

## Substrate-Selective Gold Electrodes Coated with Cationic and Nonionic Long-Chain $\beta$ -Cyclodextrins

by

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### Syniopsis

A gold electrode modified with a molecular film of cationic bis[6-deoxy-6-(N,N-dimethyldodecyl)-ammonio]- $\beta$ -cyclodextrin responds only with anthraquinones bearing a sulfonate moiety at the 2-position among several anthraquinonesulfonates examined. On the other hand, an electrode adsorbed with heptakis-(6-deoxy-6-dodecylamino)- $\beta$ -cyclodextrin is capable of recognizing the portion of the sulfonate-lacking aromatic ring because of the increased hydrophobicity of the cyclodextrin cavity with appended long alkyl chains.

**Keywords** : Cationic and nonionic long alkyl chain cyclodextrins, modified electrodes, regioselectivity, cyclic voltammetry

### 1. Introduction

Cyclodextrins (CyDs) are one of widely studied host molecules with a hydrophobic cavity selective for the size and shape of guest molecules.<sup>1)</sup> Thus, they serve as an excellent model for the study of enzyme active sites. However, only a few reports in the literature have dealt with applications of CyDs to develop molecular-shape and molecular-size selective electrodes; recently, Porter and co-workers reported that the monolayer of heptakis(6-deoxy-6-dodecanethio)- $\beta$ -CyD attached onto a gold electrode discriminated ferrocenecarboxylate (FeC) from  $\text{Fe}(\text{CN})_6^{4-}$  and  $\text{Ru}(\text{NH}_3)_6^{2+}$  ions; among them only FeC small in size will fit into the CyD cavity.<sup>2)</sup> However, we have ruled out their explanation based on additional experimental evidence and have provided an alternative interpretation that the electrochemical response could occur without FeC inclusion into the CyD cavity since the formed-membrane thickness is not enough to completely block direct electron transfer between the bulk FeC and the underlying electrode across the membrane.<sup>3)</sup>

In this work we have tried to construct modified electrode devices with molecular films of two different types of amphiphilic CyDs performing a role of substrate-selective hosts. The cyclic voltammetric (CV) method has been utilized to quantitatively assess the interaction of the substrate and the CyDs-modified electrodes.

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## 2. Experimental

**Materials.** Positional isomers, anthraquinone-1- and -2-sulfonates (1-AQS and 2-AQS, respectively), and 1,8-, 2,7-, 1,5-, and 2,6-disulfonates and anthraquinone-2- carboxylate as sodium salts were purchased from Tokyo Kasei Co., Japan, and recrystallized from water. Cationic bis(6-deoxy-6-*N,N*-dimethyldodecylammonio)- $\beta$ -CyD dibromide ( $\text{CDN}^+12$ ) was prepared from the per-6-bromo-CyD by reacting with excess *N,N*- dimethyldodecylamine in DMF at 60°C for 3 days. Evaporation of the solvent and extraction of the unreacted amine with hexane gave a glassy solid, which was then recrystallized from ethanol to afford  $\text{CDN}^+12$  in 55 % yield. The average number of the alkyl group introduced was determined almost two by NMR. In a similar manner, A,D-bis-[(6-(*N,N*-dimethyl-dodecylammonio)]- $\beta$ -CyD was synthesized by reaction of A,D-bis(6-deoxy-6-iodo)- $\beta$ -CyD (CyD-I) with the *N,N*-dimethyldodecylamine at 60°C for 1 week. CyD-I itself was synthesized from biphenyl-4,4'-disulfonyl-A,D-capped  $\beta$ -CyD which had been purified by HPLC.<sup>4)</sup> Nonionic heptakis[6-(*N,N*-dimethyldodecylamino)]- $\beta$ -CyD ( $\text{CDN}12$ ) were prepared from the corresponding heptakis-(6-bromo)- $\beta$ -CyD according to a reported method.<sup>5)</sup> The structures of the modifiers,  $\text{CDN}^+12$  and  $\text{CDN}12$ , are given in Fig. 1.

