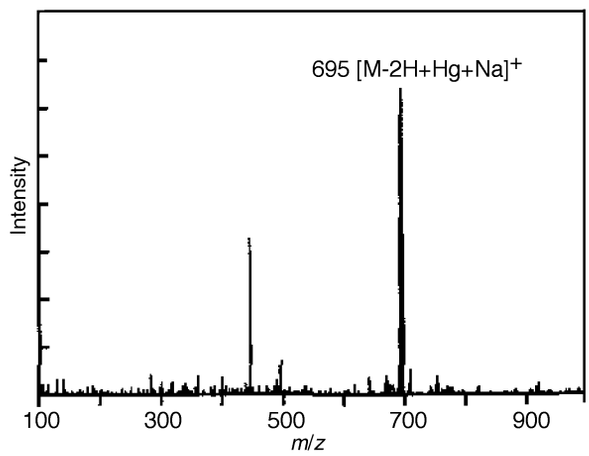


Fig. 2 MS spectrum of receptor **2a** with Hg^{2+}. The sample solution is a mixture of **2a** (2.7 mmol dm^{-3}) in Pr^iOH, $NaNO_3$ (1.1 mmol dm^{-3}) in MeOH, and $Hg(AcO)_2$ (2.7 mmol dm^{-3}) in MeOH in the volumetric proportions of 5 : 5 : 2.

the other hand, the spectrum of **2a** measured with $Hg(AcO)_2$ exhibited a strong $[M - 2H + Hg + Na]^+$ peak at $m/z = 695$ as shown in Fig. 2, but the molecular-ion peak of the charged mercury complex $[M + Hg]^{2+}$ ($m/z = 337$) was not observed. These results indicate that the formation of the Hg^{2+}–**2a** complex is accompanied by deprotonation of the receptor molecule. This behavior is also coincident with the super-Nernstian response obtained for the ISE based on ionophore **1**,[3] which can be explained by the proton response caused by deprotonation of the ionophore upon Hg^{2+} binding. Furthermore, it was found that the intensity of the Hg^{2+}–**2a** complex peak $[M - 2H + Hg + Na]^+$ was much stronger than that of the Hg^{2+}–**1** complex $[M - 2H + Hg + Na]^+$ measured under the same conditions, which is probably due to the increased binding strength caused by the additional two oxygen atoms of receptor **2a**.

^1H NMR measurements were performed in order to obtain information about the Hg^{2+}–**2a** complex in solution. Because of the limited solubility of $Hg(AcO)_2$, a mixed solvent $CDCl_3$–$(CD_3)_2SO$ (14 : 1) was used. Fig. 3 shows the ^1H NMR spectra of **2a** measured with the sequential addition of $Hg(AcO)_2$. In the presence of up to 1 eq. of $Hg(AcO)_2$, the spectra exhibited signals due to both the free receptor and the complex, indicating that the equilibrium of complexation is slow on the NMR time-scale. For example, the peak of the benzyl protons at δ 4.87 decreased followed by an increase in a new peak at

δ 4.80. As shown in Fig. 3(e), the signals of **2a** have completely disappeared with the addition of just 1 eq. of $Hg(AcO)_2$. This result shows that the binding constant of **2a** with Hg^{2+} is considerably large. In addition, it became apparent that a 1 : 1 complex is formed between **2a** and Hg^{2+}, because the addition of more than 1 eq. of $Hg(AcO)_2$ did not cause any change in the spectrum (not shown). Moreover, with the signal decrease for the NH proton at δ 9.95, no corresponding new peak of the complex was found. This observation also suggests that the complex formation of **2a** with Hg^{2+} is accompanied by elimination of two amide protons from the receptor.

