Higher quaternary ammonium salts with the sterically accessible exchange center: application for development of Selenate selective electrodes

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Abstract

A new film selenate selective electrode has been developed, with the following membrane composition: (3,4,5-tris-dodecyloxybenzyl)tetraoxyethyl trimethyl ammonium chloride (5% w/w) as an electroactive component, (poly)vinyl chloride (33% w/w) as a membrane matrix, 1-bromonaphtalene (42% w/w) as a plasticizer, (4-trifluoroacetyl) benzoic acid heptyl ester (20% w/w) as a neutral anion carrier. The electrode characteristics are as follows: linear range – 2·10–6–10–2 M by Na2SeO4; line plot slope 26,0±0,3 mV/decade; lower detection limit 1·10–6 M by Na2SeO4; working рН range 2,15 – 6,3; potential drift 0,9 mV/h; response time 15 – 90 s; selectivity in presence of chloride, bromide, sulfate and other ions; lifetime up to 3 weeks. The electrode developed has been tested on model solutions using the standard addition method in the calibration plot variant, and bracketing technique.

Keywords: Selenate Selective Electrode; Sterically Accessible Quaternary Ammonium Salts; (4-trifluoroacetyl) Benzoic Acid Heptyl Ester.

Introduction

Selenium is a necessary trace element for plants, animals and humans. It occurs in nature mainly as selenides, selenites and selenates, and sometimes in the elementary state. The majority of selenides and selenium element itself have low toxicity due to their limited bioaccessibility, while selenites and selenates are toxic and act similarly to arsenic compounds, according to [1,2]. Selenium concentration and form of its occurrence in waters of various geochemical origin depends upon their mineralization, redox potential, pH, iron content, proximity of oilfields etc.

For selenium determination, the following methods are currently in use: atomic adsorption spectroscopy, partition and ionic chromatography, stripping voltammetry, kinetic, fluorescent, photometric analysis, gas chromatography–mass spectrometry etc, as described in [1-7]. Despite the high sensitivity (approximately 10–6–10–5 mg/L), these methods often prove inefficient for direct selenium determination in complex objects. With background content of the analyte, the relative error can be as much as 50%. Moreover, the above methods require complicated sample preparation, use of expensive equipment, specialized reagents and, sometimes, chemical pre-treatment such as reduction of Se (VI) into Se (IV). For instance, in Reference1 it is reported that, in mineral waters of Caucasian region, selenium (IV) and selenium (VI) are present in comparable amounts. To convert Se (VI) into Se (IV), authors propose reduction with concentrated hydrochloric acid under heating, followed by Se (IV) determination by extraction redox photometry.
In this respect, ionometry, with its obvious objective advantages such as simple and quick sample preparation, wide range of concentrations determined and low equipment cost, looks very promising. An additional benefit is that both membranes and ion selective electrodes (ISE) themselves are easy to make and can be produced in any laboratory.

ISE developments for selenium determination are few and limited only to selenite ions, as mentioned in [8-10]. No information on selenate selective electrodes, either coated wire, film or solid contact type, or references thereof, has been found in the literature [11-18]. On the other hand, determination of selenium in selenate form is preferable in terms of greater stability of Na$_2$SeO$_4$, solutions compared to Na$_2$SeO$_3$. Long chain quaternary ammonium salts (QAS) proved themselves as promising materials for making anion selective ISEs. It has been believed that they uniformly have poor extraction capacity toward hydrophilic double charged anions (sulfate, selenate, carbonate etc.) due to strong hydration of these ions and steric hindrance by long hydrocarbon chains preventing simultaneous approach of two QAS cations to the double charged anion. The above is true, however, only for QAS cations having all four long-chain (no shorter than C$_3$) hydrocarbon substituents at the nitrogen atom. Therefore, it is interesting to test some new QAS, with improved steric access to the exchange center, against double charged anions.

It should be noted that the most spectacular successes in developing the ion-selective electrodes with nonstandard (anti-Hofmeister) selectivity were achieved with the aid of neutral anion carriers such as (4-trifluoroacetyl) benzoic acid heptyl ester (TFABAHE). That is why this compound was deemed necessary to use in the membrane of selenate selective electrodes.