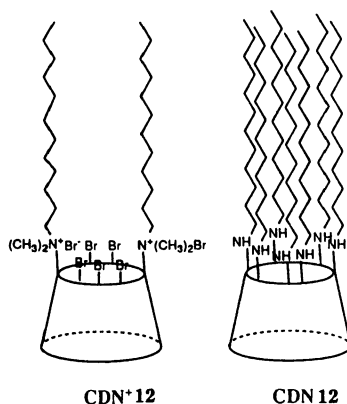


Fig. 1. Structural formula of the modifiers

**Electrode modifications.** The following procedure was adopted to obtain a gold surface coated with  $\text{CDN}^+12$  and  $\text{CDN}12$ :<sup>6)</sup> A gold plate (1 cm<sup>2</sup>) polished well with powdered almina beforehand was potential-swept between -1.7 and +1.7 V vs SCE in 1 N H<sub>2</sub>SO<sub>4</sub> for 24 h and then thoroughly rinsed with distilled water. A 1.0 mM ethanol solution of the modifier was cast on a clean gold plate, or a clean gold plate was dipped into the 1 mM ethanolic solution of the modifier. The modifier excess was removed from the electrode surface by rinsing with purified ethanol and water in this order. In the case of  $\text{CDN}12$ , pretreatment of a gold plate with thiopropionic acid gave a more stable  $\text{CDN}12$  film.

CV measurements. CV measurements were carried out by using a three-electrode configuration in a single compartment; the auxiliary electrode was a platinum wire and the reference electrode was the saturated calomel electrode (SCE). The supporting electrolyte was 0.1 M  $\text{KClO}_4$ . Solutions for measurements were deaerated by passing a slow stream of nitrogen gas through it for 10 min. The films on the electrodes were entirely stable toward repeated sweeping between -1.7 and +0.8 V. The sweeping beyond that region caused the appearance of a large peak characteristic to  $\text{Fe}(\text{CN})_6^{4-}$  added in bulk solution as the analyte, as seen in Fig. 2.

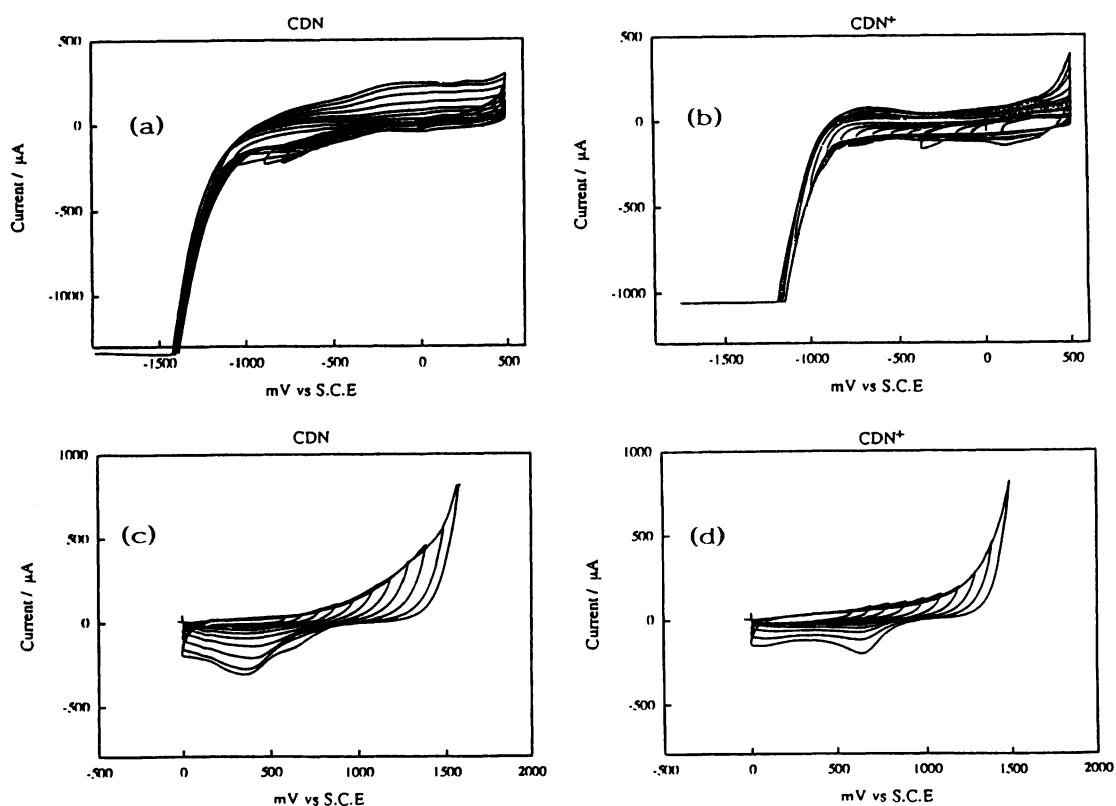
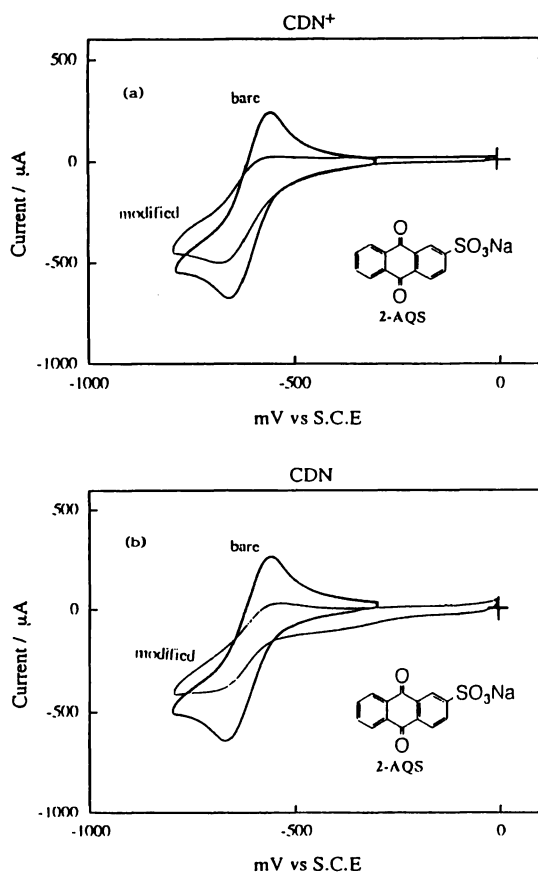


