© *2005 The Chemical Society of Japan*

Detection of Hidden Mercury in Cosmetic Products by Partially Cross-Linked Poly(4-vinylpyridine)/Screen-Printed Electrode

Ying Shih,* Annamalai Senthil Kumar,[1] Jyh-Myng Zen,*,[1] and Jaw-Cherng Hsu

Department of Applied Cosmetology, Hung Kuang University, Taichung 433, Taiwan

[1]Department of Chemistry, National Chung Hsing University, Taichung 402, Taiwan

Received November 24, 2004; E-mail: krystle@sunrise.hk.edu.tw

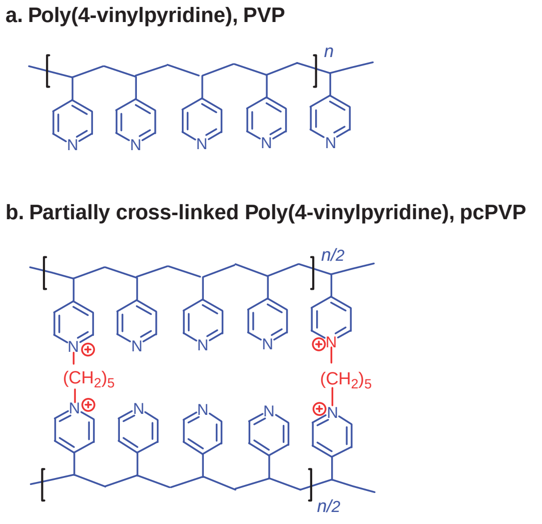
Due to the severe toxic effects of mercury (Hg) and its derivatives, they are strictly prohibited to be used as cosmetics ingredients. Nevertheless, unknown quantities of Hg are formulated in consumer cosmetic products. We demonstrate a disposable screen-printed electrode modified with 1,5-dibromopentane partially (7%) cross-linked poly(4-vinylpyridine) (SPE/pcPVP) system for the detection of hidden concentrations of mercury, [Hg] within cosmetics goods by anodic stripping analysis in 0.01 M KCl + 0.02 M H_2SO_4 (1 M = 1 mol dm^{-3}) solution. The Hg^{2+} ion in a chloride medium transforms to $[HgCl_4]^{2-}$, which then selectively preconcentrate and electro-deposite as metallic mercury, Hg^0 on the cationic SPE/pcPVP (PVP exist as PVP^+ in pH < 5). Under optimal conditions, the calibration graph is linear in the window of 25–150 ppb, with a detection limit (S/N = 3) and regression coefficient of 3.21 ppb and 0.9909 respectively for the SPE/pcPVP. Real sample assay results for the three skin-lightening agents are evidence of the precise existence of prohibited Hg (compared with ICP-MS measurements) in the products. This article further cautions the public of Hg toxicity in cosmetics. Since the approach is low cost and disposable, it is highly suitable for unskilled electrochemists.

The heavy metal Mercury (Hg) is one of the most toxic substances in existence and is known to bio-accumulate in the body of people and childs that have chronic exposure.[1] Mercury containing cosmetics have been advertised for many years as skin-bleaching agents or as applications to remove or prevent freckles and/or brown spots (so called age spots) without considering its adverse clinical effects.[2] Some of the cosmetics products that contain Hg are; hair shampoos, hair sets and rinses, hair straighteners, hair coloring, bath oils, bubble bath powders and gels, antiperspirants, deodorants, and eye-area cosmetics, etc.[3–7] It is known that Hg-compounds are readily adsorbed through unbroken skin and some micro-pores, and in turn cause numerous adverse effects.[8] Accumulating a high concentration of mercury, [Hg] may lead to symptoms such as weakness, paranoia, sleeplessness, excessive salivation or sweating, itching, swelling, fever, memory loss, and elevated blood pressure, etc.[9–11] In addition, it is also excreted in breast milk. Children may be at an increased risk for pulmonary toxicity and are more likely to develop respiratory failure.[12,13] Consequently, in the year 1992, the U.S. Food and Drug Administration (FDA) strictly prohibited the usage of mercury and its derivatives in cosmetics (except for eye make-up or preservative items with Hg concentrations below 65 ppm). But in current markets, unknown quantities of toxic Hg formulated cosmetics are still available and their Hg concentration (i.e., [Hg]) levels are specifically hidden in product labels. The aim of this work is to develop a simple and easy Hg analytical method to test cosmetics goods.

