

Sol-Gel Encapsulation Method for Nitrite-Sensitive Membranes Doped with Tetraoctylammonium Bromide

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An organic-inorganic hybrid sol-gel matrix was used as host for tetraoctylammonium bromide (TOAB) which is a dissociated ion-exchanger for anion detection. The sol-gel precursor was obtained by the reaction of 3-isocyanatopropyltriethoxysilane with 1,4-butanediol. Being mixed with TOAB with an acidic catalyst, the sol-state precursor slowly gelled to give a TOAB-containing membrane. Tributylphosphate(TBP) was used as a plasticizer. The performances of the sol-gel membrane-based electrodes were compared to those of TOAB-based poly(vinyl chloride)(PVC) membrane electrodes. Membranes with an optimum ratio of TOAB:sol-gel precursor (1.0 : 9.2 by weight), showed very stable baseline potential. Response slope toward nitrite was approximately 54 mV/decade in between 10^{-4} - 5×10^{-1} M at 20°C. Moreover, selectivity toward nitrite over salicylate and other lipophilic anions was significantly 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 0.05 M MES buffer, pH 5.5, were $\log k^{\text{pot}}_{\text{nitrite, chloride}} = -0.7$, $\log k^{\text{pot}}_{\text{nitrite, salicylate}} = 0.4$, and $\log k^{\text{pot}}_{\text{nitrite, thiocyanate}} = 1.4$.

Keywords: Anion-selective membrane electrode, Sol-gel method, Nitrite, Tetraoctylammonium bromide, FIA

1. INTRODUCTION

Nitrite plays important roles in biological and environmental areas. That is, nitrite is a precursor in the formation of carcinogenic N-nitrosamines. Also nitrite is a reaction product between NO, an atmospheric pollutant, with water and oxygen [1,2]. Traditionally, the ion can be measured by ion-exchange chromatography and spectrophotometry [3,4]. Probably more commonly employed one would be the spectrophotometric method. This utilizes nitrate reductase to converse nitrate to nitrite

then uses Griess Reagents resulting in a deep purple azo compound which is detected at 540 nm. Naturally this method has limitation in the application of some colored samples including NADPH-related ones [4].

Electrochemical sensor systems have been of considerable interest [5], owing to their low cost and simplicity. In addition, they are inherently free from sample colors and turbidity (e.g. pH glass electrode and other commercially available cation selective electrodes). Several polymer membrane-based ion-selective electrodes (ISE's) have been proposed for the analysis of nitrate/nitrite [6-11]. The active components in many of these potentiometric sensors have been quarternary ammonium salts. Because of their reduced mobilities with poor formation of dimers and water clusters other applications are also found [12]. In potentiometric membrane applications, however, the innate Hofmeister type response of such sensors to lipophilic anions such as salicylate can lead to significant positive errors for measurement nitrate/nitrite [13]. Positive interferences from bromide and added heparin are also possible [14]. Oka et al. have 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 [15]. Recently, a couple of reports have assessed the feasibility of using Cobalt(III)-porphyrin-based sensors in an appropriate flow-injection analysis (FIA) arrangement to determine nitrite levels [10,11].

