

## Chloride-selective membranes prepared with different matrices including polymers obtained by the sol–gel method

Wantae Kim<sup>a</sup>, Dae Dong Sung<sup>b</sup>, Geun Sig Cha<sup>c</sup> and Sung Bae Park<sup>\*a</sup>

<sup>a</sup> Department of Chemistry, Inje University, Kimhae, 621-749, Korea

<sup>b</sup> Department of Chemistry, Dong-A University, Pusan, 604-714, Korea

<sup>c</sup> Department of Chemistry, Kwangwoon University, Seoul, 139-701, Korea

**A series of organic–inorganic sol–gel matrices were used as hosts for a chloride ionophore in chloride-selective membranes; their potentiometric performances were compared to those obtained with traditional PVC- and carboxylated PVC-based membranes without any plasticizers.**

**Keywords:** Chloride-selective membranes; organic–inorganic sol–gel matrices; potentiometry

Among various types of chloride-selective electrodes, liquid/polymeric membrane electrodes with adequate selectivity towards chloride over other biologically important anions have been widely used.<sup>1–6</sup> For this kind of membrane electrode, quaternary ammonium salts have been used primarily as a chloride-selective ionophore. As a matrix, PVC is by far the most commonly used polymer for such membrane electrodes. A plasticizer such as *o*-nitrophenyl octyl ether (NPOE) is also employed to formulate such membranes. However, these electrodes not only show poor selectivities over salicylate and other organic anions, but also exhibit clotting effects from blood proteins.<sup>7</sup> Aspirin and its analogues are commonly used analgesics. Recommended therapeutic levels of their metabolic products in human blood, especially salicylate, range from 0.15 to 2.1 mM.<sup>8,9</sup> Positive interference from added heparin is also possible.<sup>10</sup>

To overcome the problem, independent researchers have developed new ionophores other than ammonium salts.<sup>11–13</sup> An anion-binding complex such as mercury(II) EDTA was once suggested for use in the diluting buffer to decrease possible salicylate interferences.<sup>14</sup> The need to use 'environmentally friendly' reagents, however, seems to make this particular method archaic. On the other hand, some workers have studied the effects of matrices on the performance of an electrode. For example, Oka *et al.*<sup>4</sup> suggested the use of a polystyrene membrane with covalently bound quaternary ammonium sites. Recently, Park *et al.*<sup>12</sup> reported the use of an asymmetric cellulose triacetate (CTA) membrane matrix. They employed newly developed chloride ionophores, In<sup>III</sup> porphyrins, in conjunction with a flow injection system to minimize non-specific adsorption of proteins in human serum samples. Although the method also showed improvements in terms of chloride selectivity, it may show difficulties in application (*e.g.*, in manufacturing solid-state electrodes).

Recently, we have reported that a novel organic–inorganic hybrid sol–gel matrix could be used as the host for a quaternary ammonium salt, tridodecylmethylammonium chloride (TDMAC).<sup>15</sup> Membranes with a ratio of TDMAC to sol–gel precursor of 0.1:3 by mass showed very stable baseline potentials. The membrane electrodes showed much improved selectivity towards chloride over salicylate and other lipophilic anions. If an ionophore in an anion-selective membrane is of an ion-exchanger type (*e.g.*, TDMAC), the anion selectivity will be

dictated by the ratio of the partition coefficients of primary and interfering anions in the sample solution. This results in the so-called Hofmeister selectivity pattern,<sup>16</sup> showing more responses towards more lipophilic anions. In the case of a chloride sensor, a large or an organic anion such as perchlorate or salicylate can give a significant positive error in measurements. This interference, however, may be reduced by using more hydrophilic plasticizers or by eliminating them completely.<sup>17,18</sup> It is also reported that the reduced selectivity for lipophilic anions is unfortunately accompanied by some decrease in chloride selectivity over hydrogen carbonate.<sup>19</sup>

The sol–gel derived chloride-selective membranes have unique characteristics.<sup>20–22</sup> In addition to the inherent three-dimensional network structure, the matrices do not have plasticizers as constituents. It is believed that the enhanced chloride selectivity is related to the latter. Naturally, it would be of interest to compare the electrochemical properties of membrane electrodes based on other matrices with no plasticizer.

