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ORIGINAL ARTICLE

Solvent extraction of divalent metal ions by lipophilic di-ionizable acyclic polyethers: effect of end group variation

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Abstract Three series of lipophilic acyclic di-ionizable polyethers are synthesized to probe the effect of structural variation within the acidic end groups on the solvent extraction selectivity and efficiency for divalent metal cations. Common polyether spacers of $-O(CH_2CH_2O)_3-$ connect the two aromatic carboxylic acid or *N*-(X)sulfonyl carboxamide end groups. For the latter, variation of the X group from methyl to phenyl to 4-nitrophenyl to trifluoromethyl serves to 'tune' the acidity of the ionizable group. Results for competitive solvent extractions of alkaline earth metal cations and single species extractions of Hg^{2+} and of Pb^{2+} from aqueous solutions into chloroform are reported.

Keywords Solvent extraction · Divalent metal ions · Structural variation in acyclic extractant

Introduction

Complexation of a variety of organic and metal cations by open-chain multidentate ligands has been reported. Since the open-chain ligands are inexpensive, their ability to complex alkali metal cations has led to their use in phase transfer catalysis and other organic and analytical fields [1, 2]. The most studied podands are acyclic polyether analogues of crown ethers. Due to their open-chain structure, acyclic polyethers can wrap around metal ions. Extra flexibility of the acyclic hosts allows them to engage in multiple bridging and helical binding modes which are not possible with crown ethers [3]. Acyclic polyethers offer a wide variety of complexation mechanisms and structural geometries. When rigid structural elements are located at each terminus of the polyether chain, overall organization is enhanced. This so-called 'end group concept' [4] plays an important role in the overall host behavior in metal ion binding. Conjugated aromatic moieties provide a rigid, planar and partially preorganized binding cleft. The stability of acyclic polyether host–guest complex depends on chain length, identities of the cation and anion, the end group, and the presence of other functional groups within the chain.

Previously we have investigated competitive solvent extraction of alkaline earth metal cations by lipophilic acyclic polyether dicarboxylic acids **1**–**5** (Fig. 1) [5, 6]. For both series of ligands, it was found that the hosts with four donor oxygen atoms in the polyether chain (i.e., compounds **2** and **4**) gave high selectivity for Ba^{2+} extraction. The other ligands with similar structures did not show much selectivity in alkaline earth metal cation extractions. Ligand **2** was also found to have selectivity for Ra^{2+} in solvent extraction [7]. Compounds **4** and **5** have better solubilities in hydrocarbon solvents than their di-naphthoic acid analogues **1** and **2**, a practical advantage.

To further probe the end group effect, four series of lipophilic di-ionizable acyclic polyethers were envisioned (Fig. 2). A common polyether unit separates the two *N*-(X)sulfonyl carboxamide-containing end groups in which X is varied from methyl to phenyl to 4-nitrophenyl to trifluoromethyl to 'tune' the acidity of the ligands [8]. The divalent metal ion extraction behaviors of the new ligands are compared with those for the corresponding dicarboxylic acids. Results are now reported for competitive solvent

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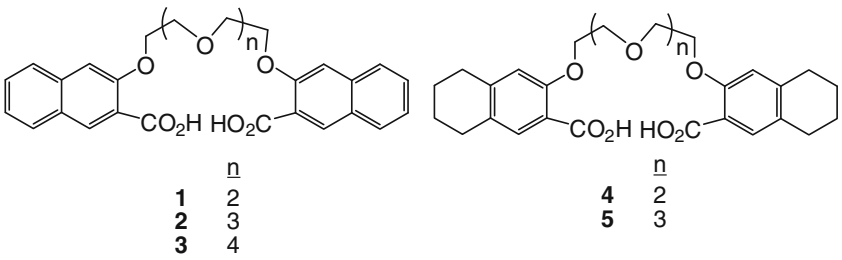


Fig. 1 Previously prepared acyclic polyether dicarboxylic acid extractants

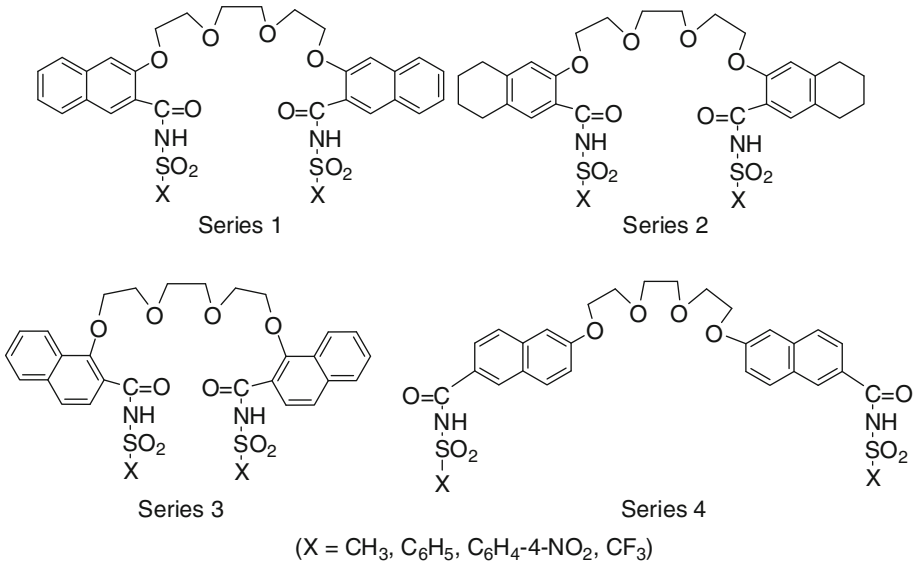


Fig. 2 Proposed new lipophilic acyclic di-ionizable polyether extractants

extractions of alkaline earth metal cations and for single species extractions of Hg^{2+} and Pb^{2+} from aqueous solutions into chloroform by the new lipophilic di-ionizable acyclic polyethers.

Experimental

Chemicals

Reagents were obtained from commercial suppliers and used directly, unless otherwise noted. Tetrahydrofuran (THF) was dried over sodium with benzophenone as an indicator and distilled just before use. Adaptations of literature procedures for the preparation and characterization of intermediates **1** [5], **4** [6], **6** [9], 7 [5], **11** [10], **12** [11], **13** [6], **18** [12], **19** [5], **20** [5], **25** [13], **26** [14] and **27** [14] are given in the Supplemental information.

Apparatus

Melting points were determined with a Mel-Temp melting point apparatus. Infrared (IR) spectra were recorded with a Perkin-Elmer Model 1600 FT–IR spectrometer as deposits from CH_2Cl_2 solutions on a NaCl plate. The ^1H and ^{13}C NMR spectra were recorded with a Varian Unity INOVA 500 MHz FT–NMR (^1H 500 MHz and ^{13}C 126 MHz) spectrometer in $CDCl_3$ with Me_4Si as internal standard unless mentioned otherwise. Chemical shifts (δ) are given in ppm downfield from TMS and coupling constants (J values) are given in Hz. Elemental analysis was performed by Desert Analytics Laboratory (now Columbia Analytical Services) of Tucson, Arizona. For the solvent extraction of divalent metal cations from aqueous solutions into chloroform experiments, vortexing of two-phase samples was conducted with a Glas-Col Multipulse Vortexer, centrifugation of two-phase samples was performed with a Becton-Dickinson Clay Adams Brand Centrifuge and pHs of aqueous solutions were measured with a Fisher Accumet Xcel XL25 pH/Ion Meter with a Corning 476157 combination electrode.

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctanes (Series 1 extractants)

*General procedure for preparation of bis-1,8-[2′-N-(X)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctanes **8–10** from diacid **1***

Oxalyl chloride (3.5 mL, 40.8 mmol) was added to diacid **1** (1.00 g, 2.04 mmol) in benzene (50 mL) and the mixure was refluxed for 10 h. After verifying the conversion by IR

spectroscopy, the benzene was evaporated in vacuo. A solution of the appropriate sulfonamide (5.1 mmol) in THF (10 mL) was added to a mixture of NaH (0.73 g, 30.6 mmol) in THF (30 mL) under nitrogen and the mixture was stirred at room temperature for 2 h. The crude di (acid chloride) was added and the mixture was stirred overnight. The excess NaH was destroyed by careful addition of water. The THF was evaporated in vacuo and the residue was washed with 6 N HCl acid to pH 1 and then extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$ and evaporated in vacuo.

