Sensing and Characterization of Neurotransmitter 2-Phenylethylamine based on Facilitated Ion Transfer at Solvent Polymeric Membranes using Different Electrochemical Techniques

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Abstract

Square Wave Voltammetry (SWV), chronoamperometry and chronocoulometry are exploited to take advantage of their different performance characteristics in the determination, characterization and sensing of the neurotransmitter 2-phenylethylamine (PEA), based on the ion transfer of its protonated form at a solvent polymeric membrane facilitated by dibenzo-18-crown-6 (DB18C6). The general voltammetric features characterizing the PEA^+ transfer are established by SWV and the standard ion transfer potential, diffusion coefficient and complexation constant value between PEA^+ and DB18C6 are calculated from the SWV recordings. Next, the performance of double pulse chronoamperometry and double pulse chronocoulometry for the determination of PEA based on its facilitated ion transfer is studied. Limits of detection between 3.6 and 9.2 µM for chronoamperometry and 1.7 and 2.7 for chronocoulometry are obtained. The influence of common ions on both chronoamperometric and chronocoulometric determination is also considered. The sensitivity ratio values found between foreign cations and PEA^+ are 0.05, 0.3 and 0.2 for Na^+, K^+ and H^+, respectively, whereas no interference was observed for Li^+. In addition, the electrode is tested as a sensor for monitoring PEA^+ concentration using a pulsed-amperometric mode. Interestingly, a simple procedure to extend the range of linear response of quantitative electrochemical techniques significantly based on a previous analysis of chronoamperometric recordings is proposed and successfully tested.

INTRODUCTION

2-Phenylethylamine (PEA) belongs to the group of so-called trace amines, a family of endogenous amines. Trace amines are believed to play a role in human disorders like schizophrenia, depression, attention-deficit and Parkinson's disease [1]. PEA is the building block of around 200 neurotransmitters, including, adrenaline, dopamine, serotonin and neurologically active molecules like psychoactive drugs [2]. It has been called ''endogenous amphetamine'' and exists in aqueous solution at physiological pH, predominantly as cation (protonated form, pKa 9.73) [3].

Electrochemical studies of the facilitated ion transfer of protonated amines and aminoacids from water to organic solvents have been reported mainly by using cyclic voltammetry (CV), square wave voltammetry (SWV) and differential pulse voltammetry (DPV) [4-11]. In general, these studies are carried out by placing an ionophore in the organic solution, so that the ion transfer is facilitated by complexation between the target amine or aminoacid and the ionophore. Examples of ionophores employed are dibenzo-18-crown-6 (DB18C6) and homo-oxo-calix[3]-arenes, which have allowed the selective detection of species such as dopamine and noradrenaline, as well as the determination of the magnitude of their complexation constants [4-9, 11]. Since ion transfer voltammetry is not reliant on the oxidation or reduction of the target ion but on its interfacial potential controlled transfer from an aqueous phase to an organic phase, it has permitted, for example, the selective detection of dopamine in the presence of ascorbate [5], an important interference in electrochemical methods for dopamine determination based on its oxidation.

The voltammetric techniques mentioned above are excellent for determining characteristic parameters of the target ion such as standard ion transfer potential (and, therefore, the Gibbs energy of ion transfer), complexation constant with the ionophore in the membrane and diffusion coefficient in the aqueous phase [12] . They have also been used in

the development of analytical methods to determine concentrations of several target ions [13, 14]. However, for sensing purpose, other electrochemical techniques offer several advantages, such as faster sampling rates. In this respect, ion amperometry, mainly under pulse mode, has been used as detection system in flow-injection analysis [15, 16], in chromatography [17] and electrophoresis [18], and it is worth noting that in sensor batch mode there are scarce precedents of the use of this technique [19].

In recent years there has been an increasing interest in the use of coulometry as a transduction mode for sensors based on ion transfer processes at liquid/liquid interfaces [20]. An important advantage of chronocoulometry over chronoamperometry is that chronocoulometric signals increase with time, so integration is effective in improving the signal-to-noise ratio, separating the non-faradaic double-layer charge from the faradaic charge [21] more effectively. The non necessity of calibration in the case of complete electrolysis and the low detection limits reached [22, 23] constitute additional advantages for using this technique.

In this paper, different electrochemical techniques are used to take advantage of their different performance characteristics to determine and characterize the neurotransmitter 2-phenylethylamine, based on the ion transfer of its protonated form at a solvent polymeric membrane facilitated by the crown ether dibenzo-18-crown-6. First, SWV is applied as a fast and reliable voltammetric technique for the characterization of the ion transfer. The potential range at with the simple and facilitated ion transfer of PEA^+ takes place, its standard ion transfer potential value, diffusion coefficient and complexation constant with DB18C6 are calculated from the SWV recordings. Next, double pulse chronoamperometry and double pulse chronocoulometry are applied for the determination of PEA based on its facilitated ion transfer, and the advantages and disadvantages of the use of the I/t and Q/t signals are discussed. To complement the study, the influence of common ions on the chronocoulometric

and chronoamperometric PEA$^+$ determination is studied. Finally, the electrode is tested for monitoring PEA$^+$ concentration by using a pulsed-amperometric mode. Despite the clear interest of recording the dynamic amperometric response for checking the performance of amperometric ion sensors for continuous detection, there are few examples of these kind of responses in the literature [19], with voltammetry being applied in the main.

