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Paper-supported thin-layer ion transfer voltammetry for ion detection

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ABSTRACT

We report here on paper-supported thin sample layer voltammetry for the determination of ions. To achieve this goal, a simple setup for the coupling of a commercially available electrode to a silver rod electrode was designed and evaluated for paper-supported thin-layer voltammetry. Linear scan ion transfer voltammetry was explored here for ion-selective membranes doped with an ionophore. The ion-transfer processes and electrochemical behaviors of the system are here evaluated and confirmed by numerical simulation. In the proof-of-concept experiments described, the ions tetrabutylammonium chloride (TBA^+) and potassium (K^+) were studied as model analytes at membranes without and with ionophore, respectively. A linear relationship from 0.1 mM to 1.0 mM K^+ was obtained between the charge and ion concentration. The coexistence of background sodium ions did not give appreciable interference, but the background wave was not completely isolated from the analyte wave, as also confirmed by the model. The methodology was successfully demonstrated for determination of K^+ in mineral water. It is anticipated that this paper-supported thin-layer detection approach may provide an attractive readout protocol for disposable paper-based analytical devices as the methodology does not place strict demands on reference electrode performance.

1. Introduction

With rapid progress in the field of paper-based analytical devices, potentiometric ion sensing and biosensing platforms have also been explored by making use of paper-based microfluidic sampling and functionalized paper substrates [1–4]. While these versatile potentiometric devices may offer adequate sensitivity and selectivity, they utilize open circuit potential (OCP) as a readout for a single measurement. This requires excellent potential stability, as the Nernst equation already dictates errors of 4% and 8% for just a 1 mV potential uncertainty in the assessment of monovalent and divalent ions, respectively. For 3 mV, the error increases to over 12% and 26%, respectively, which is already unacceptable for most analytical applications, as in routine clinical diagnostics. An important reason for this is the difficulty to incorporate a reliable reference electrode into a paper-based format, although recent progress with ionic liquid based reference electrode concepts has been encouraging [5,6]. It would therefore be desired to explore alternative transduction principles in a paper based format where the reference electrode is less important on sensor output.

Exhaustive coulometry is, ideally, an absolute measurement principle based on the strict proportionality between the concentration of the analyte and the involved charge. For cases of excellent selectivity and conversion efficiency, meaning that only the analyte, but all of it, is consumed, the approach should, in agreement with Faraday's law, allow for a calibration-free measurement.

By employing a thin-layer sample for the coulometry, the complete electrolysis can be achieved reasonably rapidly, in the time scale of seconds to minutes. Since the introduction of thin-layer coulometry for determination of redox-active species [7], its applications have expanded to non-electroactive ionic species based on ion transfer at the aqueous/organic solution interface [8–12]. In order to improve its selectivity, thin-layer coulometry based on ion-selective membrane is currently being pursued by our group and others [13–16].

In recent years, studies in the area of coulometry have focused on the use of thin-layer ionophore-based membranes [17–19]. Meanwhile, important progress has occurred in the design of suitable thin-layer cells with the introduction of new materials [12,13,16,20]. Our group designed a custom-made microfluidic electrochemical cell based on tubular materials, in which a thin layer sample is confined between an inner Ag/AgCl wire and the outer microporous hydrophobic tube doped with the ion-selective component [16]. The electrochemical response behavior of the thin-layer coulometric sensors under a controlled potential is elucidated and the membrane response model was developed by using a numerical simulation [21]. Besides the incorporation of an

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inert physical separator for cell response improvement [22], a double pulse technique was utilized for background correction [23]. By using the proposed controlled-potential thin-layer coulometry, a number of different ions including potassium, calcium, protamine, as well as nitrate, and nitrite have been measured [24].

Using the above mentioned thin-layer configuration, coulometric sensors for halides were also designed in our group by using Nafion as a permselective cation-exchanger membrane [25,26]. In contrast to the controlled potential coulometry, the application of cyclic voltammetry or a linear sweep potential to thin layer samples was explored for multianalyte halide detection. As evidenced by these studies, the proposed methodology is absolute and potentially calibration-free. Clearly, cyclic voltammetry promises to expand the scope of coulometry based on thin-layer samples, but its applicability for coulometry based on ion-selective membranes doped with an ionophore has not yet been investigated. Moreover, sensing the target ions in this manner with a simplified experimental setup may be challenging but worthwhile.

Paper is attractive for the stated purpose, as it may transport the sample to the detection compartment by its wicking properties, and additionally create an aqueous layer of well-defined thickness that is suitable for thin-layer coulometry [27]. Indeed, our previous research indicated that a paper-based thin-layer coulometric sensor based on the formation of silver halide precipitates can be used for halide determination in real samples [26]. Unlike the conventional potentiometric measurements based on the linear dependence between the logarithm of the ion activity and the OCP, the obtained charge is directly proportional to analyte concentration for coulometric measurements, which makes coulometry more suitable for detecting small analyte concentration changes. If the approach is efficient and chemically selective, the resulting signal should be temperature-insensitive, absolute and potentially calibration-free [28]. These are important potential advantages with batch-fabricated disposable single-use analytical devices such as paper-based analytical devices.