Bis-1,8-[2′-N-(methane)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctane (**8**) was obtained as a white solid (1.20 g, 92%) with mp 194–197 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3252 (N–H), 1684 (C=O), 1343 and 1154 (S=O), 1251 and 1129 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.41 (s, 6H), 3.88 (s, 4H), 3.97 (t, $J = 4.0$ Hz, 4H), 4.31 (t, $J = 4.5$ Hz, 4H), 7.10 (s, 2H), 7.27–7.33 (m, 2H), 7.47–7.53 (m, 2H), 7.55 (d, $J = 8.5$ Hz, 2H), 7.67 (d, $J = 6.0$ Hz, 2H), 8.36 (s, 2H), 10.58 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 30.9, 41.8, 67.7, 68.3, 70.2, 107.8, 119.4, 125.0, 126.4, 127.8, 129.3, 129.3, 134.8, 136.4, 153.0, 163.8. Anal. Calcd. for $C_{30}H_{32}N_2O_{10}S_2$: C, 55.89; H, 5.00, N, 4.35. Found: C, 55.65; H, 4.87; N, 4.19%.

Bis-1,8-[2′-N-(benzene)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctane (**9**) was obtained as a white solid (1.42 g, 93%) with mp 176–179 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3248 (N–H), 1688 (C=O), 1350 and 1130 (S=O), 1251 and 1090 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 4.03–4.06 (m, 8H), 4.34 (t, $J = 4.5$ Hz, 4H), 7.06 (s, 2H), 7.20–7.25 (m, 2H), 7.43–7.47 (m, 2H), 7.49 (d, $J = 8.0$ Hz, 2H), 7.51–7.55 (m, 6H), 7.62 (d, $J = 8.0$ Hz, 2H), 8.16–8.19 (m, 4H), 8.26 (s, 2H), 10.76 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 67.7, 68.0, 68.6, 70.4, 107.6, 119.7, 124.9, 126.4, 126.4, 127.8, 128.5, 128.8, 129.1, 129.2, 132.8, 133.6, 134.7, 136.3, 139.2, 153.0, 162.8. Anal. Calcd. for $C_{40}H_{36}N_2O_{10}S_2$: C, 62.49; H, 4.72, N, 3.64. Found: C, 62.67; H, 4.78; N, 3.68%.

Bis-1,8-[2′-N-(trifluoromethane)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctane (**10**) was obtained as a white solid (1.42 g, 93%) with mp 63–69 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3175 (N–H), 1717 (C=O), 1355 and 1164 (S=O), 1235 and 1124 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.81 (s, 4H), 3.94 (t, $J = 4.0$ Hz, 4H), 4.35 (t, $J = 4.5$ Hz, 4H), 7.15 (s, 2H), 7.34–7.38 (m, 2H), 7.54–7.58 (m, 2H), 7.66 (d, $J = 8.0$ Hz, 2H), 7.71 (d, $J = 8.5$ Hz, 2H), 8.45 (s, 2H), 10.90 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 67.9, 68.3, 70.1, 108.1, 118.8, 120.6, 125.5, 126.5, 128.0, 129.5, 130.0, 135.7, 136.8, 152.6, 161.9. Anal. Calcd. for $C_{30}H_{26}F_6N_2O_{10}S_2$: C, 47.87; H, 3.48, N, 3.72. Found: C, 48.22; H, 3.65; N, 3.69%.

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctanes (Series 2 extractants)

*General procedure for synthesis of bis-1,8-[2′-N-(X)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctanes **14–17** from diacid **4***

Oxalyl chloride (7.93 mL, 92.3 mmol) was added to diacid **4** (2.30 g, 4.61 mmol) in benzene (150 mL) and the mixure was refluxed for 10 h. After verifying conversion by IR spectroscopy, the solvent was evaporated in vacuo. A solution of the appropriate sulfonamide (11.53 mmol) in THF (20 mL) was added to a mixture of NaH (1.66 g, 69.15 mmol) and 50 mL of THF. The mixture was stirred at room temperature for 2 h. The crude di(acid chloride) was added and the mixture was stirred overnight. The excess NaH was destroyed by careful addition of water and the THF was evaporated in vacuo. The residue was washed with 6 N HCl acid to pH 1 and extracted with CH_2Cl_2. The solution was dried over $MgSO_4$ and the solvent was evaporated in vacuo.

Bis-1,8-[2′-N-(methane)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctane (**14**) was obtained as a white solid (2.65 g, 88%) with mp 122–125 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3251 (N–H), 1681 (C=O), 1340 and 1164 (S=O), 1260 and 1133 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 1.68–1.82 (m, 8H), 2.57–2.69 (m, 4H), 2.71–2.80 (m, 4H), 3.37 (s, 6H), 3.82 (s, 4H), 3.89 (t, $J = 4.5$ Hz, 4H), 4.22 (t, $J = 4.5$ Hz, 4H), 6.62 (s, 2H), 7.73 (s, 2H, ArH), 10.50 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 22.5, 22.9, 28.2, 29.9, 41.6, 68.0, 68.5, 70.3, 113.0, 116.1, 130.7, 132.7, 145.6, 154.7, 164.1. Anal.Calcd. for $C_{30}H_{40}N_2O_{10}S_2 \cdot 0.2C_6H_6$: C, 56.06; H, 6.21, N, 4.19. Found: C, 55.91; H, 6.25; N, 3.97%.

Bis-1,8-[2′-N-(benzene)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctane (**15**) was obtained as a white solid (2.96 g, 83%) with mp 53–55 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3242 (N–H), 1686 (C=O), 1345 and 1168 (S=O), 1259 and 1090 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 1.65–1.77 (m, 8H), 2.51–2.62 (m, 4H), 2.68–2.76 (m, 4H), 3.92–4.02 (s + t, 8H), 4.24 (t, $J = 4.5$ Hz, 4H), 6.59 (s, 2H), 7.47–7.60 (m, 6H), 7.61 (s, 2H), 8.08–8.19 (m, 4H), 10.68 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 22.5, 22.9, 28.2, 29.8, 68.1, 68.8, 70.6, 113.0, 116.5, 126.4, 128.4, 128.7, 129.2, 130.6, 132.7, 132.8, 133.4, 139.4, 145.3, 154.7, 163.0. Anal. Calcd. for $C_{40}H_{44}N_2O_{10}S_2 \cdot H_2O$: C, 60.44; H, 5.83, N, 3.52. Found: C, 60.31; H, 5.62; N, 3.90%.

Bis-1,8-[2′-N-(4-nitrobenzene)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxa-octane (**16**) was obtained as a yellow solid (3.35 g, 84%) with mp

230–232 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3225 (N–H), 1688 (C=O), 1349 and 1170 (S=O), 1260 and 1090 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 1.68–1.79 (m, 8H), 2.54–2.62 (m, 4H), 2.69–2.77 (m, 4H), 3.94–4.01 (s + t, 8H), 4.28 (t, $J = 4.5$ Hz, 4H), 6.62 (s, 2H), 7.58 (s, 2H), 8.28–8.40 (m, 8H), 10.82 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 22.5, 22.81 28.2, 29.9, 68.2, 68.7, 70.5, 113.1, 115.9, 123.9, 124.4, 127.9, 130.0, 131.0, 132.7, 144.8, 146.0, 150.5, 154.7, 163.0. Anal. Calcd. for $C_{40}H_{42}N_4O_{14}S_2$: C, 55.42; H, 4.88, N, 6.46. Found: C, 55.61; H, 4.84; N, 6.30%.

Bis-1,8-[2′-N-(trifluoromethane)sulfonyl carbamoyl-5′, 6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctane (**17**) was obtained as a white solid (2.80 g, 80%), with mp 143–146 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate) ν_{max}/cm^{-1} 3173 (N–H), 1713 (C=O), 1382 and 1130 (S=O), 1235 and 1123 (C–O); ^1H NMR ($CDCl_3$) δ 1.70–1.84 (m, 8 H, CH_2CH_2), 2.59–2.71 (m, 4 H, $ArCH_2$), 2.73–2.83 (m, 4 H, $ArCH_2$), 3.75 (s, 4 H, OCH_2CH_2O), 3.87 (t, $J = 4.5$ Hz, 4 H, OCH_2CH_2O), 4.25 (t, $J = 4.5$ Hz, 4 H, OCH_2CH_2O), 6.65 (s, 2 H, ArH), 7.71 (s, 2 H, ArH), 10.83 (s, 2 H, NH). ^{13}C NMR ($CDCl_3$) δ 22.4, 22.8, 28.2, 30.0, 68.2, 68.4, 70.2, 113.1, 115.6, 118.1, 120.6, 131.4, 133.2, 146.8, 154.6, 161.9. Anal. Calcd for $C_{30}H_{34}F_6N_2O_{10}S_2{\cdot}0.2C_6H_6$: C, 48.27; H, 4.57, N, 3.61. Found: C, 48.11; H, 4.36; N, 3.66%.

