

Sol–Gel Method for the Matrix of Chloride-Selective Membranes Doped with Tridodecylmethylammonium Chloride

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An organic–inorganic hybrid sol–gel matrix was used as host for tridodecylmethylammonium chloride (TDMAC), which is an ionophore for chloride. The sol–gel precursor was prepared by the reaction of (3-isocyanopropyl)-triethoxysilane with 1,4-butanediol. On mixing with TDMAC, the sol-state precursor slowly gelled, to give a TDMAC-containing membrane. The performances of the sol–gel membrane-based electrodes were compared to those of TDMAC-based poly(vinyl chloride) (PVC) membrane electrodes. Membranes with an optimum ratio of TDMAC:sol–gel precursor (0.1:3 by weight) showed very stable baseline potential. The response slope toward chloride was approximately 55 mV/decade between 10^{-4} and 5×10^{-1} M Cl^- at room temperature. Moreover, selectivity toward chloride over salicylate and other lipophilic anions was improved, deviating from the Hofmeister selectivity pattern which is observed in most dissociated charged carrier-based potentiometric membrane sensors. The selectivity coefficients measured by the separate solution method in 0.01 M MES buffer, pH 5.5, were $\log K_{\text{Cl},\text{sal}}^{\text{pot}} = 0.6$, $\log K_{\text{Cl},\text{citrate}}^{\text{pot}} = -1.6$, and $\log K_{\text{Cl},\text{acetate}}^{\text{pot}} = -0.6$.

Several liquid and polymer membrane-based ion-selective electrodes (ISEs) have been proposed for the analysis of chloride.^{1–6} The active components in many of these membrane electrodes have been quaternary ammonium salts. The innate Hofmeister-type response of such sensors to lipophilic anions, such as salicylate, can lead to significant positive errors for measurement of chloride in blood samples from patients who have ingested

aspirin.⁷ Positive interferences from bromide and added heparin are also possible.⁸ Oka et al. suggested that polystyrene membranes with covalently bound quaternary ammonium sites, when doped with lipophilic anionic sites, give improved chloride selectivity for blood chloride measurements. However, the mechanism of this enhancement has not been shown.¹ Recently, Park et al. assessed the feasibility of using In(III) porphyrin-based sensors in an appropriate flow injection analysis (FIA) arrangement to determine chloride levels accurately in human serum samples.⁸ The use of an asymmetric cellulose triacetate (CTA) membrane matrix to minimize protein asymmetry effects, and the use of a protein diluent reagent to bind residual salicylate, were shown to offer significant advantages for the FIA measurement of chloride in blood serum. This study may offer a generic way to apply the ISE systems for the more accurate measurement of various ionic species. However, it may show difficulties in application (i.e., in manufacturing solid-state electrodes).

Sol–gel processes have been employed to prepare organic–inorganic polymer materials of network structure.^{9–11} In general, the polymerization (or gelation) is achieved by the reaction of sol-state inorganic alkoxide molecules via hydrolysis and repetitive condensation. The reaction proceeds slowly at low temperatures with host materials encapsulated inside. Applications of the methods are found in the study of photoelectronic materials and functional composite materials.¹² Biosensor applications are quite active, in conjunction with the immobilization of biologically active species such as enzymes, antibodies, whole cells, etc.^{13–17} The