A simple method for correcting the calibration plots from non faradaic undesirable effects observed at short potential pulse durations is presented, which greatly increases the linearity range at which the target ion (i.e. PEA$^+$) can be determined, avoiding the typically observed curvature at moderately high concentrations.

2. EXPERIMENTAL

2.1. Apparatus

The design of the voltammetric ion sensor has been described previously [24]. Briefly, a Pt-wire counter electrode was accommodated inside the inner solution compartment of a Fluka ion-selective electrode (ISE) body. A glass ring of 28 mm inner diameter and 30 mm height and a glass plate were purchased from Fluka for the construction of the membranes.

2.2 Reagents and Solutions

Poly (vinyl chloride) high molecular weight, 2-nitrophenyl octyl ether (NPOE) and tetrahydrofuran (THF) were Selectophore products from Fluka. Sodium tetraphenylborate (NaTPB), 2-phenylethylamine hydrochloride (PEACl) and dibenzo-18-crown-6 (DB18C6) were purchased from Sigma. Magnesium sulfate was purchased from Merck. Crystal violet was purchased from Riedel-de Haën in the form of chloride (CVCl). All the other reagents used were of analytical reagent grade. Nanopure water (18-MΩ) prepared with a Milli-Q (Millipore) system was used throughout.

Crystal violet tetraphenylborate (CV-TPB) was obtained as a precipitate by mixing an aqueous solution of crystal violet with an aqueous solution of sodium tetraphenylborate in equimolar amounts. 2-Phenylethylammonium solutions of different concentrations were prepared by dissolving 2-phenylethylamine hydrochloride in $MgSO_4$ $5x10^{-3}$ M.
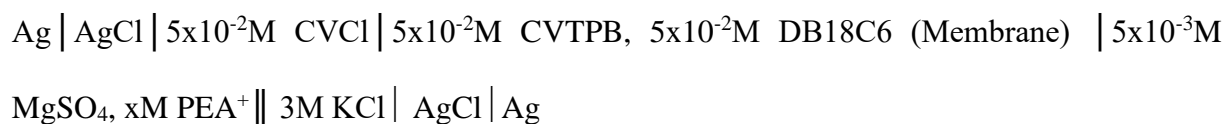
2.3 Membranes Preparation

Two different kinds of membranes were prepared for the ion transfer measurements. The membrane for simple ion transfer studies was prepared by dissolving 200 mg NPOE, 100 mg PVC and 10.4 mg CV-TPB in 3 ml of tetrahydrofuran. 5.4 mg of DB18C6 were also added to the solution to prepare the membrane for the facilitated ion transfer. These solutions were poured into a glass ring resting on a glass plate and were left overnight to allow the

solvent THF to evaporate slowly. A 6-mm diameter piece of each membrane was cut out with the punch and incorporated into a modified ISE body as described above.

2.4 Electrochemical Measurements

The electrochemical cells used can be expressed as

$Ag \mid AgCl \mid 5 \times 10^{-2} M$ $CVCl \mid 5 \times 10^{-2} M$ $CVTPB$, $5 \times 10^{-2} M$ $DB18C6$ (Membrane) $\mid 5 \times 10^{-3} M$ $MgSO_4$, xM $PEA^+ \parallel 3M$ $KCl \mid AgCl \mid Ag$

The applied potential, E, is maintained at the pre-set value by the four-electrode potentiostat, which applies the necessary potential between the right and left counter electrodes and allows automatic compensation of the ohmic potential drop. A positive current corresponds to the transfer of positive charge from the aqueous phase which contains the target ion PEA^+ to the organic phase. All computer programs were written in our laboratory. To perform the background subtraction, a blank experiment (i.e. concentration of PEA was 0 mM) was recorded.
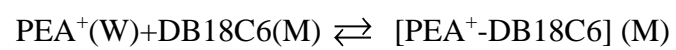
2.5. Chemical structures and scheme of the complexation reaction
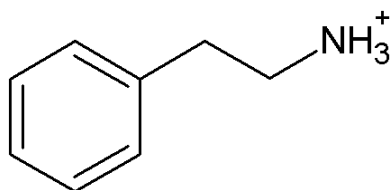
2-Phenylethylammonium

(PEA$^+$)

Dibenzo-18-crown-6

(DB18C6)

$$PEA^+(W)+DB18C6(M) \rightleftarrows [PEA^+\text{-}DB18C6]\ (M)$$
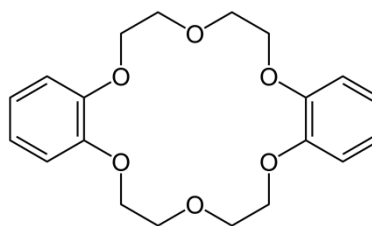
where the complexation could take place at the bulk of the organic phase or at the interface between both electrolyte solutions [12].