Electrochemical methods, in particular anodic stripping voltammetry (ASV), have been proven to be equal or even superior in efficiency and accuracy for trace metal analysis when compared to conventional spectroscopic approaches.[14,15] Nevertheless, the classical ASV approach for Hg is always complicated by the interference caused by other transition-metal cations and the requirement for long reductive preconcentration steps. Even though the use of gold and its modified electrodes favours Hg preconcentration (through the formation of Au–Hg amalgamation), the Au^{III} chloride co-stripping process seriously renders the practical assays.[16] Meanwhile, anionic modifiers or complexing ligands modified electrodes like zeolite,[17] clay,[18] crown ether,[19] carbazone,[20] carbazide,[21] polypyrrole, and polyamine derivatives[22,23] were reported to trap the ionic mercury, Hg^{2+} inside its matrix, enabling ASV analysis. Unfortunately, either of these methods suffer from a fairly high detection limit or an electrode surface that can not be easily regenerated. Alternatively, anionic permselective membrane modified systems were worked out for the Hg assays, where the Hg^{2+} is transform in to $[HgCl_4]^{2-}$ anionic species (formation constant = 1.2×10^{15}) and in turn allowing ASV.[23,24] The method can selectively eliminate interference from the co-existing cations like Cu^{2+} and Zn^{2+} in the practical samples. Examples for the approach are; Tosflex® (anionic exchange polymer similar to Nafion® backbone),[23,24] poly[1-methyl-3-(pyrrol-1-ylmethyl)pyridinium][16] and poly(4-vinylpyridine)–Au[25] modified glassy carbon electrode (GCEs). Note that poly(4-vinylpyridine) (PVP) is an easily available polymer that exists in cationic form at pH < 5 (i.e., PVP^+Cl^-) and is expected to efficiently preconcentrate the $[HgCl_4]^{2-}$ even without the Au layer, if the solution phase and instrumental conditions are properly tuned.[26]

In recent times, screen-printed electrodes (SPEs) have been used for innovative and novel electro-analytical applications.[27,28] The disposable, low cost, and mass producible natures of the SPE allow easy extension to diverse fields of

Published on the web December 9, 2005; DOI 10.1246/bcsj.78.2130



Scheme 1.

research applications and are suitable for use by unskilled electro-analytical chemists. Unfortunately, very limited attention has been paid to SPE technology for trace Hg analysis. Wang and Baomin first developed Au plated SPE[29] and later Ugo et al. used a chelating resin, Sumichelate Q10R (contains dithiocarbamate groups) modified SPE[30] for trace Hg ASV analysis. We demonstrate here a 1,5-dibromopentane partially cross-linked PVP modified SPE (designated as SPE/pcPVP, Scheme 1) for Hg analysis, through $[\mathrm{HgCl_4}]^{2-}$ in a chloride media. The pcPVP over layer is chemically inert, nonelectroactive, hydrophilic, and insoluble in water and thus possesses almost ideal properties for the preparation of chemically modified electrodes (CME). Finally, three different skin-lightening products, samples #1 to #3 (where there is no indication for Hg in the labels) were examined in parallel with ICP-MS analysis. The results show the specific existance of Hg in all of the products.

Results and Discussion

Voltammetric Behavior. Figure 1 is the comparative cyclic voltammetric (CV) response for 5 ppm of Hg^{2+} on pcPVP modified and unmodified SPEs with and without 0.01 M KCl in the potential window of −0.2 to 0.7 V vs Ag/AgCl. The unmodified SPE (Fig. 1a) shows a feeble increase in current response at ∼−0.2 V (cathodic, C) and a small and irreversible oxidation peak at 0.3 V (anodic, A). Based on earlier reports,[24,25] Hg^{2+} in a chloride medium transformed to $[\mathrm{Hg^{II}Cl_4}]^{2-}$ form and was electro-deposited at about −0.2 V as Hg^0 (process-C, pre-concentration process) on the underlying electrode, which then led to an ASV peak at 0.3 V (process-A). It is obvious that SPE/pcPVP modified film yielded the highest ASV peak current response for process-C and -A due to its ion-exchanging pathways as per the following mechanism.