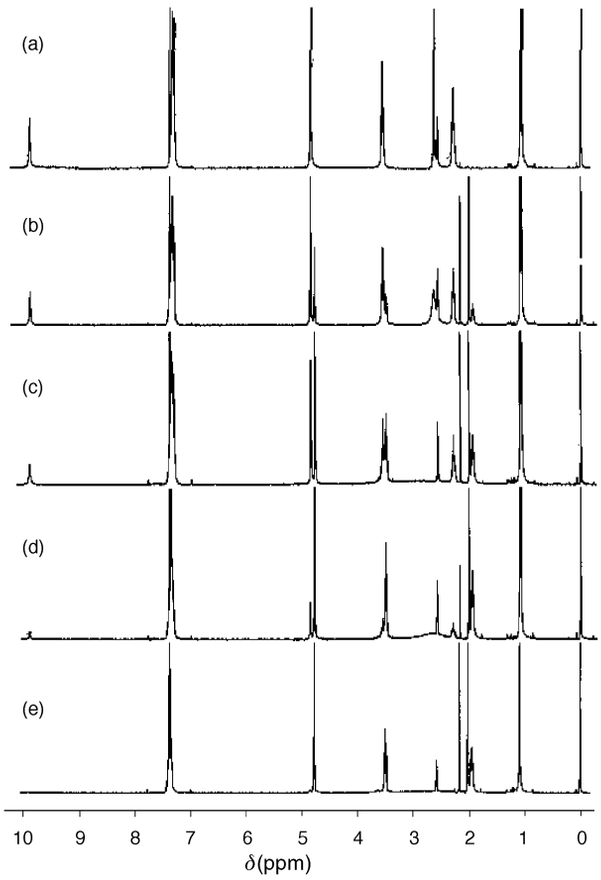


Fig. 3 ^{1}H NMR spectra [$CDCl_3$–$(CD_3)_2SO$, 14 : 1] of (a) receptor **2a**, (b) **2a** with 0.2 eq. $Hg(AcO)_2$, (c) **2a** with 0.5 eq. $Hg(AcO)_2$, (d) **2a** with 0.75 eq. $Hg(AcO)_2$, and (e) **2a** with 1 eq. $Hg(AcO)_2$.

Anion-selective electrode based on the Hg^{2+}–2b complex

Because the Hg^{2+}–**2a** complex was found to be stable in solution, the application of the complex to an ISE as an anion ionophore was examined. In order to increase the lipophilicity of the ionophore to prevent leaching from the ISE membrane, the Hg^{2+}–**2b** complex having a long alkyl chain was used for the ISE measurements. The selectivity coefficients of the electrodes based on the Hg^{2+}–**2b** complex are shown in Fig. 4. Without the cationic additive [tridodecyl(methyl)ammonium chloride, TDDMACl], the electrode based on the complex showed almost no response to anions except for iodide. This behavior is similar to that observed for organic mercury compounds[9] rather than that for inorganic mercury complexes,[10] suggesting that the deprotonated Hg^{2+}–**2b** complex is essentially an electrically neutral species as illustrated in Fig. 5. Therefore, the amount of the cationic additive was optimized until the best result was found at 10 mol% of TDDMACl relative to the ionophore. When more than 10 mol% of the cationic additive was added, the selectivity of the electrode gradually approached that of the Hofmeister series (TDDMACl; Fig. 4, column 1). The electrode based on the Hg^{2+}–**2b** complex combined with 10 mol% TDDMACl exhibited a strong preference for the iodide anion, similar to those of organic mercury compounds,[9] but with a non-linear response. At the same time, it should be noted that the selectivity for the biologically important chloride anion is also excellent, so that this electrode can be regarded as an example of a chloride-selective electrode. The electrode showed a Nernstian response to chloride in the linear range from 10^{-4} to 10^{-1} mol dm^{-3} with a slope of