Herein, we report on a paper-supported thin-layer ion transfer voltammetry for the determination of ions. To realize this concept, we developed a system in which a commercial electrode body mounted with an ion-selective membrane doped into microporous polypropylene (Celgard) and a silver rod were used as working and reference/counter electrode, respectively. Thin-layer ion transfer voltammetry was evaluated on tetrabutylammonium chloride (TBA^+) and potassium (K^+) as representative analytes.

2. Experimental section

2.1. Materials

Sodium tetrakis[3,5-bis-(trifluoromethyl)phenyl]borate (NaTFPB), Potassium tetrakis(4-chlorophenyl)borate (KTpClPB), potassium ionophore I (Valinomycin), dodecyl 2-nitrophenyl ether (DDNPE), tetrabutylammonium chloride (TBA^+), potassium chloride, tetrahydrofuran (THF), Whatman filter papers 2 (90-mm diameter, 8-μm pore size, 190-μm thickness), and Whatman filter papers 3 (qualitative) were purchased from Sigma-Aldrich. Porous polypropylene membranes (Celgard membrane 20 μm thickness) were kindly provided by Membrana, Wuppertal, Germany and used as a supporting material. The cocktail for TBA^+ impregnation of the Celgard membranes contained 90 mg of DDNPE (a more lipophilic plasticizer compared to the *o*-NPOE to avoid leaching) and 10 mg of NaTFPB. The membrane cocktail for K^+ was composed of 97.8 mg of DDNPE, 1.8 mg (16 mmol/kg) of valinomycin, and 0.4 mg of KTpClPB (25 mol % relative to the ionophore). Aqueous solutions were prepared by dissolving the appropriate salts in Milli-Q-purified distilled water.

2.2. Experimental setup

Cyclic voltammograms were obtained on a PGSTAT 302 N potentiostat (Metrohm Autolab, Utrecht, The Netherlands) controlled by a personal computer using Nova 1.8 software (supplied by Autolab). A piece of silver (with a diameter of 5.0 mm and a thickness of ca 2.0 mm) was attached to a stainless steel rod by using conductive glue. The home-made silver rod was electrochemically coated with AgCl and used as a reference/counter electrode. Electrode bodies (OSTEC, Oesch Sensor Technology, Sargans, Switzerland) were used to mount the Celgard membranes. All experiments were carried out at room temperature.

For TBA^+ determination, the inner solution was 10^{-3} M TBA^+ with 10^{-2} M NaCl. All experiments were performed in 10 mM NaCl background, unless otherwise indicated. For K^+ measurements, 10^{-3} M KCl with 10^{-3} M NaCl was used as inner filling solution. Prior to the experiments, the membrane was conditioned in the same solution that was also used as the inner filling solution of the electrode. The membranes were then mounted onto electrode bodies as they are used commonly for ion-selective electrodes.

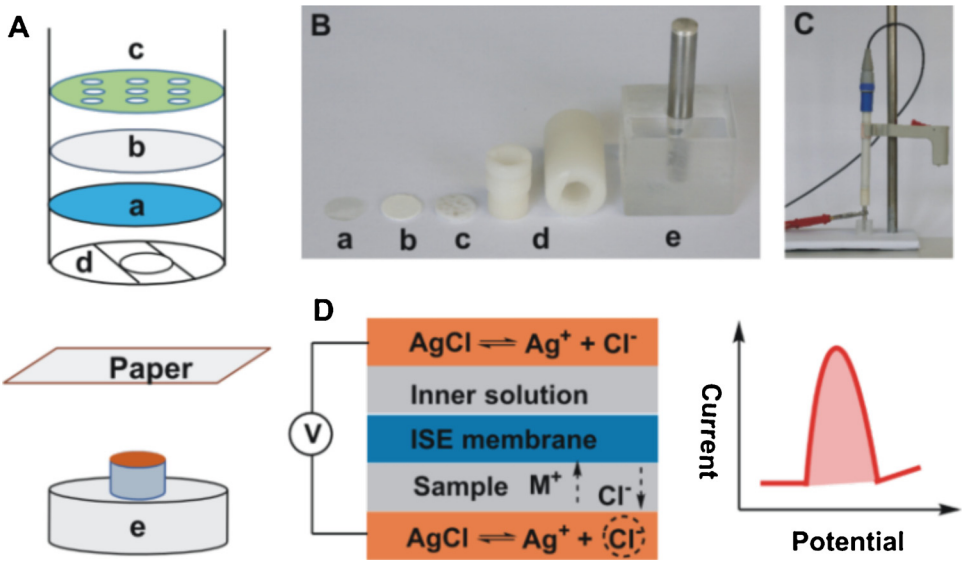
2.3. Preparation of the detection cell

In previous research, we designed a simple paper-based electrochemical cell for halide determination [24]. Experiments revealed that the stability and performance of the cell is not adequately suited for coulometric ion sensing using ionophore-based membranes: the free hanging ion-selective membrane is not sufficiently rigid to define a constant thin layer sample volume. In the present work, a simplified setup that has compatibility with a commercial electrode body was designed, which can also improve the stability of the ion sensor. As shown in Scheme 1 A to C, the custom-built setup consists of three parts: (1) Ag rod coated with AgCl (Scheme 1 A-e), as a reference/counter electrode, allowing the oxidation/reduction modulated transfer of ions in the sample, (2) a commercial electrode body (Scheme 1 A-d) with cocktail impregnated Celgard membrane (Scheme 1 A-a), allowing transfer of target ions across the membrane to the inner solution with high selectivity, and (3) filter paper, which is used for thin-layer sampling. For the working electrode, a home-made porous Teflon pad (Scheme 1 A-c) was placed on the bottom of the Celgard membrane, which places the membrane in close contact with the sample solution and the Ag rod. In addition, to avoid the mechanical failure of the ion-selective membrane, we introduce a paper layer (Scheme 1 A-b, a diameter of 7.0 mm, Whatman filter papers 3) between the membrane and the porous support.