Process-C

$$\text{Step-1: } 2\mathrm{pcPVP}^+\cdot\mathrm{Cl}_{\mathrm{surf}} + [\mathrm{Hg^{II}Cl_4}]^{2-}{}_{\mathrm{soln}} \rightarrow 2\mathrm{pcPVP}^+\cdot[\mathrm{Hg^{II}Cl_4}]^{2-}{}_{\mathrm{surf}} + 2\mathrm{Cl}^-{}_{\mathrm{soln}}, \tag{1}$$

$$\text{Step-2 } (-0.2\text{ V})\text{: } 2\mathrm{pcPVP}^+\cdot[\mathrm{Hg^{II}Cl_4}]^{2-}{}_{\mathrm{surf}} + 2e^- \rightarrow 2\mathrm{pcPVP}^+\cdot\mathrm{Cl}/\mathrm{Hg}^0{}_{\mathrm{surf}} + 2\mathrm{Cl}^-{}_{\mathrm{soln}}. \tag{2}$$

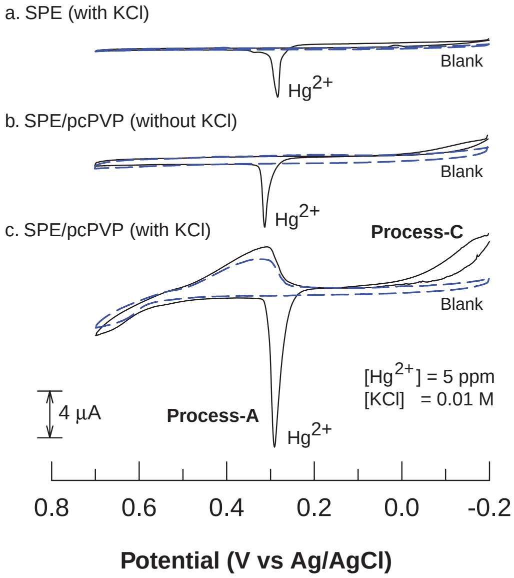


Fig. 1. Cyclic voltammetric response of SPE and SPE/pcPVP with and without (blank) 5 ppm of Hg in 0.02 M $\mathrm{H_2SO_4}$ solution at a scan rate of 50 mV s^{-1}. Captions C and A corresponding to cathodic and anodic, respectively.

Process-A

$$\text{Step-1}'\text{ (stripping 0.3 V): } 2\mathrm{pcPVP}^+\cdot\mathrm{Cl}/\mathrm{Hg}^0{}_{\mathrm{surf}} \rightarrow 2\mathrm{pcPVP}^+\cdot\mathrm{Cl} + \mathrm{Hg}^{2+}{}_{\mathrm{soln}} + 2e^-, \tag{3}$$

$$\text{Step-2}'\text{: } \mathrm{Hg}^{2+}{}_{\mathrm{soln}} + 4\mathrm{Cl}^-{}_{\mathrm{soln}} \rightarrow \mathrm{Hg^{II}Cl_4}{}^{2-}{}_{\mathrm{soln}}. \tag{4}$$

In the above equations, the subscripts "soln" and "surf" correspond to solution and surface of the system. As per the above mechanistic scheme, during the cathodic process-C, the $[\mathrm{HgCl_4}]^{2-}$ in the solution phase (i.e., $[\mathrm{HgCl_4}]^{2-}{}_{\mathrm{soln}}$, step-1) first ion-changed at the electrode surface (i.e., $[\mathrm{HgCl_4}]^{2-}{}_{\mathrm{surf}}$) through the replacement of surface-bound counter Cl^- ions and subsequently reduced to metallic mercury, $\mathrm{Hg}^0{}_{\mathrm{surf}}$ (step-2) on the working electrode surface. At the anodic process-A, the electro-deposited Hg^0 film gets stripped to Hg^{2+} peak (step-1′) and in turn to the $[\mathrm{HgCl_4}]^{2-}{}_{\mathrm{soln}}$ reformation (step-2′). Control experiments in the absence of chloride and pcPVP in the working system resulted in poor ASV signals (Fig. 1), evidence of the above mechanism. The observation is parallel with the mechanisms of Tosflex® and polymer film polyammonium macrocyclic receptor coated GCEs.[16,23] Overall, the SPE/pcPVP system is effective for the selective preconcentration of $[\mathrm{HgCl_4}]^{2-}$ and increasing ASV signals. Further experiments are for the optimization of solution phase and instrument conditions by square wave voltammetry (SWV).

