

Anodic Stripping Voltammetry Combined On-Line with Inductively Coupled Plasma-MS via a Direct-Injection High-Efficiency Nebulizer

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A direct-injection high-efficiency nebulizer (DIHEN) is used to couple a thin-layer electrochemical flow cell on-line with an ICP-mass spectrometer to perform anodic stripping voltammetry (ASV) at a thin mercury film followed by subsequent ICPMS measurements for the stripped metal analytes. The resultant hyphenated technique (ASV-DIHEN-ICPMS) is capable of analyzing select heavy metals present at ultratrace levels (down to low-ppt to sub-ppt levels) that are lower than the detection limits obtained by conventional ICPMS. In addition to its good analytical performance, the technique offers other attractive features such as the ability to eliminate detrimental matrix effects that can compromise ICPMS analyses and the possibility of probing electrode reactions involving trace amounts metal species with ICPMS. For conducting ASV on-line with ICPMS, the DIHEN was found to be more advantageous than the microconcentric nebulizer in terms of minimizing memory effects and potential artifacts caused by the erosion of the Hg film into the flowing solution stream. Compared to a direct injection nebulizer (DIN), the DIHEN was easier to operate. Moreover, its simpler design and the lack of back pressure from the DIHEN capillary made it more compatible with coupling to the thin-layer electrochemical cell than a DIN system.

In the past three decades, electrolytic preconcentration has been used in conjunction with a variety of atomic spectroscopic techniques for detecting metal species at low levels.^{1–8} Recently, the on-line combination of anodic stripping voltammetry (ASV) or adsorptive stripping voltammetry with inductively coupled plasma (ICP)MS^{4,9–15} has generated renewed interest in this field,

because several studies have demonstrated that metal species present at ultratrace levels (down to ppt or even ppq) can be analyzed by such a hyphenated technique (ASV-ICPMS). The exquisite sensitivity of ASV-ICPMS stems in part from the preconcentration effect inherent in the ASV procedure.¹⁶ In addition, the deposition of trace elements from solution onto the electrode surface provides the flexibility of cleaning the electrochemical cell assembly surface and carrying out the stripping step, after a medium-exchange procedure,¹⁶ in a suitable electrolyte solution that minimizes matrix effects detrimental to the ICPMS measurements.^{17,18} Similar to conventional ion-exchange or adsorptive methods, sample solutions can be analyzed without extensive pretreatment or significant dilution.

Van Berkel and co-workers were the first to utilize a thin-layer, flow-by electrochemical cell for ASV-ICPMS.^{11–13,15} They showed that this type of cells was more advantageous than other cells (e.g., a flow-through cell incorporating porous electrodes) for ASV-ICPMS, in terms of its remarkable preconcentration efficiency (which results in a greater signal enhancement), high sample throughput (due to the low cell volume), small sample consumption, and relatively simple physical design. Coupling of such a cell with the ICPMS sample introduction is typically accomplished using a nebulizer that can tolerate relatively slow solution flow rates (e.g., a microconcentric nebulizer, MCN, or a direct injection

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nebulizer, DIN¹⁹). Although the MCN is simpler in design and operation than the DIN, it has yet to be demonstrated to be compatible with ASV for the analysis of amalgam-forming elements at a thin mercury film (TMF, the most commonly electrode for trace metal analysis^{16,20}). One of the potential problems associated with the use of a TMF with a MCN is the need for the use of a conventional spray chamber. TMFs are known to have limited mechanical stability (even at a slow flow rate^{16,21}) and, depending on the flow rate and cell design, can be physically eroded by the flowing solution stream. The Hg²⁺ accumulated in the spray chamber and the Hg²⁺-containing aerosol can cause serious memory effects and introduce unwanted artifacts.^{19,22} In a preliminary study, Zhou et al.¹⁵ showed that the use of a DIN could circumvent this problem by directly introducing the sample solution into the plasma and thereby obviating the need to use a spray chamber. Unfortunately, the incorporation of a DIN raised several new problems. These included the complexity of the DIN assembly, the high back pressure of the sample capillary (which frequently resulted in the leakage of the thin-layer flow cell), and the susceptibility of the capillary to clogging. Montaser and co-workers also illustrated that the large and high-velocity droplets from the DIN could lead to impaired precision and increased matrix effects.^{22–25}

