Self-assembled monolayers of bis-thioctic ester derivatives of oligoethyleneglycols: remarkable selectivity for K⁺/Na⁺ recognition†

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Bis-thioctic ester terminated derivatives of oligoethylene glycols form extremely stable self-assembled monlayers (SAMs) on gold electrodes and these can recognize K⁺ selectively over Na⁺, as measured by cyclic voltammetry and impedance spectroscopy.

The incorporation of crown-ether groups into self-assembled monolayers (SAMs) and their potential as metal ion sensors was reported very recently and almost simultaneously by Moore *et al.*[1] and by Flink *et al.*[2] In one case they prepared simple 12-crown-4 and 15-crown-5 derivatives with appended single chains terminated in thiol groups, and impedance spectroscopy was used to monitor ion binding events on the surface.[2] The other reported crown-annelated TTF derivatives which also contained single alkyl chains terminated in thiol groups.[1] The latter work exploited the direct response of the electroactive surface-confined crown-TTF groups to measure the effect of ion complexation, similar to previously reported work in homogeneous solution by Hansen *et al.*[3] These SAMs were apparently not very stable under several sets of conditions and the electrochemical responses observed were very weak and poorly resolved.[1] We have recently prepared and studied bis-thioctic ester derivatives of crown ether annelated TTFs, and these form remarkably stable SAMs, some of which are able to detect alkali metal ion binding electrochemically.[4] Here we report the easy synthesis, remarkable stability, and electrochemical (cyclic voltammetric and impedance) responses of SAMs of bis-thioctic ester derivatives of oligoethylene glycols (podands). The general idea was to use the glycols to form ion binding domains on the surface (similar to crown ethers) *via* self-assembly. The SAMs prepared showed amazing stabilities and selectivities for K⁺ over Na⁺ binding, making them potentially useful monolayer sensors.

Compounds **1–3** were easily synthesized in high yield by reacting the corresponding bis-alcohols [HO(CH₂CH₂O)₄CH₂-CH₂OH or HO(CH₂)₁₂OH] with thioctic acid in CH₂Cl₂ in the presence of DCC and 4-pyrrolidinopyridine or DMAP.[5] Compounds **1** and **3** were obtained from the same reaction as two separate products.
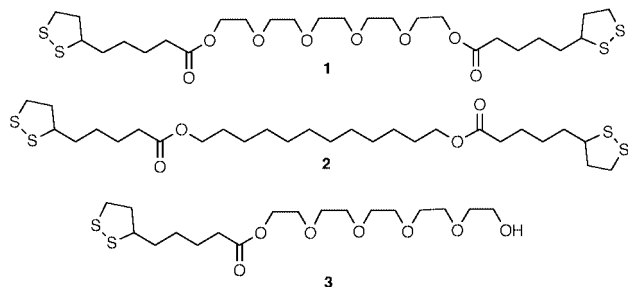
Glass-sealed, ultra-clean spherical gold bead electrodes prepared from ϕ 250 μm gold wire (99.9999%) were dipped into 5 mM EtOH solutions of the corresponding bis- or mono-

thioctic ester compounds **1–3** for 24 h to form the corresponding SAMs.[6] After washing these with absolute EtOH and drying them in an Ar flow, these SAM modified electrodes were placed into 0.1 M aqueous Et₄NCl and the cyclic voltammograms (CVs) for 1 mM Ru(NH₃)₆³⁺/²⁺ were recorded, using a platinum coil as counter and a Ag/AgCl as reference electrodes. The impedance response was also measured at the $E_{1/2}^0$ (−0.25 V) for the Ru(NH₃)₆³⁺/²⁺ redox couple, between 1 kHz and 0.1 Hz.[7]