- (7) Lewandowski, R.; Sokalski, T.; Hulanicki, A. *Clin. Chem.* **1989**, *35*, 2146.
- (8) Park, S. B.; Matuszewski, W.; Meyerhoff, M. E.; Liu, Y. H.; Kadish, K. M. *Electroanalysis* **1991**, *3*, 909.
- (9) Brinker, C. J.; Scherer, G. W. *Sol–Gel Science*; Academic Press: London, 1990.
- (10) Gesser, H. D.; Goswami, P. C. *Chem. Rev.* **1989**, *89*, 765.
- (11) Corriu, R. J. P.; Moreau, J. J. E.; Thepot, P.; Man, M. W. C. *Chem. Mater.* **1992**, *4*, 1217.
- (12) Novak, B. M. *Adv. Mater.* **1993**, *5*, 442.
- (13) Dave, B. C.; Dunn, B.; Valentine, J. S.; Zink, J. I. *Anal. Chem.* **1994**, *66*, 1120A.
- (14) Avnir, D.; Braun, S.; Lev, O.; Ottolenghi, M. *Chem. Mater.* **1994**, *6*, 1605.
- (15) Ellerby, L. M.; Nishida, C. R.; Nishida, F.; Yamanaka, S. A.; Dunn, B.; Valentine, J. S.; Zink, J. I. *Science* **1992**, *255*, 1113.
- (16) Yoshinaga, K.; Kito, T.; Yanaye, M. *J. Appl. Polym. Sci.* **1990**, *41*, 1443.

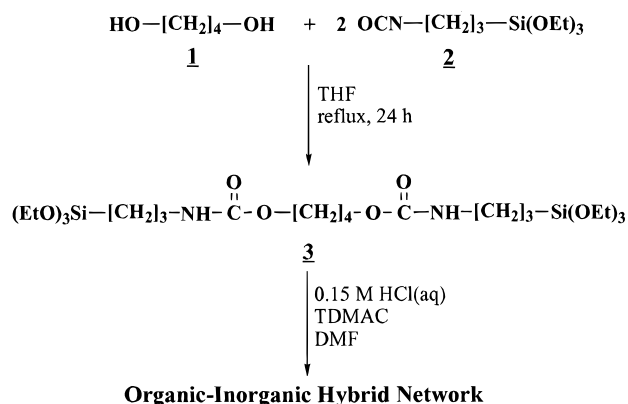
[†] Inje University.

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- (1) Oka, S.; Sibasaki, Y.; Tahara, S. *Anal. Chem.* **1981**, *53*, 588.
- (2) Hartman, K.; Luterotti, S.; Osswald, H.; Oehme, M.; Meyer, P.; Ammann, D.; Simon, W. *Mikrochim. Acta (Wien) II* **1978**, 235.
- (3) Willis, J.; Young, C.; Martin, R.; Stearns, P.; Pelosi, M.; Magnanti, D. *Clin. Chem.* **1983**, *29*, 1193.
- (4) Hitachi, Ltd. Jpn. Tokkyo Koho No. 5,757,655, 1982.
- (5) Coetzee, C. V.; Freiser, H. *Anal. Chem.* **1968**, *40*, 2071.
- (6) Coetzee, C. V.; Freiser, H. *Anal. Chem.* **1969**, *41*, 1128.

Scheme 1. Low-Temperature Sol–Gel Process for Organic–Inorganic Polymer Network Containing TDMAC



concept of sol–gel encapsulation of an ionophore is applied in the present study for the matrix of chloride-selective membrane electrodes. Then electrochemical properties of the sensors are compared to those of conventional electrodes prepared with PVC.

EXPERIMENTAL SECTION

Reagents. TDMAC, PVC, and 2-(*N*-morpholino)ethanesulfonic acid monohydrate (MES) were purchased from Fluka (Ronkonkoma, NY). 1,4-Butanediol and tetrahydrofuran (THF) were obtained from Aldrich (Milwaukee, WI) and were purified over calcium hydride and sodium, respectively. (3-Isocyanopropyl)triethoxysilane was purchased from Hüls America Co. (Piscataway, NJ) and was used without further purification. Buffer solutions consisting of 0.01 M MES, adjusted with NaOH to different pH's, were used as the working buffer for the potentiometric measurements. All other chemicals used were analytical-reagent grade. The buffer and standard solutions were prepared with deionized water.