Fig. 2. Cyclic voltammograms at the  $\text{CDN}^{+12}$  and  $\text{CDN}12$  electrodes in  $\text{H}_2\text{O}$  (0.1 M  $\text{KClO}_4$ ) for reduction (a, b) and oxidation (c, d) of 1 mM  $\text{Fe}(\text{CN})_6^{4-}$ ; scan rate  $100 \text{ mV s}^{-1}$ .

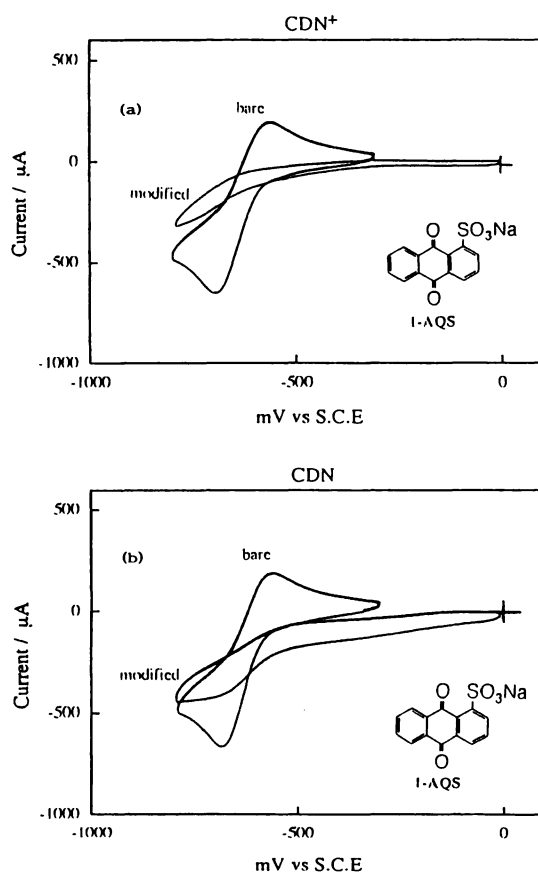
### 3. Results and Discussion

Typical cyclic voltammograms for anthraquinonesulfonates on the  $\text{CDN}^{+12}$ -modified and unmodified electrodes are shown in Fig. 3a and Fig. 4a. These results, together with other CV data (not shown), reveal that the range of the guest molecules investigated in this study falls into two groups. The 1-, 1,5-, and 1,8-sulfonate guests, commonly bearing a sulfonate group at the 1-position give no indication of their interaction with the underlying surface. Evidently, the  $\text{CDN}^{+12}$ -assembled layer hinders the accessibility of the anthraquinone-1-sulfonates to the electrode metal surface for electrode reaction.