Therefore, the goal of this work is to develop the new selenate selective electrode of high analytical performance based on long-chain QAS and TFABAHE. Several recently synthesized (as described in [19, 20]) long-chain QAS with high steric accessibility of the exchange center such as (3,4,5-tris-dodecylbenzoyloxyethyl)trimethyl ammonium chloride (oxyethyl),trimethyl ammonium chloride (oxyethyl),TM; where n = 2–4; and 4-(3,4-bis-hexadecyloxyphenyl)butyl trimethyl ammonium bromide (BHPBTM) have been tested as anion exchangers for the first time.

### Experimental

(Oxyethyl),TM; BHPBTM; trinonyl octadecyl ammonium iodide (TNODA), 3,4,5-tris-dodecylbenzoyl tributyl ammonium chloride (TB), 3,4,5-tris-dodecylbenzoyl triethyl ammonium chloride (TE) and 3,4,5-tris-dodecylbenzoyl trimethyl ammonium chloride (TM) were used as electroactive membrane components; dibutyl phthalate (DBP, Sigma-Aldrich), 1-bromonaphthalene (1-BN) p.a., o-nitrophenyl decyl ether (o-NPDE), bis(2-ethylhexyl) decanedioate (BEHD), didecyl phthalate (DDP) as plasticizers; TFABAHE as the neutral anion carrier. Synthetic procedures for quaternary ammonium salts have been presented on Figure 1 and described in full detail in [19, 20]. Structures of all new compounds have been confirmed by elemental analysis, NMR and IR spectra, which are also given in the same [19, 20]. Solutions for ionometry were prepared from K$_2$SeO$_4$ p., K$_2$SO$_4$ p., H$_2$PO$_4$ p., KCl p.a., NaBr p. and KNO$_3$ p.a.

ISE membranes contained the following components: (poly)vinyl chloride (PVC) 33% w/w, the ion exchanger (QAS) 5% w/w, the neutral anion carrier (TFABAHE) 20% w/w; and the plasticizer – 42%, with tetrahydrofuran (Fluka AG) as a solvent. They have been made according to a standard procedure described in [21]. All components were weighed precisely, dissolved in THF and mixed together. The obtained mixture was poured into the glass ring fixed on the glass plate and the solvent was allowed to evaporate overnight. Membrane disks (approximately 0.5-0.6 mm thick) were cut out from the master membrane and glued on the top of the PVC tubes with PVC-THF composition, and for the membrane composition.

The above proportions of membrane components have been selected on the basis of our previous works. In particular, in the [22] it has been shown that, for the membrane to be mechanically strong enough, the PVC content in the membrane should be no less than 33% w/w. From preliminary experiments it has been established that the most stable performance of the ISE (potential reproducibility) is achieved at 5% w/w of QAS. The effect of the neutral anion carrier content on the analytical characteristics of ISE reversible to doubly charged inorganic ions, including selenate ions, was studied in Reference$^2$, and it has been demonstrated that the optimum content of the neutral carrier is 20% w/w. The rest of the membrane, i.e. 42% w/w, is the plasticizer.

All newly made membranes have been soaked for 1-2 days in 1·10$^{-1}$ M solutions of potassium selenate. The mixture of potassium selenate (1·10$^{-2}$ M) and potassium chloride (1·10$^{-3}$ M) was used as an internal solution for all ISEs. In selenate solutions, pH was kept about 3·2±0.1 using phosphoric acid solution, in order to remove the interference from carbonates and for better reproducibility. The same pH value was kept also in the interfering ion solutions while studying the selectivities of ISEs developed. ISE calibration was done by the double dilution method.

Activities of SeO$_4^{2-}$ ions in calibration solutions were calculated according to the Debye–Hückel theory (for 20°C), as described in Reference$^2$. Potentiometric selectivity coefficients were determined by the separate solutions method in the equal potential variant according to the formula given in [25].

$$K_{i,j} = \frac{a_i}{a_j}$$

where $a_i$ is the activity in the main ion solution at the $E$ potential, $M$; $a_j$ is the activity in the interfering ion solution at the $E$ potential, $M$; $z_i$ and $z_j$ are charges of the main and the interfering ions, respectively.