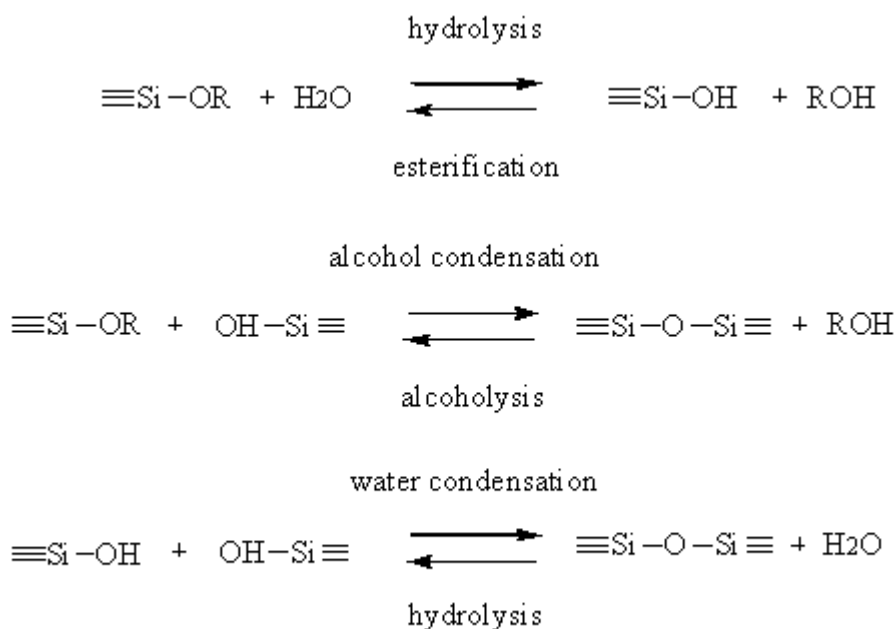


Figure 1. A general sol-gel process

Sol-gel processes have been employed to prepare organic/inorganic polymer materials of network structure [16-18]. In general, the polymerization (or gelation) is achieved by the reaction of sol-state inorganic alkoxide molecules via hydrolysis and repetitive condensation (Fig.1). The reaction proceeds slowly at low temperatures with host materials encapsulated inside. Applications of the methods are found in the study of photoelectronic material and functional composite materials [19].

Biosensor applications are quite active, in conjunction with the immobilization of biologically active species such as enzymes, antibodies, whole cells, etc [20-22]. The concept of sol-gel encapsulation of an ionophore is applied in the present study for the matrix of nitrite-sensitive membrane electrodes. Then electrochemical properties of the sensors are compared to those of conventional electrodes prepared with PVC.

2. EXPERIMENTAL SECTION

2.1. Reagents

TOAB, PVC, 3-Isocyanatopropyltriethoxysilane, and 2-morpholinoethanesulfonic 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. Buffer solutions consisting of 0.05 M MES, adjusted with NaOH to pH 5.5, 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 (resistivity, 18 M Ω -cm).

2.2. 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-isocyanatopropyltriethoxysilane (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 Fig. 2). After evaporation of THF, the highly viscous sol-state precursor (1,4-precursor, 3) was obtained and stored in refrigerator. An appropriate amount of the precursor was dissolved in N,N-dimethylformamide (DMF) with TOAB according to the formulation shown in Table 1. After shaking the mixture for 1 min., 15 μ L of 0.072 M hydrochloric acid was added. After shaking the mixture vigorously for another 30 s, the mixture was poured onto a boat (1.4 x 1.4 cm) of poly(ethylene terephthalate) film. The polymerization was carried out at 40°C for 48 h to obtain transparent gels that contain the ionophore and the ion-exchanger. Before use, the gel membrane was vacuum-dried at 40°C for another 48 h. PVC-based membranes were prepared according to the method of Simon and co-workers [23]. 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, Zürich, Switzerland). As an internal filling solution, 0.01 M NaNO₂/0.1 M NaCl solution was used.