3. RESULTS AND DISCUSSION

3.1. Square Wave Voltammetry

Figure 1a depicts the experimental background subtracted SWV recordings corresponding to the simple and DB18C6 facilitated ion transfer of PEA$^+$ (white and black circles, respectively), together with the theoretical fittings (the voltammograms without background subtraction are shown in Fig.1c). Figure 1b shows the calibration curve obtained using SWV with a series of PEA$^+$ solutions over the concentration range 0.025 to 0.2 mM with the membrane system containing the crown ether (solid black line) together with the corrected calibration curve (solid red line, see explanation below).

From Figure 1a it can be seen that, as expected, the signal corresponding to the facilitated ion transfer of PEA$^+$ appeared at less positive potentials than that corresponding to the simple ion transfer, on account of the decrease in the Gibbs energy of transfer of PEA$^+$ when interacting with the crown ether.

Theoretical curves for the facilitated ion transfer were obtained by applying the following equation, deduced in [25]

$$I_{SWV} = I_{2p-1} - I_{2p} = I_{lim}(\tau) \left[\sum_{j=1}^{2p-1} \left(\frac{1}{1+\Omega e^{\eta_j}} - \frac{1}{1+\Omega e^{\eta_{j-1}}} \right) \left(\frac{1}{\sqrt{2p-j+1}} - \frac{1}{\sqrt{2p-j}} \right) + \frac{1}{1+\Omega e^{\eta_{2p}}} - \frac{1}{1+\Omega e^{\eta_{2p-1}}} \right] \quad (1)$$

where η_j is the dimensionless overpotential, $I_{lim}(\tau)$ is the current corresponding to the simple ion transfer under diffusion controlled conditions and Ω is a function that contains the dependence on the effective diffusion coefficient and the complexation equilibrium constant between DB18C6 and PEA$^+$ in the membrane (given in the Notation of definitions and symbols), which is assumed to be of pseudo-first order with respect to PEA$^+$

$$K' = \frac{c_{PEA-DB18C6}^M(x,t)}{c_{PEA}^M(x,t)} = K c_{DB18C6}^M(x,t) \quad (2)$$

with K being the real equilibrium constant. Eq.(1) was also used in order to plot the theoretical simple ion transfer voltammograms, by making $K' = 0$.

To build the theoretical curves $A\sqrt{D_{PEA^+}^W}$ and $E_{PEA^+,i}^{1/2}$ (i = simple, facilitated) were used as fitting parameters [12], with $E_{PEA^+,i}^{1/2}$ being the half wave potential (see Notation) which coincides with the SWV peak potential for a reversible ion transfer [26]. The values that yielded the best fitting were $A\sqrt{D_{PEA^+}^W} = 6.1 \times 10^{-4}$ cm³ s⁻¹/² and $E_{PEA^+}^{1/2} = 375$ mV for the simple ion transfer and 7.6×10^{-4} cm³ s⁻¹/² and 197 mV for the facilitated one.

Under the assumption of equal diffusion coefficients for the ion and the complex in the membrane ($D_{PEA^+}^M = D_{PEA-DB18C6}^M$), the complexation constant between PEA⁺ and DB18C6 can be calculated from the difference between the half-wave potentials of the simple and facilitated ion transfer. Under these conditions it is fulfilled that [12]

$$K' = e^{-\frac{F}{RT}\Delta E_{1/2}} - 1 \tag{3}$$

where

$$\Delta E_{1/2} = E_{PEA^+,facilitated}^{1/2} - E_{PEA^+,simple}^{1/2} = \frac{RT}{F}\ln\left(\frac{1}{1+K'}\right) \tag{4}$$

Therefore, by considering Eqs.(2) and (3) and by taking into account that the concentration of DB18C6 in the membrane was $c_{DB18C6}^M = 50$ mM (see Section 2.3), the value of the real equilibrium constant was determined as log(K) = 4.32. As far as we know there are no precedent studies on the determination of this equilibrium constant, although Dvořák *et al* [7] have reported the assisted transfer of β-phenylethylammonium ions (such as dopamine or noradrenaline) by DB18C6 in a water/nitrobenzene system.

The standard ion transfer potential ($\Delta_M^W\phi_{PEA^+}^0$) and diffusion coefficient of PEA⁺ in the aqueous solution ($D_{PEA^+}^W$) were calculated by using the TEA⁺ as reference, as described in [12].

With this aim, SWV voltammograms corresponding to the simple ion transfer of TEA$^+$ were also recorded (not shown). Thus, the standard ion transfer potential was determined from the difference between the peak potentials of both ions (see Notation) as $\Delta_M^W \phi_{PEA^+}^0$ = 86.5 mV. The diffusion coefficient of PEA$^+$ was calculated from the ratio between $A\sqrt{D_{PEA^+}^W}$ and $A\sqrt{D_{TEA^+}^W}$, taking $D_{TEA^+}^W$ as 9×10^{-6} cm^2/s [27] and obtaining $D_{PEA^+}^W$ = 8.3×10^{-6} cm^2/s. The values obtained for the two parameters ($\Delta_M^W \phi_{PEA^+}^0$ and $D_{PEA^+}^W$) match quite well with previously reported data [28, 29], which shows the reliability of the procedure. Thus, SWV allowed an easy and fast electrochemical characterization of the system PEA$^+$(Water)/PEA$^+$-DB18C6(Membrane).