If not otherwise specified, a piece of Whatman filter paper 2 (a diameter of 5.0 mm) was placed on the silver rod. 3.0 μL sample solution was added on the Whatman filter paper 2 for measurements. For practical applications, a 6.0 mm wide gap was designed on the top of the commercial electrode cap to insert the filter paper for sampling via capillary wicking (as shown in Scheme 1B). A single filter paper (0.6 cm × 4.0 cm) was used for sampling. A 5 min exposure time ensured that the sample liquid wicked through the paper. The filter paper was dipped into a small beaker containing the sample solution during the entire analysis. A new piece of paper was used for each standard and sample solution.

2.4. Real sample analysis

The potassium concentration in mineral water (obtained from local supermarket) was determined using the standard addition method. Specifically, 100 μL of mineral water was added into 900 μL background solution with 1.0 mM NaCl and different amounts of added KCl (0, 0.25, 0.50, and 0.75 mM). 3.0 μL sample solution was added on a filter paper (Whatman filter paper 2 with a diameter of 5.0 mm) for measurements. A new piece of paper was used for each sample solution. The concentration of potassium was also measured by atomic emission spectroscopy. Potassium was measured at a wavelength of 766.5 nm with a slit width of 0.2 nm.



Scheme 1. (A) Scheme of the electrochemical set up used in this work. (B) and (C) are the photographs of the setup. (D) Illustration of the electrochemical mechanism of the sensing processes. With this configuration, a 3 μL sample solution was dropped onto the filter paper sample holder for analysis, thereby precisely defining the amount of sample.

2.5. Theoretical model

The treatment follows a recent procedure based on one dimensional diffusion kinetics that improves on the earlier approach given by Morf [29,30]. As in previous work, a one dimensional space (x) is subdivided into finite distance elements of spacing Δx that evolve in a time (t) grid with time distance Δt. Elements $-x_{aq}$ to 0 and 1 to x_{mem} represent the elements for the aqueous layer and membrane, respectively.

By treating the sample-membrane interface using the phase boundary potential equation, the difference between the applied potential (E_{app}) and the open circuit potential (OCP) can be obtained without consideration of accumulation and depletion in the inner solution, see also reference [22]:

$$E_{APP}-OCP = slog\frac{C_{[0,t]}}{C_{[0,0]}}\frac{C_{[1,0]}}{C_{[1,t]}}\frac{C_{[x_m,t]}}{C_{[x_m,0]}} \quad (1)$$

where s is the Nernstian slope and $c_{[position,0]}$ are the initial concentrations. The potential scan (ν is the scan rate) is performed in a defined interval of time ($0 \le t \le t_{max}$), which modulates the applied potential starting from the initial potential (E_{init}) as follows:

$$E_{app}-OCP = E_{init}-\upsilon t,\ 0 \le t \le t_{max} \quad (2)$$

Taking an interfering ion J of the same charge as the primary ion into consideration, the following ion-exchange equilibrium can be formulated [18]:

$$\frac{c_{[1,t]}}{c_{[1,t]} + c_{J\,[1,t]}} = \frac{c_{[0,t]}}{c_{[0,t]} + K_{IJ}^{pot}c_{J,0}} \quad (3)$$

Where K_{IJ}^{pot}, $c_{J,0}$ are the selectivity coefficient and the concentration (strictly, activity) of the interfering ion in the aqueous phase. Since the sum of $c_{1,t}$ *and* $c_{J,1,t}$ dictates the ion-exchanger concentration of the membrane (R_m), the last membrane element is given as follows:

$$c_{x_{mem,t}} = 2R_m - \frac{c_{[0,t]} + K_{IJ}^{pot}c_{[J,0]}}{c_{[0,t]}}c_{[1,t]} \quad (4)$$

The relationship is inserted into Eq. 1 to give:

$$c[1,\,t] = \frac{2R_m}{1 + (K_{IJ}^{pot}c_{[I,0]} + C_{initial}10^{(E_{init}-\upsilon t)}/c[0,\,t]} \quad (5)$$

The parameters used here were a sample-layer thickness of 200 μm, a membrane thickness of 50 μm, diffusion coefficients in the sample, D_a, and membrane, D_m, of 10^{-5} cm^2 s^{-1} and 10^{-7} cm^2 s^{-1}, respectively and an ion-exchanger concentration, R_m, of 5.0 mM; finite distance steps, d, of 10 μm; time steps, Δt, of 1 ms and scan rate of 5 mV s^{-1}. All calculations were performed in Mathematica 10 (Wolfram Research).