Sulfate, chloride, nitrate and bromide ions were selected as the interference, being the most frequently found in real objects. Slopes in the interfering ion solutions were, respectively, 24-25.5 mV/decade for sulfate, 50-51 mV/
decade for chloride, 51-52 mV/decade for bromide and 49-50 mV/decade for nitrate. Other characteristics were determined as recommended in [21].

The ISE potential drops at pH>6.3, due to interference of hydrogen carbonate and hydroxide ions. At pH below 2.25 selenate ions gradually convert to hydrogen selenate ions (since $\log K_a(\text{HSeO}_4^-)=-1.8$, according to Reference 24, about 20% of Se (VI) exist as HSeO$_4^-$ at pH=2.25).

As it was noted above, the pH value for potentiometric measurements has been maintained at 3.2±0.1, excluding interference from hydrogen carbonate, sulfite, selenite, sulfide, hydrogen phosphate, fluoride etc. anions, as well as the majority of organic anions such as acetate, oxalate etc., due to their protonation. This makes unnecessary taking their interference into account, as it has been done in [8-10].

Lower detection limits and function slopes for selenate electrodes. Figures 3, 4 show electrode functions of ISEs, Table 1 contains LDL values and electrode function slopes.

Figure 1. Synthesis of sterically accessible quaternary ammonium salts

The potential of the electrochemical cell was measured by the I-160.1MP (Republic of Belarus, Gomel Plant of Measuring Devices) ionometer at 20±1°C. The EVL-1M3.1 silver chloride electrode (Republic of Belarus, Gomel Plant of Measuring Devices) was used as a reference, and the ESL-43-07SR glass electrode (Republic of Belarus, Gomel Plant of Measuring Devices) – for pH measurement.

Results and Discussion

Selecting the working pH range. Figure 2 shows that the potential of the SeO$_4^{2-}$selective electrode (based on (oxyethyl)$_2$TM, TFABAHE and 1-BN) is stable in the pH range from 2.25 to 6.3 and equals -217±0.4 mV (at $C(K_2\text{SeO}_4)=2.5\times10^{-3}$ M).

The ISE potential drop at pH>6.3, due to interference of hydrogen carbonate and hydroxide ions. At pH below 2.25 selenate ions gradually convert to hydrogen selenate ions (since $\log K_a(\text{HSeO}_4^-)=-1.8$, according to Reference 24, about 20% of Se (VI) exist as HSeO$_4^-$ at pH=2.25).

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Lower detection limits and function slopes for selenate electrodes. Figures 3, 4 show electrode functions of ISEs, Table 1 contains LDL values and electrode function slopes.
It is evident (Table 1), that all ISEs developed have near-theoretical electrode function slopes and low LDL that decreases further with QAS exchange center steric access improvement, i.e. from TNODA to (oxyethyl)2TM by 1.4 orders in absence of TFABAHE and by 0.9 orders in presence of it. Within the QAS series with improved steric access (from TM to (oxyethyl)4TM), LDL decreases by 0.8 and 0.3 orders, respectively.

The effect of plasticizer nature upon LDLs, selectivity and function slope. Figure 5 shows electrode functions for selenate ISEs with such plasticizers as 1-BN, BEHD and o-NPDE; LDL values, slopes and lgKpot(SeO42–) are given in the Table 3.

Table 3. Characteristics of selenate ISEs with various plasticizers

<table>
<thead>
<tr>
<th>Plasticizer</th>
<th>Slope, mV/decade</th>
<th>LDL, M</th>
<th>lgKpot(SeO42–), j</th>
<th>n=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>o-NPDE</td>
<td>25.0±0.4</td>
<td>5.8±0.1</td>
<td>-0.5±0.1</td>
<td>-1.7±0.1</td>
</tr>
<tr>
<td>BEHD</td>
<td>26.0±0.4</td>
<td>5.8±0.1</td>
<td>-0.7±0.1</td>
<td>-1.9±0.1</td>
</tr>
<tr>
<td>DBP</td>
<td>25.2±0.5</td>
<td>4.0±0.1</td>
<td>-0.7±0.1</td>
<td>-2.0±0.2</td>
</tr>
<tr>
<td>DDP</td>
<td>25.9±0.3</td>
<td>3.2±0.1</td>
<td>-0.75±0.1</td>
<td>-2.1±0.1</td>
</tr>
<tr>
<td>1-BN</td>
<td>25.6±0.4</td>
<td>1.8±0.1</td>
<td>-0.9±0.1</td>
<td>-2.3±0.1</td>
</tr>
<tr>
<td>1-BN</td>
<td>25.3±0.3</td>
<td>3.5±0.1</td>
<td>-0.7±0.1</td>
<td>-1.7±0.1</td>
</tr>
</tbody>
</table>

