Guest Selective Molecular Recognition by an Octadecylsilyl Monolayer Covalently Bound on an SnO_2 Electrode

Kazuo Yamamura,* Hitoshi Hatakeyama, Kensuke Naka, (the late) Iwao Tabushi, and Kazue Kurihara

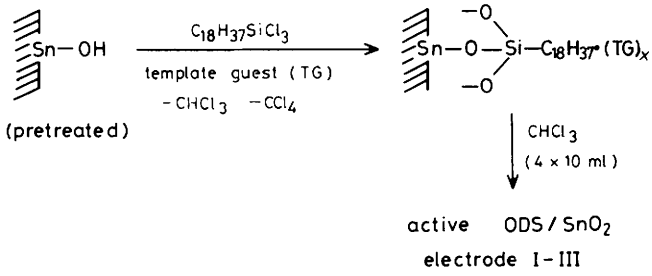
Department of Synthetic Chemistry, Kyoto University, Sakyo-ku, Kyoto 606, Japan

An octadecylsilyl monolayer on SnO_2, which was prepared in the presence of a template guest molecule, was guest binding selective.

The linking of monolayer[1—4] and molecular recognition chemistry[5—7] should provide a new promising area of research. For example, we have shown recently that an octadecylsilyl (ODS) monolayer, ODS/SnO_2 (covalently bound on an SnO_2 electrode by Sagiv's surface modification technique),[4] acquired molecular recognition ability towards guest molecules having long, thin hydrophobic tails (*e.g.*, chlorophyll, or vitamins K_1, K_2, or E *etc.*).[8] The results provided a new access to a 'supramolecular' sensor, the amperometric response of which was sensitive enough to detect vitamin K_1 at a concentration as low as 10^{-6} M.[8]

Herein we report that the molecular recognition by the ODS/SnO_2 monolayer has been made guest selective through co-implanting template guest (TG) in the ODS monolayer followed by extracting out the TG to leave host binding sites (Scheme 1).

The first example of the present type of surface modification was reported by Sagiv,[4] and the nature of the adsorbate/surface bonding has been intensively investigated.[4] In the present work, the template guest molecule, n-hexadecane (**1**), 2-cholesteryl 3,6-dioxadecyl carbonate (**2**), or decyl adamantane-1-carboxylate (**3**),[9] plays a key role in the SnO_2 modification by the ODS monolayer (*vide infra*). Thus, SnO_2 electrodes (1 × 3 cm, pretreated with conc. HNO_3, H_2O, 2 × 10^{-2} M aqueous NaOH, and H_2O successively) were treated with a 6.3 × 10^{-4} M solution of octadecyltrichlorosilane in a 10 ml mixture of TG (**1**), (**2**), or (**3**)–$CHCl_3$–CCl_4 (8:0.8:1.2, v/v/v) (Scheme 1) for 10 min at room temperature. The ODS/SnO_2 monolayers were soaked in $CHCl_3$ (4 × 10 ml) to extract out the TG, affording 'active' ODS/SnO_2 electrodes, I—III, respectively (Scheme 1). When used as the working electrode in a cyclic voltammetric cell system, the 'active' ODS/SnO_2 electrode III respond to vitamin K_1 (**4**) at −0.7 V *vs.* Ag/AgCl at a scanning rate of 200 mV/s in MeOH–H_2O (3:2, v/v) containing 0.1 M KCl and 20 mM phosphate buffer (pH 7.0). As a typical example, the observed cyclic voltammetric response of electrode I is depicted in the inset of Figure 1. The cathodic peak current, i_{pc}, due to the vitamin K_1 reduction increased from 2.8 to 53 μA/cm² with an increase of vitamin K_1 concentration from 7.5 × 10^{-8} to 4.5 × 10^{-6} M. For the 'inactive' ODS/SnO_2 electrodes without $CHCl_3$ treatment,



Scheme 1

Electrode Template guest (TG)

I

$n\text{-}C_{16}H_{34}$, (1)

II

(2)

III

(3)

(4), vitamin K_1

(5)

(6)

i_{pc} was very small, *e.g.*, 8 ± 1 μA/cm² for electrode I even at a high concentration of vitamin K_1 (3×10^{-6} M).