The CV response for the Ru(NH₃)₆³⁺/²⁺ couple at a modified gold electrode of **1** is shown in Fig. 1(*a*) (dotted line).[8] It is clear that the insulating effect of the monolayer is poor, since the redox couple relatively easily undergoes electron transfer at the interface. This probably reflects poor surface coverage or good electron permeability through the monolayer. Interestingly, addition of 30 mM KCl to the solution results in a drastically reduced cathodic current and in the disappearance of the
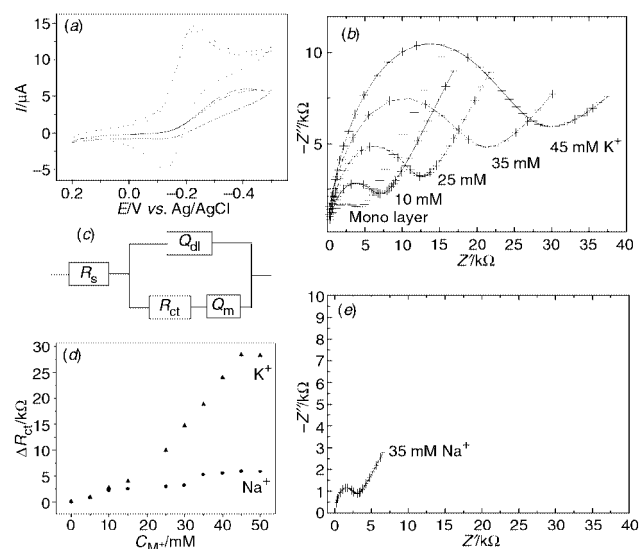
Fig. 1 (*a*) Cyclic voltammogram of Ru(NH₃)₆³⁺/²⁺ in 0.1 M Et₄NCl using a monolayer-modified gold electrode (area = 0.02 cm²) prepared from **1** before (dotted line) and after (solid line) addition of 30 mM of K⁺ to the solution at a scan rate of 100 mV s⁻¹. (*b*) Impedance response of the same modified gold electrode in the absence and in the presence of varying amounts of [K⁺]. The solid lines represent the fits of the experimental points to the equivalent circuit shown in (*c*). (*c*) Equivalent circuit used to fit the experimental data: R_S represents the solution resistance. The monolayer is described by a constant phase element Q_{dl} (used here as a generalized capacitance) in parallel with a resistance R_{CT} (the charge transfer resistance) and another constant phase element (Q_m) (related to diffusion controlled processes) in series. In admittance representation, a constant phase element is defined as $Y(\omega) = Y_0 (j\omega)^n$ where Y_0 and n are adjustable parameters, n = 0, 1 and 0.5 correspond to an ideal resistor, a capacitor and a Warburg element, respectively, and ω is the angular frequency. The R_{CT} values can also directly be obtained from the diameter of the high frequency 'semicircle'. (*d*) Plot of the relative change of R_{CT} with [K⁺] and with [Na⁺]. (*e*) Impedance response of the same modified gold electrode in the presence of 35 mM NaCl. The response is essentially identical to that of the initial monolayer, see Fig. 1(*b*).

corresponding anodic process, indicating that electron transfer at the interface is dramatically inhibited, see Fig. 1(*a*) (solid line). On the other hand, addition of Na$^+$ has essentially no effect on the voltammetric response of this redox couple. These observations are consistent with complexation of K$^+$ (but not Na$^+$) with the monolayer, resulting in partial repulsion of the positively charged Ru(NH$_3$)$_6^{3+/2+}$ redox pair when K$^+$ is present. Note that the blocking effect due to K$^+$ addition is not perfect and some current is still observed.

Since none of the structural components of the SAM are electroactive, impedance spectroscopy was used to further probe ion recognition at the interface.[2] The impedance response for the same monolayer for which the CV is shown in Fig. 1(*a*) was measured in the absence and in the presence of increasing [K$^+$], and the data are presented in Fig. 1(*b*), as a Nyquist plot. Note that a very small R_{CT} (charge transfer resistance, determined as the diameter of the high frequency semicircle) is observed for the monolayer alone in the absence of K$^+$, 4.8 kΩ, and a significant diffusion component is observed as the linear portion at lower frequencies, indicating inefficient blocking to charge transfer. The fractional surface coverage (θ) was calculated to be 0.96 following well-established procedures.[9] These observations are consistent with the CV data already described, which showed that the SAM is either loosely packed or allows close approach of the redox probe to the modified electrode surface. Addition of K$^+$ to the solution resulted in dramatic and *reversible* increases in the R_{CT} values, from 7 kΩ at 5 mM to a limiting value of 31 kΩ at 45 mM, indicative of K$^+$ complexation at the interface and repulsion of the positively charged redox probe, in perfect agreement with the CV observations.[2] These values were obtained by a non-linear least-square fit of the experimental data to the equivalent circuit shown in Fig. 1(*c*), using the program EQUIVALENT CIR-CUIT.[2] A plot of ΔR_{CT} *vs.* [K$^+$] shows two linear regions at different concentration ranges, and these intersect around 17 mM [K$^+$]. This complex ion response is in agreement with the non-linear fits, which yield different slopes for the CPE [Fig. 1(*b*)] and thus different '*n*' parameter values. At 45 mM KCl the surface binding sites must be saturated and no R_{CT} changes are observed with further salt additions. These SAMs are very stable and the results can be reproduced repeatedly over the course of days. With a useful range of 17–45 mM [K$^+$], this is not a practical sensor, but the novel principles established here should lead to improved designs in the future.