With respect to the raw and corrected calibration curves shown in Figure 1b, we can see that the non-corrected calibration started to curve for a value of concentration 0.1mM. Logarithmic calibration curves have already been reported by some authors when using pulse voltammetry methods at the ITIES [5, 6, 30]. The origin of this effect is unclear, although uncompensated IR drop at short pulse durations could be a reason of this behavior [5]. In order to extend the linear interval of the calibration plot obtained by SWV, chronoamperometric experiments using the same concentrations assayed in SWV were recorded and the current was measured at two different times: 0.5 seconds (which coincides with the pulse duration in SWV) and 5 seconds. For the latter, it can be considered that undesirable effects related to uncompensated ohmic drop and double layer charging are negligible (see Section 3.2) and so the increase of the current due to concentration changes could be ascribed only to the faradaic process. A correction factor was calculated for each concentration from the following expression

$$f_i = \frac{y_i y_0'}{y_0 y_i'} \quad ; \quad i = 1, 2 \ldots N_p - 1 \tag{5}$$

where N_p is the number of concentrations assayed, y_i and y_i' refers to the current values at 5s and 0.5s, respectively, and the subscript 0 is used to denote the data corresponding to the lowest concentration. Thus, for the latter it is taken that $f_0 = 1$ given that the experimental current response is not noticeably perturbed by the effects above-mentioned as will be discussed in Section 3.2. Finally, the peak current in SWV at each concentration was multiplied by this correction factor, given rise to the corrected voltammetric calibration plot showed in Figure 1b.

As can be seen, by applying this simple correction factor we obtained a totally straight calibration for all the range of concentration studied, which means a significant enlargement of the concentration range in which the target ion could be determined. This result implies that a chronoamperometric analysis previous to the SWV one would be convenient when the SWV technique is used with analytical purposes and the concentration of the target ion is not low enough. Note that SWV enables more accurate values of diffusion coefficients and formal potentials to be obtained, since the voltammograms show a peak shape whose position is independent of the concentration of the target ion.

3.2. Chronoamperometric and Chronocoulometric Detection

Double pulse chronoamperometry was studied to compare the goodness of different electrochemical techniques for the analytical determination of PEA$^+$ based on ion transfer. The values of E_1 and E_2 were selected from the SWV responses recorded for the facilitated ion transfer (Fig.1). Thus, the potential was switched between an uptake potential step $E_1 = 0.320$ V, at which the facilitated ion transfer of PEA$^+$ from the aqueous sample to the membrane is controlled by diffusion (limiting current conditions), applied for $t_1 = 5$ seconds, and a base potential $E_2 = 0.080$ V, at which the reverse process occurs (exit of PEA$^+$ from the membrane) applied for $t_2 = 50$ seconds. The current recordings i-t were integrated numerically

to obtain the corresponding Q-t recordings. The relatively high value selected for t_1 allowed a relatively high quantity of charge to be obtained, due to the extraction of PEA into the membrane (see below), while the duration of t_2, equal to ten-fold the t_1 value ensured complete regeneration of the membrane before applying E_1 again. This double potential step was applied four times to check the reproducibility.

Figure 2 shows the typical i/t (solid lines) and Q/t (dotted lines) background subtracted responses obtained. As can be seen, a continuous increase of electric charge (Q) due to the ion transfer of PEA$^+$ facilitated by DB18C6 was observed during the application of the first potential (E_1), followed by the corresponding decrease until near zero charge upon application of the second potential (E_2). Note that the difference between the quantity of electricity at the end and beginning of the first pulse (Q peak height) is very reproducible, especially if the first peak is excluded, which will be done hereinafter. The slight difference observed between the first chronocoulometric peak and the following ones can be explained by slightly different initial conditions for the first step.

The chronoamperograms and their respective chronocoulograms obtained for different PEA$^+$ concentrations are depicted in Figures 3a and 3b, respectively, together with the corresponding calibration graphs I and Q *versus concentratio*n at three different experiment times, which are shown in the insets. Note that short pulse times gave rise to non-linear calibration plots, whose curvature is related to non-faradaic effects. The standard deviation interval obtained for the different concentrations are also depicted together with their corresponding points, showing a high reproducibility at all concentrations.

The slope, linear range and detection limit at each time value selected for both chronoamperometric and chronocoulometric measurements are given in Table 1. The limit of detection value was calculated as the PEA$^+$ concentration corresponding to three times the standard deviation of the blank.

Table1. Slope, limit of detection and upper limit of linear response for the chronoamperometric and chronocoulometric calibration plots at the three different times assayed.