The effects of the exchange center steric accessibility on the selenate ISE selectivity can be qualitatively interpreted in terms of the corresponding change of ion association constants for ions being exchanged: in the model where QAS exists in the form of ion triples with double charged anions and no associates of greater complexity are formed, the ion association constant k_{a,s} is described by Eigen-Denison-Ramsey-Fuoss equation [28].

\[
\lg k_{a,s} = -2.6 + 245 \left[ \frac{z}{\epsilon} + \frac{\varepsilon}{\epsilon} - 3 \cdot \lg a \right]
\]

Where are charges of the anion and QAS cation being associated; \(\varepsilon\) is the dielectric constant of the solvent; a is the closest approach parameter for cations and anions being associated, \(\Delta\).

Selectivities of selenate ISEs. Table 2 contains lgKpot(SeO42–, j) values for all selenate selective electrodes plasticized with DBP. The results show that the effect of exchange center steric accessibility increases from hydrophilic to hydrophobic anions: while switching from TNODA to (oxyethyl)4TM brings down lgKpot(SeO42–, SO42–) only by 0.8 orders, the same change decreases lgKpot(SeO42–, NO3–) by as much as 5.5 orders.

Introducing TFABAHE into membranes improves selectivity dramatically. For instance, chloride and bromide ions show no interference with selenate. Somewhat unexpected is the fact that some selectivity is observed in presence of structurally similar sulfate ions; one of the possible terms of the corresponding change of ion association constants is described by Eigen-Denison-Ramsey-Fuoss equation [28].

\[
\lg k_{a,s} = -2.6 + 245 \left[ \frac{z}{\epsilon} + \frac{\varepsilon}{\epsilon} - 3 \cdot \lg a \right]
\]

Where are charges of the anion and QAS cation being associated; \(\varepsilon\) is the dielectric constant of the solvent; a is the closest approach parameter for cations and anions being associated, \(\Delta\).

Figure 5. Electrode functions of selenate ISEs with TFABAHE as a neutral anion carrier and various plasticizers: 1 – TM, BEHD, 2 – TM, o-NPDE, 3 – TM, 1-BN, 4 – (oxyethyl)2TM, 1-BN, 5 – (oxyethyl)4TM, 1-BN.
According to [28], in close ion pairs, where no solvent molecules are present between the associated ions, for QAS cations and anions, the parameter is about 4–7 Å. Hence, with solvents with low or medium dielectric constant, such as DBP (ε=6.4), DDP (ε=4.4), BEHD (ε=6) or 1-BN (ε=5) [24], the second member of Eigen-Denison-Ramsey-Fuoss equation makes the main contribution in $k_{as}$ value.

The $a$ parameter is, at least in the first approximation, an additive function of the anion and cation radii. It seems obvious that the effect of QAS exchange center steric accessibility on association constants must depend upon the size of ions being associated. Clearly, the improvement of accessibility on association constants must depend upon the obvious that the effect of exchanging ion size itself.

This trend for selectivity improvement is retained also in presence of such neutral carrier as TFABAHE. It should be noted that introduction of the neutral carrier levels both selectivity improvement and LDL decrease effects, that can be explained by solvate formation between anions and TFABAHE diminishing the effect of exchanging ion size itself.

Potential drift, response time, life time. Figures 6 and 7 show the time dependencies for the selenate ISE with optimized membrane composition by QAS, plasticizer and solvating additive. The potential drift has been observed for 1 hour.

It is evident that ISE potential establishes quickly, but with decreasing concentration (activity) the response time becomes longer, the reason being the decreased content of main ions in the near-electrode layer and stronger interference from other ions.

The life time for selenate ISEs is about 3 weeks in presence of TFABAHE and up to 9 weeks in its absence.