3. Results and discussion

The aim of this work is to develop a potentially general, simple and reliable paper-supported thin-layer ion sensor with ion-selective membrane. To this end, a simplified experimental setup was developed and applied for ion sensing (Scheme 1A–C). The experimental setup has two main advantages: First, it enables measurements using the commercially available electrode with ion-selective membrane. Second, thin-layer solutions can be adjusted by using different filter papers. The principle of the proposed ion sensor is shown in Scheme 1D. Cyclic voltammetry, which is a valuable technique for the study of electrochemical mechanisms was used to study the transfer of the target ions across the sensing membrane [12]. When an anodic potential scan is applied at the electrode, the background chloride ions confined in the paper are electrodeposited on the silver electrode, while the cation will selectively transfer from the confined sample across the ion-selective membrane to the inner solution of the electrode. The ion transfer process between inner solution and ISE membrane is opposite to that of the sample solution and ISE membrane. If quantitative and exhaustive transfer of the target ions can be achieved within the potential window, the paper-supported thin-layer ion transfer voltammetry could be used for calibration-free analysis.

In our initial experiments, the tetrabutylammonium cation, an ion of relatively high lipophilicity and a common model species for liquid/liquid ion transfer was selected to achieve an adequate experimental setup. Porous Celgard membrane doped with lipophilic plasticizer and cation-exchanger was prepared. 10^{-3} M TBA^+ with 10^{-2} M NaCl was used as inner solution, which keeps the potential at the Ag/AgCl-inner solution and membrane-inner solution from changing significantly during measurements. These relatively high concentrations should remain unperturbed during the measurement.

The TBA^+ extraction into and out of the membrane layer triggered by the oxidation-reduction of Ag/AgCl was first studied in bulk solution. As shown in Fig. 1, with increasing applied potential, the oxidation of Ag results in the cation transfer from the sample to the inner solution of the electrode. Increasing the hydrophilicity of the ions results in an increasing potential to transfer ions across the membrane [31]. Therefore, the cation exchanger membrane with its higher selectivity in the Hofmeister series exhibits a high preference for TBA^+ over other ions in the sample. Indeed, the transfer of TBA^+ is obtained at a lower potential in comparison with Na^+ (Fig. 1). Based on the above, TBA^+ is established as the main contributor to ion-transfer

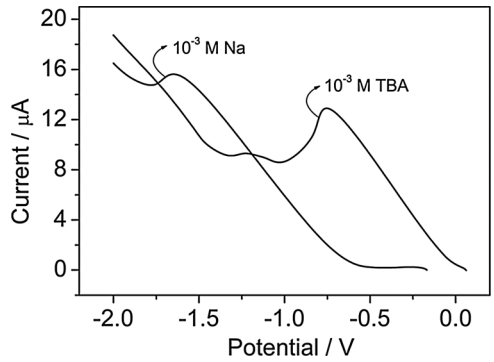


Fig. 1. Cyclic voltammograms obtained in bulk solutions. The inner solution was 10^{-3} M tetrabutylammonium chloride with 10^{-2} M NaCl. The sample solutions contain the target ions without supporting electrolyte.

behavior of the sample and may be measured selectively in the presence of Na^+ by cyclic voltammetry. This current may in principle force the anions to move in the opposite direction, but the cation-exchanger in the membrane suppresses the extraction of anions from the inner solution into the membrane. The potential was consequently back-scanned to the initial potential to reverse the process and guarantee the reproducible responses for the oxidation of Ag and the unperturbed state of the membrane.

For exhaustive thin-layer cyclic voltammetry, all target ions should be consumed/transferred within the potential window. The scan rate may therefore play an important role for the exhaustive measurement. Fig. 2A presents cyclic voltammograms for 2.5×10^{-4} M TBA^+ at different scan rates (1-10 mV s^{-1}). The peak current is linear with scan rate, which is consistent with an exhaustive extraction, also called thin layer behavior (Fig. 2B). It should be noted that the separation between forward and reverse peaks is 320 mV, which is affected by both the aqueous-solid and aqueous-membrane interfaces (Fig. S1). At first glance, this separation would indicate an irreversible process but may instead be given by relatively long diffusion times in the two phases

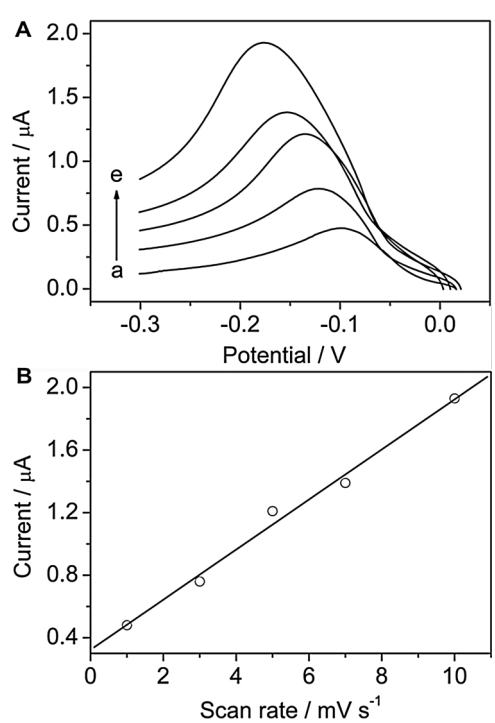


Fig. 2. (A) Cyclic voltammograms obtained for 2.5×10^{-4} M TBA and 10^{-2} M NaCl with different scan rate (1, 3, 5, 7, 10 mV s^{-1} from a to e). (B) Peak current as a function of scan rate.