Chronoamperometry			
Time(s)	**Slope ($\mu A\ mM^{-1}$)**	**Upper limit (mM)**	**LD (μM)**
0.5	49.8	0.10	3.6
2	27.3	0.20	6.5
5	17.3	0.20	9.2
Chronocoulometry			
Time(s)	**Slope ($\mu C\ mM^{-1}$)**	**Upper limit (mM)**	**LD (μM)**
0.5	19.1	0.08	1.7
2	66.6	0.13	2.7
5	124.3	0.20	1.9

As can be seen, with chronoamperometry, the detection limit increased with the duration of the potential pulse while the upper limit of linear response doubled from a pulse time of 2 seconds with respect to 0.5s. In turn, chronocoulometry allowed an improvement in the detection limit over chronoamperometry for all the pulse lengths considered, being particularly noticeable for the longest time (five times lower). In addition, the upper limit of linear response increased with the pulse time. Taking all of this into account, in terms of sensitivity and linear range, chronocoulometry at 5 seconds yielded the best results and was used for further studies.

3.3. Effect of other ions

The effect of other cations on the chronocoulometric determination of PEA$^+$ was studied by obtaining the corresponding recording of a PEA$^+$ solution at 5×10^{-5} M in MgSO$_4$ 5×10^{-3} M, in the absence and in the presence of a concentration 10-fold higher of lithium, sodium and potassium cations, as well as proton. Lithium cation did not change the PEA$^+$ signal at all. The relative increase in the Q peak height obtained in the presence of the other foreign ions was used to evaluate its interfering effect. The following selectivity parameter $K_{\text{PEA,J}}$, equivalent to the sensitivity ratio between foreign cation J$^+$ and PEA$^+$, was calculated from

$$K_{\text{PEA,J}} = \frac{\Delta Q}{Q} \frac{c_{\text{PEA}}}{c_{\text{J}}} \tag{6}$$

The values obtained were 0.05 for Na$^+$, 0.3 for K$^+$ and 0.2 for H$^+$. This means for instance, that the presence of Na$^+$ together with PEA$^+$, at equal concentrations, would produce an error of +5% in the PEA determination. No significant differences were found between the $K_{\text{PEA,J}}$ values calculated from chronoamperometry and chronocoulometry.

3.4. Continuous amperometric PEA monitoring

In order to study the capability of the electrode for the continuous amperometric monitoring of protonated phenylethylamine, the dynamic response of the electrode to PEA$^+$ concentration changes was tested by immersing the electrode in 50 ml of 5×10^{-3} M MgSO$_4$ and injecting, while stirring, small volumes of a PEA solution to achieve final concentrations in the range 1.0×10^{-5} to 2.2×10^{-4} M. For these experiments, the potential was switched continuously between the values 0.320 and 0.080 mV (for the uptake and release of PEA$^+$ into the membrane as described above) and the current was sampled at the end of each uptake potential (0.320 V). In this case the corresponding pulse durations were 0.5 and 5.0 s, for E_1 and E_2 respectively, i.e. 10-fold shorter than in chronocoulometry, in order to increase the

sampling rate. The corresponding dynamic response of the electrode, current versus time, is shown in Figure 4. As can be seen, a rapid current stabilization was obtained after each concentration increase. The calibration plots both corrected and uncorrected as described in section 3.1 are shown in the inset.

As can be seen, while a linear portion is observed up to about 0.05 mM PEA$^+$ in the uncorrected calibration plot curve, the corrected curve shows linearity in all the range of concentrations assayed.

4. CONCLUSIONS

The combined application of different electroanalytical techniques to a suitable solvent polymeric membrane electrode has permitted the characterization and sensitive detection and sensing of the neurotransmitter 2-phenylethylamine, based on its ion transfer facilitated by DB18C6. Square wave voltammetry was used for the fast and accurate electrochemical characterization of the ion transfer and chronoamperometry and chronocoulometry were tested as detection electrochemical tools. Chronocoulometry outperformed chronoamperometry in the determination of PEA in terms of detection limit, and we have shown that the analytical performance characteristics of both techniques can be tuned by a proper selection of the pulse duration. Besides, pulse amperometry allowed continuous PEA monitoring. A procedure to extend the range of linear response of quantitative electrochemical techniques based on a previous analysis of chronoamperometric recordings has also been developed. This procedure has proved very useful for square wave voltammetry and pulse voltammetry. These findings could be applicable for the detection and sensing of other target ions, using suitable ionophores.