In this work, we compared the potentiometric data obtained with our sol–gel method-based membranes with those with traditional polymer matrices, PVC and carboxylated PVC. In addition, the electrodes were utilized as a flow-through detector to observe salicylate interferences in chloride determinations.

### Experimental

#### Reagents

TDMAC, PVC and 2-morpholinoethanesulfonic acid monohydrate (MES) were obtained from Fluka (Ronkonkoma, NY, USA). Carboxylated PVC (PVC-COOH, carboxyl content 1.8% by mass) was purchased from Scientific Polymer Products (Ontario, NY, USA). Reagents for the sol–gel matrix (butane-1,4-diol and 3-isocyanatopropyltriethoxysilane) were the same as used previously.<sup>15</sup> Tetrahydrofuran (THF) was purchased from Aldrich (Milwaukee, WI, USA) and purified over sodium. A buffer solution consisting of 0.01 M MES, adjusted with NaOH to pH 5.5, was used as the working buffer for the potentiometric measurements. All other chemicals were of analytical-reagent grade. The buffer and standard solutions were prepared with de-ionized water.

#### Polymer membranes and electrodes

Polymerization and drying processes for the sol–gel membranes were performed according to previously reported details.<sup>15</sup> In this study, however, different ratios of the membrane components (precursor to ionophore) were employed (Table 1) to obtain transparent gel membranes which contained the ionophore. Before use, the membrane was vacuum dried at 40 °C for 24 h. PVC and carboxylated PVC membranes were prepared by the method of Schulthess *et al.*<sup>23</sup> The compositions are listed in Table 1. After allowing the membranes 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.

### Static mode potentiometric measurements

Cell potentials were measured at an ambient temperature of 18 °C. The potentiometric cell used was 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 towards chloride over other anions in the static mode. Selectivity coefficients,  $k^{pot}_{Cl,X}$ , were obtained by using the separate solution method.<sup>24</sup>

### Flow-injection analysis (FIA) mode

The arrangement shown in Fig. 1 was used to evaluate the performance of the PVC-, PVC-COOH and sol-gel membrane electrodes in the FIA mode. A Phillips electrode body was fitted with a flow cap for use as a flow-through detector in a large volume wall-jet cell.<sup>25</sup> Teflon tubing (0.012 in id) connected the flow cap to the injection valve. A peristaltic pump (Ismatec, Zurich, Switzerland) and a Rheodyne (Cotati, CA, USA) four-way rotary Teflon valve (Model 7125) equipped with a 60  $\mu$ l sample loop completed the flow injection set-up. 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 1 Hz to observe small changes in the mV response. To increase the S/N of the data obtained, the moving average technique was employed using every three data points.<sup>26</sup>

### Results and discussion

Although the sol-gel method with TDMAC, the mass percentage of which in membranes is > 6, resulted in slightly turbid membranes, the quality of the membranes was sufficient for them to be cut with a No. 2 cork cutter and mounted within Phillips electrode bodies (0.15 mm in thickness). Calibration curves of typical TDMAC-based sol-gel membrane electrodes and PVC- and PVC-COOH electrodes with respect to chloride in the concentration range 0–500 mM are shown in Figs. 2 and 3, respectively. Related data are summarized in Table 1. As can be seen, the sol-gel based membrane electrodes give comparable detection limits and higher response slopes than those obtained with high amounts of PVC and PVC-COOH. In these traditional polymer based electrodes, < 20 mass% TDMAC resulted in minor or negligible responses. Interestingly, a higher

amount of TDMAC (*i.e.*, 60 mass%) in PVC and PVC-COOH have improved slopes.