The 'active' ODS monolayer similarly made on SiO_2 [ODS/SiO_2 I, TG = $n\text{-}C_{16}H_{34}$ (**1**)] adsorbed other guest molecules having long, thin hydrophobic tails such as chlorophyll a, 3-phytyloxypyrene-5,8,10-trisulphonate, or 3-hexadecyloxypyrene-5,8,10-trisulphonate, as shown by the observed electronic absorption band at $\lambda_{max.}$ 436, 375, or 375 nm, respectively. When the $C_{18}H_{37}SiCl_3$ treatment was repeated on the 'active' ODS/SiO_2 monolayer I 3, 5, and 7 times successively, the adsorption density of chlorophyll a (*ca.* 1.3 molecules/100 Å² apparent surface area) decreased to *ca.* 0.5, 0.2, or 0.1 molecules/100 Å², respectively, suggesting that the density of the molecular recognition sites on ODS monolayer is controllable.

The quantity of electricity (Q_i)† that passed during the current response showed saturation behaviour when the vitamin K_1 concentration was increased; typical results are shown in Figure 1. This observation again supports the operation of molecular binding mechanism. The number of adsorbed vitamin K_1 molecules, N_i, is given by $N_i = Q_i/2F$. The adsorption equilibrium constant, K_G, which is given by equation (1) (Langmuir isotherm) was found to be satisfactorily constant over the vitamin K_1 concentration range investigated (see Figure 1). The treatment also allowed n values (number of host binding sites) to be determined uniquely, *e.g.*, *ca.* 3.5/100 Å² (apparent surface area) for electrode I.

$$K_G = N_i/(n - N_i)G \quad (1)$$

† Q_i was determined as the peak area of the cathodic current at −0.7 V. Under the present condition, i_{pc} varied linearly with scan rate (v) in the 2—100 mV/s range (see ref. 10).

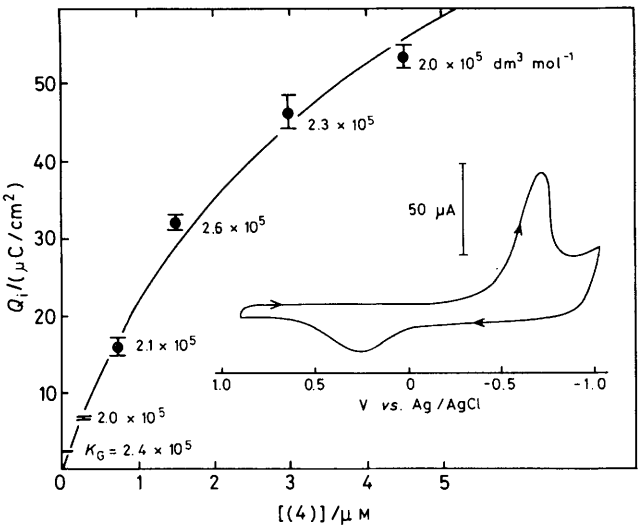


Figure 1. Quantity of electricity (Q_i) due to vitamin K_1 reduction by electrode I. Average of independent experiments of five ODS/SnO_2 I electrodes. The inset shows the typical cyclic voltammogram of the electrochemical response of electrode I at 3×10^{-6} M vitamin K_1 concentration in MeOH–H_2O (3 : 2, v/v) containing 0.1 M KCl, 20 mM phosphate buffer (pH 7.0), 20.0 ± 0.5 °C.