In this note, we report the on-line combination of ASV with ICPMS via a direct injection high-efficiency nebulizer (DIHEN). The reduced cost and ease of operation associated with the DIHEN^{22–25} relative to the DIN not only greatly simplifies the tandem coupling of ASV and ICPMS but also yields analytical “figures of merit” (i.e., linearity, precision, accuracy, and sample consumption and throughput) that are as good as or better than those reported using the DIN.¹⁵ The resultant hyphenated technique (ASV-DIHEN-ICPMS) enables one to conveniently conduct metal analysis in relatively complicated media at concentrations lower than the detection limits obtained by conventional ICPMS. The simultaneous acquisition of voltammograms and time-resolved ICPMS signals could also allow certain electrode reactions involving metal-transfer processes^{26,27} to be probed at a more sensitive and accurate level.

EXPERIMENTAL SECTION

Reagents and Chemicals. Cadmium, thallium, lead, and mercury standard solutions were purchased from Aldrich. Nitric acid used for preparing the carrier solution or other dilute sample solutions was doubly distilled from Vycor (GFS Chemicals, Powell, OH). All samples were prepared in a clean room and diluted with deionized water from a water purification system (Nanopure II, Barnstead, Newton, MS). CASS-4 open ocean seawater reference

Table 1. Operating Parameters for the ICPMS

rf power	1500 W
nebulizer gas flow rate	0.9 L/min
auxiliary gas flow rate	1.25 L/min
plasma gas flow rate	15 L/min
analog stage voltage	–2325
pulse stage voltage	1450
lens voltage (¹¹⁵ In)	7.2
autolens	on
sample introduction system	DIHEN
capillary (i.d.)	0.082 mm
capillary wall thickness	0.035 mm
solution uptake rate	45–55 μ L/min
solution flow mode	flow injection
scan mode	peak hopping
MCA channels (points/mass)	1
resolution	0.7 amu
sweeps/reading	1
replicate	7000
replicates	1
dwel time/mass	350 ms

(National Research Council, Ottawa, Canada) was used to determine the accuracy of ASV-DIHEN-ICPMS for the analysis of a sample having a challenging saline matrix.

Electrodes and Cells. The design of the flow cell for ASV-DIHEN-ICPMS experiments has been described elsewhere.^{26,27} Briefly, the working electrode was a 6-mm-diameter glassy carbon electrode embedded in a PEEK block (Bioanalytical Systems, Inc., West Lafayette, IN). A small Ag wire was implanted into the PEEK block with a separation of 1.2 mm from the working electrode. The resultant electrode assembly was polished with diamond and alumina pastes (Buehler, Lake Bluff, IL) and sonicated in a water bath for 30 s to remove adherent polishing materials from the electrode surfaces. A layer of AgCl was deposited on top of the Ag disk by carefully applying a small drop of a coating solution (Bioanalytical Systems, CF-2200) for 60 s, followed by rinsing with water. The electrode potential was then calibrated against a standard Ag/AgCl reference electrode. A 127- μ m-thick Teflon gasket employed for the flow cell provided an internal cell volume of \sim 8.7 μ L.

Instruments. The ICPMS was a double-quadrupole mass spectrometer (Elan 6100DRC, Perkin-Elmer/Sciex Corp., Norwalk, CT). The conventional quartz cyclonic spray chamber and concentric nebulizer (J. E. Meinhard, Inc., Santa Ana, CA) were replaced with a DIHEN (DI-HEN-170-AA, J. E. Meinhard, Inc.). The operating conditions for the ICPMS and the DIHEN are given in Table 1. The flow cell was connected to the DIHEN through a six-port injection valve (Figure 1) which was controlled by a Microneb 2000 control module (CETAC Technologies Inc., Omaha, NE). As described in refs 22 and 23, the Teflon tubing interconnecting the valve and the DIHEN was extended into the nebulizer to the point where the capillary tapers. The control module was also used to regulate the gas pressure in a gas displacement pump. A flow rate of 45–55 μ L/min was chosen to maximize the lifetime of the TMF at the glassy carbon electrode and maintain a flow rate sufficient for the transmission of the sample through the DIHEN to the plasma. The delivery of the sample solution from a microsyringe to the flow cell was accomplished by using a syringe pump (Harvard Apparatus, Holliston, MA). Control of the electrode potentials for TMF deposition,