Next studied was the anion selectivity of the three different matrix based membranes. In this experiment, all the electrodes (E4 to E9 in Table 1) were soaked in the buffer solution for 100 s. Then we added sodium salicylate standard solution to give a salicylate concentration of 1 mM. After waiting another 100 s, the chloride standard addition was made every 30 s (Fig. 4). Results for a typical sol-gel based membrane electrode (22 mass% ionophore) are also included in Fig. 4. The data for the sol-gel based membrane electrode indicate that the detection limit (approximately 1 mM) and response slope (approximately 52 mV per decade between the detection limit and 100 mM) did not vary significantly from those obtained with chloride calibration without salicylate (see Table 1). However, the curves for the PVC- and PVC-COOH-based electrodes (E6 and E9) showed an ambiguous response behavior at lower concen-

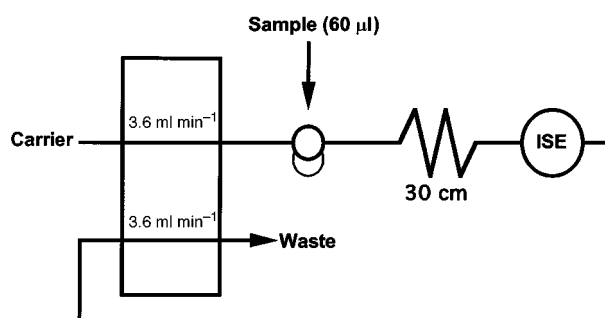


Fig. 1 Schematic diagram of the membrane electrode-based flow injection system.

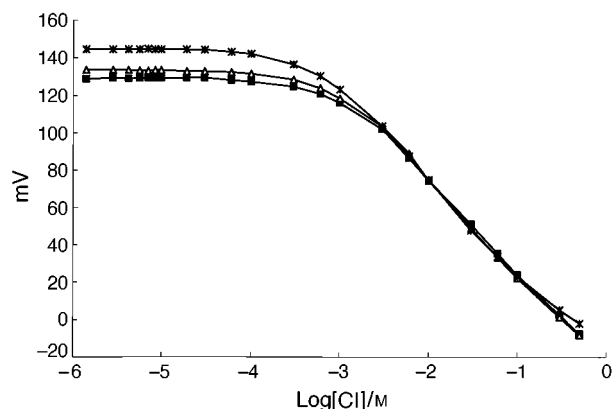


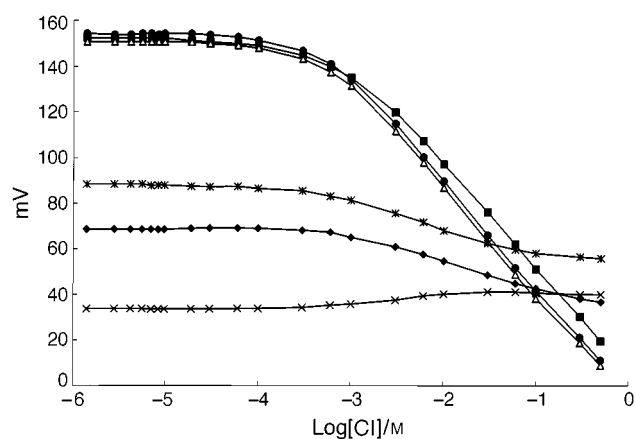
Fig. 2 Calibration curves for membranes prepared by the sol-gel method: ■, E1;  $\Delta$ , E2; \*, E3 in Table 1.

Table 1 Formulation and electrochemical properties of chloride-selective membrane electrodes

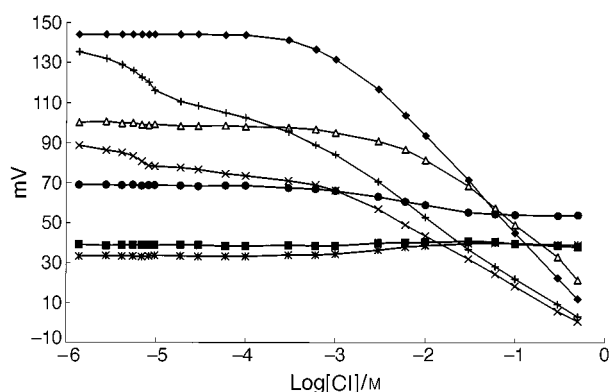
Electrode	Sol-gel precursor*	PVC*	PVC-COOH*	TDMAC*	Detection limit/ mM <sup>†</sup>	Slope/mV per decade after 1 week <sup>‡</sup>
E1	85			15	1.0	53.0
E2	78			22	1.0	55.0
E3	50			50	0.5	53.8
E4		95		5	—	—
E5		80		20	0.5	44.2
E6		40		60	0.6	51.1
E7			95	5	—	—
E8			80	20	—	—
E9			40	60	0.5	48.5