Analytical Applications. The effect of chloride ions derived from ammonium, sodium, and potassium salts were investigated for the detection of 5 ppm Hg^{2+} on the SPE/pcPVP with 0.02 M $\mathrm{H_2SO_4}$ under identical experimental conditions (data is not shown). When $\mathrm{NH_4Cl}$ and NaCl salts were added, almost similar ASV response by SWV were yield, while on the other hand, KCl salt resulted in about a 30% increase in peak current signal. The exact reason for the effect is unknown to us now.

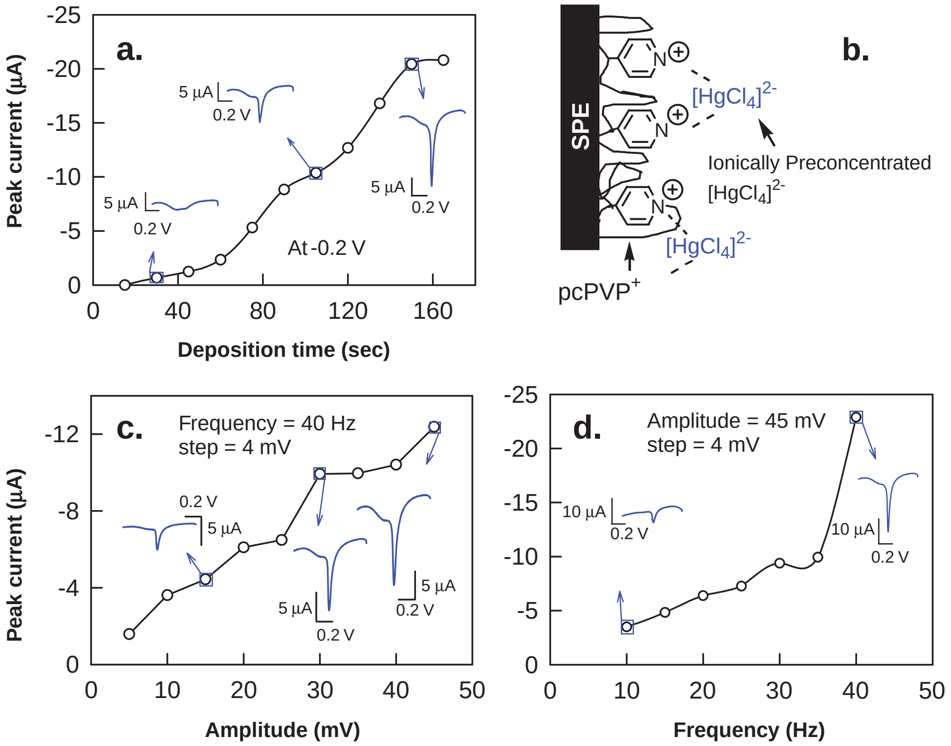


Fig. 2. (a) Plot of ASV peak current against plating time (t_p) for the detection of 5 ppm Hg at SPE/pcPVP. (b) Conceptional representation of the preconcentration of $[HgCl_4]^{2-}$ form on SPE/pcPVP (first step in process-C) in 0.01 M KCl + 0.02 M H_2SO_4 solution. (c) and (d) are the effect of SWV's amplitude and frequency on the detection of 5 ppm Hg in 0.01 M KCl + 0.02 M H_2SO_4 solution.