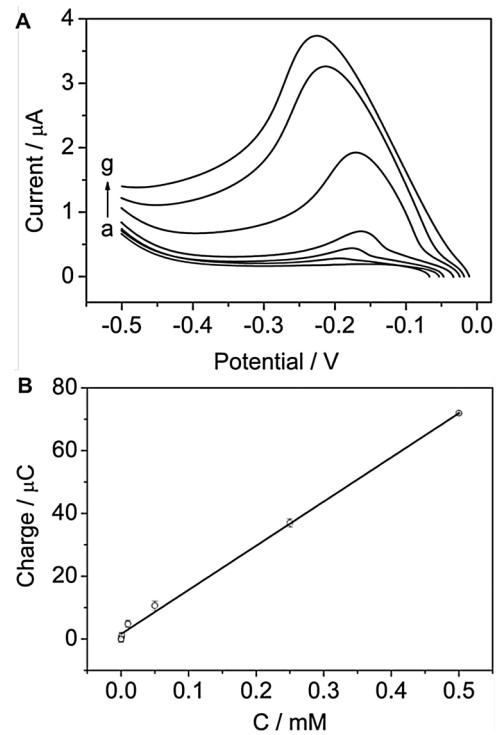


Fig. 3. (A) Cyclic voltammograms obtained for different concentrations of TBA with a scan rate of 10 mV s^{-1}. (a), 0.01 M NaCl, and 0.01 M NaCl with different concentrations of TBA, 1.0×10^{-6} (b), 1.0×10^{-5} (c), 5.0×10^{-5} (d), 2.5×10^{-4} (e), 5.0×10^{-4} (f), and 1.0×10^{-3} (g) M TBA. (B) Calibration curve for TBA with a scan rate of 10 mV s^{-1}. Error bars represent one standard deviation for three measurements.

(aqueous sample and organic membrane). The effect of sample volume on the electrochemical responses was also studied in the range from 1.5 to 5.0 μL. As expected, the observed charge increased with larger sample volume up to 5.0 μL, which indicates the effective transfer of the TBA^+ across the membrane. For a 5.0 mm (190-μm-thickness) filter paper, the sampling volume was 3.7 μL without considering the porosity of the paper. To achieve a wider concentration range, 3.0 μL of sample solution was used in all subsequent experiments.

Fig. 3A shows the cyclic voltammograms obtained with the setup to which 3.0 μL sample solution containing different concentrations of TBA^+ was added. The overall charge at various concentration differences was determined from current integration of the linear scans in Fig. 3A. If the TBA^+ ions are exhaustively transferred, the remaining TBA^+ concentration in the thin-layer paper approaches zero. In that case, a linear relationship is expected between the charge and total TBA^+ concentration, which is indeed observed (Fig. 3B). Other cations such as Na^+, K^+, H^+, and Ca^{2+} did not exhibit any significant increase of current (data are not shown). Similar results were also obtained using paper sampling via capillary action (Fig. S2). It should be noted that exhaustive extraction can be achieved in concentrations lower than 10^{-5} M. However, tailing of peak current can be observed at negative potential at a high sample concentration (Fig. 3A), which indicates that exhaustive transfer of all amount of ion is not realized. Indeed, Faraday's law dictates that the total electric charge passed through the electrode should be 14.5 mC for 0.05 mM TBA^+ and a 3.0 μL sample volume, while the integrated charge at 10 mV s^{-1} was found as 12.1 mC. This gives a 84% coulometric efficiency. When the TBA^+ concentration reaches 0.5 mM, only a 50% coulometric efficiency can be obtained.

A deviation from thin-layer behavior may result in a deviation from linearity at a high sample concentration. Moreover, the effective sample volume is smaller than the added one, which may be due to the electrostatic adsorption of TBA^+ on paper. Despite this, the setup is simple