Polymer Membranes and Electrodes. The sol–gel precursor was prepared by the reaction of 1,4-butanediol (**1**, 3.08 g, 34 mmol) and (3-isocyanopropyl)triethoxysilane (**2**, 16.90 g, 68 mmol) (stoichiometric ratio NCO/OH = 1) in THF. The reaction mixture was refluxed for 24 h under N₂ atmosphere (see Scheme 1). After evaporation of THF, the highly viscous sol-state precursor (**3**, 2.500 g) was dissolved in *N,N*-dimethylformamide (15.0 mL) with 80 mg of the ionophore, to which hydrochloric acid (0.150 M, 4.6 mL) was added. The mixture was poured onto the flat surface of poly(ethylene terephthalate) film. The hydrolysis was carried out at 40 °C for 4 days to obtain transparent gel membranes which contain the ionophore. Before use, the membrane was vacuum-dried at 40 °C for 24 h. Nitrogen sorption analyses were performed with a Micromeritics ASAP 2000. PVC-based ISE membranes were prepared according to the method of Simon and co-workers.¹⁸ The composition was 10 wt % TDMAC, 57 wt % diisodecyl adipate, and 33 wt % PVC. After the membranes were allowed to cure, 5.5-mm-diameter disks were cut out and placed in Phillips electrode bodies (ISE-561, Glasblaserei Möller, Zurich, Switzerland). As an internal filling solution, 0.1 M KCl was used for all electrodes.

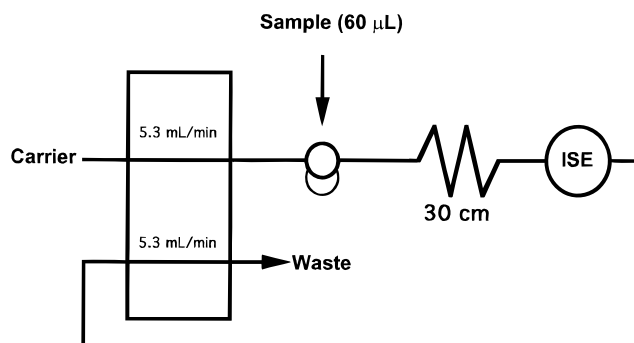


Figure 1. Schematic of the sol–gel membrane electrode-based flow injection system.

Static Mode Potentiometric Measurements. Cell potentials were measured at an ambient temperature of 18 °C. The potentiometric cell used was as follows: Ag/AgCl(s)/4 M KCl saturated with AgCl/MES buffer/sample solution/ion-selective membrane/0.1 M KCl/AgCl(s)/Ag. The ion-selective and Ag/AgCl reference electrodes were connected through a high-impedance amplifier to an IBM AT-type computer equipped with an A/D converter with a sampling rate of 0.5 Hz. This apparatus was used to determine the selectivity of each membrane toward chloride over other anions in the static mode. Selectivity coefficients, $K_{\text{Cl}/X}^{\text{pot}}$, were obtained by using the separate solution method¹⁹ unless indicated otherwise.

Flow Injection Mode Measurements. The arrangement shown in Figure 1 was used to evaluate the performance of the PVC and sol–gel membrane electrodes in the FIA mode. A Phillips electrode body was fitted with a wall-jet-type flow-through cap similar to that described previously.²⁰ The flow cap was connected to the injection valve by Teflon tubing (0.012 in. i.d.). A peristaltic pump (Ismatech SA, Zurich, Switzerland) and a Rheodyne four-way rotary Teflon valve (Model 7125) equipped with a 60- μL sample loop completed the flow injection setup. The MES buffer was used as the carrier stream. The chloride-selective and Ag/AgCl reference electrodes were connected as described above. The sampling rate was adjusted to 2 Hz to observe delicate changes in the millivolt-level potential response.