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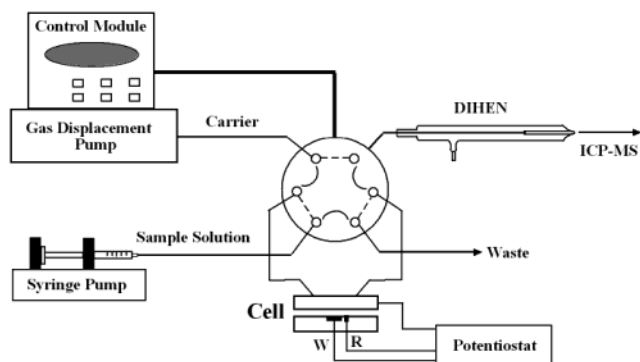


Figure 1. Schematic representation of the ASV-DIHEN-ICPMS assembly. The dotted lines that interconnect the ports of the six-port valve represent the configuration for the sample preconcentration and cleanup steps, whereas the solid curves show that for the subsequent stripping of the metal analytes. The thick line in the schematics is the electrical cable, and the thin lines are Teflon-encapsulated PEEK or Teflon tubings for connecting the valve to the DIHEN, the electrochemical cell, the pumps, and the sample waste. The disk working and reference electrodes and the auxiliary electrode are shown to be connected to the potentiostat.

for analyte preconcentration, and for anodic stripping was achieved using a CHI 615A electrochemical analyzer (CH Instruments, Austin, TX).

Procedures. TMFs were deposited onto the glassy carbon electrode by holding the potential at -0.4 V versus Ag/AgCl for 5 min in a 5 mM Hg^{2+} /1% HNO_3 solution. The average thickness of these TMFs was estimated to be ~ 100 nm from the charges consumed by Hg^{2+} reduction. The deposited TMFs were found to be hydrodynamically stable for at least 3 h under the current experimental conditions.

Metals of interest (e.g., Cd^{2+} , Pb^{2+} , and Tl^+) were accumulated into the TMFs at -0.9 V with deposition times ranging from 120 to 500 s. Metal ions stripped off the electrode and eluted downstream to the ICPMS were monitored using time-resolved acquisition and analyzed in the peak-hopping mode. Differential pulse voltammograms (DPVs) were acquired using a 50-ms pulse width and a 50-mV amplitude between -0.9 and -0.3 V.

RESULTS AND DISCUSSION

On-Line Combination of Anodic Stripping Voltammetry with ICPMS via a DIHEN. A mixture of three amalgam-forming metal ions (Cd^{2+} , Tl^+ , Pb^{2+}) was used to validate the methodology of ASV-DIHEN-ICPMS. The solid curve in Figure 2a is a DPV acquired at a TMF electrode after a 120-s preconcentration of Cd^{2+} , Tl^+ , and Pb^{2+} (50 ppb each) by holding the electrode potential at -0.9 V. Note that only two ASV peaks (at -0.66 and -0.53 V, respectively) were observed. It is well known that, due to the overlapping stripping potentials of Tl^+ (-0.530 V) and Cd^{2+} (-0.548 V),^{16,28} the stripping peaks of these two metals are difficult to resolve voltammetrically. However, the elution of the three metal ions downstream to the ICPMS can be clearly differentiated by their mass-to-charge ratio. As can be seen in Figure 2b, there are appreciable time lapses among the elution peaks. The temporal sequence of these elutions (i.e., the order of anodic stripping at

