An extended tetrathiafulvalene redox-ligand incorporating a thiophene spacer

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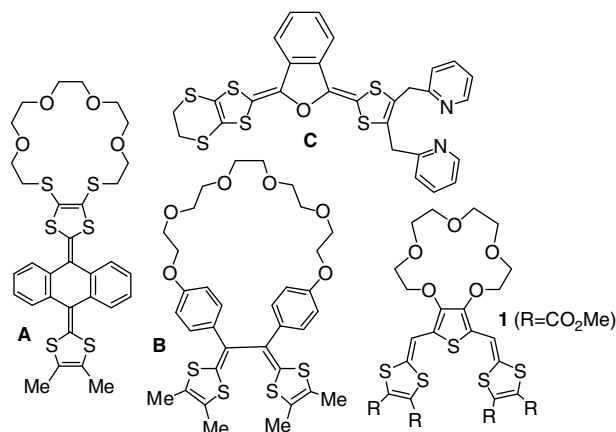
ABSTRACT

An extended tetrathiafulvalene derivative incorporating a thiophene spacer and a fused crown-ether unit has been synthesized. This highly delocalized system exhibits remarkable electrochemical recognition properties for Na^+ and Ba^{2+} as shown by cyclic voltammetry in methylene chloride. This result is attributed to the proximity between the guest metal cation and the positive charge of the oxidized ligand, which is located on the central conjugated thiophenic part.

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Redox-responsive ligands[1–5] are built from the association of a binding unit and an electroactive moiety (ferrocene, quinone, tetrathiafulvalene (TTF), etc.). In this context, a broad range of TTF-based receptors presenting various binding sites have been described,[6–9] such as crown-ether derivatives[10–13] or receptors with a coordinating acyclic domain.[14–16] The recognition process between the receptor and a cationic guest is accompanied by a modification of the redox potentials of the TTF unit, resulting in an electrochemical sensing of the binding event. Anion sensing has also been recently described from analogous TTF-based systems incorporating suitable binding units.[17–24] One important interest of TTF-based systems lies in their two fully reversible one electron oxidation steps (Ep_a^1, Ep_a^2), which are associated to three stable oxidation states. Therefore, the binding ability of these host assemblies can be tuned as a function of the oxidation state of the electroactive TTF part.[15] Another interest of the TTF unit resides on chemical structural flexibility, which allows to tune the redox potentials of the electroactive signalling unit by a suitable substitution on the periphery, or by insertion of a π-conjugated spacer between the 1,3-dithiol-2-ylidene rings.[25,26] In that case, a strong modification of the charge distribution is observed in the donating molecule, which explains why π-extended TTF structures have been extensively explored in particular as precursors for the preparation of solid-state electroconducting cation radical salts,[27–29] or as strong donating (D) counterparts in donor–acceptor (D–A) dyads.[30] Extended-TTF skeletons are much rarely found in redox-active receptors. Considering that recognition process with

redox-responsive ligands is strongly dependent on electrostatic interactions occurring between the guest cation and the electroactive unit, it is of strong interest to study the case in which the redox moiety consists in an extended-TTF derivative. One case is **A**,[31] and related polyether derivatives which have been described recently.[32] Also, a crown-ether vinylogous TTF receptor **B** has been very recently used for tuning molecular movements,[33] and a new extended TTF-based receptor **C** presenting two pyridyl functional groups for guest coordination has been built by inserting a furano-quinonoid spacer between both 1,3-dithiol-2-ylidene rings.[34]

It is well established that the nature of the conjugated spacer in extended-TTF derivatives has a strong influence on the electrochemical properties of the π-donors.[27] In particular, insertion of a