\* Concentrations in mass%. <sup>†</sup> Data were obtained with three membranes. <sup>‡</sup> The slopes were calculated using the linear portion of the response curve (detection limits and 0.1 M).

trations (*i.e.*, <0.1 mM). By performing calibrations repeatedly, however, it was found that the membranes with these particular formulations reached a blank equilibrium slowly. That is, the PVC- and PVC-COOH-based electrodes (E6 and E9) needed an extended period of time for equilibration with salicylate anion in the buffer. Indeed, an independent study indicated that the time for equilibration depends on the composition of the membrane. For example, the time for equilibration with 1 mM salicylate (time required to reach the point where the rate is



**Fig. 3** Calibration curves for PVC- and PVC-COOH-based membrane electrodes in 0.01 M MES (pH 5.5):  $\blacklozenge$ , E4;  $\blacksquare$ , E5;  $\triangle$ , E6;  $\times$ , E7;  $*$ , E8;  $\bullet$ , E9 in Table 1.



**Fig. 4** Calibration curves for PVC- and PVC-COOH-based membrane electrodes in 0.01 M MES (pH 5.5) containing 1 mM sodium salicylate:  $\blacklozenge$ , E2;  $\blacksquare$ , E4;  $\triangle$ , E5;  $\times$ , E6;  $*$ , E7;  $\bullet$ , E8;  $+$ , E9.

**Table 2** Potentiometric selectivity coefficients\*,  $\log k^{pot}_{Cl,X}$ , of different membrane electrodes

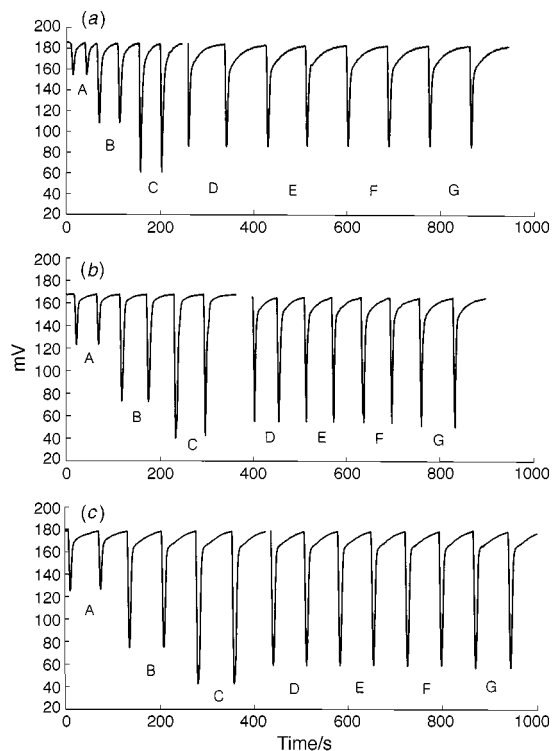
Anion	Electrodes <sup>†</sup>				
	E1	E2	E3	E6	E9
Cl <sup>-</sup>	0.0	0.0	0.0	0.0	0.0
Br <sup>-</sup>	-0.3	-0.1	-0.1	0.0	0.0
ClO <sub>4</sub> <sup>-</sup>	0.2	-0.1	0.8	1.0	0.5
SCN <sup>-</sup>	0.0	0.0	1.4	0.3	0.2
Acetate	-0.5	-0.4	-0.6	-0.2	-0.2
Hydrogen carbonate	-0.3	-0.1	-0.6	0.0	-0.1
Lactate	-0.5	-0.3	-0.7	-0.1	-0.2
Citrate	0.1	-0.1	-0.3	0.2	0.2
Salicylate	0.3	-0.1	1.0	-0.1	-0.1

\* Measured by the separate solution method at 1 mM anion concentration in 0.01 M MES buffer (pH 5.5). <sup>†</sup> Membrane compositions (E1–E9) are listed in Table 1.