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctanes (Series 3 extractants

*General procedure for synthesis of bis-1,8-[2′-N-(X)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctanes **21–24***

The general procedure given above for the preparation of **8–10** was utilized but with the replacement of diacid **1** with diacid **4**.

Bis-1,8-[2′-N-(methane)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctane (**21**) was obtained as a white solid (1.15 g, 88%) with mp 143–146 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3252 (N–H), 1686 (C=O), 1346 and 1166 (S=O), 1251 and 1098 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.41 (s, 6H), 3.94 (s, 4H), 4.02–4.06 (m, 4H), 4.30–4.34 (m, 4H), 7.52–7.64 (m, 4H), 7.68 (d, $J = 8.5$ Hz, 2H), 7.86 (d, $J = 8.0$ Hz, 2H), 8.04 (d, $J = 8.5$ Hz, 2H), 8.17 (d, $J = 8.5$ Hz, 2H), 10.65 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 25.6, 69.5, 70.7, 76.6, 119.5, 123.2, 125.2, 125.9, 127.0, 127.1, 128.4, 129.1, 137.5, 155.6, 164.0. Anal. Calcd for $C_{30}H_{32}N_2O_{10}S_2$: C, 55.89; H, 5.00, N, 4.35. Found: C, 55.93; H, 4.84; N, 4.15%.

Bis-1,8-[2′-N-(benzene)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctane (**22**) was obtained as a white solid (1.38 g, 88%) with mp 53–55 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3251 (N–H), 1688 (C=O), 1350 and 1172 (S=O), 1231 and 1089 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 4.10 (s, 4H), 4.10–4.16 (m, 4H), 4.21–4.28 (m, 4H), 7.49–7.62 (m, 12H), 7.81 (d, $J = 8.0$ Hz, 2H), 7.90 (d, $J = 8.5$ Hz, 2H), 8.14 (d, $J = 8.5$ Hz, 2H), 8.21–8.27 (m, 4H), 10.90 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 69.6, 70.9, 76.4, 119.5, 123.2, 125.0, 125.9, 126.4, 127.0, 127.1, 128.3, 128.6, 128.8, 129.0, 129.2, 132.8, 133.6, 137.4, 139.2, 155.4, 162.8. Anal. Calcd. for $C_{40}H_{36}N_2O_{10}S_2$: C, 62.49; H, 4.72, N, 3.64. Found: C, 62.16; H, 4.88; N, 3.78%.

Bis-1,8-[2′-N-(4-nitrobenzene)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctane (**23**) was obtained as a yellow solid (1.62 g, 93%) with mp 86–88 °C. IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3235 (N–H), 1688 (C=O), 1351 and 1175 (S=O), 1230 and 1089 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 4.13 (s, 4H), 4.14–4.17 (m, 4H), 4.25–4.29 (m, 4H), 7.51–7.56 (m, 2H), 7.57–7.63 (m, 4H), 7.82 (d, $J = 8.0$ Hz, 2H), 7.87 (d, $J = 8.5$ Hz, 2H), 8.08–8.13 (m, 2H), 8.31–8.37 (m, 4H), 8.41–8.45 (m, 4H), 11.05 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 69.6, 70.9, 76.4, 119.5, 123.2, 125.0, 125.9, 126.4, 127.0, 127.1, 128.3, 128.6, 128.8, 129.0, 129.2, 132.8, 133.6, 137.4, 139.24, 155.4, 162.8. Anal. Calcd. for $C_{40}H_{34}N_4O_{14}S_2$: C, 55.94; H, 3.99, N, 6.52. Found: C, 55.67; H, 3.56; N, 6.76%.

Bis-1,8-[2′-N-(trifluoromethane)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctane (**24**) was obtained as a yellow oil (1.21 g, 79%). IR (deposit from CH_2Cl_2 solution on a NaCl plate): 3175 (N–H), 1714 (C=O), 1317 and 1130 (S=O), 1251 and 1093 (C–O) cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.90 (s, 4H), 4.00–4.04 (m, 4H), 4.32–4.39 (m, 4H), 7.56–7.67 (m, 4H), 7.70 (d, $J = 8.5$ Hz, 2H), 7.88 (d, $J = 8.5$ Hz, 2H), 8.04 (d, $J = 8.5$ Hz, 2H), 8.14 (d, $J = 8.0$ Hz, 2H), 11.13 (s, 2H). ^{13}C NMR ($CDCl_3$): δ 69.2, 70.5, 75.6, 118.6, 123.2, 124.0, 125.6, 125.8, 126.8, 127.4, 128.5, 129.6, 137.9, 155.8, 162.0. Anal. Calcd. for $C_{30}H_{26}F_6N_2O_{10}S_2$: C, 47.87; H, 3.48, N, 3.72. Found: C, 48.09; H, 3.31; N, 3.37%.

Procedure for extraction of Pb^{2+} from aqueous solutions into chloroform

A 1.00 mM aqueous solution of $Pb(NO_3)_2$ with tetramethylammonium hydroxide (TMAOH) or HNO_3 for pH adjustment (2.0 mL) and a 0.50 mM ligand solution in chloroform (2.0 mL) in a capped, polypropylene, 15-mL centrifuge tube were vortexed for 10 min at room temperature. The tube was centrifuged for 10 min to promote phase separation. A 1.5-mL portion of the organic phase was removed and placed in a new, 15-mL polypropylene centrifuge tube containing 3.0 mL of 4.0 M HNO_3. The tube was vortexed for 10 min and centrifuged for 10 min. The Pb^{2+} concentration of the aqueous phase from

stripping was determined with a Shimadzu AA-6300 spectrophotometer. The pH of the aqueous phase from the initial extraction was determined.

Procedure for extraction of Hg^{2+} from aqueous solutions into chloroform

An aqueous solution of 0.25 mM $Hg(NO_3)_2$ with HNO_3 or TMAOH for pH adjustment (3.0 mL) and a 0.25 mM ligand solution in chloroform (3.0 mL) were placed in a capped, polypropylene, 15-mL centrifuge tube. The tube was vortexed for 10 min at room temperature and centrifuged for 10 min to promote phase separation. A 0.50-mL sample of the aqueous phase was removed and diluted to 5.0 mL with deionized water. The pH of the aqueous phase from the initial extraction step was measured. A 1.0-mL portion of the diluted aqueous sample was added to 100 mL of 1.0 N H_2SO_4 in a glass reaction bottle which was then attached to a Shimadzu MVU-1A Mercury Vaporizor Unit. The Hg^{2+} in the sample was reduced using 5.0 mL of a 0.50 M solution of $SnCl_2$. The reduced mercury vapor was then pumped through a flow cell and the mercury concentration was measured at 253.6 nm with a Shimadzu AA-6300 spectrophotometer.

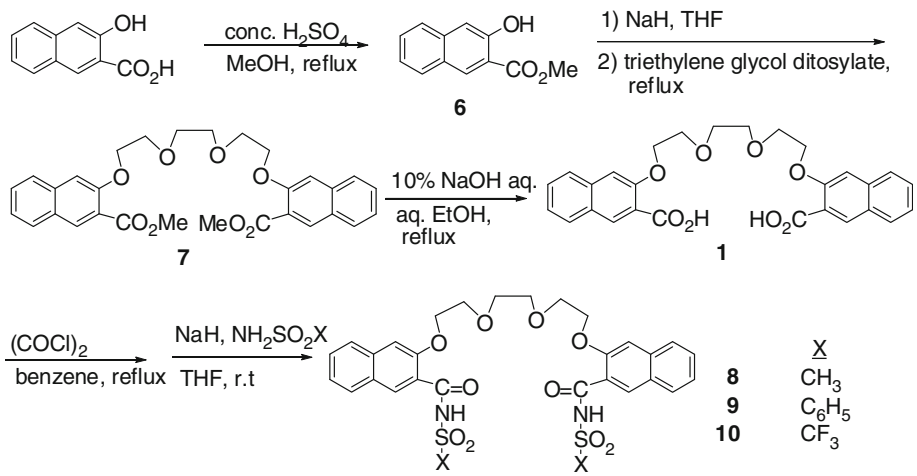
Procedure for competitive extraction of alkaline earth metal cations from aqueous solutions into chloroform

An aqueous solution of the alkaline earth metal chlorides with $Ba(OH)_2$ or HCl for pH adjustment (2.0 mL, 20.0 mM in each of the four alkaline earth metal cation species) and 2.0 mL of a 1.0 mM ligand solution in chloroform were placed in a capped, polypropylene, 15-mL centrifuge tube and vortexed for 10 min at room temperature. The tube was centrifuged for 10 min for phase separation. A 1.5-mL portion of the organic phase was removed and placed with 3.0 mL of 0.10 M HCl in a new capped, polypropylene, 15-mL centrifuge tube. The tube was vortexed for 10 min and centrifuged for 10 min. A 1.0 mL portion of the aqueous phase from stripping was removed and diluted to 10.0 mL with deionized water. The alkaline earth metal cation concentrations were determined with a Dionex DX-120 ion chromatograph with a Dionex CS12A column. The pH of the aqueous phase from the initial extraction step was measured.