The same SAM electrode used to probe [K$^+$] was placed in solutions with increasing NaCl concentrations. The impedance results are presented in Fig. 1(*e*). In agreement with the results obtained by cyclic voltammetry, Na$^+$ showed almost no effect on the R_{CT} value of the monolayer [Fig. 1(*d*)], indicating that it is not binding significantly with the surface and thus not increasing its blocking effect. Simply based on the observations presented in Fig. 1(*b*) and (*e*) it is fair to say that a monolayer of **1** can act as a reversible and highly selective sensor for K$^+$ over Na$^+$. The selectivity for K$^+$ over Na$^+$ suggests the formation of a surface-confined *pseudo*-18-crown-6 structure, but further characterization is needed. Sensitivity, on the other hand, is not high, partly due to the inherent limitations of impedance response under the present conditions.

Control experiments with compounds **2** and **3** confirm the stated hypothesis. Compound **2** forms an initial monolayer which is a better insulator than **1** for charge transfer, as indicated by a high R_{CT}, 25 kΩ, but it exhibits no R_{CT} changes upon

exposure to either K$^+$ or Na$^+$. That the initial monolayer is a good insulator is not surprising in view of its high hydrocarbon content. The mono-ester compound **3** has almost no charge transfer blocking ability in the absence or presence of alkali metal ions, and behaves essentially as a bare gold electrode.

In summary, we have prepared remarkably stable monolayers containing oligoethylene glycols on gold beads, and these exhibit impedance changes in the presence of K$^+$ but not with Na$^+$. While far from being useful sensors, the present SAMs are conceptually novel structures with unique cation binding properties exhibiting high selectivity.

Notes and references

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5 All new compounds were fully characterized by spectroscopic tech-niques. *Selected data* for **1**: yellow liquid, yield 72%; δ_H (CDCl$_3$) 4.23 (4H, t, *J* 6.0), 3.65–3.70 (16H, m), 3.53–3.62 (2H, m), 3.07–3.20 (4H, m), 2.42–2.51 (2H, m), 2.35 (4H, t, *J* 7.2), 1.86–1.96 (2H, m), 1.61–1.69 (8H, m), 1.41–1.50 (4H, m); δ_C(CDCl$_3$) 173.61, 70.99, 70.95, 70.93, 69.52, 63.76, 56.66, 40.55, 38.82, 34.91, 34.29, 29.00, 24.98; *m/z* (FAB$^+$) 614 (M$^+$, 60%) [HRMS (FAB$^+$): found 614.2074, calc. for C$_{26}$H$_{46}$O$_8$S$_4$: 614.2074]; v_{max}(neat)/cm^{-1} 2918, 2851, 1733, 1457, 1380, 1247, 1128, 947, 857, 733. For **2**: yellow liquid, yield 71%; δ_H(CDCl$_3$) 4.06 (4H, t, *J* 6.6), 3.52–3.61 (2H, m), 3.09–3.22 (4H, m), 2.43–2.49 (2H, m), 2.31 (4H, t, *J* 7.2), 1.87–1.96 (6H, m), 1.59–1.76 (16H, m), 1.43–1.51 (4H, m), 1.24–1.32 (8H, m); δ_C(CDCl$_3$) 173.85, 140.08, 64.82, 40.55, 38.81, 38.78, 36.94, 35.25, 34.44, 34.39, 33.56, 29.86, 28.99, 26.71, 25.08, 25.01, 23.38; *m/z* (FAB$^+$) 578 (M$^+$, 100%). For **3**: yellow solid, yield 45%; δ_H(CDCl$_3$) 4.22–4.25 (2H, m), 3.66–3.73 (18H, m), 3.59–3.62 (1H, m), 3.13–3.19 (2H, m), 2.41–2.52 (1H, m), 2.33—2.38 (2H, m), 2.13 (1H, s), 1.90–1.94 (1H, m), 1.59–1.75 (4H, m), 1.23–1.34 (2H, m); *m/z* (FAB$^+$) 426 (M$^+$, 100%).
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7 Impedance measurements were performed using a three electrode cell configuration with a monolayer-coated gold bead, a coiled platinum wire and Ag/AgCl as working, counter and reference electrode, respectively. The potential was held at the formal potential of the redox couple, and readings were taken at ten discrete frequencies per decade with an ac amplitude of 5 mV. The formal redox potential [$E_{\frac{1}{2}} = (E_p^c + E_p^a)/2$], where [Ru(NH$_3$)$_6^{3+}$] = [Ru(NH$_3$)$_6^{2+}$] was determined from cyclic voltammetry. Impedance analysis was carried out using the commercially available program EQUIVALENT CIRCUIT written by B. A. Boukamp (University of Twente), which determines the parameters of the assumed equivalent circuit by a non-linear least-square fit.
8 All electrochemical experiments were performed using a BAS-100W system. Electrolyte solutions were prepared from recrystallized materials using spectroscopic grade solvents and purged with argon prior to use. A three-electrode configuration was used with a Ag/AgCl reference electrode and a platinum wire as the counter electrode.
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