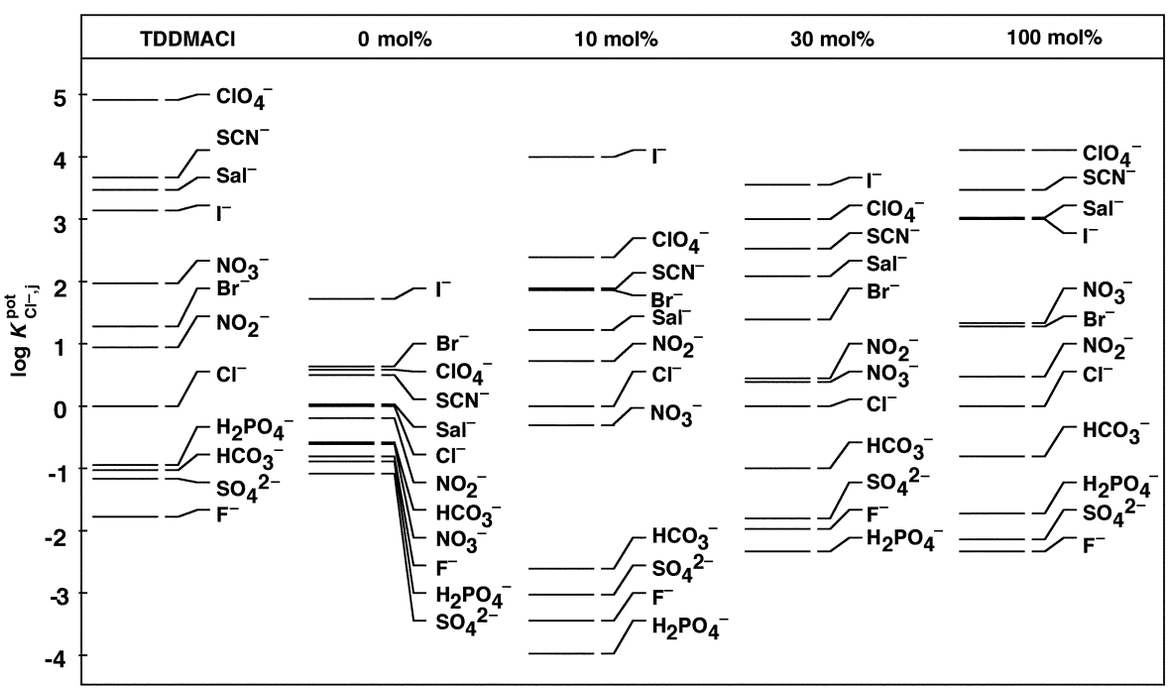


Fig. 4 Potentiometric selectivity coefficients (log $K_{Cl^-,j}^{pot}$, j = interfering ion) of the electrodes based on the Hg^{2+}–**2b** complex with different concentrations of tridodecyl(methyl)ammonium chloride (TDDMACl). The membrane compositions were 3% (by weight) ionophore, 64% membrane solvent *o*-nitrophenyl octyl ether (*o*-NPOE), 33% poly(vinyl chloride) (PVC), and 0–100 mol% (relative to the ionophore) TDDMACl. The measurements were carried out at 25.0 ± 0.5 °C.

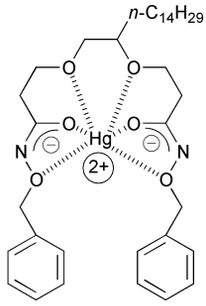


Fig. 5 Proposed structure of the Hg^{2+}–**2b** complex.

−55 mV/decade. The detection limit was calculated to be 5.0×10^{-5} mol dm^{-3}. Although the interference of Br^- is still high, the response to major interfering anions like SCN^-, salicylate$^-$, or HCO_3^- was relatively limited (log $K_{Cl^-,j}$: SCN^-, +1.9; salicylate$^-$, +1.2; HCO_3^-, −2.6). The degree of response to these anions is comparable to that of the ISEs based on a neutral thiourea derivative, which was recently reported to be a chloride-selective ionophore.[11]

Conclusions

We have synthesized two *N*-benzyloxyamide derivatives and examined their novel Hg^{2+} complex structures caused by deprotonation of the amide groups. Moreover, the stable Hg^{2+} complex was applied to an ISE as an anion-selective ionophore. The ISE based on this electrically neutral complex combined with a cationic additive showed a selective response to halide anions, especially to the iodide anion. As a chloride-selective electrode, it was found that the effect of lipophilic anions like SCN^- and salicylate$^-$ but also of the more hydrophilic HCO_3^- could be considerably reduced compared with the conventional chloride electrode based on TDDMACl.

Experimental

^{1}H NMR spectra were recorded on a JEOL JNM-GSX270 (^{1}H, 270 MHz) or a JEOL JNM-LA300 (^{1}H, 300 MHz) spectrometer in $CDCl_3$. Coupling constants *J* are given in Hz and all chemical shifts are relative to an internal standard of tetramethylsilane. IR spectra were measured with a BIO-RAD FTS-60A instrument. Mps were determined on a BÜCHI B-545 apparatus and are uncorrected. All moisture-sensitive reactions were carried out under an atmosphere of nitrogen. All reagents were used as obtained from commercial suppliers. THF was distilled from benzophenone ketyl under nitrogen before use. All other solvents were purified according to standard procedures.