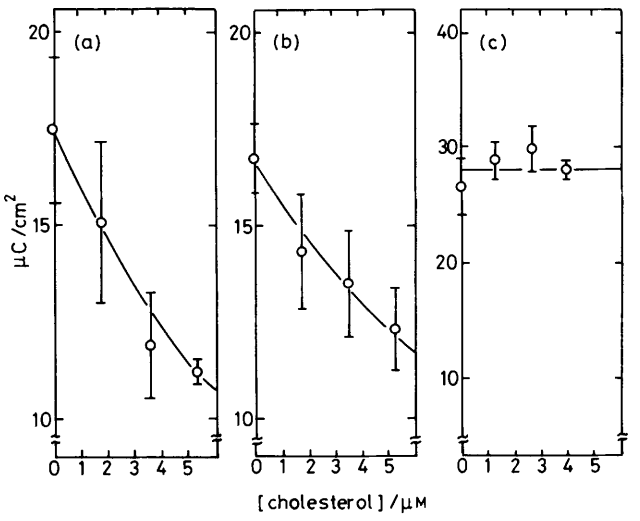


Figure 2. Inhibition of vitamin K_1 response of (a) electrode I, (b) electrode II, (c) electrode III by cholesterol. Vitamin K_1 concentration, (a) 1.50×10^{-6} M, (b) 1.43×10^{-6} M, (c) 2.8×10^{-6} M in aqueous MeOH (2 : 3, v/v) containing 20 mM phosphate (pH 7.0) and 0.1 M KCl, temp. 20.0 ± 0.5°. (a) and (b) show the theoretical curves: K_I values are given in Table 1. Each data point is the average of vitamin K_1 responses of five independent SnO_2 electrodes.

The electrochemical response (Q_i) to vitamin K_1 was inhibited by a competitive inhibitor that was recognizable by each ODS/SnO_2 monolayer. Figure 2 shows the plot of Q_i *vs.* cholesterol (**5**) concentration for electrodes I—III. Clearly, cholesterol is recognized by the host binding sites of electrodes I or II, blocking the access of vitamin K_1 (probe molecule) to the electrode, while no appreciable competitive inhibition was seen for electrode III. The inhibition constant, K_I, of cholesterol was evaluated as (3.3 ± 0.1) × 10⁴ and (5.3 ± 0.3) × 10⁴ dm³ mol⁻¹ for electrodes I and II, respectively (Table 1), suggesting that the overall inhibition equilibria: $G_jM + I \rightleftarrows G_{j-1}M$ (j = 1—n), have an identical inhibition constant, K_I.

Table 1. Adsorption equilibrium constant (K_G) and inhibition constant (K_I) for ODS modified electrodes I—III.[a]

Electrode, TG	K_G vit. K_1 (**4**)	K_I		
		n-$C_{16}H_{34}$ (**1**)	Cholesterol (**5**)	Adamantane (**6**)
I, (**1**)	2.2×10^5	$(1.9 \pm 0.1) \times 10^4$	$(3.3 \pm 0.1) \times 10^4$	[b]
II, (**2**)	5.0×10^5	$(1.6 \pm 0.1) \times 10^4$	$(5.3 \pm 0.3) \times 10^4$	[b]
III, (**3**)	5.8×10^4	$(4.8 \pm 0.1) \times 10^3$	[b]	14 ± 0.5

[a] $dm^3\ mol^{-1}$ in MeOH–H_2O (3 : 2, v/v) containing 0.1 M KCl and 20 mM phosphate buffer (pH 7.0). [b] No appreciable inhibition observed.

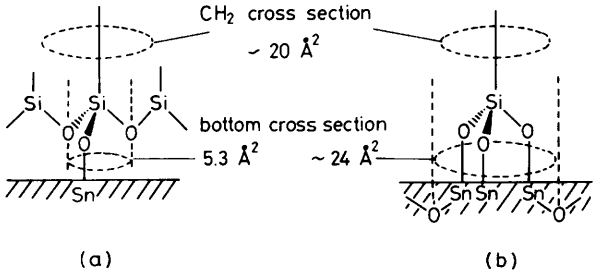


Figure 3. Mismatching between CH_2 cross section and bottom cross section. Bonding (b) (idealized) seems more favourable than bonding (a) (idealized) for steric reasons, when the monolayer including TG is covalently fixed onto the support through such bonding.

Therefore, the template cavity made with (**3**) on ODS/SnO_2 monolayer III is inappropriate for cholesterol recognition. By contrast, electrode III showed appreciable recognition ability towards adamantane (**6**), judged from the inhibition of vitamin K_1 response of electrode III by (**6**), the value of K_I for which was $14 \pm 5\ dm^3\ mol^{-1}$ (Table 1). Adamantane [globular guest molecule, (**6**)] was not adsorbed on electrodes I and II (Table 1).

The conclusion then may be drawn that molecular recognition sites have been made in the 'active' ODS/SnO_2 monolayer, and that guest binding selectivity results which reflects the shape and size of the template guest molecule employed. The mechanism by which the monolayer provides supramolecular cavities is interesting but needs further studies. There are certain basic requirements: (i) the presence of an appropriate template molecule and (ii) selection of an appropriate modifying reagent which bears a hydrocarbon chain of desired cross section. The latter requirement may be important to induce mismatching: the bottom cross section mismatches the top cross section in the system schematically depicted in Figure 3.

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