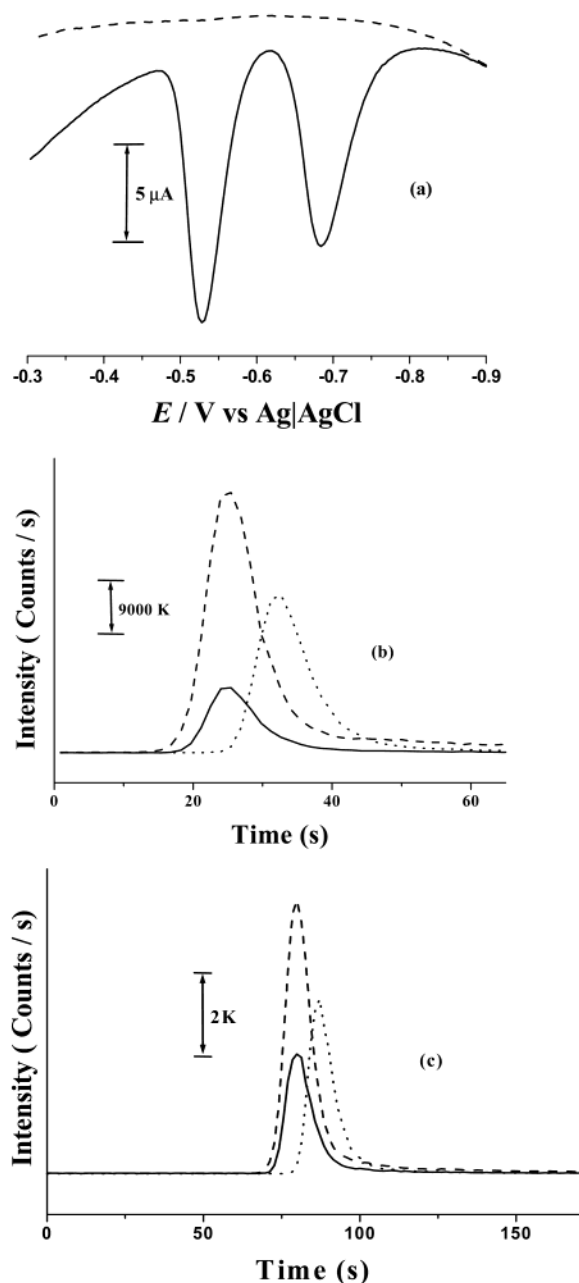


Figure 2. (a) Differential pulse voltammograms of Cd, Tl, and Pb at a TMF electrode acquired in a 0.1% HNO_3 solution after a 120-s preconcentration from a solution containing Cd^{2+} , Tl^+ , and Pb^{2+} (50 ppb each, solid line) and from a solution containing Cd^{2+} , Tl^+ , and Pb^{2+} (10 ppt each, dotted line). (b) Time-resolved ICPMS responses to the elution of Cd^{2+} , Tl^+ , and Pb^{2+} corresponding to the stripping of these metals (solid-line voltammogram in a). (c) ICPMS responses to the elution of Cd^{2+} , Tl^+ , and Pb^{2+} corresponding to the stripping of these metals (dotted-line voltammogram in a).

the electrode and the elution of the stripped metal ions to ICPMS) correlates well with the oxidation potentials of the metal analytes. The acquisition of both voltammograms and the time-resolved ICPMS signals could make studies of electrode processes involving ultratrace concentrations of metals feasible. We have recently reported the utility of electrochemical ICP-atomic emission spectrometry for the quantifications of metals released from electrochemical reactions involving metallothioneins²⁶ and from changing the redox states of conducting polymers.²⁷ The present

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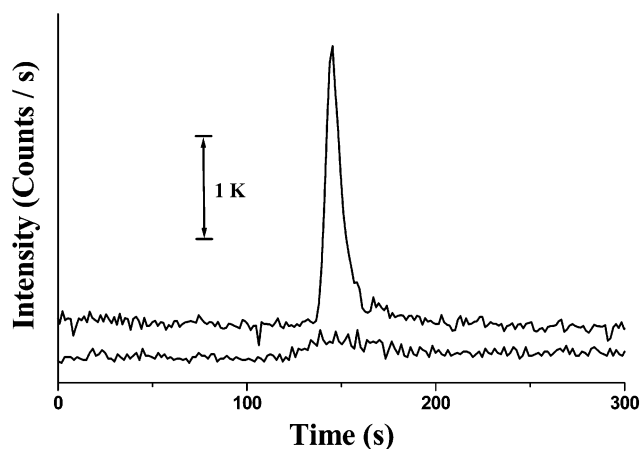


Figure 3. Time-resolved ICPMS responses to a Cd^{2+} elution plug generated by stripping Cd after a 340-s preconcentration from a solution containing 5 ppt Cd^{2+} . The bottom line curve corresponds to the signal arising from a direct flow injection of the 5 ppt Cd^{2+} .

data suggest that similar studies can be carried out at more sensitive and accurate levels.