RESULTS AND DISCUSSION

In previous studies, tetraethylorthosilicate or tetramethylorthosilicate has been used as the sol precursor.^{13,14} As the precursors condense, however, the reaction results in a glass membrane which is inadequate to be cut and mounted on top of Phillips electrode bodies. In the present study, however, a precursor made from linkages between organic and inorganic components is used as indicated in Scheme 1. The density of membranes (TDMAC, 3.3 wt %) was found to be 1.24 g/cm³ ($n = 3$). Membranes made from 2–6 wt % ionophore exhibited very similar electrochemical responses. However, membranes of higher than 6 wt % resulted in physically less strong membranes with some turbidity. The membrane (TDMAC, 3.3 wt %) was flexible enough to be cut with a No. 2 cork cutter. Membranes of 0.15-mm thickness were mounted within Phillips electrode bodies. The structure of the organic–inorganic hybrid polymeric network of blank membranes (without ionophore) was characterized by solid-state ¹³C and ²⁹Si

(17) Braun, S.; Rappoport, S.; Zusman, R.; Avnir, D.; Ottolenghi, M. *Mater. Lett.* **1990**, *10*, 1.

(18) Wuthier, U.; Pham, H. V.; Zund, R.; Welti, D.; Funk, R. J. J.; Bezegh, A.; Ammann, D.; Pretsch, E.; Simon, W. *Anal. Chem.* **1984**, *56*, 535.

(19) Srinivasan, K.; Rechnitz, G. A. *Anal. Chem.* **1969**, *41*, 1203.

(20) Trojanowicz, M.; Meyerhoff, M. E. *Anal. Chem.* **1989**, *61*, 787.

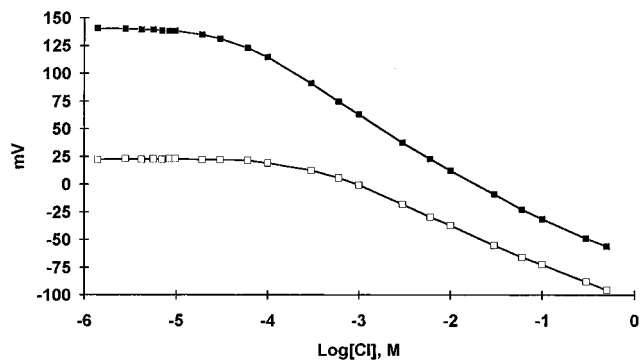


Figure 2. Calibration curves of membranes prepared by the sol-gel method (■, TDMAC:precursor = 0.1:3 by weight) and by traditional PVC formulation (□, TDMAC:diisodecyl adipate:PVC = 10:57:33 by weight).

Table 1. Static Mode Potentiometric Selectivity Coefficients, $\log k_{Cl,x}^{pot}$ for Chloride-Sensitive Electrodes Prepared by Different Methods

anion	TDMAC (PVC) ^a	TDMAC (sol-gel) ^a	In[OEP]Cl ^b	Mn[TPP]Cl ^c
Cl ⁻	0.0	0.0	0.0	0.0
Br ⁻	0.6	0.3	0.3	0.3
I ⁻	2.8	0.8	1.6	1.5
ClO ₄ ⁻	4.5	1.0	-0.2	1.5
SCN ⁻	2.9	1.3	0.9	1.3
salicylate	2.7	0.6	1.6	2.1

^a Obtained by using the separate solution method at 10 mM anion concentrations in 0.01 M MES buffer, pH 5.5. Average of three determinations. ^b From ref 8. ^c From ref 23.

cross-polarization magic-angle spinning (CP-MAS) spectroscopy.²¹

The calibration curve of a typical TDMAC-based sol-gel membrane electrode response toward chloride in the concentration range 0–500 mM is shown in Figure 2. In use, the stability of the sensors was at least 6 months. As tested in the static mode, the membrane electrode did not show any significant deterioration in the response behavior after 6 months. The average response slope decreased from 55 to 54 mV/decade between 0.1 mM and 5×10^{-1} M Cl⁻ at 18 °C ($n = 3$). This slope is comparable to that of a typical, traditional PVC-based membrane electrode. However, the detection limit of the sol-gel matrix-based electrode is as low as 0.05 mM, which is almost one-tenth that of the traditional one.