Results and discussion

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctanes (Series 1 extractants)

The synthetic route for new lipophilic di-ionizable acyclic polyether ligands of Series 1 is presented in Scheme 1. Acid-catalyzed esterification of 3-hydroxy-2-naphthoic acid in methanol produced a 94% yield of methyl ester **6**. Reaction of **6** with NaH and triethylene glycol ditosylate in THF at reflux for 2 days gave a 57% yield of diester **7**. A longer reaction time did not improve the yield. From hydrolysis of **7** with aqueous NaOH in ethanol at reflux followed by acidification, an 81% yield of dicarboxylic acid **1** was obtained. Diacid **1** was converted into the corresponding di(acid chloride) by reaction with oxalyl chloride at reflux in benzene. Formation of the acid chloride was monitored by IR spectroscopy with the appearance of the strong carbonyl group absorption at around 1,775 cm^{-1} and the disappearance of the carbonyl group absorption for an aromatic carboxylic acid at 1,735 cm^{-1}. NaH was reacted with the appropriate sulfonamide in THF to give the sodium sulfonamide salt to which was added the di(acid chloride) to afford the new lipophilic di-ionizable acyclic polyethers **8**–**10** in 92–93% yields. However, from the attempt to prepare the analogue with X = C_6H_4-4-NO_2 from the di(acid chloride) derivative of **1**, the crude product

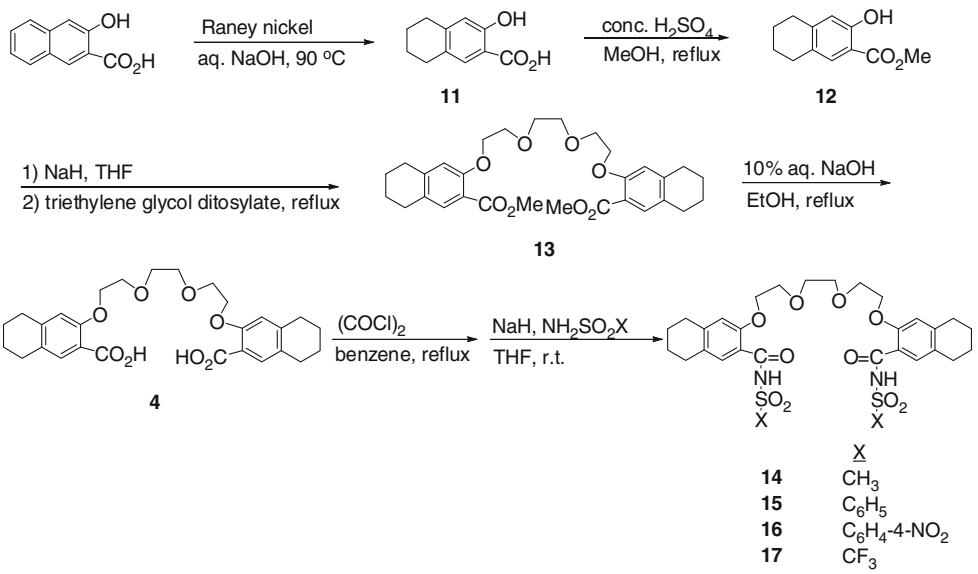


Scheme 1 Synthesis of bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-3′-naphthoxy]-3,6-dioxaoctane extractants **8**–**10** (Series 1)

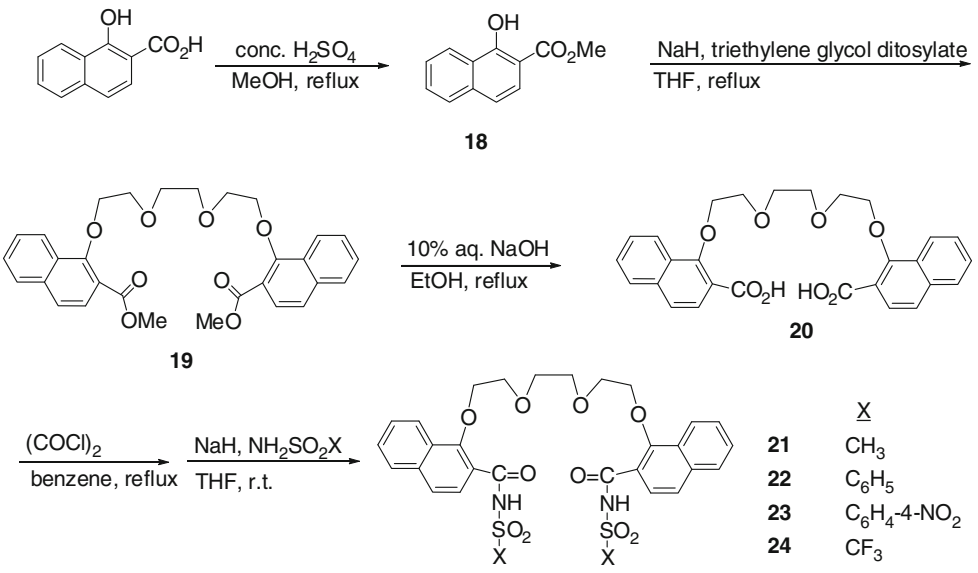
was a solid that was insoluble in all solvents. Therefore, the synthesis of the Series 1 extractant with X = C_6H_4-4-NO_2 was abandoned.

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctanes (Series 2 extractants)

To evaluate the influence of end group rigidity in the acyclic di-ionizable polyether hosts and enhance the solubility of the extractants in hydrocarbon solvents, Series 2 extractants were prepared (Scheme 2). Structures for Series 2 extractants are similar to those of Series 1, except that the naphthalene rings in the end groups are partially reduced in the former. Reduction of 3-hydroxy-2-naphthoic acid with Raney nickel in alkaline solution was accomplished by adaptation of a literature method [15–17]. Modifications were made to the reported procedure to achieve better conversion. The weight ratio of Raney nickel to the starting material was changed from three to four. Also the Raney nickel was added in four portions with 1 hour intervals between additions. This allowed the evolved hydrogen gas to be consumed more efficiently before it escaped from the reaction mixture. Addition of the Raney nickel was performed with caution to prevent excessive foaming. The modified method gave 5,6,7,8-tetrahydro-3-hydroxy-2-naphthoic acid (**11**) in 80% yield. Acid-catalyzed esterification of **11** was carried out in methanol under reflux for 2 days to give ester **12** in 69% yield. The resulting substituted naphthol **12** was reacted with NaH in THF and



Scheme 2 Synthesis of bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-5′,6′,7′,8′-tetrahydro-3′-naphthoxy]-3,6-dioxaoctane extractants **14**–**17** (Series 2)



Scheme 3 Synthesis of bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctane extractants **21**–**24** (Series 3)

then triethylene glycol ditosylate to afford diester **13** in 60% yield. Diester **13** was hydrolyzed with NaOH in aqueous THF to form diacid **4** in 94% yield.

Diacid **4** was converted into the corresponding di(acid chloride) by reaction with oxalyl chloride in benzene at reflux for 12 hours. Formation of the di(acid chloride) was monitored by IR spectroscopy with the appearance of the strong carbonyl group absorption at 1,774 cm^{-1} and disappearance of the carbonyl group absorption for the conjugated carboxylic acid at 1,730 cm^{-1}. The di(acid chloride) was reacted with sodium salts of appropriate sulfonamides in THF to produce the Series 2 extractants **14–17** in 70–88% yields**.**

Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctanes (Series 3 extractants)

The bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-1′-naphthoxy]-3,6-dioxaoctanes in Series 3 differ from the extractants in Series 1 in the positions on the naphthalene end groups to which the polyether chain and ionizable groups are attached. The synthetic route to the Series 3 extractants is illustrated in Scheme 3.