Figure 2a is the response of $[HgCl_4]^{2-}$ plating (to Hg^0) time (t_p) (Step-1 and -2 are expected to occur simultaneously under the working conditions) on the detection of 5 ppm Hg^{2+} with a fixed applied potential of −0.2 V vs Ag/AgCl in 0.01 M KCl + 0.02 M H_2SO_4 solution. In the initial time window of 20–60 s, the ASV peak current slowly increased, but at 60–150 s there was a steep increase in the response followed by saturation of current signals. About a 20 time increase in the ASV was noticed at $t_p = 150$ s than compare to the $t_p = 20$ s, and hence the highest working condition is uniformly taken for further analytical assays. Figure 2b is a pictorial representation of the preconcentration of $[HgCl_4]^{2-}$ on the SPE/pcPVP under present working condition.

Further experiments were the optimization of conditions for the SWV parameters (Figs. 2c and d). These parameters are interrelated and have a combined effect on the response SWV peak, but here only the general trends are examined. It was found that these parameters had little effect on the peak potential. When the SW amplitude was varied between 5 and 45 mV, the peak currents increased with increasing amplitude. However, the peak width also increased at the same time, in particular when the amplitude was higher than 45 mV. The step height together with the frequency defines the effective scan rate. Hence, an increase in either the frequency or the step height results in an increase in the effective scan rate. The response of ASV current increases with SW frequency up to 40 Hz, above which the peak current was unstable and obscured by a large residual current which in turn decreased the peak current. By maintaining the frequency at 40 Hz, the effect of step height was studied (data not included). As step height was greater than 4 mV, few points were sampled, thus affecting the reproducibility of the detection. Overall, the optimized parameters can be summarized as follows: SW frequency, 40 Hz; SW amplitude, 45 mV; step height, 4 mV.

Under the optimal experimental conditions, a constructed calibration plot is linear for the [Hg] window of 25–125 ppb with a linear equation and regression of $y = 0.4572 + 0.1145x$ and 0.9909 respectively on the SPE/pcPVP (Fig. 3 and its insert plot). Ten continuous ASV responses using SPE/pcPVP resulted in an RSD value of 4.97% with $t_p = 2.5$ min, which yielded the theoretical detection limit (S/N = 3, D_L) value of 3.15 ppb (i.e., 15.7 nM) for Hg analysis. The value is closer to the PVP–Au (0.49 nM with $t_p = 6$ min) and the Tosflex® (100 nM with $t_p = 5$ min) modified classical GCEs systems.[24,25] Considering the advantages of the SPE, such as being disposable, low price, and mass producible, makes the system superior to classical electrodes. The reproducibility of the electrode was tested using five-repeated SWV of 5 ppm of Hg using freshly prepared SPE/pcPVP under optimal conditions. An RSD value of 4.8% was noticed, which further validates the usefulness of the SPE/pcPVP for practical analysis.

As for the interference effect, the SPE/pcPVP is tolerable of commonly co-existing metals like Zn^{II}, Ni^{II}, Sn^{II}, Pb^{II}, Co^{II}, Cu^{II}, Cr^{VI}, and Bi^{III} up to 100 fold excess (with respect to 25 ppb of Hg) under the optimal experimental conditions.

Finally, the SPE/pcPVP was applied to the quantitative and qualitative analysis of Hg in cosmetics products. Since the

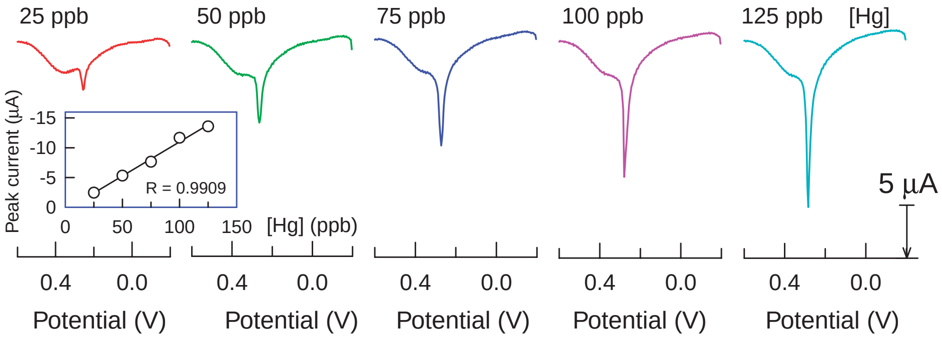


Fig. 3. SWV response for increasing [Hg^{2+}] at SPE/pcPVP. Inserted plot is a calibration response of the base-line corrected SWV peaks. Other conditions are as in Fig. 2.