Interestingly, selectivity toward chloride over salicylate and other lipophilic anions is significantly improved, deviating from the Hofmeister selectivity pattern which is observed in most dissociated charged carrier-based potentiometric membrane sensors. Table 1 provides the potentiometric selectivity coefficient data of the TDMAC-based sol-gel membrane for several anions relative to chloride. For comparison purposes, selectivity data are also given for the PVC membranes doped with TDMAC, as well as for membranes doped with other ionophores, chloro(octaethylporphyrinato)indium(III) (In[OEP]Cl) and chloro(5,10,15,20-tetraphenylporphyrinato)manganese(III) (Mn[TPP]Cl). As can be seen, there is a substantial change in the selectivity pattern for the TDMAC-based sol-gel membrane electrodes. For example, more than 100 times selectivity improvement toward chloride over salicylate is achieved, compared to the traditional PVC-based membrane electrodes.

(21) Kim, C.; Kim, E.; Chin, I.; Park, K.; Kim, Y. *Polym. Prepr.* **1995**, *36*, 117.

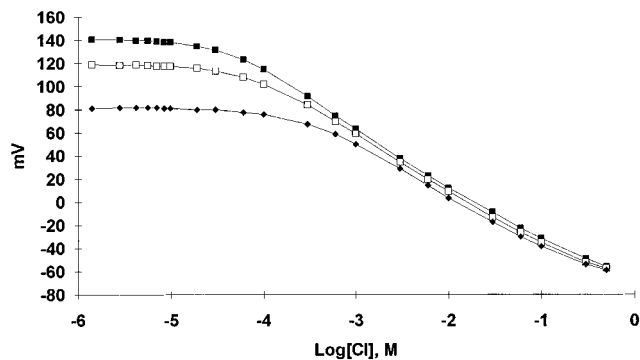


Figure 3. Chloride response of TDMAC-based membrane electrode prepared by the sol-gel process in 0.01 mol/L MES buffer at various pH values: ■, pH 5.5; □, pH 6.2; and ◆, pH 7.2.

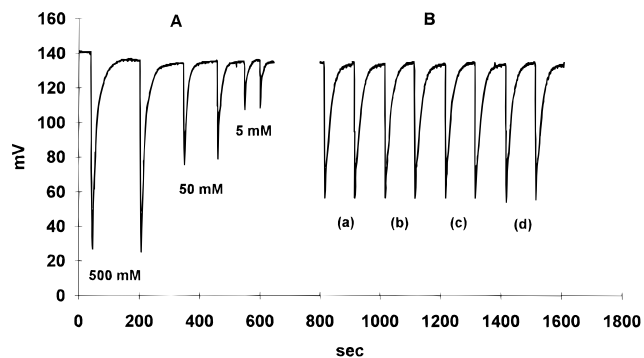


Figure 4. (A) Potentiometric responses obtained for injections of chloride standards in the FIA system with the TDMAC-based membrane electrode detector. (B) Responses for double injections of 0.12 M NaCl containing (a) 0, (b) 0.5, (c) 1, and (d) 2 mM sodium salicylate, using 0.01 M MES buffer, pH 5.5, as the carrier stream.

The analytical implications of the novel chloride-selective membrane electrode can be assessed more accurately by testing the response toward chloride in the same buffer system, but at different pH values. As shown in Figure 3, detection limits toward chloride deteriorate as the pH of the buffer increases. Because the concentrations of MES are all the same, the observed behavior is not due to higher concentrations of anionic MES in the pH 6.2 and 7.2 buffers. In separate experiments at constant pH, it was found that the membrane shows little or no response to anionic MES. Thus, the data in Figure 3 can be used to calculate an effective selectivity coefficient for chloride over hydroxide ion using the fixed interferent method.²² The value calculated, $\log k_{Cl,OH}^{pot} = 3.1$ (at pH 7.2), seems to be somewhat high. In light of the normal chloride range in human serum samples (98–106 mmol/L), however, the detection limit of the sol-gel chloride membrane electrode is still low enough.