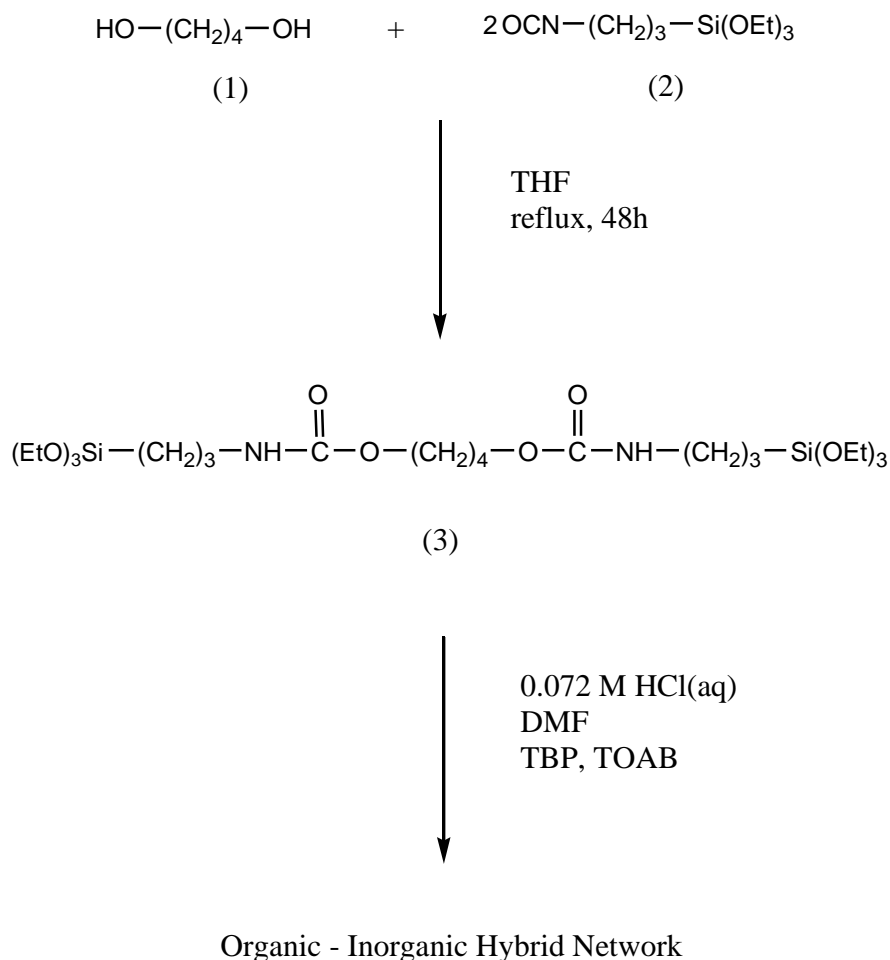


Figure 2. A scheme for a low-temperature sol-gel process for an organic-inorganic polymer network containing TOAB

2.3. Static Mode Potentiometric Measurements:

Cell potentials were measured at an ambient temperature of $20(\pm 2)^\circ\text{C}$. The potentiometric cell used was as follows: Ag/AgCl(s)/4 M KCl saturated with AgCl/MES buffer/sample solution/ion-selective membrane/internal filling solution/AgCl(s)/Ag. Potential differences between the membrane electrodes and the Fisher double-junction Ag/AgCl reference electrode were measured using a computer equipped with a high-impedance input 8-channel A/D converter (Kosentech, Model KST101, Busan, Korea) with a sample rate of 1 Hz. This apparatus was used to determine the selectivity of each membrane toward nitrite over other anions in the static mode. Selectivity coefficients, $k^{\text{pot}}_{\text{nitrite}/y}$, were obtained by using the separate solution method [24] at 10 mM standard solutions prepared from sodium salts of anions.

2.4 Flow-Injection Mode Measurements:

The arrangement shown in Figure 3 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 [25]. The flow cap was connected to the injection valve by teflon tubing (0.012 in. i.d.). A peristaltic pump (Ismatech SA, Zurich) and a Rheodyne four-way rotary Teflon valve (Model 7125) equipped with a 60- μ L sample loop completed the flow-injection setup. The MES buffer was used as the carrier stream. The nitrite-selective and Ag/AgCl reference electrodes were connected as described above. Sampling rate was adjusted to 2 Hz to observe delicate changes in the mV response.

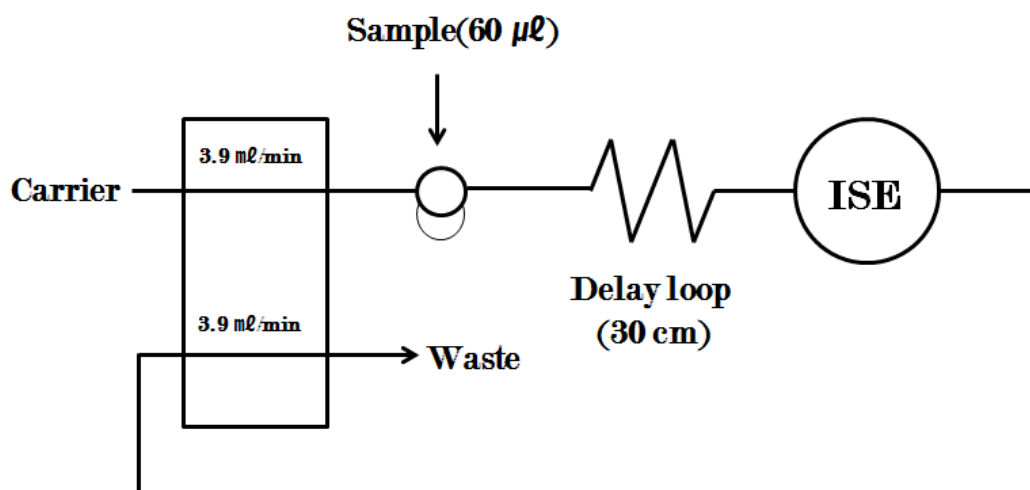


Figure 3. Schematic of the sol-gel membrane electrode-based flow injection analysis (FIA) system