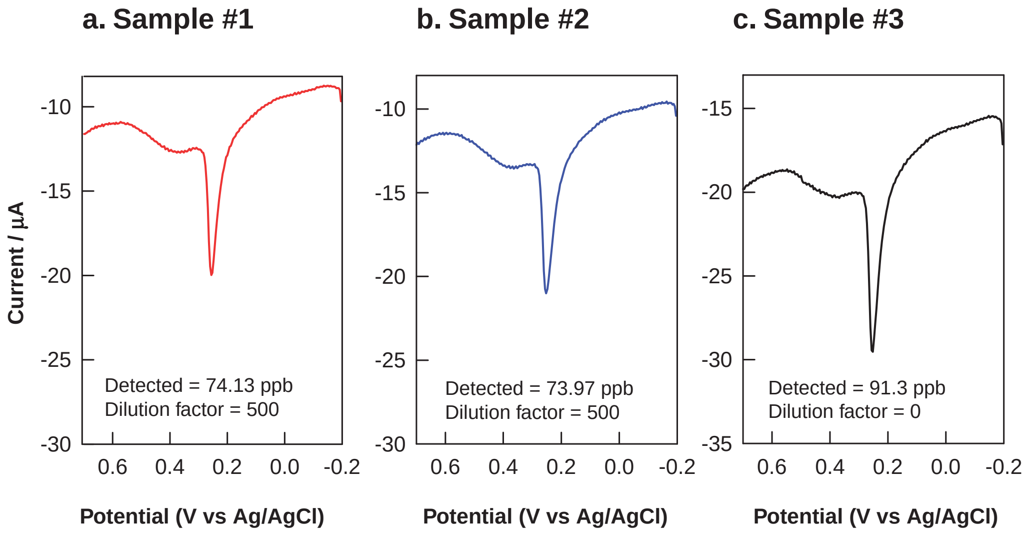


Fig. 4. SWV response for the different skin lightening agents at SPE/pcPVP in 0.01 M of KCl + 0.02 M H_2SO_4 solution. Other SWV conditions are as in Fig. 2. Samples #1 and #2 were diluted to 500 times. Detected values were not corrected with dilution factor.

concentration of KCl is greater than the real sample concentration, under the experiment conditions, almost all of the Hg^{2+} in the matrix was transformed to $[HgCl_4]^{2-}$ complex in the working conditions. Figure 4 is the typical SWV response for the three diluted skin lightening samples (#1 to #3) at SPE/pcPVP under optimal conditions. It is surprising to notice that all three samples show significant ASV signals for Hg. Since the present assays are highly reproducible, the ASV peak currents were directly extended to the standard calibration graphs (given in the earlier section) for the quantitative analysis of mercury. The determined [Hg]s are 37.07 mg/g, 36.99 mg/g, and 0.18 µg/g, respectively for samples #1 to #3 (dilution factor corrected). Corresponding ICP-MS data are 38.77 mg/g, 37.33 mg/g, and 0.19 µg/g. It is obvious that SPE/pcPVP is accurate and comparative to classical ICP-MS in this work. This observation also indicates the absence of any matrix effect in the real sample for the practical assays.

In order to validate the analytical assays; the SPE/pcPVP was further subjected to recovery tests (samples #1 and #3) by spiking 25–75 ppb of Hg to the diluted real samples under optimized conditions. The resulting data, which fell in the window of 96.28–106.04, validates the usefulness of the present working electrode for wider cosmetics Hg analysis.

Conclusion

Partially cross-linked poly(4-vinylpyridine) modified SPE (SPE/pcPVP) was found to be effective for the ASV analysis of mercury through selective preconcentration of $[HgCl_4]^{2-}$ and Hg^0 processes in a chloride medium. The SPE/pcPVP allows straightforward detection of hidden Hg trace in cosmetic products with results similar to that of ICP-MS data. Since the SPE approach is less expensive and allows on-the-spot analysis, this method can be useful to do routine Hg analysis on cosmetic products in day-to-day life. This article also cautions the cosmetic user of the toxicity of mercury.