Acid-catalyzed esterification of 1-hydroxy-2-naphthoic acid was performed in methanol under reflux. An elongated reaction time of 4 days gave ester **18** in a reasonable yield of 67%. Ester **18** was reacted with NaH and triethylene glycol ditosylate in THF at reflux for 4 days to give a 36% yield of diester **19**. Compared with its isomer **6**, the anion from methyl 1-hydroxy-2-naphthoate (**18**) had much lower reactivity in coupling with triethylene glycol ditosylate. Basic hydrolysis of diester **19** gave an 85% yield of dicarboxylic acid **20**, which was treated with oxalyl chloride in benzene at reflux to give the corresponding di(acid chloride). Formation of the acid chloride was verified by IR spectroscopy. The appearance of the strong carbonyl group absorption at 1,771 cm^{-1} and disappearance of the carbonyl group absorption for an aromatic carboxylic acid at 1,716 cm^{-1} were observed. The crude di(acid chloride) was treated with the sodium salts of appropriate sulfonamides in THF to afford the Series 3 extractants **21–24** in 79–92% yields**.**

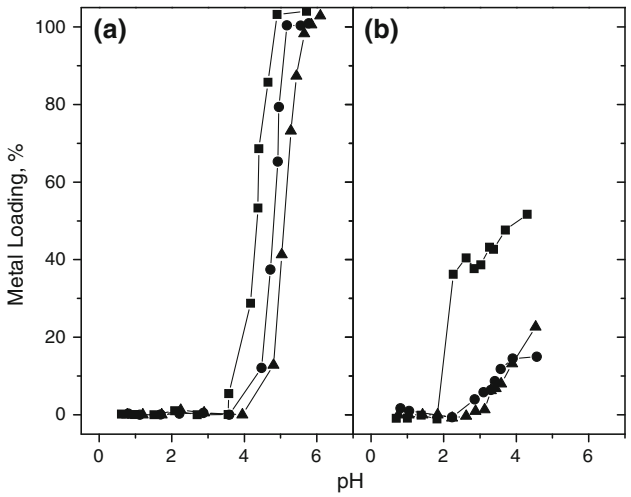
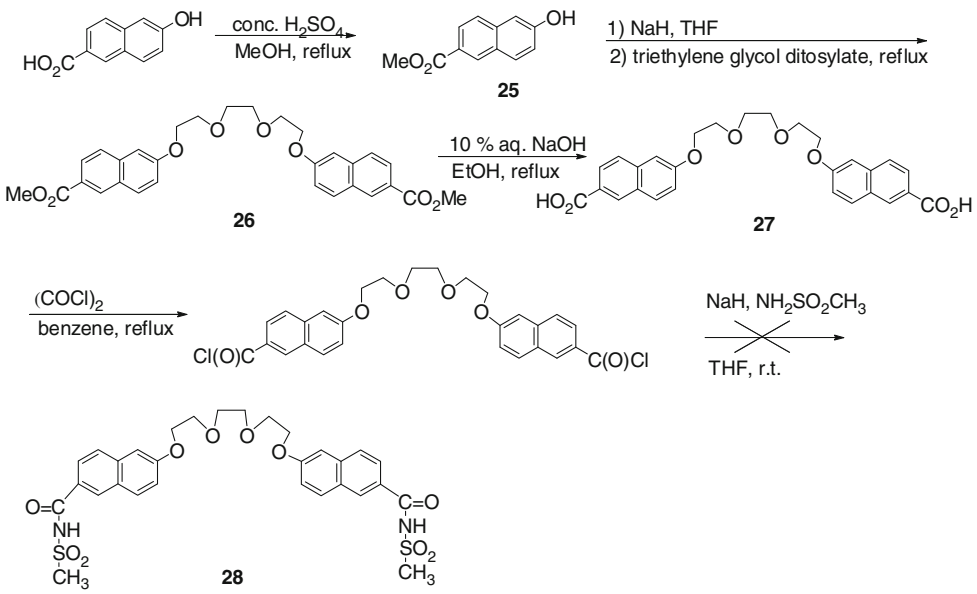


Fig. 3 Metal loading of the organic phase versus pH of the aqueous phase for single species extractions of **a** Pb^{2+} and **b** Hg^{2+} into chloroform by lipophilic acyclic polyether dicarboxylic acids **1** (*circle*), **4** (*triangle*) and **20** (*square*)

Scheme 4 Attempted synthesis of bis-1,8-[2′-*N*-(methane)sulfonyl carbamoyl-6′-naphthoxy]-3,6-dioxaoctane



Attempted Synthesis of Bis-1,8-[2′-*N*-(X)sulfonyl carbamoyl-6′-naphthoxy]-3,6-dioxaoctanes (Series 4 extractants)

The proposed Series 4 extractants differ from those of the other three series in the relative connection sites for the polyether chain and the acidic function in the end groups. The attempted preparative route to the Series 4 extractant with X = CH_3 is presented in Scheme 4.

Under acidic conditions, 6-hydroxy-2-naphthoic acid was refluxed in methanol for 24 h to give ester **25** in 82% yield. Ester **25** was reacted with NaH and then refluxed with triethylene glycol ditosylate for 2 days to give diester **26** in a 54% yield. Diester **26** was hydrolyzed with NaOH

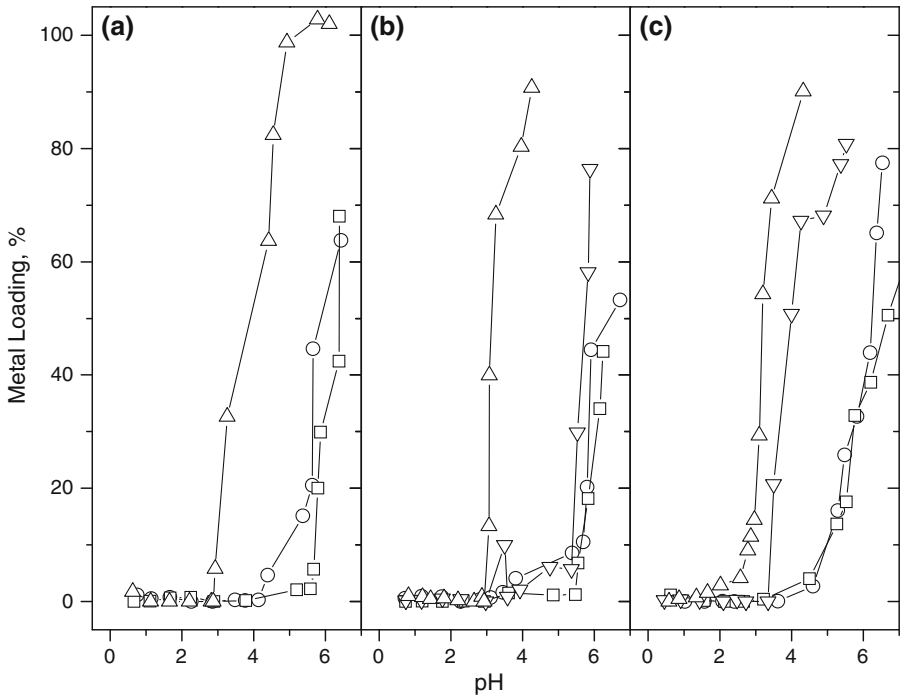


Fig. 4 Metal loading of the organic phase versus pH of the aqueous phase for single species extractions of Pb^{2+} into chloroform by lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamides] (**a**) **8** (*circle*), **9** (*square*), and **10** (*triangle*) of Series 1; (**b**) **14** (*circle*), **15** (*square*), **16** (*down-pointing triangle*) and **17** (*up-pointing triangle*) of Series 2, and (**c**) **21** (*circle*), **22** (*square*), **23** (*down-pointing triangle*) and **24** (*up-pointing triangle*) of Series 3