**Fig. 3.**

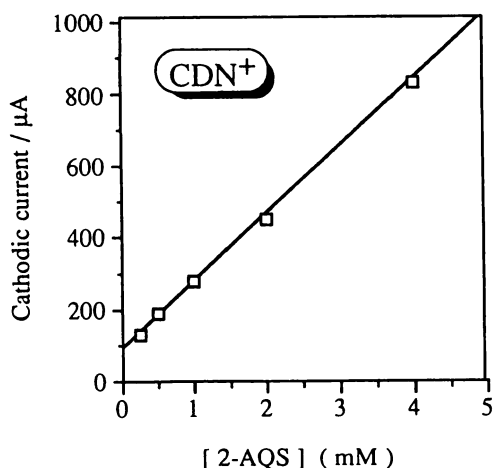
Cyclic voltammometry of a 1 mM solution of 2-AQS as a permeability marker at the  $\text{CDN}^{+12}$  (a) and  $\text{CDN}12$  (b) electrodes in  $\text{H}_2\text{O}$ .



**Fig. 4.**

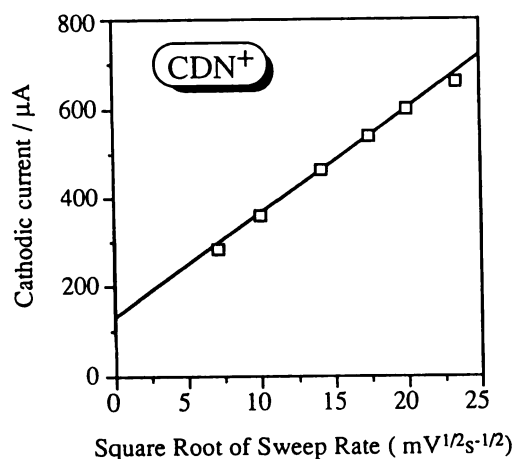
Cyclic voltammometry of a 1 mM solution of 1-AQS as a permeability marker at  $\text{CDN}^{+12}$  (a) and  $\text{CDN}12$  (b) electrodes in  $\text{H}_2\text{O}$ .

In contrast, the other 2-, 2,6-, and 2,7-sulfonates gave definitely a CV redox peak with respect to the  $\text{CDN}^+$ -saturating electrode; for example, the guest anthraquinone-2-sulfonate underwent quasi-reversible electrochemical redox reaction, and the Faradic cathodic current intensity is proportional to both the square root of the potential sweep rate (Fig. 5a) and the substrate concentration (Fig. 5b), which are the criteria for occurrence of a diffusion-controlled redox reaction.<sup>7)</sup> The corresponding 2-carboxylate substrate also displays essentially a similar electrochemical redox behavior. However, the peak height for the disulfonate derivatives are generally very low compared to that of the monosulfonate due to the more hydrophilic character of the disulfonate. Indeed, complexation of disulfonates with cyclodextrins has been reported to be about one tenth of that of the corresponding monoanion.<sup>8)</sup>



**Fig. 5a.**

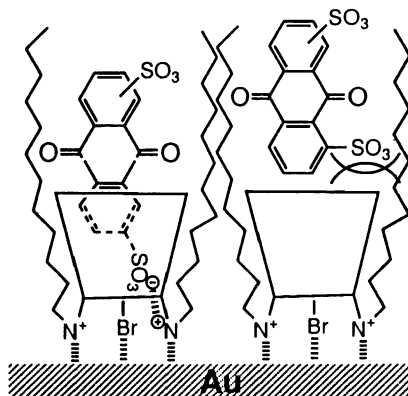
A plot of cathodic current vs the square root of sweep rate ; 0.1 M  $\text{KClO}_4$ , [2-AQS]=1 mM.