<0.2 mV min<sup>-1</sup>) was >10 min for electrodes E6 and E9, but <1 min for E2. This indicates that we should have waited for a long enough time (>10 min) to obtain and compare thermodynamic selectivity coefficients using the fixed interference method.<sup>27</sup> Electrodes E6 and E9 in Fig. 4 are really responding to chloride on top of salicylate, because the electrodes are still in the course of sensing salicylate. In fact, after the full equilibration with salicylate, the total mV change towards 100 mM chloride was <10 mV.

The selectivity coefficients were then measured using the separate solution method. In this experiment we soaked the electrodes, all together, in the buffer solution for 100 s, then we added sodium salt standard solutions of various anions. After waiting a further 100 s with constant stirring, the total responses ( $\Delta$ mV) were measured to obtain selectivity coefficients. The values of the selectivity coefficients in Table 2 indicate that larger amounts of TDMAC lower the interference from different anions. As can be seen, there is a substantial change in the selectivity pattern for the TDMAC-based sol-gel membrane electrodes. For example, a more than fivefold selectivity improvement towards chloride over salicylate was achieved for the E2 formulation (22 mass% TDMAC) compared with the previously reported formulation (3 mass% TDMAC). Moreover, E6 and E9 exhibited nearly 600-fold improvements in selectivity when compared with the electrodes with a plasticizer (see Table 2 in ref. 15).

In general, sophisticated instruments (*e.g.*, CX3 series clinical autoanalyzers from Beckman Instruments, Brea, CA, USA) employ a flow-cell composed of several sensor ports which detect different chemistries. This kind of system, based on potentiometric concepts for electrolyte measurements, may not employ equilibrium methods primarily because of the necessity for higher throughput. Each instrument measures



**Fig. 5** (a), (b) and (c) are potentiometric responses obtained for double injections of chloride standards in the FIA system with E2, E6 and E9, respectively. A, B and C are calibration peaks for 5, 50 and 500 mM NaCl; D, E, F and G are responses towards 150 mM NaCl containing 0, 0.1, 1 and 2 mM sodium salicylate, respectively, using 0.01 M MES buffer (pH 5.5) as the carrier stream.

electronically the mV span ( $\Delta mV$ ) following pre-set time schemes rather than waiting for each electrode to reach full equilibrium. Naturally, the transient response behavior of each membrane electrode should be studied.

For this purpose, E2 (sol-gel), E6 (PVC), and E9 (PVC-COOH) were utilized as detectors in the non-equilibrium flow injection system shown in Fig. 1. Fig. 5(a) shows typical data obtained with electrode E2 for double injections of chloride standard solutions (from 5 to 500 mM) under the FIA conditions and also 150 mM chloride standard solutions with and without a salicylate spike. The peak heights with respect to 150 mM chloride standard solution are reproducible to  $\pm 1$  mV (SD, 10 replicates) (data not shown) at a sampling rate of 0.01 Hz. In the flow injection system, the response slopes towards chloride tend to be smaller than those observed in static mode experiments. That is, the response slope is about 48 mV per decade when the chloride level changes from 50 to 500 mM. Note that the peak heights ( $\Delta mV$ ) for a series of 150 mM NaCl standard solutions containing up to 2 mM salicylate are essentially the same. Fig. 5(b) and (c) illustrate a typical flow-through diagram obtained with electrodes E6 and E9, respectively. It can be seen that the peak heights ( $\Delta mV$ ) for a series of 150 mM NaCl standard solutions containing 2 mM salicylate increase only slightly.

In conclusion, we compared the potentiometric response behaviors of the sol-gel matrix- and PVC- and PVC-COOH-based membranes without any lipophilic plasticizers. The experimental results confirmed the notion that an ion sensor can reduce interferences from lipophilic ions by eliminating the plasticizer in the polymeric membrane.<sup>17,18</sup>

D.D.S. and S.B.P. acknowledge financial support from the Korean Ministry of Education (BSRI-97-3446). G.S.C. acknowledges financial support from the Korean Ministry of Education (BSRI-97-3405).