Preparation of receptors

5,5,6,6-Tetramethyl-4,7-dioxadeca-1,9-diene 4a. To a stirred solution of pinacol **3a** (10.0 g, 84.6 mmol) in THF (100 cm^3) was added NaH (8.12 g, 338 mmol) in small portions. The mixture was stirred at room temperature for 1 h, after which a solution of allyl bromide (41.0 g, 338 mmol) in THF (100 cm^3) was added. The reaction mixture was heated under reflux for 22 h, then MeOH was added to quench the reaction followed by addition of water. The mixture was extracted with EtOAc and the extract was dried over Na_2SO_4. The solvent was evaporated under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane–EtOAc, 6 : 1) to give the diene **4a** (12.2 g, 89%) as a yellow oil, ν_{max} (neat)/cm^{-1} 1648, 1361, 1157, 917; δ_H (270 MHz) 1.20 (12H, s, Me), 3.99 (4H, ddd, *J* 1.8, 1.8 and 5.0, OCH_2), 5.06 (2H, ddt, *J* 1.8, 1.8 and 10.4, CH=CH_2) and 5.25 (2H, ddt, *J* 1.8, 1.8 and 17.2, CH=CH_2), 5.91 (2H, ddt, *J* 1.8, 10.4 and 17.2, C*H*=CH_2).

5,5,6,6-Tetramethyl-4,7-dioxadecane-1,10-diol 5a. To a solution of $NaBH_4$ (6.56 g, 173 mmol) in THF (200 cm^3) was added a solution of diene **4a** (38.2 g, 193 mmol) in THF (200 cm^3). A solution of boron trifluoride–diethyl ether complex (32.8 g, 231 mmol) in THF (100 cm^3) was then added dropwise over a period of 1.5 h at 0 °C. The reaction mixture was stirred for 20 h, after which 3 mol dm^{-3} aq. NaOH was added followed by addition of 30% H_2O_2. The mixture was stirred for 2 h and extracted with EtOAc. The extract was dried over Na_2SO_4 and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (hexane–EtOAc, 1 : 4) to give the diol **5a** (21.3 g, 47%) as a colorless oil, ν_{max} (neat)/cm^{-1} 3392, 1363, 1154, 1072; δ_H (270 MHz) 1.17 (12H, s, Me), 1.76 (4H, quintet, *J* 5.6, $CH_2CH_2CH_2$), 3.51 (2H, br s, OH), 3.58 (4H, t, *J* 5.6, OCH_2CH_2), 3.74 (4H, br s, $HOCH_2CH_2$).

5,5,6,6-Tetramethyl-4,7-dioxasebacic acid diethyl ester 6a. To a solvent mixture (CCl_4, 100 cm^3; acetonitrile, 100 cm^3; water, 150 cm^3) were added diol **5a** (5.01 g, 24.2 mmol) and sodium periodate (31.1 g, 145 mmol). The mixture was vigorously stirred for 20 min, and ruthenium(III) chloride hydrate (22 mg, 0.10 mmol) was then added in the dark. After being stirred for 1 h, the mixture was extracted with CH_2Cl_2. The extract was dried over Na_2SO_4 and evaporated under reduced pressure to leave a green solid. Toluene-*p*-sulfonic acid monohydrate (569 mg, 3.0 mmol) and molecular sieves 3 Å (57 mg) were added to a solution of the above crude acid in benzene–EtOH (1 : 1; 80 cm^3). The mixture was heated under reflux for 24 h. After cooling of the mixture, water was added and the mixture was extracted with EtOAc. The extract was dried over Na_2SO_4 and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel (hexane–EtOAc, 4 : 1) to give the ester **6a** (3.88 g, 50% for two steps) as a colorless oil, ν_{max} (neat)/cm^{-1} 1740, 1186, 1151, 1064; δ_H (270 MHz) 1.12 (12H, s, Me), 1.25 (6H, t, *J* 7.1, OCH_2CH_3), 2.47 (4H, t, *J* 6.2, $COCH_2$), 3.66 (4H, t, *J* 6.2, $COCH_2CH_2$), 4.13 (4H, q, *J* 7.1, OCH_2CH_3).