3. RESULTS AND DISCUSSION

A known sol-state precursor, either tetraethylorthosilicate (TEOS) or tetramethylorthosilicate (TMOS), can be employed to proceed the condensation reaction resulting in a glassy three-dimensional network structure (Fig. 1). These membranes are, however, too brittle to be cut and mounted on top of typical membrane electrode bodies. In the present study, a precursor, **3**, made from linkages between organic and inorganic components was utilized as indicated in Fig. 2. Note that the organically modified precursor (1,4-precursor, **3**) contains urethane moieties as well as silicates at both ends. As well known, the former relate to increased biocompatibility while the latter are compatible with glass. In the sol-gel applications for creating anion-selective membranes, however, the problems mainly relate to the precipitation of membrane components and cracking phenomena during gelling. Because of this, several reaction conditions are to be taken into consideration: (1) Effect of an acid/base catalyst, (2) Use of a plasticizer, (3) Dependency on reaction temperature and (4) Aging.

First, the effects of the acid/base catalyst in the hydrolysis and condensation were studied (see Fig. 1). To prepare a single gel membrane, usually an appropriate amount of the precursor as well as inophore/plasticizer were dissolved in DMF. Then acid or base catalyst is then added. The whole mixture was then cast on PET boat (15mm x 15mm). Earlier studies have revealed that acid-catalyzed condensations yield primarily linear or randomly branched polymers, while base-catalyzed ones tend to give highly branched clusters [26]. Clustering phenomena would obviously not be useful in order

for a well-defined membrane to be made. This led to the use of an acid catalyst, HCl. A previous report recommended that acid catalysts of pH lower than 2.5 should be employed for the polymerization of the traditional precursor, tetraethylorthosilicate (TEOS) [26]. In this pH range, it was also found that hydrolysis is preferred while condensation is accelerated at relatively higher pH's. In general, the condensation is known to be rate-determining. Redissolution (reverse reaction of the condensation) also accompanies usually the condensation. In the present study, different pH's of HCl were tested. This is because an organically modified precursor rather than traditional TEOS was employed. The lowest concentration for the reaction to yield a good membrane was 0.05 M HCl. If the concentration is higher, the reaction goes faster. However, the resulting membrane tends to brittle. If the concentration is lower than 0.05 M, much more time was required for the membrane to cure (ex. 1 week for 0.025 M) giving no apparent advantages.

Second, effects of a plasticizer on membrane physical properties were tested. In the case of TOAB-doped films, the use of a plasticizer was required for better flexibility. A frequently used plasticizer *o*-nitrophenyloctyl ether, however, resulted in a turbid membrane. Turbidity commonly relates to precipitate formation. To solve the problem, ninety one plasticizers in a plasticizer sample kit (Scientific Polymer Products, Inc.) were tested. Among these, tributyl phosphate (TBP) was chosen for further studies because the resulting membranes showed the best transparency as well as homogeneity (e.g., kimwipes didn't give any evidence of plasticizer exudation).

Third, temperatures ranging from 22°C to 65°C were thus tested for the sol-gel reaction, because hydrolysis and condensation reactions in Fig.1 are affected by heat [27]. If the temperature was raised to 65°C, there are more chances for the gel to crack. Membrane quality was quite acceptable when the films were processed at 40°C.

Table 1. Formulation of different nitrite sensitive membranes from the sol-gel and the traditional method

membrane ID*	TOAB (mg)	Plasticizer (mg)	Matrix (mg)	solvent
SG-1	10.3	TBP 5.6	95.2	0.4 mL DMF
SG-2	5.1	TBP 5.6	95.2	0.4 mL DMF
SG-3	15.3	TBP 5.6	95.2	0.4 mL DMF
PVC	10.3	NPOE 112.1	50.0	1.5 mL THF