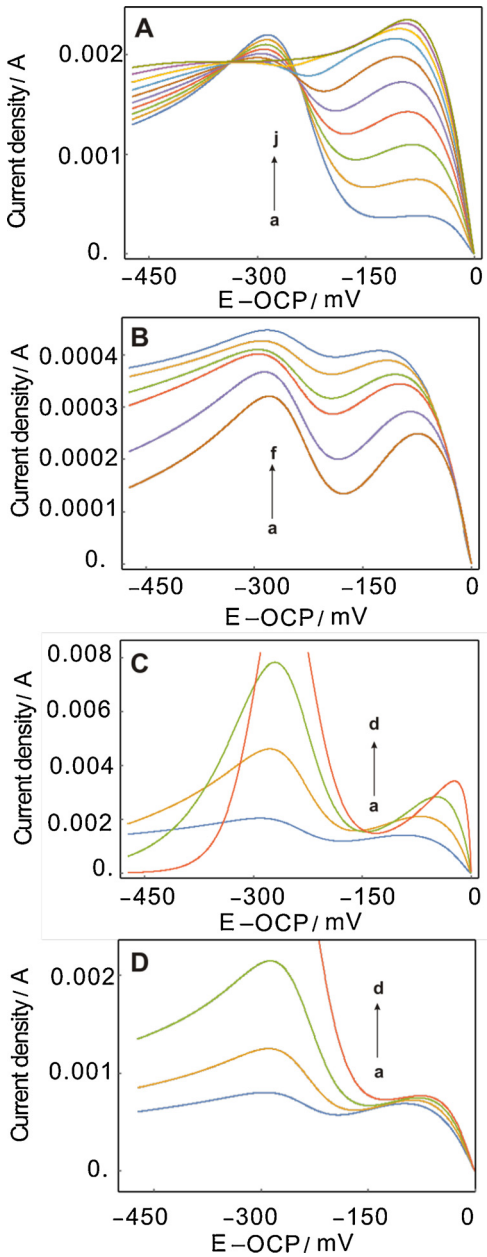


Fig. 4. Calculated cyclic voltammograms obtained for (A) different concentrations of KCl (0.1 mM (a) to 1.0 mM (j), the concentration increment was 0.1 mM); (B) different scan rate (ν = 2 (a), 3 (b), 5 (c), 6 (d), 8 (e), and 10 mV s^{-1} (f)); (C) different diffusion coefficients ($D_m = 10^{-7}$ (a), 5×10^{-7} (b), 10^{-6} (c), and 10^{-5} $cm^2\ s^{-1}$ (d)), and (D) different concentrations of ion-exchanger (2 (a), 3 (b), 5 (c), and 10 mM (d)). Parameters: sample-layer thickness, δ_a = 200 μm; membrane thickness, δ_m = 50 μm; diffusion coefficients in the sample and membrane, $D_a = 10^{-5}\ cm^2\ s^{-1}$ and $D_m = 10^{-7}\ cm^2\ s^{-1}$, respectively; ion-exchanger concentration, R_m = 5.0 mM; finite distance steps, d = 10 μm; time steps, Δt = 1 ms. Scan rate: 5 mV s^{-1}. Sample analyte concentration, c(0,0) = 200 μM.

and effective for paper-based thin-layer voltammetry. In addition, background corrections can be used to eliminate undesired interference, which will be discussed below. While TBA^+ was selected as a model here, other comparatively hydrophobic ions such as perchlorate or ionic drugs may be detected using the paper-supported system.

The facilitated ion transfer of hydrophilic ions with ionophore-containing membranes was subsequently investigated. To our knowledge, thin-layer ion sensors with ionophore-based membranes have scarcely been investigated using cyclic voltammetry. Herein, a potassium-selective system based on valinomycin was selected as a model. In order to evaluate the thin-layer voltammetry for the determination of ions, the characteristics of the sensing system are modeled by numerical simulation. For simplicity, all sample-independent potential contributions were neglected in the course of the sensing protocol.

The theoretical voltammograms for different concentrations of potassium ions were simulated without considering the ohmic drop. As shown in Fig. 4A, the current of the first (potassium dependent) peak increases linearly with the concentration of potassium. At higher scan potentials, the ion transfer can no longer be assisted by the ionophore, and background ions start to extract into the membrane. Therefore, an obvious peak appearing at ca -300 mV is ascribed to the transfer of sodium ions. At higher concentrations of K^+, the sodium peak decreases gradually and eventually almost disappears in the potential window owing to the larger quantity of the K^+ that needs to be transferred. Even so, the background wave was not completely isolated from the analyte wave. Therefore, the target ion-transfer process was not exhaustive with 100% coulometric efficiency. The theoretical prediction was consistent with the experimental results cited below. The resolution between the two peaks could be further improved with decreasing scan rates. Plots of the voltammograms curves with different scan rates were calculated (Fig. 4B). As expected, peak resolution becomes more pronounced as the scan rate is decreased. However, complete isolation of the two waves was not observed even at a scan rate of 2 mV s^{-1}.

The simulated cyclic voltammograms with different membrane diffusion coefficients were also demonstrated. As predicted theoretically (Fig. 4C), the current increases significantly with the increase of the membrane diffusion coefficient. Moreover, the position of the peaks shifts to more positive potential and an enhancement of peak resolution can be obtained. Therefore, this method places important demands on the design of the membrane materials, which have an impact on the electrochemical behaviors of the system. Other porous supporting materials resulting in larger diffusion coefficients may be alternative options. Moreover, increasing the amount of the lipophilic ion-exchanger (R_m) also resulted in an increase of peak current (Fig. 4D). With the simulation tool, the performance of the sensors can be predicted and improved for the proposed methodology.

In this study, the ion transfer process places great demands on the selectivity of the membrane. As shown in the simulated cyclic voltammograms, the coexistence of background sodium ions did not give appreciable interference, but the background wave was not completely isolated from the potassium wave. Therefore, the contributions from the undesired interference may be reduced via background correction. Two different approaches for background subtraction were proposed. For the first approach ("inflection point" approach), the inflection point for the background wave can be found. The slope at the point was extrapolated down to zero current to calculate the charge. The obtained charge was then used for the background correction (Fig. S3 A). The charge is linear up to the point where the background wave is similar in height to the sample wave. At higher concentrations, an obvious deviation from the linear range can be observed (Fig. S3B). As a simple comparative approach ("cut off" approach), by integrating the charge up to the minimum between the sample wave and background wave in the voltammogram, the total charge can be obtained and used for background compensation (Fig. 5A). Compared to the first protocol, a good linear relationship between the charge and the concentration can be observed even at higher concentrations for the simple "cut off" approach (Fig. 5B). Therefore, the "cut off" approach may be used to partially reduce the undesired interference.