Acknowledgments

NOTATION

<u>Symbols</u>

A	area of the interface
c^*	initial concentration of ion PEA$^+$ in the aqueous solution
c_i^p	concentration of the ion i in phase p ($p = W, M$)
D_i^p	diffusion coefficient of the species i in phase p
E_s	staircase amplitude in SWV
E_{SW}	square wave amplitude
E_j	potential applied in the pulse j in SWV
K	complexation equilibrium constant based on concentrations or real equilibrium constant
K'	complexation equilibrium constant under pseudo-first order assumption
I_{2p-1}	forward current in SWV
I_{2p}	backward current in SWV
I_{SWV}	net current in SWV
F	Faraday constant (96485 C mol^{-1})
R	molar gas constant (8.31 J K^{-1} mol^{-1})
T	working absolute temperature (K)
$\Delta_M^W \phi_{PEA^+}^{0'}$	formal transfer potential of the ion PEA$^+$
τ	duration of each potential pulse in SWV

Definitions

D_{eff}^{M} effective diffusion coefficient in the membrane $\left(= \dfrac{D_{PEA^+}^{M} + K' D_{PEA-DB18C6}^{M}}{1 + K'} \right)$

$I_{\lim}(\tau)$ limited current for the transfer of PEA$^+$ under diffusion controlled conditions

$\left(= FAc^* \sqrt{\dfrac{D_{PEA^+}^{W}}{\pi \tau}} \right)$

$E_{PEA^+,simple}^{1/2}$ half-wave potential for the simple ion transfer of PEA$^+$

$\left(= \Delta_M^W \phi_{PEA^+}^{0'} + \dfrac{RT}{F} ln\left(\sqrt{\dfrac{D_{PEA^+}^{W}}{D_{PEA^+}^{M}}} \right) \right)$

$E_{PEA^+,facilitated}^{1/2}$ half-wave potential for the facilitated ion transfer of PEA

$\left(= \Delta_M^W \phi_{PEA^+}^{0'} + \dfrac{RT}{F} ln\left(\sqrt{\dfrac{D_{PEA^+}^{W}}{D_{eff}^{M}}} \right) + \dfrac{RT}{F} ln\left(\dfrac{1}{1 + K'} \right) \right)$

η function containing the dependence with the applied potential

$\left(= \begin{cases} \eta_{j>0} = \dfrac{F}{RT}\left(E_j - \Delta_M^W \phi_{PEA^+}^{0'} \right) \\ \eta_0 = 0 \end{cases} \right)$

Ω function containing the dependence with the complexation constant and diffusion

coefficients $\left(= (1 + K') \sqrt{\dfrac{D_{eff}^{M}}{D_{PEA^+}^{W}}} \right)$

FIGURE LEGENDS

FIGURE 1. a) Experimental background subtracted SWV recordings corresponding to the simple and facilitated ion transfer of PEA^+ (white and black circles, respectively), together with the theoretical fittings (solid lines). $E_s = 10$ mV, $E_{SW} = 50$ mV, $\tau = 0.5$ s, $c^* = 25$ μM (see Notation for definitions of symbols). **b)** Raw and corrected calibration curves (black and red lines, respectively) obtained from the peak current of the facilitated ion transfer voltammograms at different concentrations of PEA^+. **c)** Experimental SWV voltammograms obtained for $c^* = 25$ μM without background subtraction.

FIGURE 2. Chronoamperometric (solid lines) and chronoculombimetric (dotted lines) background subtracted responses for the facilitated ion transfer of PEA^+ from the aqueous sample to the membrane containing the crown ether. $E_1 = 0.32$ V, $t_1 = 5$ s, $E_2 = 0.08$V, $t_2 = 50$s, $c^* = 0.15$ mM.

FIGURE 3. I/t (a) and Q/t (b) background subtracted responses recorded at different concentrations of PEA^+, from 0.025 mM (black lines) to 0.2 mM (dark cyan). Insets: calibration curves and linear regressions at different times of experiment. Standard deviations for each concentration are shown in the plots. Experimental conditions as in Fig.2.

FIGURE 4. Dynamic amperometric response of the electrode towards PEA^+ concentration, from 0.01 mM to 0.22 mM. The initial baseline corresponds to the background response. $E_1 = 0.32$ V, $t_1 = 0.5$ s, $E_2 = 0.08$V, $t_2 = 5$s. Inset: calibration curve and its corresponding correction.