**Fig. 5b.**

A plot of cathodic current vs 2-AQS concentration; 0.1 M  $\text{KClO}_4$ , sweep rate  $100 \text{ mVs}^{-1}$

There are two distinctly different possible pathways through which negatively charged anthraquinone-2-sulfonates can move from the bulk solution to the underlying electrode surface; one is the way through a pinhole or a film defect, which functions as a leading way for the sulfonate ions, but not for  $\text{Fe}(\text{CN})_6^{4-}$ . This possibility might be easily eliminated because we could not accept such a defect that it is highly substrate-selective. The other is through deeper inward diffusion or penetration of the anionic group of the sulfonate molecule. The hydrophobic part of anthraquinone-2-sulfonate could be possibly entrapped so strongly into the rather hydrophobic CD cavity by van der Waals interactions with the help of charge-charge interactions between the sulfonate anion and the ammonium cations, as illustrated in Fig. 6. The observation that the transportation to the electrode surface is



**Fig. 6.** A plausible mechanism for ion-selective sensing at the  $\text{CDN}^{+12}$  electrode.

diffusion controlled also supports that the electrostatic bonding would favor the diffusion of the sulfonate anion through the even hydrophobic membrane, entirely different from prevented transportation of ions as occurring in natural or model phospholipid bilayers.<sup>9)</sup> Meanwhile, with an amphiphilic molecule ( $\text{CDN}^{+18}$ ) having longer octadecyl tails instead of dodecyl tails as a surface modifier, the increased methylene segments exerted an undesirable effect on the self-assembling mode where the multi-layered, probably disordered thick membrane film must have been formed. The disorder caused by random accumulation of hydrophobic cyclodextrins with longer chains will prevent the diffusion of the ionic substrate in the membrane and will not permit it to reach the metal surface. In fact, the formation of the thick film is evidenced by remarkably increased film-resistance and significantly small capacitive current. Meanwhile,  $\text{CDN}^{+8}$  having shorter tails failed to self-assemble to construct regularly packed arrangements because of its less hydrophobic nature.

On the other hand, for the nonionic modifier  $\text{CDN}^{12}$  the situation was very different in substrate-selectivity from  $\text{CDN}^{+12}$ ; the response was observed not only with anthraquinone-2-sulfonate and -2-carboxylate, but also with anthraquinone-1-sulfonate, as shown in Figs. 3b and 4b; it should be noticed that either side of these anthraquinone skeletons lacks a sulfonate group. Incidentally, the substrate underwent the invasion by the diffusion-controlled mechanism, as indicated by linear plots of the cathodic current against substrate concentration and the square root of the sweep rate. Meanwhile, no evidence for response was found with disulfonates such as 1,5-, 1,8-, 2,6-, and 2,7-disulfonates, irrespective of the substituent position being 1 or 2. It is evident, therefore, that the invasion of the anionic substrate into the  $\text{CDN}^{12}$  film is capable of taking place only with the hydrophobic benzo group in the lead, as depicted in Fig. 7. Thus, it is apparent that the selectivity mode of the  $\text{CDN}^{12}$  cavity was complementary to that of  $\text{CDN}^{+12}$ .

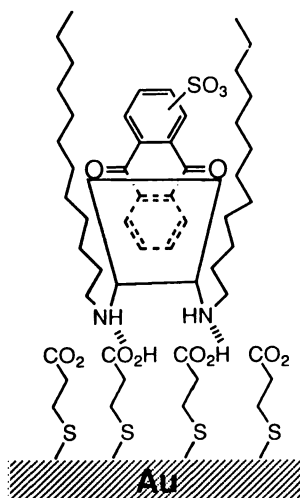


Fig. 7. A plausible mechanism for ion-selective sensing at the CDN12 electrode.

In biological cells, the translocation of small ions across the membranes is restricted because of the nonpolar nature of the lipid phase. Then, the importance of ion permeation in biomembranes has been recognized recently. Nevertheless, its mechanism has not yet been unequivocally elucidated. The present work would provide one of useful modellings or methodologies for understanding the mechanism of selective ion transportation by inclusion. The details on the morphology of the surface-confined amphiphiles will be published elsewhere in the near future and practical applications to the building up of chemical sensors is in progress.

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