The concept was then evaluated experimentally with a potassium-selective membrane. The ion transfer voltammetry was again first explored in bulk solution. As shown in Fig. 6, an obvious (ca. 300 mV) potential difference was observed for the transfer of target ion (K^+) and background ion (Na^+). As in the presence of the ionophore, the transfer of K^+ is obtained at a lower potential in comparison with Na^+ owing to

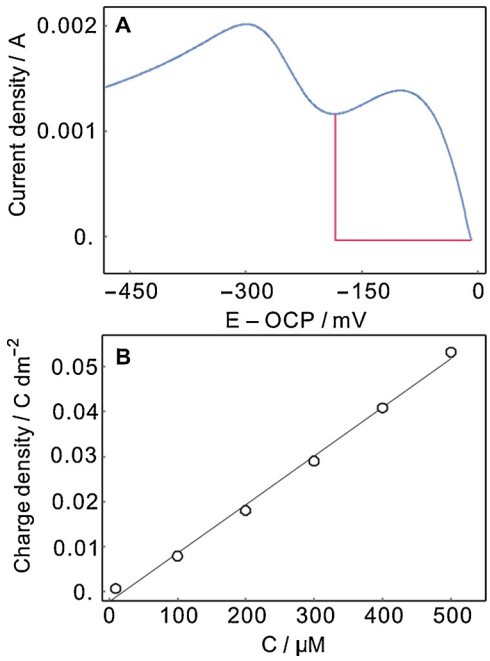


Fig. 5. (A) Background subtraction method based on the "cut off" approach. The straight red line indicates the area for charge calculations. The Calculated cyclic voltammogram was obtained for 0.4 mM KCl with 1.0 mM NaCl. All other parameters as for Fig. 4. (B) Background-corrected charge obtained from the simulated results by using the "cut off" approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

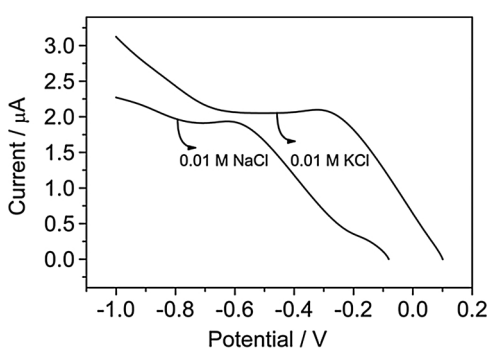


Fig. 6. Cyclic voltammograms obtained in bulk solutions. The inner solution was 10^{-3} M KCl with 10^{-3} M NaCl. The sample solutions contain the target ions without supporting electrolyte.

the lower free energy of transfer and the higher binding affinity between ionophore and analyte. The separation of the two observed transfer peaks, which is dependent on the selectivity of the membrane, allows the proposed methodology for potassium detection.

The electrochemical response behavior of the sensor with a paper-supported thin-layer solution was investigated. For the thin-layer sample, ion-transfer of the target ions may occur in a potential window that depends on membrane selectivity. During the forward scan, the K^+ undergoes assisted ion transfer into and across the ion-selective membrane by the ionophore. At higher potentials, solution background ions are also extracted and deteriorate the selectivity of the membrane. Indeed, two peaks are clearly distinguished. The peak at -350 mV is ascribed to the transfer of K^+ while the one at -650 mV to that of Na^+. While sodium ions did not give appreciable interference, the analyte wave was not completely isolated from the background wave. This phenomenon was consistent with the theoretical results mentioned above (Fig. 4A). The close match between the calculated data and the

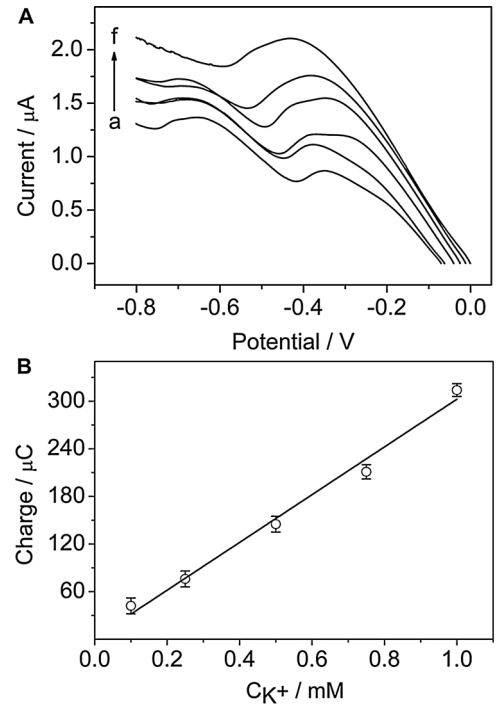


Fig. 7. (A) Cyclic voltammograms obtained for different concentrations of KCl with a scan rate of 2 mV s^{-1}. (a, 0.001 M NaCl, and 0.001 M NaCl with different concentrations of KCl, 1.0×10^{-4} (b), 2.5×10^{-4} (c), 5.0×10^{-4} (d), 7.5×10^{-4} (e), and 1.0×10^{-3} M (f) KCl. (B) Calibration curve for K^+ with a scan rate of 2.0 mV s^{-1}. Error bars represent the standard deviation for three measurements.

experimental data shows that the model adequately predicts the thin sample layer voltammetry.