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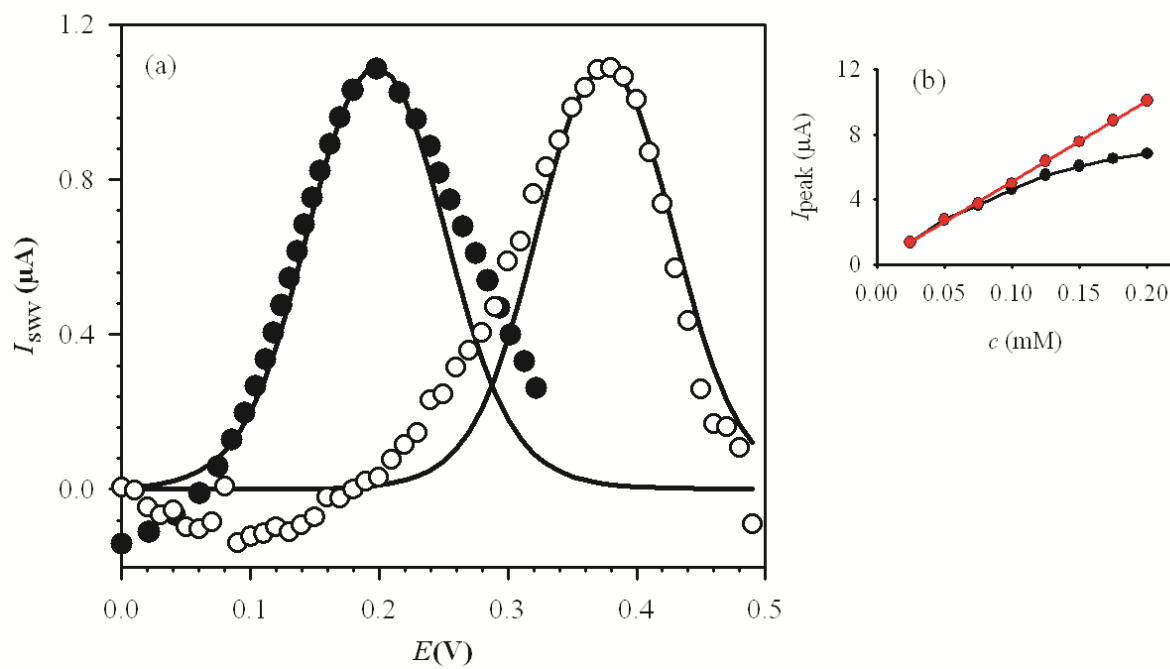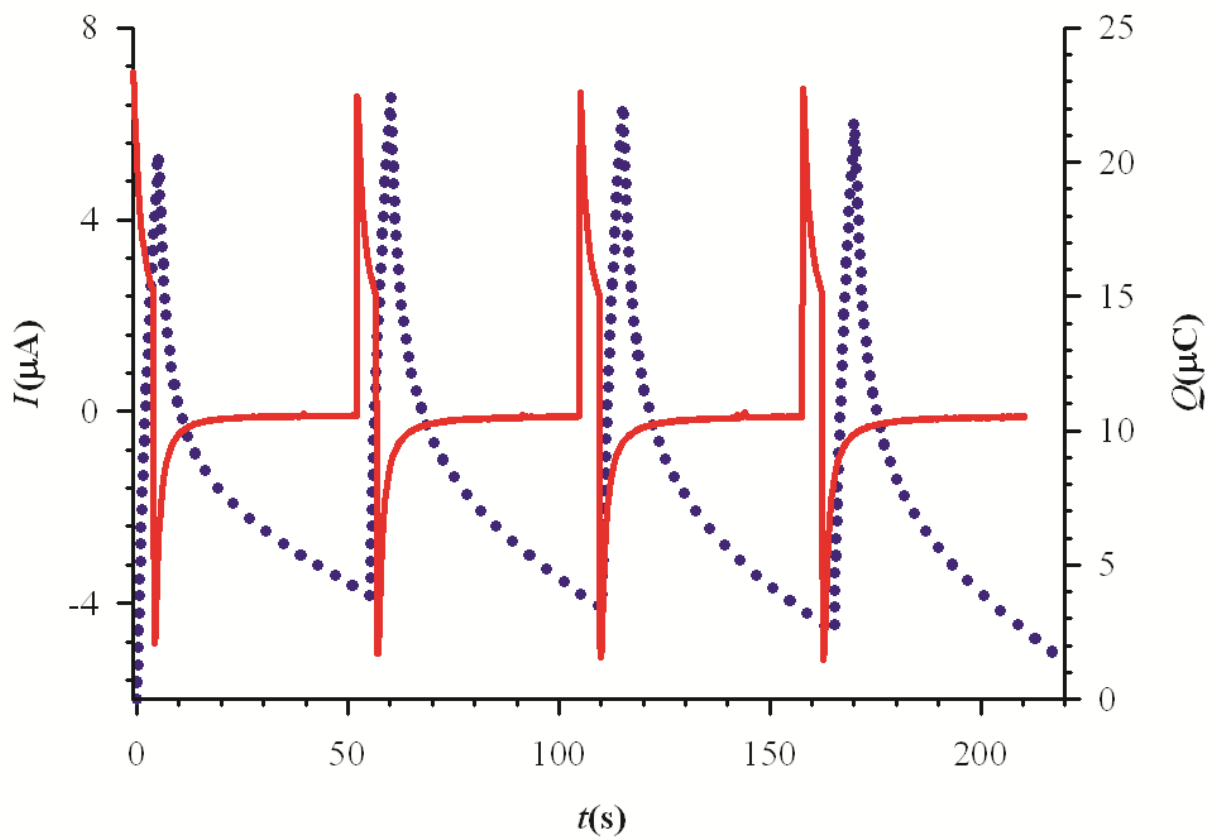