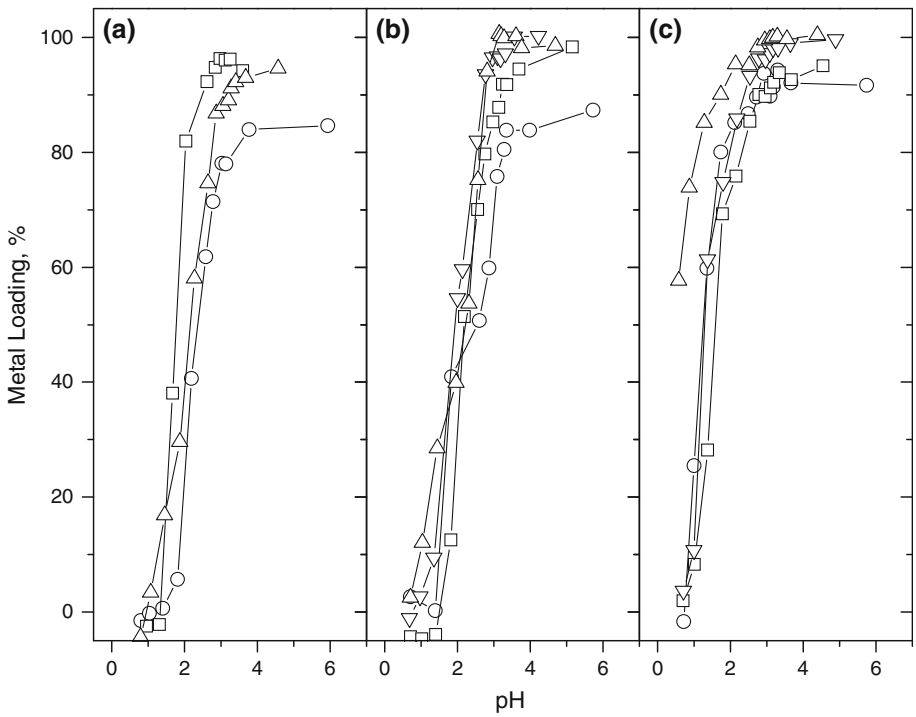


Fig. 5 Metal loading of the organic phase versus pH of the aqueous phase for single species extractions of Hg^{2+} into chloroform by lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamides] (**a**) **8** (*circle*), **9** (*square*) and **10** (*triangle*) of Series 1 (**b**) **14** (*circle*), **15** (*square*), **16** (*down-pointing triangle*) and **17** (*up-pointing triangle*) of Series 2, and (**c**) **21** (*circle*), **22** (*square*), **23** (*down-pointing triangle*), and **24** (*up-pointing triangle*) of Series 3

in aqueous EtOH at reflux to produce diacid **27** in 68% yield. Conversion of the diacid **27** to the di(acid chloride) proved to be difficult. Finally it was found that refluxing a mixture of diacid **27** and oxalyl chloride in benzene for 48 hours gave the corresponding di(acid chloride). Formation of the acid chloride was verified by IR spectroscopy.

A carbonyl group absorption at 1,740 cm^{-1} replaced the carbonyl group absorption at 1,680 cm^{-1}. The di(acid chloride) was treated with the sodium salt of methanesulfonamide in THF. Instead of the desired bis-1,8[2′-*N*-(methane)sulfonyl carbamoyl-6′-naphthoxy]-3,6-dioxaoctane (**28**), the reaction gave an inseparable mixture with six or seven components.

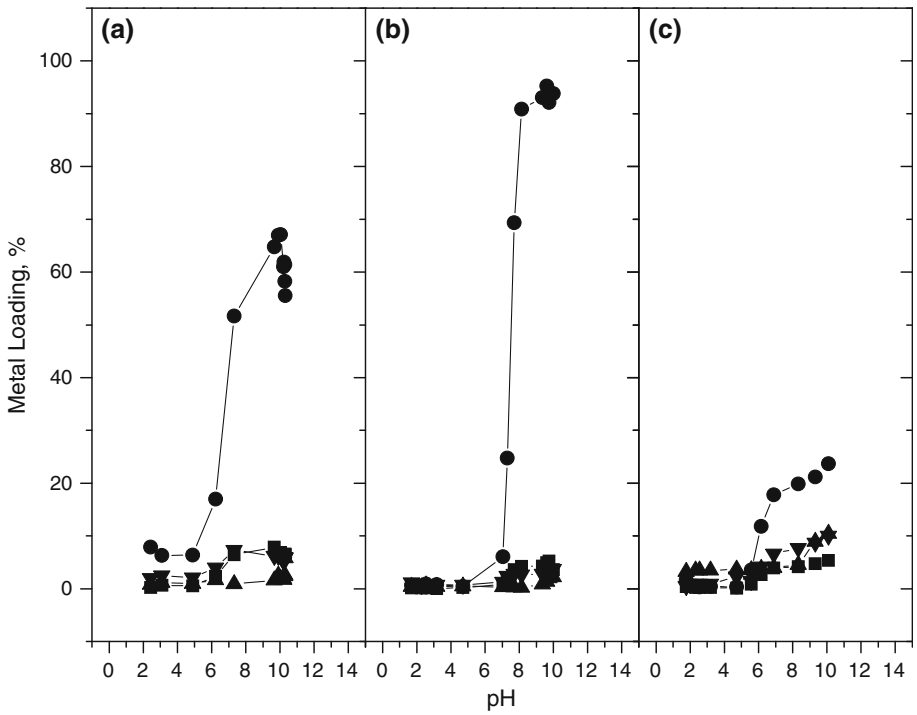


Fig. 6 Metal loading of the organic phase versus pH of the aqueous phase for competitive extractions of alkaline earth metal cations into chloroform by lipophilic acyclic polyether dicarboxylic acids **a 1**, **b 4**, and **c 20** (*up-pointing triangle* Mg^{2+}, *down-pointing triangle* Ca^{2+}, *square* Sr^{2+}, *circle* Ba^{2+})

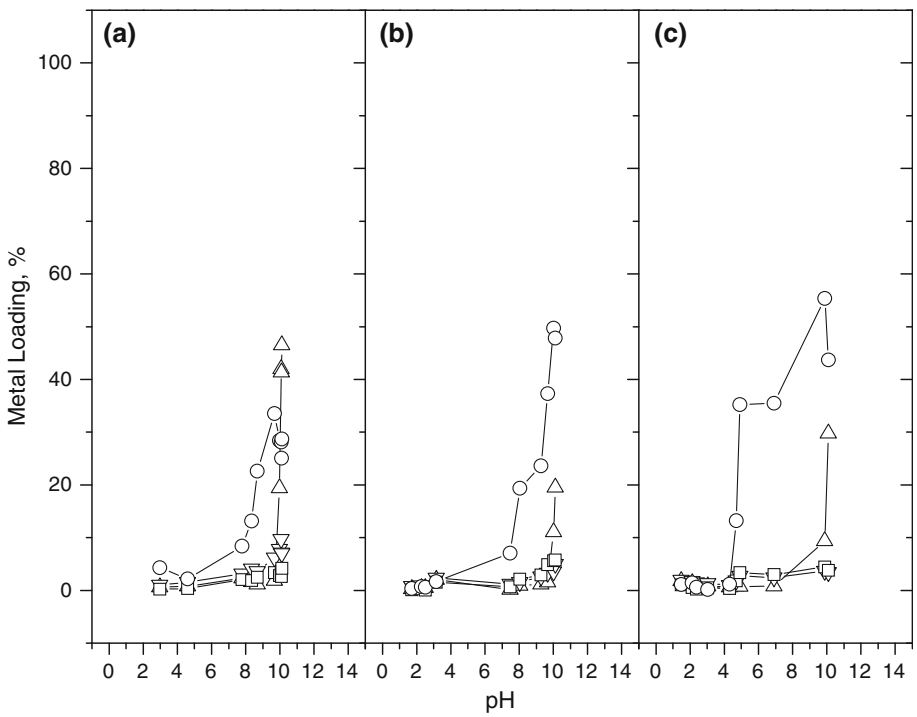


Fig. 7 Metal loading of the organic phase versus pH of the aqueous phase for competitive extractions of alkaline earth metal cations into chloroform by Series 1 lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamides] **a 8**, **b 9**, and **c 10** (*up-pointing triangle* Mg^{2+}, *down-pointing triangle* Ca^{2+}, *square* Sr^{2+}, *circle* Ba^{2+})

Due to this inability to synthesize **28**, the attempt to prepare the Series 4 extractants was terminated.

Single species solvent extractions of Pb^{2+} and Hg^{2+} by lipophilic di-ionizable acyclic polyether ligands

Profiles for the single species extractions of Pb^{2+} from 1.00 mM aqueous solutions into 0.50 mM chloroform solution solutions of lipophilic acyclic polyether di(carboxylic acids) **1** (Series 1), **4** (Series 2), and **20** (Series 3) are presented in Fig. 3a. As can be seen, the Pb^{2+} loading of the ligands was negligible when the aqueous phases were strongly acidic (pH < 3). This demonstrates that the neutral forms of the ligands are poor extractants. On the other hand, when the aqueous phase pH was 5–6, Pb^{2+} loading of the ligands was quantitative for formation of 1:1 Pb^{2+}-di-ionized ligand extraction complexes. Although all three ligands are effective extractants for Pb^{2+}, the extraction efficiency increases in the order **20 > 1 > 4**.