Despite the similarities in response behavior between experimental and calculated voltammograms, the actual peaks are broader because of the contribution of the other processes to the electrochemical reaction. As predicted by the simulation (Fig. 4B), peak resolution can be improved with decreasing the scan rate. Indeed, with a slow scan rate (2 mV s^{-1}), the sensor was found to adequately respond to potassium (Fig. 7A), and a linear relationship between integrated charge (as indicated below) and the concentration of added potassium was found from 100 μM to 1.0 mM (Fig. 7B). It should be noted that the tailing of peak current at negative potentials indicates that the complete transfer of all ion is not realized. However, as shown in the simulated results, background corrections can be used to reduce undesired interference. Even though both of the two approaches give a value for the charge that is lower than the theoretically expected charge, experimental measurements reveal that better results can be obtained for the simpler approach (Fig. S4). The values for the charge are almost consistent with the theoretically expected charge when the potassium concentrations were lower than 0.75 mM. Therefore, the simple "cut off" approach may be a good choice for background correction and used for quantitative analysis.

It is interesting to note that the observed open circuit potentials of the membrane correspond to a Nernstian response (61.6 ± 4.0 mV) and can be converted to the potassium (Fig. S5). Compared to controlled potential coulometry, cyclic voltammetry can provide more useful information about the membrane process. For the situation in which exhaustive transfer is not achieved, the reporting of current peak height may be a good alternative choice. Using this experimental configuration, any presence of a spontaneous leakage of potassium should negatively affect the detection limit of the sensor (as indicated the presence of the current peak at -0.35 V for the background voltammogram). The potassium leakage may also arise from the tight contact

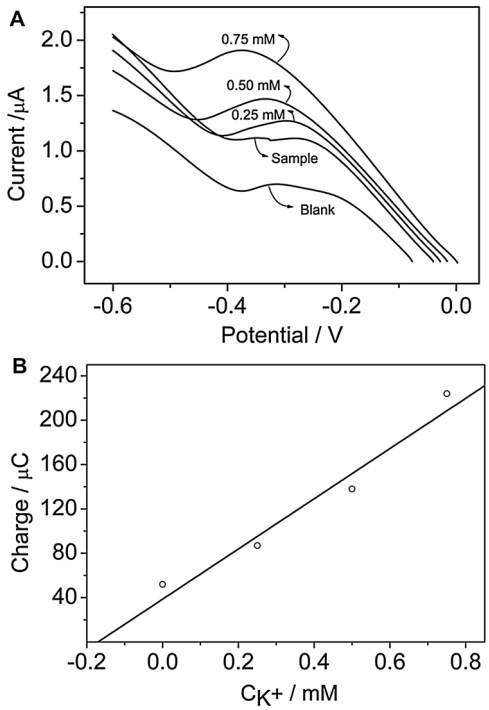


Fig. 8. (A) Cyclic voltammograms obtained for K^+ in mineral water with standard addition method. (B) Calibration line used to determine the K^+ concentration.

between the silver rod and the membrane. It is therefore expected that the linear dynamic range and the low detection limit could be further improved by optimizing the sensor design. For practical applications, the dynamic range may be adjusted by using different filter papers and different concentrations of sample solution. The reproducibility was found to be less than 5% RSD, which may originate in the variations of the thickness and sampled concentrations for each new filter paper.

As an early stage application, the proposed method was used to measure the potassium concentration in mineral water, with Fig. 8A showing the corresponding cyclic voltammograms. The background subtracted charge was used for quantification. The potassium concentration in the mineral water was determined as 66.5 ± 1.9 mg/L by standard addition calibration (as shown in Fig. 8B). The result was in accordance with the value obtained by atomic emission spectroscopy (63.8 ± 1.0 mg/L) and the labelled value (66.0 mg/L), which confirms the viability of the proposed method.

4. Conclusions

In short, we have demonstrated the concept of paper-supported thin-layer voltammetry for ion sensing. The setup chosen here combines paper sampling and a commercial electrode based on ion-selective membrane for thin-layer voltammetry. Unlike a conventional constant potential coulometric measurement, cyclic voltammetry is applied to modulate the ion transfer across an ionophore based ion- selective membrane. The proposed sensor can provide not only consumed charge but also gives useful information about the membrane such as open circuit potential and selectivity. Of particular interest is that the ion-transfer voltammetry with 100% electrolysis efficiency may be integrated with paper-based thin-layer sampling for potentially calibration-free analysis. Moreover, a simple and reasonable "cut off" approach was used for quantitative analysis in order to minimize the contribution of the background electrolyte to the total charge. While this study focused only on potassium detection based on paper sampling, this technique may allow for potentially calibration-free detection of other target ions and find valuable applications in batch-fabricated disposable single-use analytical devices. With the introduction of alternative materials and an adapted design, the performance of this type of sensors may be further improved.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.snb.2018.10.046.

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