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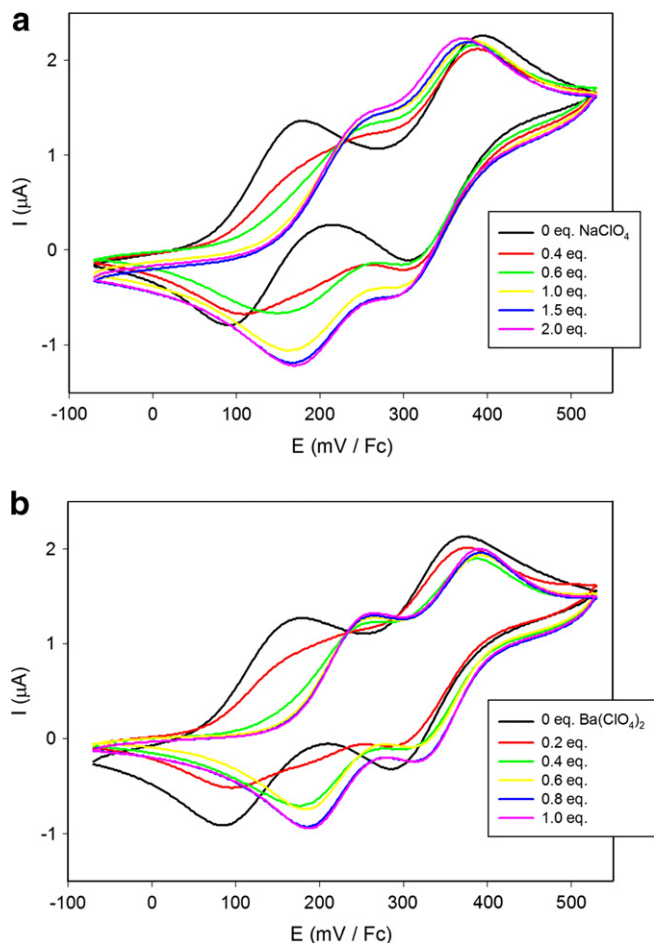
Figure 1. Cyclic voltammograms of 1 (10^{-3} mol L^{-1} in 0.1 M Bu_4NPF_6 in CH_2Cl_2) in the presence of increasing amounts of $NaClO_4$ (a) and $Ba(ClO_4)_2$ (b); vs Fc/Fc^+.

Scheme 1.

Table 1
Peak−potentials versus Fc/Fc^+, $C = 10^{-3}$ mol L^{-1} in CH_2Cl_2 (Bu_4NPF_6, 0.1 M), $v = 100$ mV s^{-1}, Pt, rt

	1	**D**[45]	**E**[46]
E_{ox}^1	0.18	0.50	0.22
E_{ox}^2	0.39	0.90	0.41

thiophene ring as a spacer has been achieved,[35,36] and the reversible electrochemical properties of these π-donors[28] make this extended skeleton a suitable candidate as an electroactive moiety in redox sensors. Finally, it has been demonstrated that crownethers fused to thiophene units present a good ability to recognize alkali ions in corresponding polythiophene and oligothiophene systems.[37–41]

In this context, recent reports on ligands **B** and **C** prompt us to report the synthesis and the recognition properties of a molecular receptor **1**, presenting a thiophene-based extended-TTF skeleton as the redox-active unit.

Diester derivative **3** was synthesized according to the literature procedure,[42] by [1+1] cyclocondensation of 3,4-dihydroxythiophene-2,5-dicarboxylate **2** with tetraethylene glycol ditosylate in the presence of CsF (Scheme 1). Reduction using lithium aluminium hydride afforded diol **4** in 45% yield. Conversion to the 2,5-diformyl thiophene derivative **5** was carried out using pyridinium dichromate (40%). Note that attempts to directly reduce diester **3**–**5** with Dibal-H failed. The final step involves a double Wittig-type olefination of **5** with an excess of the phosphonium-ylid **6** [43] bearing a 1,3-dithiol moiety, in the presence of triethylamine. The target compound **1** was obtained as a red powder, in good yields (70%) considering the double olefination step.[44]