* PVC- and SG- denote PVC-and sol-gel-based membrane electrodes

Fourth, aging of gel membranes were considered, because this is a step for the condensation reactions to go forward to the right through the evaporation of ethanol and water (Fig. 1). This step will be crucial for creating a higher molecular weight cross-linked polymer. As the polymerization proceeds, condensation becomes a more time-consuming step [28]. DMF also evaporates slowly, leaving behind the gel structure. This is an important step, because, under harsh reaction conditions of

temperature and/or strong catalyst acidity, membrane cracking may become a problem. This is due to the so-called capillary forces at the gel surface. To prevent this from happening, a “supercritical drying” method was employed [29]. In the present study, however, drying was performed without employing the supercritical drying. That is, as the membrane cured after 48 h, the membrane was allowed to dry for at least 48 h in a vacuum oven at 48 mmHg and 40°C. Under these mild conditions, membrane cracking was minimized.

Following the above procedure transparent membranes (0.15 mm in thickness and 1.24 g/Cm³ in density) were obtained and tested for electrochemical responses. Membranes made from different ionophore/matrix ratio (SG1 to SG3 in Table 1) exhibited very similar electrochemical responses. Therefore SG1 membranes were further employed throughout the study. The membranes were flexible enough to be cut with a #2 cork cutter [11, 30, 31]. For characterization of the sol-gel membranes, our previous reports can be referred. The calibration curve of typical TOAB-based sol-gel membrane electrodes toward nitrite in the concentration range 0-500 mM is shown in Figure 4. In use stability of the sensors was at least one month. As tested in the static mode, the membrane electrode did not show any significant deterioration in the response behavior after one month. Average response slope decreased from 55 mV/decade to 50 mV/decade in between 0.1 mM – 500 mM nitrite at 20(±2)°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 0.02 mM which is almost ten times lower than that of the traditional PVC membranes.

Table 2. Static mode potentiometric selectivity coefficients*, $\log k^{\text{pot}}_{\text{nitrite},y}$ of TOAB-based electrodes prepared by the sol-gel method and PVC-based electrodes

Anion	PVC	SG-1	SG-2	SG-3
HCO ₃ ⁻	-0.7	-0.8	-0.8	-1.0
Cl ⁻	-0.7	-0.7	-0.7	-0.8
NO ₂ ⁻	0	0	0	0
Br ⁻	0.7	-0.1	-0.1	-0.1
NO ₃ ⁻	1.4	0.5	0.4	0.6
salicylate	2.4	0.4	0.2	0.6
I ⁻	2.8	0.4	0.4	0.6
SCN ⁻	3.0	1.4	1.3	1.6
IO ₄ ⁻	4.0	0.4	0.3	0.5
ClO ₄ ⁻	4.3	1.1	0.9	1.3

* Average of three determinations. All values obtained in 0.05 mol/L MES buffer, pH 5.5, at an anion concentration of 10 mmol/L.

Table 2 provides the potentiometric selectivity coefficient data of the TOAB-based sol-gel membrane for several anions relative to nitrite. For comparison purposes, selectivity data are also given for the PVC membranes doped with TOAB. As can be seen, the sol-gel membranes exhibited similar selectivities toward nitrite over hydrophilic anions such as chloride. However, selectivities over

more lipophilic anions were significantly improved, deviating from the Hofmeister selectivity pattern which is observed in most dissociated charged carrier-based potentiometric membrane sensors. For example, more than 100 times selectivity improvement toward nitrite over salicylate is achieved when compared to the traditional PVC-based membrane electrodes.