Experimental

Chemicals and Reagents. Poly(4-vinylpyridine) (PVP, MW = 50000) solution in methanol containing ~20 wt % polymer, was purchased from Aldrich. The standard solutions (1000 ppm) of Hg^{II}, and other metal solutions were obtained from Merck (Darmstadt, Germany). The supporting electrolyte solutions were prepared from Merck reagents. The other compounds (ACS-certified reagent grade) were used without any further purification. Aqueous solutions were prepared with doubly distilled deionized water by reverse osmosis technique.

Apparatus. Electrochemistry was performed on a CHI 620A electrochemical workstation (Austin, TX, USA). A conventional three-electrode set-up was used for square-wave anodic stripping voltammetry (SWASV). A BAS VC-3 electrochemical cell (10 mL) was employed in these experiments. The three-electrode system consisted of a modified or unmodified screen-printed system (0.196 cm^2) as a working electrode (Zensor R&D, Taiwan), an Ag/AgCl reference electrode (Model RE-5, BAS), and a platinum wire auxiliary electrode. Since dissolved oxygen did not interfere with the working potential window, no deaeration was performed.

Electrode Preparation. The SPE/pcPVP was prepared following the procedure mentioned previously.[25] In brief, a 4 µL mixture containing 0.25 wt % PVP + 7% (vs the pyridine moiety) 1,5-dibromopentane (cross-linking agent) in methanol was spin coated (at 3000 rpm) on a cleaned SPE for 5 min. The coated electrode was subsequently heated in an oven at 90 °C for about 2 h in order to fasten the cross-linking process and to prevent dissolution of the films in aqueous solutions. Scheme 1 sketches the typical structure of the PVP and its cross-linked units (i.e. pcPVP). Note that more than 7% cross-linking agent resulted in a gel-like polymeric matrix which is less stable and not suitable for further electro-analytical applications.

Procedure. Prior to the regular electrochemical measurements, the SPE/pcPVP was equilibrated in 0.01 M KCl + 0.02 M H_2SO_4 solution for about 120 s. SWVs were obtained by scanning the potential from −0.2 to +0.7 V at a frequency of 40 Hz, amplitude of 45 mV and a step height of 4 mV. Mercury preconcentration on the working electrode was performed at a fixed applied potential of −0.2 V vs Ag/AgCl for 150 s. Mercury quantification was achieved by measuring the current of the oxidation peak after background subtraction. Unless otherwise stated, a 0.01 M KCl + 0.02 M H_2SO_4 solution was used as a supporting electrolyte for this study.

Real Samples. Two kinds of skin lightening agents, unbranded (#1 and #2) and branded (#3), were purchased from a local supermarket. The following are the ingredients labeled for sample #3; water, 1,2-butanediol, triacyl (octanoyl, decanoyl, etc.) glycerol, glycerol, propylene glycol, methyl *p*-hydroxybenzoate (methylparaben), ethyl *p*-hydroxybenzoate (ethylparaben), butyl *p*-hydroxybenzoate (butylparaben), propyl *p*-hydroxybenzoate (propylparaben), poloxamer 186, imidazolidinyl urea, carbomer, 2-phenoxyethanol, triethanolamine, xanthan gum, Na-Mo PK82, and parfum. There are no details about the ingredients for the case of samples #2 and #3. The real sample solutions were prepared as follows: about 0.1 g of skin-lightening lotion samples #1 and #2 were first weighed and carefully transferred to 500 mL conical flasks with 0.01 M KCl + 0.02 M H_2SO_4 solutions. For the case of sample #3, about 5 g of the lotion was directly added to 10 mL of working base-electrolyte solution. All of the samples were subjected to ICP-MS (PE Sciex 5000, Canada) in parallel. The ICP-MS samples were prepared by dissolving about 0.2 g of the skin-lightening agents with selected volumes of HNO_3 + H_2O_2 mixture solutions. Prior to analysis, the samples were heated to 180 °C for 10 min, followed by filtration.

The authors gratefully acknowledge financial supports from the National Science Council of the Republic of China.