Redox properties of **1** have been evaluated by cyclic voltammetry (CV) in methylene chloride (Fig. 1). As expected, ligand **1** presents two fully reversible monoelectronic oxidation processes (Table 1), corresponding to the successive formation of cation radical and dication species.
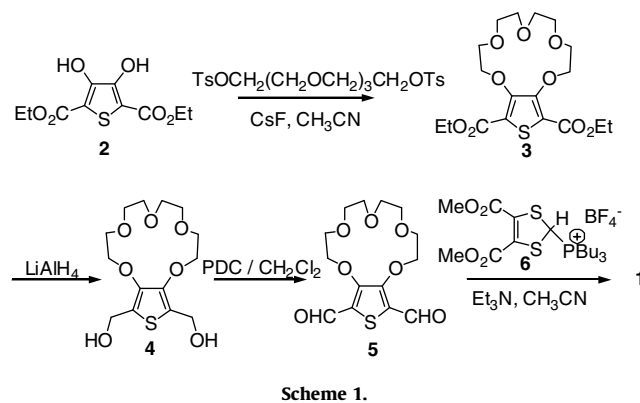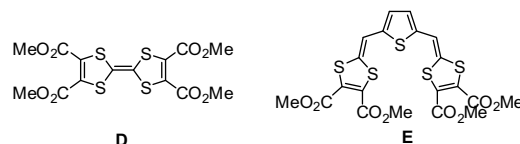
Comparison of **1** with the reference TTF analogue **D** bearing four tetracarbomethoxy substituents is meaningful (Table 1). The significantly lower oxidation potentials observed for **1** relative to **D** are due to the combined effect of the occurrence of a more extended conjugation in the former case and the presence of donating alkoxy substituents at the 3,4-positions of the central thiophene ring. The difference between the two oxidation potentials in **1** ($\Delta E_{2-1} = E_{ox}^2 - E_{ox}^1 = 210$ mV) is lower than the value observed for **D** ($\Delta E_{2-1} = 400$ mV).[45] Indeed, extension of the conjugated spacer between both dithiole units favors the access to the dication state by decreasing the coulombic repulsion between both positive charges. Conversely, the value of ΔE_{2-1} for **1** is higher than for the parent system **E**[46] devoid of any substituent on the central thiophene ring ($\Delta E_{2-1} = 190$ mV). This observation indicates that in the case of **1**, a larger coulombic repulsion exists in the dication state. A similar effect was also observed for extended-TTFs built with a 3,4-dialkoxythiophene unit as the spacer, and reveals a tendency for the oxygen atoms directly linked to the thiophene moiety, to localize positive charge in the central position.[47]

Such an electrochemical characteristic is of course of importance when considering the context of redox-responsive ligands, for which electrostatic effects between a bound cation and the electroactive unit play a crucial role.

Binding ability of receptor **1** for various cations was studied by CV(CH_2Cl_2, Bu_4NPF_6 0.1 mol L^{-1}). Important modifications could be observed upon addition of increasing amounts of $NaClO_4$ or $Ba(ClO_4)_2$. Addition of controlled amounts of sodium perchlorate caused a strong positive shift ($\Delta E_{ox}^1 = +90$ mV) of the first oxidation potential (E_{ox}^1), whereas E_{ox}^2 remained approximately constant (Fig. 1a). The reason why the first oxidation wave is shifted to more anodic potentials is explained by the electrostatic inductive effect promoted by the bound metal cation, which decreases the π-donating ability of the adjacent redox unit. Such a positive shift of ΔE_{ox}^1 is remarkably high and comparable to the highest values reported for TTF-based redox-responsive ligands. This result is

attributed to the localization of the positive charge in $1^{.+}$ on the median thiophene ring[47] (*see above*), that is near the bound cationic guest. On the other hand, the constant value of E_{ox}^2 upon addition of sodium cation indicates that for the dicationic stage (1^{2+}), expulsion of the metal cation outside from the polyether-cavity takes place, because of the repulsive electrostatic interaction. A very similar electrochemical behaviour was observed for **1** in presence of LiClO$_4$ (see Supplementary data) ($\Delta E_{ox}^1 = +55$ mV, $\Delta E_{ox}^2 \approx 0.0$ mV). Also, the addition of a group II cation (Ba(ClO$_4$)$_2$) is accompanied by an electrochemical signature ($\Delta E_{ox}^1 = +90$ mV, $\Delta E_{ox}^2 \approx 0.0$ mV) (Fig. 1b). In this case, no additional evolution of the CV was observed for more than 0.5 equiv in barium perchlorate, which suggests a 2:1 stoichiometry for the corresponding complex.