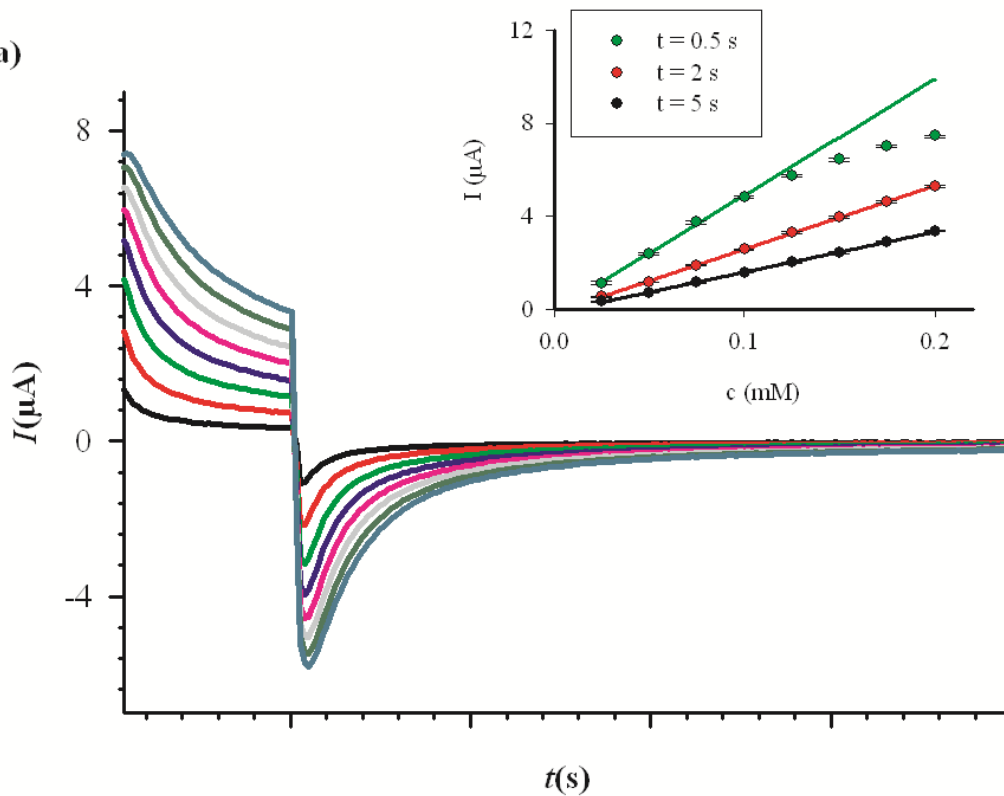
FIGURE 1
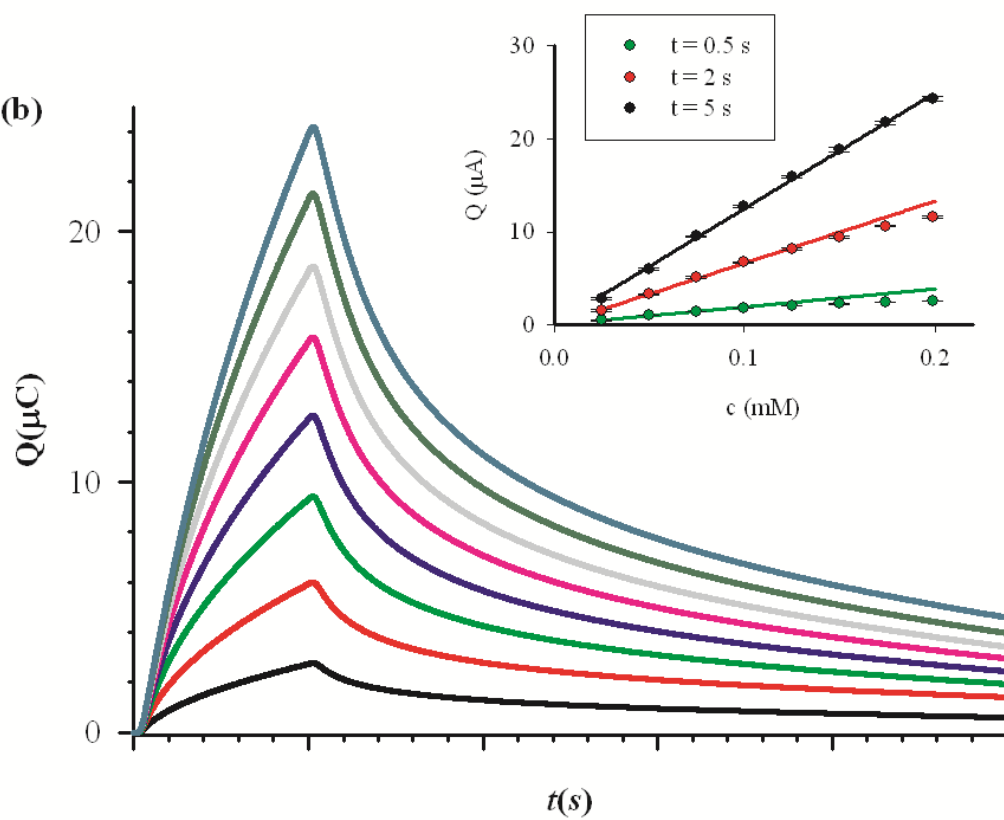

FIGURE 2

FIGURE 3

(a)

(b)

FIGURE 4