***N*,*N*′-Bis(benzyloxy)-5,5,6,6-tetramethyl-4,7-dioxasebacic acid diamide 2a.** To a solution of KOH (2.54 g, 45 mmol) in EtOH–water (1 : 2, 80 cm^3) was added ester **6a** (2.00 g, 6.28 mmol), and the mixture was stirred for 12 h at room temperature. The mixture was then concentrated and the resulting dicarboxylic acid was dried under vacuum and dissolved in CH_2Cl_2 (5 cm^3) with one drop of DMF. To this solution was slowly added $SOCl_2$ (1.68 g, 14 mmol). After being stirred for 2 h, the mixture was filtered through a pad of Celite, and the filtrate was concentrated to leave a yellow oil (1.33 g). To a solution of *O*-benzylhydroxylamine hydrochloride (1.49 g, 9.3 mmol) in pyridine (20 cm^3) was added the above acid chloride at 0 °C, and the mixture was stirred for 2 h at room temperature. The mixture was acidified with dil. aq. HCl and extracted with $CHCl_3$. The extract was dried over Na_2SO_4 and evaporated under reduced pressure. The residue was purified by column chromatography on silica gel ($CHCl_3$–EtOAc, 1 : 2) to give the *receptor* **2a** (714 mg, 24% for three steps) as a white solid, mp 94–95 °C; ν_{max} (KBr)/cm^{-1} 3133, 1660, 699; δ_H (270 MHz) 1.04 (12H, s, Me), 2.30 (4H, br s, $COCH_2$), 3.51 (4H, t, *J* 5.3, $COCH_2CH_2$), 4.86 (4H, s, $PhCH_2$), 7.32–7.38 (10H, m, Ph), 9.23 (2H, s, NH) (Found: C, 66.03; H, 7.82; N, 5.93. Calc. for $C_{26}H_{36}N_2O_6$: C, 66.08; H, 7.68; N, 5.93%).

5-Tetradecyl-4,7-dioxadeca-1,9-diene 4b. The reaction of hexadecane-1,2-diol **3b** (10.0 g, 38.7 mmol) with allyl bromide (18.7 g, 155 mmol) using NaH (6.2 g, 155 mmol) was carried out as described for the preparation of **4a**. The reaction mixture was worked up as above, and subsequent purification by chromatography on silica gel (hexane–EtOAc, 24 : 1) gave

diene **4b** (10.8 g, 82%) as a colorless oil, δ_H (270 MHz) 0.88 (3H, t, *J* 6.6, Me), 1.26–1.54 (26H, m, CH_2), 3.41–3.53 (3H, m, OCH_2CHO), 3.98–4.19 (4H, m, $2 \times CH_2CH{=}CH_2$), 5.12–5.31 (4H, m, $2 \times CH_2CH{=}CH_2$), 5.84–6.00 (2H, m, $2 \times CH_2CH{=}CH_2$).

5-Tetradecyl-4,7-dioxadecane-1,10-diol 5b. The hydroboration of diene **4b** (10.8 g, 31.9 mmol) with $NaBH_4$ (1.09 g, 28.7 mmol) and boron trifluoride–diethyl ether complex (5.44 g, 38.3 mmol) was carried out as described for the preparation of **5a**. The reaction mixture was worked up as above, and purification by chromatography on silica gel (hexane–EtOAc, 1 : 4) gave diol **5b** (2.90 g, 24%) as a colorless oil, ν_{max} (neat)/cm^{-1} 3400, 1120, 1083; δ_H (300 MHz) 0.88 (3H, t, *J* 6.6, Me), 1.26 (24H, br s, CH_2), 1.46 (2H, br s, $CHCH_2$), 1.76–1.86 (4H, m, $HOCH_2CH_2$), 3.07 and 3.27 (2H, br, OH), 3.39–3.50 (3H, m, OCH_2CHO), 3.62–3.78 (8H, m, $HOCH_2CH_2CH_2$).

5-Tetradecyl-4,7-dioxasebacic acid diethyl ester 6b. The oxidation of diol **5b** (1.62 g, 4.32 mmol) with sodium periodate (5.55 g, 25.9 mmol) and ruthenium(III) chloride hydrate (40 mg, 0.19 mmol) was carried out as described for the preparation of **6a**. The crude dicarboxylic acid was converted to the ethyl ester as above and purified by chromatography on silica gel (hexane–EtOAc, 4 : 1) to give ester **6b** (1.03 g, 52% for two steps) as a colorless oil, ν_{max} (neat)/cm^{-1} 1738, 1186, 1120; δ_H (300 MHz) 0.88 (3H, t, *J* 6.8, Me), 1.23–1.49 (32H, m, CH_2 and OCH_2CH_3), 2.55 and 2.57 (4H, t, *J* 6.2, $2 \times COCH_2$), 3.38–3.47 (3H, m, OCH_2CHO), 3.70–3.89 (4H, m, $2 \times COCH_2CH_2$), 4.14 and 4.15 (4H, q, *J* 7.1, $2 \times OCH_2CH_3$).