References

1 A. Bhan and N. N. Sarkar, *Int. Med. J.*, **10**, 271 (2003).

2 J. J. Hostynek and H. I. Maibach, *Cosmet. Toiletries*, **116**, 26 (2001).

3 J. Handley, D. Todd, and D. Burrows, *Contact Dermatitis*, **29**, 258 (1993).

4 M. Z. Fiume, *Int. J. Toxicol.*, **20**, 1 (2001).

5 L.-H. Wang and S.-J. Tsai, *Anal. Chim. Acta*, **441**, 107 (2001).

6 C. Demanze, L. Rugroff, A. Karleskind, and Alain, *Parfums, Cosmet., Aromes*, **58**, 69, 73, 76 (1984).

7 L. G. Gracia and M. D. Luque de Castro, *J. Anal. At. Spectrom.*, **14**, 1615 (1999).

8 I. Al-Saleh, F. Khogali, M. Al-Amodi, I. El-Doush, N. Shinwari, and R. Al-Baradei, *J. Environ. Pathol., Toxicol. Oncol.*, **22**, 287 (2003).

9 H. Satoh, *Ind. Health*, **38**, 153 (2000).

10 S. B.-O'Reilly, G. Drasch, C. Beinhoff, S. Maydl, M. R. Vosko, G. Roider, and D. Dzaja, *Sci. Total Environ.*, **307**, 71 (2003).

11 A. B. Kobal, M. Horvat, M. Prezelj, A. S. Briski, M. Krsnik, T. Dizdarevic, D. Mazej, I. Falnoga, V. Stibilj, N. Arneric, D. Kobal, and J. Osredkar, *J. Trace Elem. Med. Biol.*, **17**, 261 (2004).

12 S. Skerfving, *Bull. Environ. Contam. Toxicol.*, **41**, 475 (1988).

13 R. M. Parr, E. M. DeMaeyer, V. G. Iyengar, A. R. Byrne, G. F. Kirkbright, G. Schoch, L. Niinisto, O. Pineda, and H. L. Vis, *Biol. Trace Elem. Res.*, **29**, 51 (1991).

14 J. Wang, "Analytical Electrochemistry," 2nd ed, John Wiley & Sons, Inc., New York (2001).

15 J.-M. Zen, "Mercury Detection by Electroanalytical Techniques," in "Encyclopedia of Environmental Analysis and Remediation," ed by R. A. Meyers, John Wiley & Sons, Inc., New York (1998), pp. 2725–2737.

16 A. Doménech, M. T. D.-Carbó, E. G. España, and M. D. Soriano, *Analyst*, **124**, 1661 (1999).

17 P. Hernández, E. Alda, and L. Hernández, *Fresenius' Z. Anal. Chem.*, **327**, 676 (1987).

18 W. Huang, C. Yang, and S. Zhang, *Anal. Bioanal. Chem.*, **374**, 998 (2002).

19 J. Wang and M. Bonkadar, *Talanta*, **35**, 277 (1988).

20 J. Labuda and V. Plaskon, *Anal. Chim. Acta*, **228**, 259 (1990).

21 Z. Navaratilova, *Electroanalysis*, **3**, 799 (1991).

22 M. D. Imisides and G. G. Wallace, *J. Electroanal. Chem.*, **246**, 181 (1988).

23 P. Ugo, L. M. Moretto, and G. A. Mazzocchin, *Anal. Chim. Acta*, **305**, 74 (1995).

24 L. M. Moretto, G. A. Mazzocchin, and P. Ugo, *J. Electroanal. Chem.*, **427**, 113 (1997).

25 J.-M. Zen and M.-J. Chung, *Anal. Chem.*, **67**, 3571 (1995).

26 P. Ugo, L. Sperni, and L. M. Moretto, *Electroanalysis*, **9**, 1153 (1997).

27 J.-M. Zen and A. S. Kumar, "Screen-Printed Electrochemical Sensor, Encyclopedia of Sensors," ed by A. G. Craig, E. C. Elizabeth, and V. P. Michael, American Scientific Publisher, California (2004), in press.

28 J. Wang, *Acc. Chem. Res.*, **35**, 811 (2002).

29 J. Wang and T. Baomin, *Anal. Chim. Acta*, **274**, 1 (1993).

30 P. Ugo, L. M. Moretto, P. Bertoncello, and J. Wang, *Electroanalysis*, **10**, 1017 (1998).