## References

- 1 Srivastava, S. K., and Jain, C. K., *Talanta*, 1984, **31**, 1021.
- 2 Lima, J. L. F. C., and Machado, A. A. S. C., *Analyst*, 1986, **111**, 151.
- 3 Wuthier, U., Pham, H.-V., Rusterholz, B., and Simon, W., *Helv. Chim. Acta*, 1986, **69**, 1435.
- 4 Oka, S., Sibasaki, Y., and Thara, S., *Anal. Chem.*, 1981, **53**, 588.
- 5 Willis, J., Young, C., Martin, R., Stearns, P., Pelosi, M., and Magnanti, D., *Clin. Chem.*, 1983, **29**, 1193.
- 6 Hitachi, *Jpn. Tokkyo Koho*, No. 5757 655, 1982.
- 7 Lewandowski, R., Sokalski, T., and Hulanicki, A., *Clin. Chem.*, 1989, **35**, 2146.
- 8 Chaniotakis, N. A., Park, S. B., and Meyerhoff, M. E., *Anal. Chem.*, 1989, **61**, 566.
- 9 Stewart, M. W., and Watson, I. D., *Ann. Clin. Biochem.*, 1987, **24**, 552.
- 10 Wang, E., Meyerhoff, M. E., and Yang, V. C., *Anal. Chem.*, 1995, **67**, 522.
- 11 Rothmaier, M., and Simon, W., *Anal. Chim. Acta*, 1993, **271**, 135.
- 12 Park, S. B., Matuszewski, W., Meyerhoff, M. E., Liu, Y. H., and Kadish, K. M., *Electroanalysis*, 1991, **3**, 909.
- 13 Huser, M., Morf, W. E., Fluri, K., Seiler, K., Schulthess, P., and Simon, W., *Helv. Chim. Acta*, 1990, **73**, 1481.
- 14 Scott, W. J., Chapoteau, E., and Kumar, A., *Clin. Chem.*, 1986, **32**, 137.
- 15 Kim, W., Chung, S., Park, S. B., Lee, S. C., Kim, C., and Sung, D. D., *Anal. Chem.*, 1997, **69**, 95.
- 16 Hofmeister, F., *Arch. Exp. Pathol. Pharmacol.*, 1888, **24**, 247.
- 17 Oesch, U., Ammann, D., Pham, H., Wuthier, U., Zund, R., and Simon, W., *J. Chem. Soc., Faraday Trans. 1*, 1986, **82**, 1179.
- 18 Sugahara, K., and Mori, J., *Ger. Pat.* DE 3 040 269, 1984.
- 19 Wegmann, D., Weiss, H., Ammann, D., Morf, W. E., Pretsch, E., Sugahara, K., and Simon, W., *Mikrochim. Acta*, 1984, **III**, 1.
- 20 Brinker, C. J., and Scherer, G. W., *Sol-Gel Science*, Academic Press, London, 1990.
- 21 Gesser, H. D., and Goswami, P. C., *Chem. Rev.*, 1989, **89**, 765.
- 22 Corriu, R. J. P., Moreau, J. J. E., Thepot, P., and Man, M. W. C., *Chem. Mater.*, 1992, **4**, 1217.
- 23 Schulthess, P., Ammann, D., Simon, W., Caderas, C., Stepanek, R., and Krautler, B., *Helv. Chim. Acta*, 1984, **67**, 1026.
- 24 Srinivasan, K., and Rechnitz, G. A., *Anal. Chem.*, 1969, **41**, 1203.
- 25 Trojanowicz, M., and Meyerhoff, M. E., *Anal. Chem.*, 1989, **61**, 787.
- 26 Binkley, D., and Dessy, R., *J. Chem. Educ.*, 1979, **56**, 148.
- 27 Moody, G., and Thomas, J. D. R., *Selective Ion-Selective Electrodes*, Merrow Books, Watford, 1971.

Paper 7/05788A  
Received August 7, 1997  
Accepted October 9, 1997