Results for the single species extractions of Pb^{2+} with the lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamide] ligands are given in Fig. 4a–c for extractant Series 1–3, respectively. From comparison with the data shown in Fig. 3a for the dicarboxylic acid ligands, it is generally observed that *N*-(X)sulfonyl carboxamide analogues are less effective Pb^{2+} extractants. Only with ligand **10** (Series 1 extractant with X = CF_3) was quantitative metal loading noted. As X of the *N*-(X)sulfonyl carboxamide group is varied, its electron-withdrawing ability and the acidity of the ionizable function are expected to increase in the order methyl ~ phenyl < 4-nitrophenyl < trifluoromethyl [8, 18]. In general, the Pb^{2+} extraction efficiency within each ligand series follows this ordering.

For single species extractions of Hg^{2+} from 0.25 mM aqueous solutions into 0.25 mM chloroform solutions of

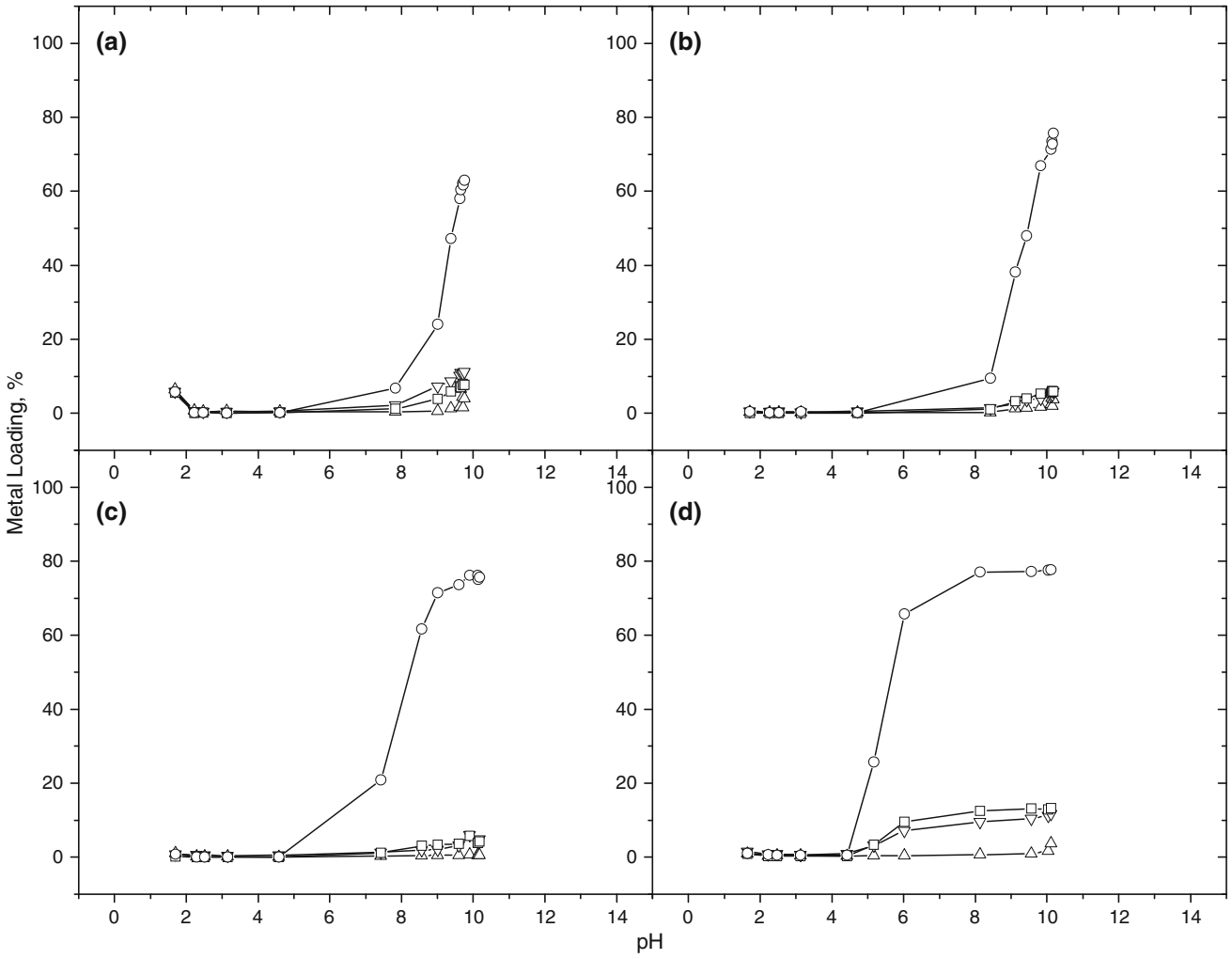


Fig. 8 Metal loading of the organic phase versus pH of the aqueous phase for competitive extractions of alkaline earth metal cations into chloroform by Series 2 lipophilic acyclic polyether di[*N*-(X)sulfonyl carboxamides] **a 14**, **b 15**, **c 16**, and **d 17** (*up-pointing triangle* Mg^{2+}, *down-pointing triangle* Ca^{2+}, *square* Sr^{2+}, *circle* Ba^{2+})

lipophilic acyclic polyether dicarboxylic acids **1** (Series 1), **4** (Series 2), and **20** (Series 3), the profiles are shown in Fig. 3b. Once again for this series of extractants, ligand **20** is the best but its metal loading is only modest. Ligands **1** and **4** exhibited only poor metal loading.

Results for the single species extractions of Hg^{2+} with the lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamide] ligands are given in Fig. 5a–c for extractant Series 1–3, respectively. In striking contrast to low levels of Hg^{2+} extraction found with the lipophilic acyclic polyether dicarboxylic acids **1**, **4**, and **20**, the *N*-(X)sulfonyl carboxamide analogues in Series 1–3 all exhibit high Hg^{2+} loading levels. The Hg^{2+} loading is observed to remain quantitative or nearly so for each of the three extractant series and essentially unaffected as the X group is varied within a series. Clearly the lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamides] in Series 1–3 are very effective agents for extraction of Hg^{2+} from highly acidic aqueous solutions.

Competitive solvent extractions of alkaline earth metal cations by lipophilic di-ionizable acyclic polyether ligands

Competitive extractions for four alkaline earth metal cation species (Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+}) from aqueous solutions (20.0 mM in each) with 1.0 mM chloroform solutions of Series 1–3 extractants were performed. Results for the lipophilic acyclic polyether dicarboxylic acids **1** (Series 1), **4** (Series 2), and **20** (Series 3) are shown in Fig. 6a–c, respectively. All three ligands exhibit selectivity for Ba^{2+} extraction with loading increasing in the order **20** > **4** > **1.**

