Complexing Ability of *p-tert*-Butylthiacalix[6]arene toward Metal Ions. Predominant Effect of Coordination by the Bridging Sulfur Rather than That of the Ring-Size

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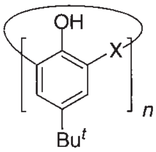
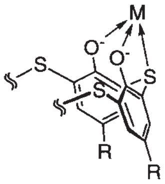
p-tert-Butylthiacalix[6]arene extracted soft to intermediate metal ions to the same extent as the [4] counterpart did, indicating that the O^-,S,O^--tridentate binding manner rather than the effect of ring extension is critical to determine the complexing ability.

Calixarenes are versatile macrocycles which are easily modified with a wide variety of functional groups at the narrower (OH group) and wider rim (the *para* position) in regio- and stereoselective fashions.[1] As one of the potential applications of calixarenes, extractants for specific metal ions have been designed and synthesized by introduction of ligating groups containing O, N, S, and P donor atoms as described in several reviews.[2] In contrast, there have been only few reports on the extraction behavior of metal ions with *p-tert*-butylcalix[*n*]arenes themselves (**C*n*A**, $n = 4$ and 6). For instance, only known example for *p-tert*-butylcalix[4]arene (**C4A**) was Cs^+ ion transport through a liquid membrane containing **C4A** as studied by Izatt.[3] It seems that **C4A** *per se* has quite low binding ability toward metal ions in solvent extraction; we have confirmed that *p*-(1,1,3,3-tetramethylbutyl)calix[4]arene[4] shows almost no extractability toward as many as 42 kinds of commercially available metal ions.[5] On the other hand, extraction behavior of **C6A** consisting of six phenol units has been reported in a couple of publications; extraction of Cu^{2+} ion from ammoniacal alkaline solution by Yoshida,[6] and Pd^{2+}, Ni^{2+}, and Ag^+ ions from the same media by Masuda.[7] These results suggest that extension of the calix skeleton enhances the complexing ability to some extent probably by increase in the donating atoms, namely phenolate O^-, and/or in conformational flexibility to allow the optimization of the coordination geometry.[8]



C*n*A : X = CH_2
TC*n*A : X = S
(n = 4, 6)

In the hope of improving the metal-binding ability of the calix-type molecular framework, we proposed an alternative approach other than modification at the aromatic rims of calixarenes by replacing the methylenes with epithio groups to provide *p-tert*-butylthiacalix[4]arene (**TC4A**).[5,9] We were pleased to know that **TC4A** has a remarkable binding ability toward so called "soft" to "intermediate" metal ions according to the classification based on the "hard and soft acids and bases (HSAB) rule."[10] Elucidated X-ray crystal structures of **TC4A**-metal complexes clearly show that the metal-binding ability of **TC4A** should be brought almost by the ligation of the bridging sulfur with cooperative chelation of the adjacent phenolates (Scheme 1).[11] Then, what would happen in metal extraction upon extension of the ring size of the **TC*n*A** series? Could we expect further enhancement in the complexing ability to **TC6A**, by considering the above-mentioned ring-size effect of **C*n*A** family? Our recent success in obtaining an appreciable amount of **TC6A** by a "dimer method"[12] allowed us to study solvent extraction behavior of it for representative metal ions, and herein we report relevant preliminary results.



Scheme 1. Coordination manner of **TC4A** toward metal ion. For clarity, partial structure of **TC4A** is drawn.