UV–vis titration experiments were also carried out with receptor **1** in the presence of alkali and alkali earth cations (see Supplementary data). In methylene chloride, the addition of controlled amounts of sodium perchlorate up to 1 equiv provokes a strong variation of the shape of the absorption band with in particular the decreasing of the vibronic fine structure and the formation of isosbestic points. For more than 1 equiv, no significant additional modification of the absorption spectrum is observed. In presence of Ba(ClO$_4$)$_2$, the change in the spectrum is similar with, in this case, an evolution of the absorption band until the addition of 0.5 equiv, as expected for the 2:1 stoichiometry observed by the CV study. On the other hand, no metal complexation occurs in more polar solvents, as shown by the absence of any evolution by addition of sodium or barium cation with CH$_3$CN as solvent.

Attempts for reproducing these results by ^{1}H NMR failed because the resulting complex precipitates at NMR concentrations in the NMR tube, when using a chlorinated solvent (CDCl$_3$, CD$_2$Cl$_2$). Conversely, use of a more solvating mixture (CDCl$_3$–CD$_3$CN; 1/1) did not allow observation of any chemical shift upon introduction of a metallic salt (NaClO$_4$, Ba(ClO$_4$)$_2$).

In summary, we have presented a synthetic access to a redox-responsive ligand built around an extended tetrathiafulvalene unit incorporating a thiophene ring as spacer. The electrochemical recognition properties for Na$^+$ and Ba^{2+} are remarkable in methylene chloride. This ability to electrochemically detect a guest cation is assigned to the conjunction of a suitable location of the binding site related to the redox unit, associated to a contribution of the electrodonating O-atoms which are directly connected to the central conjugated thiophene spacer.

Acknowledgements

Supplementary data

Uv-vis and CV titration studies of receptor **1** in presence of alkali and alkali earth cations. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2008.07.005.

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44. *All new compounds exhibited spectral properties consistent with the assigned structures*: Compound **4**: white viscous oil, ^{1}H NMR (500 MHz, CDCl$_3$): 2.41 (br s, 2H, OH), 3.68 (br s, 8H, OCH$_2$), 3.85 (t, 4H, OCH$_2$), 4.21 (t, 4H, OCH$_2$), 4.63 (s, 4H, CH$_2$OH); ^{13}C NMR (125.7 MHz, CDCl$_3$) 56.8, 70.5, 70.6, 71.0, 73.3, 123.5, 146.1. Compound **5**: pale yellow solid, mp 88 °C; ^{1}H NMR (500 MHz, CDCl$_3$): 3.68 (br s, 4H, OCH$_2$), 3.72 (br s, 4H, OCH$_2$), 3.92 (t, 4H, OCH$_2$), 4.52 (t, 4H, OCH$_2$), 10.06 (s, 2H, CHO); ^{13}C NMR (125.7 MHz, CDCl$_3$): 70.0, 70.6, 70.8,75.1, 130.4, 154.4, 181.9; MS (EI) 330 [M$^+$]. Compound **1**: red–orange solid, mp 159 °C; ^{1}H NMR (500 MHz, CDCl$_3$): 3.71 (s, 8H, OCH$_2$), 3.85 (s, 6H, OCH$_3$), 3.88 (s, 6H, OCH$_3$), 3.89 (t, 4H, OCH$_2$), 4.16 (t, 4H, OCH$_2$), 6.64 (s, 2H, =CH); ^{13}C NMR (125.7 MHz, CDCl$_3$): 53.3, 70.3, 70.7, 71.1, 73.6, 105.9, 122.3, 127.1, 130.9, 131.2, 144.8, 159.9, 160.0; HRMS (ESI+) Calcd for C$_{28}$H$_{30}$O$_{13}$S$_5$: 734.0290; found: 734.0310.
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