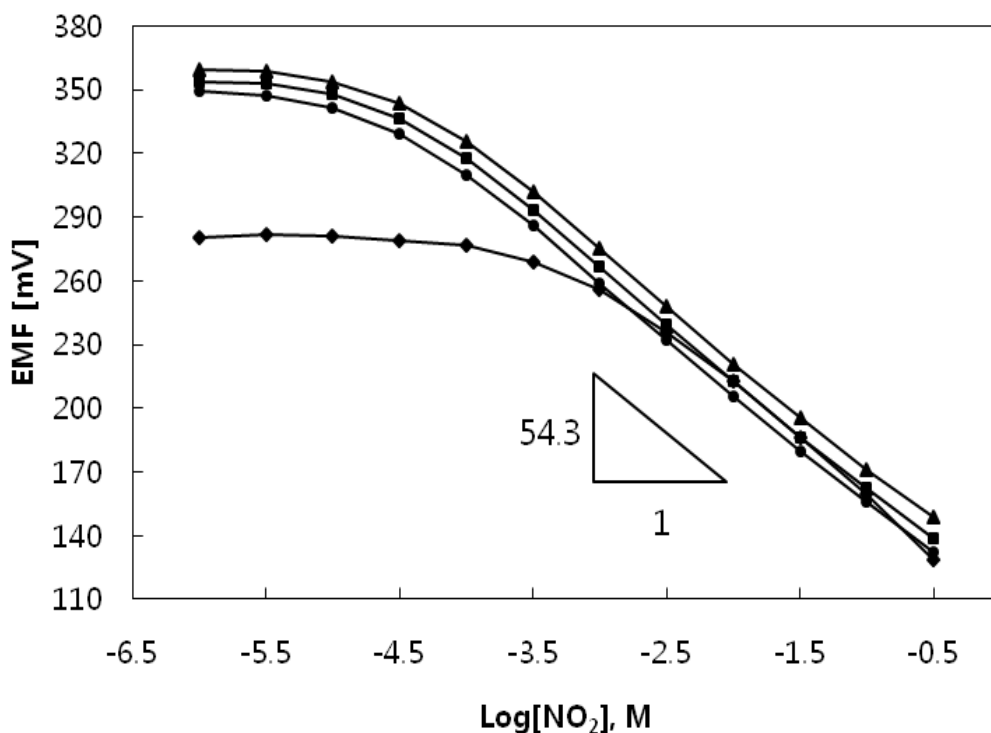
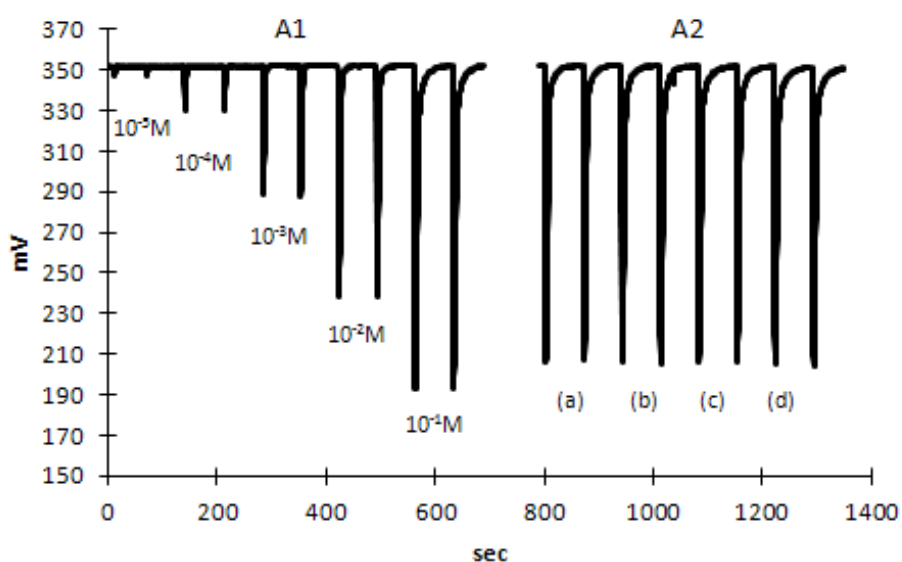


Figure 4. Potentiometric response of electrodes constructed with a membrane: (♦) PVC; (■) SG-1; (▲) SG-2; (●) SG-3, respectively (see table 1 for the membrane ID).