The sulfur bridged **TC6A** was synthesized by condensation of a dimer, 2,2′-thiobis(4-*tert*-butylphenol), with elemental sulfur as described previously.[12] For comparison, extraction behavior of **C6A** was also studied here. The extraction procedure is as follows: To a vial tube (30 cm^3) were pipetted an aqueous solution (10 cm^3) containing a metal ion ($[\mathrm{Metal}]_{\mathrm{aq,init}} = 1.0 \times 10^{-4}$ M) ($\mathrm{M} \equiv \mathrm{mol\,dm^{-3}}$) as well as a pH buffer (0.05 M) and a 10 cm^3 of chloroform solution ([**TC6A** or **C6A**] $= 5.0 \times 10^{-4}$ M).[13] The mixture was shaken for 24 h at 300 strokes per min at 20 ± 3 °C. After the aqueous phase was separated by centrifugation, the total concentration of the metal species remaining in the aqueous phase, $[\mathrm{Metal}]_{\mathrm{aq}}$, was measured by flame AAS or ICP-AES. Percent extraction, $E\%$, was estimated by eq 1.

$$E\% = ([\mathrm{Metal}]_{\mathrm{aq,init}} - [\mathrm{Metal}]_{\mathrm{aq}})/[\mathrm{Metal}]_{\mathrm{aq,init}} \times 100\% \qquad (1)$$

Hence one of the aims of this study was to know the general trend of complexing ability of **TC6A** towards various metal ions, we carried out extraction at varied pHs so wide as no metal hydroxides were formed. The pH dependence of $E\%$ for hard (Na^+, Mg^{2+}, Al^{3+}, Cr^{3+}, and Pr^{3+}), soft (Ag^+ and Au^{3+}), and intermediate metal ions (Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+}) is shown in Figure 1. It can be seen from Figure 1a that **TC6A** does not have coordination ability toward hard metal ions, which is quite similar to the case of **TC4A**.[5,9] Considering the results of the liquid membrane transport study of **C6A**, strong alkaline conditions are necessary for **TC6A** to complex with Na^+. The conditions, however, would precipitate metal hydroxides for other hard metal ions.

Among the soft metal ions, it should be noted that Ag^+ was extracted quantitatively from acidic to weakly basic pH region (Figure 1b), showing very high affinity of **TC6A** to Ag^+ ion. This sharply contrasts the fact that **C6A** extracts Ag^+ ion only at extremely high pH (>13).[7] The difference clearly indicates the

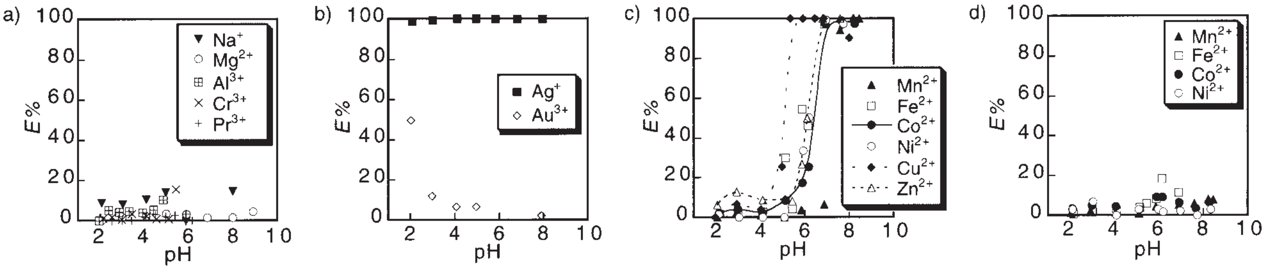


Figure 1. The pH dependence of percent extraction for a) hard, b) soft, and c) intermediate metal ions by **TC6A** and d) by **C6A**. $[\text{Metal}]_{\text{aq,init}} = 1.0 \times 10^{-4}$ M, [**TC6A** or **C6A**]$_{\text{org}} = 5.0 \times 10^{-4}$ M, 300 strokes per min, 20 ± 3 °C, 24 h.

contribution of bridging sulfur of **TC6A** in the binding to Ag^+ ion. Figure 1b also shows that Au^{3+} was preferably extracted at lower pH region. In fact, Au^{3+} in 2.0 M HNO_3 solution was extracted by **TC6A** at $E\% = 86\%$ (data not shown). In the highly acidic media, all the six OH group of **TC6A** may retain the protons so that **TC6A** might act as a neutral ligand to form a cationic complex with Au^{3+} to be extracted as an ion-associate with NO_3^- ions. However, Au^{3+} was not extracted ($E\% = 0\%$) from 2.0 M HCl solution, suggesting that formation of the tetrachloro complex, $[AuCl_4]^-$, inhibited the extraction.