**Conclusions**

It has been established that, of all ISEs studied, the electrode based on (oxyethyl)$_4$TM, TFABAHE and 1-BN has the best characteristics. Considerable LDL decrease and selenate selectivity improvement occurs in the following QAS series: TNODA–TB–TE–TM–BHPBTM–(oxyethyl)$_2$TM–(oxyethyl)$_3$TM–(oxyethyl)$_4$TM. Therefore, the feasibility of «improved steric access» approach to designing ISEs for double charged anions is confirmed.

It has been found that, in the plasticizer series o-NPDE–BEHD=DBP–DDF–1-BN analytical characteristics improve considerably, that warrants recommendation of 1-bromonaphtalene as a plasticizer for selenate ISEs.

It has been shown that introducing TFABAHE as a neutral additive function of the anion and cation radii. It seems that the potential drift for the ISE based on (oxyethyl)$_4$TM, TFABAHE and 1-BN is about 0.9 mV/h, for C($\text{SeO}_4^{2–}$) = 4.5·10$^{-4}$ M.

**Figure 6. The potential drift for the ISE based on (oxyethyl)$_4$TM, TFABAHE and 1-BN**

The potential drift for the ISE based on (oxyethyl)$_4$TM, TFABAHE and 1-BN is about 0.9 mV/h, for C($\text{SeO}_4^{2–}$) = 4.5·10$^{-4}$ M.

**Figure 7. The response time for the ISE based on (oxyethyl)$_4$TM, TFABAHE and 1-BN**

**Determination of selenate ions in model solutions with the ISE based on (oxyethyl)$_4$TM, TFABAHE and 1-BN was performed by the calibration plot method and the limiting solutions method. In all solutions, pH has been maintained at 3.2±0.1. In the limiting solutions method, two standard solutions were used, with selenate concentrations above (C$_2$) and below (C$_1$) their content in the target solution (C$_0$). The calculations were done according to the formula:**

$$\log C_x = \frac{E_x - E_1}{E_1 - E_2} \cdot (\log C_2 - \log C_1) + \log C_1$$

**The results are presented in the Table 4.**

Therefore, the limiting solutions method is preferable for determining selenate ions in model solutions as it provides more precision.

**Table 4. Results of determination of selenate ions in model solutions**

<table>
<thead>
<tr>
<th>Introduced, mol L$^{-1}$</th>
<th>Found, mol L$^{-1}$ (calibrating plot)</th>
<th>S$_x$, %</th>
<th>Found, mol L$^{-1}$ SeO$_4^{2–}$ (the limiting solutions method)</th>
<th>S$_x$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1·10$^{-3}$</td>
<td>9.7·10$^{-4}$</td>
<td>8.4</td>
<td>9.8·10$^{-4}$</td>
<td>5.5</td>
</tr>
<tr>
<td>1·10$^{-4}$</td>
<td>1.3·10$^{-4}$</td>
<td>9.1</td>
<td>9.9·10$^{-5}$</td>
<td>4.8</td>
</tr>
<tr>
<td>5·10$^{-5}$</td>
<td>4.5·10$^{-5}$</td>
<td>9.6</td>
<td>5.2·10$^{-5}$</td>
<td>6.7</td>
</tr>
</tbody>
</table>

**Conclusions**

It has been established that, of all ISEs studied, the electrode based on (oxyethyl)$_4$TM, TFABAHE and 1-BN has the best characteristics. Considerable LDL decrease and selenate selectivity improvement occurs in the following QAS series: TNODA–TB–TE–TM–BHPBTM–(oxyethyl)$_2$TM–(oxyethyl)$_3$TM–(oxyethyl)$_4$TM. Therefore, the feasibility of «improved steric access» approach to designing ISEs for double charged anions is confirmed.

It has been found that, in the plasticizer series o-NPDE–BEHD=DBP–DDF–1-BN analytical characteristics improve considerably, that warrants recommendation of 1-bromonaphtalene as a plasticizer for selenate ISEs.

It has been shown that introducing TFABAHE as a neutral
anion carrier improves selectivity of selenate ISEs considerably. The possibility of selenate determination in model solutions both by calibration plot method and limiting solutions method has been demonstrated.

References