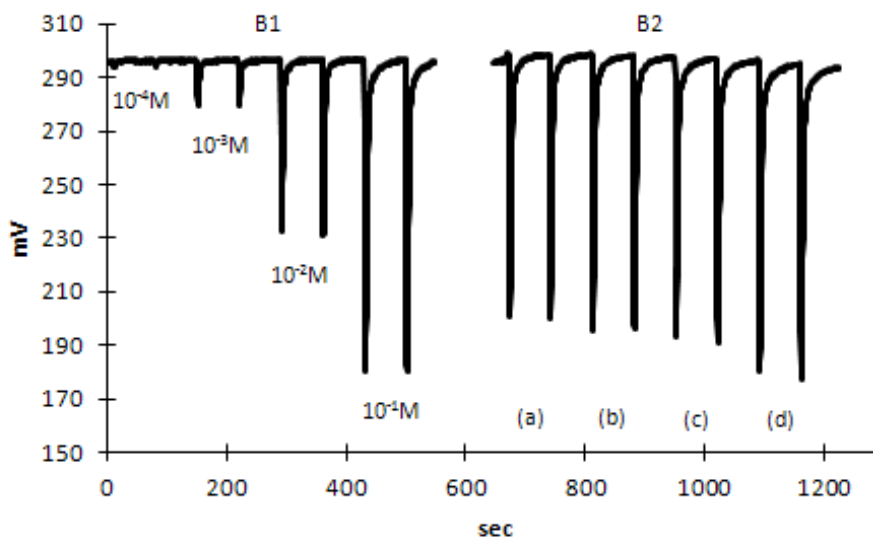


Figure 5. (A1) Potentiometric responses obtained for double injections of sodium nitrite standards in the FIA system with the TOAB-based sol-gel membrane detector; (A2) Responses for double injections of 50 mM sodium nitrite spiked with (a) 0, (b) 0.5, (c) 1, and (d) 2 mM sodium salicylate, using 0.05 M MES buffer, pH 5.5, as the carrier stream; (B1) Responses obtained for double injections of sodium nitrite standards with the TOAB-based PVC membrane detector; (B2) Responses for double injections of 50 mM sodium nitrite spiked with (a) 0, (b) 0.5, (c) 1, and (d) 2 mM sodium salicylate, using 0.05 M MES buffer, pH 5.5, as the carrier stream

Figure 5(A1) shows the typical data obtained for double injections of nitrite standards (from 0.01 to 100 mM) under the FIA conditions when one of three-week old membranes prepared with the sol-gel method was used as the detector. During the period, the electrodes had been tested almost on daily basis. If not in use, they had been stored in the 0.05 M MES buffer, pH 5.5, containing 0.1 mM sodium nitrite. Peak heights toward 50 mM nitrite standard were reproducible to ± 1 mV (SD, 10 replicates)(data not shown) at a sampling rate of 0.01 Hz. A fast baseline return was observed when the FIA-membrane electrode system was exposed to even higher concentrations of 100 mM nitrite. In the non-equilibrium flow-injection system, response slopes toward nitrite tend to be somewhat less than that observed in static mode experiments. That is, the response slope was about 42 mV/decade when the nitrite level changes from 1 to 100 mM. In the static mode, the nitrite sensitive membranes prepared with the sol-gel method showed an improved selectivity toward nitrite over more lipophilic anions (Table 2). Indeed this was confirmed in the FIA mode. Figure 5(A2) illustrates the effectiveness of this novel approach. Note that peak heights (ΔmV) for a series of 50 mM sodium nitrite standards containing up to 2 mM salicylate are essentially the same. At these concentrations of nitrite and salicylate, the baseline return was relatively quick and reproducible. Typical t_{90} values (time required to reach 90% of equilibrium mV value) are shorter than 40 sec while average difference in baseline potential at 50 sec after sample injections is less than 0.5 mV for consecutive measurements. These results can be compared to those obtained with the traditional PVC-based membranes doped with TOAB. As can be seen Fig. 5 (B1), the PVC membrane electrode showed detectable signal only at above 0.1 mM. Also B2 of Fig. 5 indicates that the PVC-based membrane electrode experience severe salicylate interferences.

It is believed that the improved selectivities and other characteristics are related to the inherent properties of the matrix. The sol-gel matrix has urethane (NHCOO) and silicate (Si-O-Si) functional groups, making itself more hydrophilic than PVC. This difference from a regular PVC-based electrode seems to cause improved selectivities toward nitrite which is more hydrophilic than salicylate and other bulky/organic anions. Second, the sol-gel matrix has an infinite molecular weight, theoretically, with a three-dimensional network structure, due to the three-dimensional consecutive condensation reaction of the sol-state precursor. In general, sol-gel matrix can be characterized by extended porous structure of the surface [21]. In our previous BET experiment, average pore size of the gel membrane surface and its surface area were 17 Å and 8.3 m²/g, respectively [30]. It is not clear how these numbers relate the observed chloride selectivity quantitatively. Efforts aimed at understanding further the surface chemistry in conjunction with the improved nitrite selectivity of the sol-gel matrix-based membrane electrodes are in progress.

4. CONCLUSIONS

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

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