The $E\%$ for transition metal ions classified as intermediate showed pH dependence (Figure 1c); all the metal ions were hardly to sparingly extracted from acidic to weakly acidic solutions, while the extractability increased rapidly at the pH of 4–6 to reach to almost quantitative extraction. This suggests that OH groups of **TC6A** released the protons to coordinate to metal ions as O^-. This is in sharp contrast to the extraction behavior of **C6A**; Cu^{2+} and Ni^{2+} were only extracted from ammoniacal alkaline solutions of pHs >10 and >13, respectively.[6,7] For comparison, we performed the extraction of selected transition metal ions with **C6A** under the same conditions used for **TC6A** (Figure 1d). It may be obvious that **C6A** has little extractability, here again guaranteeing a superior complexing ability of **TC6A** to **C6A**.

In order to compare the extractability of **TC6A** with that of **TC4A**, half extraction pH of the former, at which $E\% = 50\%$, was roughly estimated from Figure 1c to be $pH_{1/2} = 6.4$, (Co^{2+}), 5.1 (Cu^{2+}), and 6.1 (Zn^{2+}). On the other hand, $pH_{1/2}$ for **TC4A** was calculated from the extraction constant, K_{ex}, reported previously;[9] $pH_{1/2} = 6.2$, (Co^{2+}), 5.3 (Cu^{2+}), and 6.2 (Zn^{2+}). Although the composition of the extracted **TC6A** complex in the organic solvent is unknown, it may be said that the extension of the thiacalix[n]arene ring from $n = 4$ to 6 does not bring about so much change in the extractability, showing obvious difference from the above-mentioned case of **C*n*A** that has small but distinct ring-size effect. In other words, increased conformational flexibility and number of available coordination sites such as phenolate and bridging sulfur do not so much enhance the extraction ability of **TC*n*A** derivatives. This may suggest that the complexing ability of **TC6A** mainly relies on the binding fashion via O^-,S,O^- similar to that of **TC4A** (Scheme 1). The tridentate binding mode is compatible with the metal-ion selectivity of **TC6A** preferring soft to intermediate metal ions, as **TC4A** likes these entities.

In conclusion, the present study has shown that **TC6A** has considerably higher complexing ability toward soft to intermediate metal ions than **C6A**, which should be ascribed to the coordination of the bridging sulfur. On the other hand, the enlargement of the **TC4A** ring to **TC6A** scarcely affected the extraction ability and selectivity toward metal ions, showing that the O^-,S,O^--tridentate coordinating manner surpasses the effect of the increase in the number of phenolate and flexibility of the macrocyclic ring.

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8 It should be also noted that liquid membrane containing **C6A** has higher flux for alkali cations than the **C4A** counterpart does, although mass flux through a liquid membrane is controlled by rate processes for complexation and mass transfer.[3]

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13 Calixarene ligand **C6A** was purchased from Tokyo Kasei Kogyo Co., Ltd. (Tokyo) and was recrystallized from dichloromethane-methanol prior to use. The pH of the aqueous phase was adjusted with buffers HNO_3-NH_3 (2.0), glycine-HNO_3 (2.5–3.5), succinic acid-NH_3 (4.0–5.0), MES-NH_3 (5.5–6.0), PIPES-NH_3 (6.5–7.0), Tris-HNO_3 (7.5–8.5), and CHES-NH_3 (9.0–10.0). To suppress spontaneous oxidation of Fe^{2+} to Fe^{3+}, L-ascorbic acid was added to the aqueous phase (2.0×10^{-4} M).