Figure 4A shows the typical data obtained for double injections of chloride standards (5–500 mM) under the FIA conditions when a 5-month-old membrane prepared with the sol-gel method is used as the detector. During that period, the electrodes had been tested almost daily. If not in use, they had been stored in the 0.01 M MES buffer, pH 5.5, containing 10 mM NaCl. Peak height responses to 120 mM chloride standard are reproducible to ± 1 mV (SD, 10 replicates, data not shown) at a sampling rate of 0.01 Hz. Incomplete baseline return is observed when the FIA membrane electrode system is exposed to higher concentrations

(22) IUPAC. *Pure Appl. Chem.* **1976**, *48*, 127.

(23) Chaniotakis, N. A.; Chasser, A. M.; Meyerhoff, M. E.; Grove, J. T. *Anal. Chem.* **1988**, *60*, 185.

of chloride (>120 mM, e.g., 500 mM). This problem can be partly solved by adding a small amount of chloride to the carrier buffer stream. However, this approach increases the detection limits and, therefore, was not employed here. In the nonequilibrium flow injection system, response slopes toward chloride tend to be somewhat less than those observed in static mode experiments. That is, the response slope is about 50 mV/decade when the chloride level changes from 50 to 500 mM. In the static mode, the chloride-selective membranes prepared with the sol-gel method showed an improved selectivity toward chloride over more lipophilic anions (Table 1). Indeed, this is confirmed in the FIA mode. Figure 4B illustrates the effectiveness of this novel approach. Note that peak heights (millivolt changes) for a series of 0.12 M NaCl standard containing up to 2 mM salicylate are essentially the same. At these concentrations of chloride and salicylate, the baseline return is relatively quick and reproducible. Typical t_{90} values (time required to reach 90% of equilibrium potential (mV) value) are shorter than 40 s, while the average difference in baseline potential at 50 s after sample injections is less than 0.5 mV for consecutive measurements. These results can be compared to those obtained with asymmetric CTA-based membranes doped with In[OEP]Cl, which was designed to measure chloride levels in serum samples. That is, the asymmetric CTA-based asymmetric membrane electrodes showed t_{90} values of more than 1 min at the same chloride and salicylate levels.⁸

It is believed that the improved selectivities and other characteristics are related to the inherent properties of the matrix. First, the sol-gel matrix has hydrophilic urethane (NHCOO) and silicate (Si-O-Si) functional groups. Also, the sol-gel matrix does not contain lipophilic plasticizers. The coupled differences from a regular PVC-based electrode seem to cause improved selectivities toward chloride, which is more hydrophilic. Second, the sol-gel matrix has an infinite molecular weight, theoretically,

with a three-dimensional network structure. This is due to the three-dimensional consecutive condensation reaction of the sol-state precursor. In general, the sol-gel matrix can be characterized by extended porous structure of the surface.¹⁴ In our BET experiment, the average pore size of the membrane surface and its surface area were 17 Å and 8.3 m²/g, respectively. It is not clear how these numbers relate to the observed chloride selectivity quantitatively. Efforts aimed at understanding further the surface chemistry in conjunction with the improved chloride selectivity of the sol-gel matrix-based membrane electrodes are in progress. In addition, modifications of the experimental procedure are being tested for a better manufacturing of solid- and liquid-state ISEs.

CONCLUSION

A novel sol-gel encapsulation method for the matrix of potentiometric chloride-selective membranes was developed by using TDMAC as an ionophore. The organic-inorganic polymer membrane-based electrode showed a similar response slope and a lower detection limit when compared to those of a traditional PVC-based membrane electrode. Moreover, the electrode system showed a better selectivity toward chloride over more lipophilic anions such as salicylate.

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