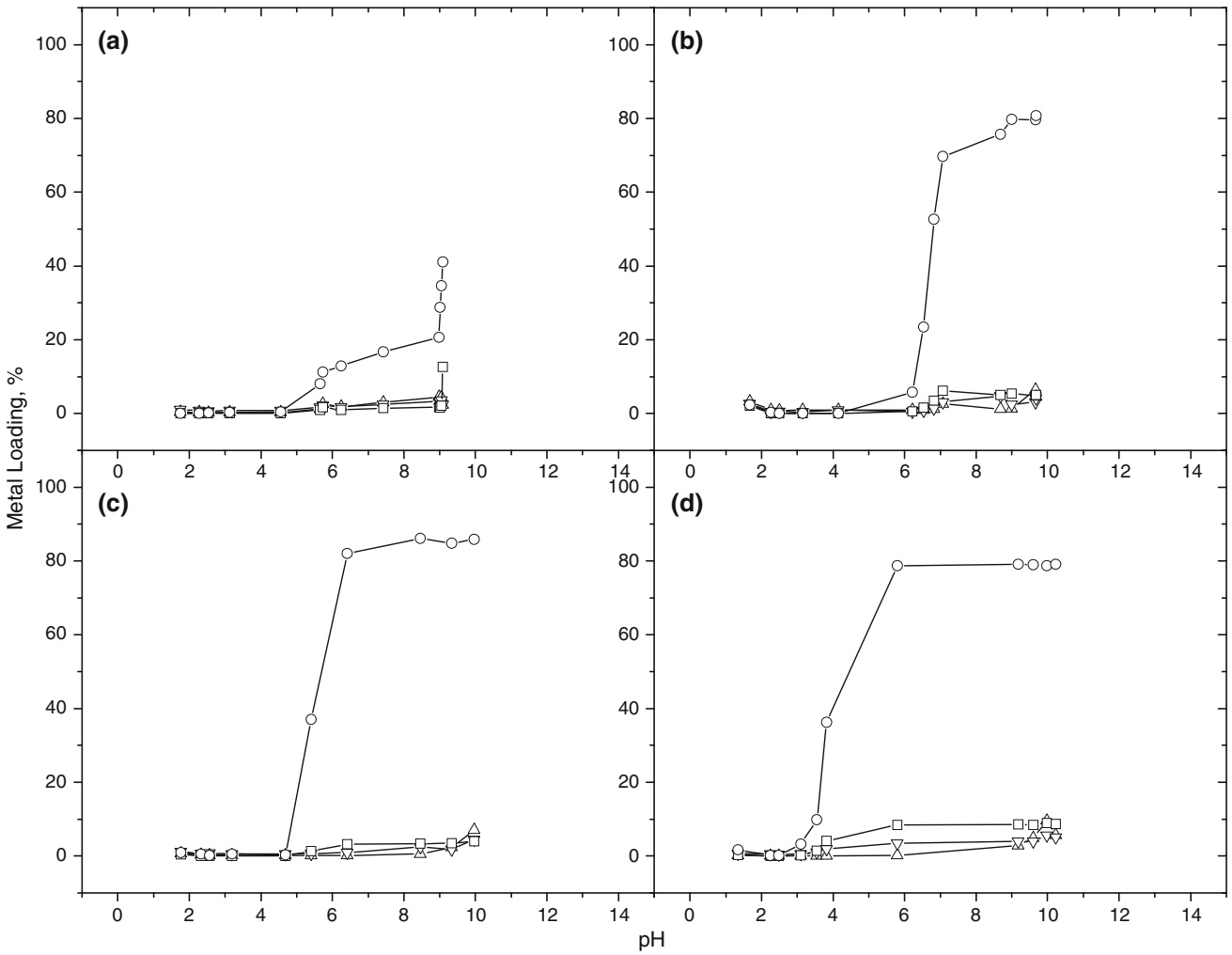


Fig. 9 Metal loading of the organic phase versus pH of the aqueous phase for competitive extractions of alkaline earth metal cations into chloroform by Series 3 lipophilic acyclic polyether di[*N*-(X)sulfonyl carboxamides] **a 21**, **b 22**, **c 23**, and **d 24** (*up-pointing triangle* Mg^{2+}, *down-pointing triangle* Ca^{2+}, *square* Sr^{2+}, *circle* Ba^{2+})

Results for competitive alkaline earth metal cation extractions by the Series 1 lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamide ligands **8–10** are presented in Fig. 7. For all three ligands, the extraction selectivity order is $Ba^{2+} \geq Mg^{2+} > Ca^{2+}$, Sr^{2+} with the greatest Ba^{2+} selectivity observed for **10** with X = CF_3.

For competitive alkaline earth metal cation extractions by the Series 2 lipophilic acyclic polyether dicarboxamide ligands **14–17**, the profiles are recorded in Fig. 8a–d. As can be seen, all four ligands exhibit pronounced Ba^{2+} selectivity with good metal loading. The selectivity for Ba^{2+} extraction over the other alkali metal cations is significantly greater when X is an aryl group (phenyl in **15** and 4-nitrophenyl in **16**) than when X is methyl or trifluoromethyl.

Results for competitive alkaline earth metal cation extractions by the Series 3 lipophilic acyclic polyether di-[*N*-(X)sulfonyl carboxamide] ligands **21–24** are given in Fig. 9a–d, respectively. Ligands **22–24** with X = phenyl, 4-nitrophenyl and trifluoromethyl show excellent Ba^{2+} selectivity with high metal loading. In terms of extraction selectivity and efficiency, lipophilic acyclic polyether dicarboxamide ligands from Series 2 and 3 are superior to those in Series 1.

Summary

Three series of lipophilic di-ionizable acyclic polyethers with common $-O(CH_2CH_2O)_3-$ spacers connecting two aromatic carboxylic acid or aromatic *N*-(X)sulfonyl carboxamide end groups have been synthesized and characterized. The effects of systematic structural variation within the end groups upon their abilities to extract divalent metal ions from aqueous solutions into chloroform were determined. For single species extractions of Pb^{2+}, all of the ligands showed good metal loading from acidic aqueous solutions. For single species extractions of Hg^{2+}, much higher metal loading from acidic aqueous solutions was observed when the end groups were *N*-(X)-sulfonyl carboxamides compared with carboxylic acid analogues. For competitive solvent extractions of alkaline earth metal cations, certain series members with both types of end groups showed high selectivity and efficiency for Ba^{2+} extraction. In general, the extraction propensities of these lipophilic di-ionizable acyclic polyether ligands decreased as divalent metal ion species was varied $Hg^{2+} > Pb^{2+} > Ba^{2+}$.

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References

1. Totten, G.E., Clinton, N.A.: Poly(ethylene glycol) derivatives as phase transfer catalysts and solvents for organic reactions. J. Macromol. Sci., Rev. Macromol. Chem. Phys. **28**, 293–337 (1998)
2. Halpern, M.E. (ed.): Phase-Transfer Catalysis: Mechanisms and Synthesis. ACS Symposium Series 659. American Chemical Society, Washington (1997)
3. Pfeil, A., Lehn, J.M.: Helicate self-organization: positive cooperativity in the self-assembly of double-helical metal complexes. J. Chem. Soc., Chem. Commun. 838–840 (1992)
4. Tummler, B., Maass, G., Weber, E., Wehner, W., Vögtle, F.: Noncyclic crown-type polyethers, pyridinophane cryptands, and their alkali metal ion complexes: synthesis, complex stability, and kinetics. J. Am. Chem. Soc. **99**, 4683–4690 (1977)
5. Kang, S.I., Czech, A., Czech, B.P., Stewart, L.E., Bartsch, R.A.: Competitive solvent extraction of alkaline-earth cations into chloroform by lipophilic acyclic polyether dicarboxylic acids. Anal. Chem. **57**, 1713–1717 (1985)
6. Walkowiak, W., Stewart, L.E., Lee, H.K., Czech, B.P., Bartsch, R.A.: Competitive solvent extraction of alkaline-earth cations into chloroform by lipophilic acyclic diionizable polyethers. Anal. Chem. **58**, 188–191 (1986)
7. McDowell, W.J., Case, G.N., Bartsch, R.A., Czech, B.P.: Solvent extraction of radium and barium cations into chloroform by a lipophilic acyclic polyether dicarboxylic acid. Solvent Extr. Ion Exch. **4**, 411–419 (1986)
8. Elshani, S., Chun, S., Amiri-Eliasi, B., Bartsch, R.A.: Highly selective Ba^{2+} separations with acyclic, lipophilic di-[*N*-(X)sulfonyl carbamoyl] polyethers. Chem. Commun. 279–281 (2005)
9. Love, B.E., Bills, R.A.: Facile synthesis of binol in the absence of solvent. Synth. Commun. **32**, 2067–2073 (2002)
10. Broka, C.A.: Photorearrangements of carbomethoxy-substituted cyclohexadienones in neutral media. J. Org. Chem. **53**, 575–583 (1988)
11. Chan, T.H., Brownbridge, P.: Chemistry of enol silyl ethers. 5. A novel cycloaromatization reaction. Regiocontrolled synthesis of substituted methyl salicylates. J. Am. Chem. Soc. **102**, 3534–3538 (1980)
12. Tamura, Y., Wada, A., Sasho, M., Kita, Y.: Cycloaddition of homophthalic anhydride: a new and simple route to linearly condensed phenolic compounds. Tetrahedron Lett. **22**, 4283–4286 (1981)
13. Gao, Y., Voigt, J., Zhao, H., Pais, G.G., Zhang, X., Wu, L., Zhang, Z., Burke Jr., T. R.: Utilization of a peptide lead for the discovery of a novel PTP1B-binding motif. J. Med. Chem. **44**, 2869–2878 (2001)
14. Tanaka, S., Takesawa, Y., Takahashi, H.: Carboxylic acids and epoxy compounds therefrom and cured epoxy resins. JP Patent 2005162746 (2005)
15. Papa, D., Schwenk, E., Breiger, H.: Reductions with nickel–aluminum alloy and aqueous alkali. Part VI. Naphthalene and its substitution products. J. Org. Chem. **14**, 366–374 (1949)
16. Schwenk, E., Papa, D., Whitman, B., Ginsberg, H.: Reductions with nickel–aluminum alloy and aqueous alkali. Part II. The displacement of groups by hydrogen. J. Org. Chem. **9**, 1–8 (1944)
17. Papa, D., Schwenk, E., Whitman, B.: Reductions with nickel–aluminum alloy and aqueous alkali. J. Org. Chem. **7**, 587–590 (1942)
18. Huber, V.J., Ivy, S.N., Lu, J.P., Bartsch, R.A.: Lariat ethers with a novel proton-ionizable group. Synthesis and solvent extraction of alkali metal cations. Chem. Commun. 1499–1500 (1997)