***N*,*N*′-Bis(benzyloxy)-5-tetradecyl-4,7-dioxasebacic acid diamide 2b.** The hydrolysis of ester **6b** (500 mg, 1.09 mmol) followed by conversion to the acid chloride and subsequent reaction with *O*-benzylhydroxylamine hydrochloride were carried out as described for the preparation of **2a**. The crude product was purified by chromatography on silica gel ($CHCl_3$–EtOAc, 1 : 2) to give the *receptor* **2b** (379 mg, 57% for three steps) as a white solid, mp 73–74 °C; ν_{max} (KBr)/cm^{-1} 3220, 1653, 697; δ_H (300 MHz) 0.88 (3H, t, *J* 6.7, Me), 1.25 (26H, br s, CH_2), 2.26–2.35 (4H, m, $COCH_2$), 3.22–3.74 (7H, m, $2 \times COCH_2CH_2$ and OCH_2CH), 4.83–4.93 (4H, m, $PhCH_2$), 7.30–7.37 (10H, m, 2 × Ph), 9.03 and 9.41 (2H, br s, NH) (Found: C, 70.58; H, 9.42; N, 4.56. Calc. for $C_{36}H_{56}N_2O_6$: C, 70.56; H, 9.72; N, 4.57%).

Hg^{2+}–2b complex

The Hg^{2+}–**2b** complex was prepared by shaking a $CHCl_3$ solution of **2b** several times with aq. $Hg(NO_3)_2$. The organic phase was collected, and the solvent was evaporated to dryness. The formation of the complex was confirmed by ^{1}H NMR spectroscopy, δ_H (300 MHz) 0.88 (3H, t, *J* 6.6, Me), 1.26 (26H, br s, CH_2), 2.30–2.38 (4H, m, $COCH_2$), 3.23–3.74 (7H, m, $2 \times COCH_2CH_2$ and OCH_2CH), 4.79–4.90 (4H, m, $PhCH_2$), 7.26–7.36 (10H, m, 2 × Ph). The disappearance of the two kinds of NH protons clearly shows the formation of the complex.

ESI-MS measurement

ESI-MS spectra were recorded on a Hitachi M-1200 mass spectrometer with an M-1206 ES probe. Stock solutions (2.7 mmol dm^{-3}) of receptors **1** and **2a** were prepared in Pr^{i}OH. Stock solutions (2.7 mmol dm^{-3}) of $AgNO_3$, $Hg(AcO)_2{\cdot}H_2O$, $Ca(NO_3)_2{\cdot}4H_2O$ and $Ca(AcO)_2{\cdot}H_2O$ were prepared in MeOH. The sample solutions were prepared by mixing the receptor and the cation stock solutions in suitable volumetric ratios. When the samples containing only the receptor or the Hg^{2+}–receptor complexes were investigated, 1.1 mmol dm^{-3} $NaNO_3$ solution in MeOH was added in order to promote ionization of the neutral species.

Electrode preparation and EMF measurements

PVC matrix-based ion-sensitive membranes were prepared according to the procedures described previously.[12] The polymeric membrane composition was 3 wt% ionophore, 64 wt% membrane solvent *o*-NPOE, 33 wt% PVC, and 0–100 mol% (relative to the ionophore) TDDMACl. The membrane thickness was ≈100 μm. A 6 mm diameter circle was cut from a prepared membrane and placed on the tip of a PVC ion-selective electrode body assembly (Liquid Electrode Membrane Kit, DKK Co., Ltd., Tokyo, Japan). The prepared electrodes were immersed in 0.1 mol dm^{-3} aq. NaCl for more than 24 h for preconditioning before use. The external reference electrode was a double-junction-type Ag–AgCl electrode (HS-305DS, Toa Electronics, Ltd., Tokyo, Japan). The electrode potential (EMF) measurements were performed according to the reported procedure at 25 ± 0.5 °C using the electrochemical cell system, Ag|AgCl| saturated KCl | 0.3 mol dm^{-3} NH_4NO_3 || sample solution|ISE membrane|0.1 mol dm^{-3} NaCl|AgCl|Ag.

All sample solutions were prepared from sodium salts with 0.1 mol dm^{-3} HEPES–NaOH buffer solution at pH 7.0. The selectivity coefficients $K_{i,j}^{pot}$, where i stands for the primary ion (Cl^-) and j for the interfering ion, were calculated from the response potentials in the sodium anion salt solution using the separate-solution method (SSM; [i] = [j] = 0.1 mol dm^{-3}) according to the recommendations of IUPAC[13] and JIS.[14]

Acknowledgements

D. C. gratefully acknowledges a post-doctoral fellowship granted by the Science and Technology Agency of Japan (STA).

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