Replicate experiments using lower concentrations of analytes (10 ppt each) did not yield any discernible DPV peaks (dotted curve in Figure 2a), although the signal generated from the elution of the analytes could still be readily detected by ICPMS (Figure 2c). Ten ppt approaches the detection limit of the ICPMS instrument for Cd^{2+} in the time-resolved acquisition mode (4.4 ppt measured by a separate flow injection experiment). Thus, it appears that the improved signal-to-noise ratios displayed in Figure 2c are largely attributable to the signal enhancement (vide infra) inherent in the ASV procedure.¹⁶

Signal Enhancement Using ASV-DIHEN-ICPMS. To investigate the extent of signal enhancement resulted from the simultaneous incorporation of ASV with ICPMS with the aid of a DIHEN, a 5 ppt Cd^{2+} standard was measured to quantify the effect of electrochemical preconcentration. The peak resulting from directly injecting this sample into a carrier solution without electrochemical preconcentration (bottom curve in Figure 3) is quite small, suggesting that 5 ppt was very close to the detection limit of the ICPMS instrument. The elution of Cd^{2+} from the same solution stripped off a TMF electrode after preconcentration for 340 s (top line curve) enhanced the signal-to-noise ratio by a factor of ~ 11 . Therefore, for signal levels that are close to the detection limits of conventional ICPMS, ASV-DIHEN-ICPMS can dramatically improve the signal-to-noise ratios. While it is known that the signal enhancement is dependent on a number of factors (e.g., rate of the analyte mass flow through the cell, the cell volume, and the concentration of the analyte¹¹), it appears that the enhancement factor achievable with ASV-DIHEN-ICPMS is greater than those recorded from other studies. For example, Pretty et al. showed an enhancement factor of 17 for 20 ppb Ag^+ (i.e., a mass of 3.2 ng of Ag^+ flowing through the cell) could be obtained by combining ASV with ICPMS via a MCN.¹¹ In the current experiment, a total mass of only 1.3 pg of Cd^{2+} was used (top line curve in Figure 3), which is at least 3 orders of magnitude lower than that employed by Pretty et al.¹¹ Thus, it appears that the slow flow rate tolerated by the DIHEN together with the high sampling efficiency associated with the system contributes to the signal enhancement. In this respect, the former factor is important

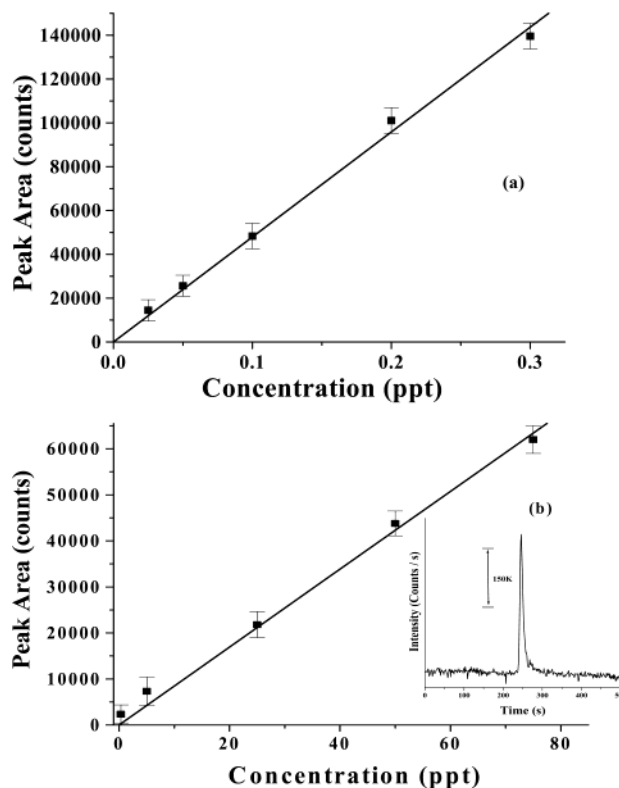


Figure 4. Calibration curves for Ti^+ (panel a) and Cd^{2+} (panel b) constructed from measuring a series of Ti^+ and Cd^{2+} standard solutions using ASV-DIHEN-ICPMS. The preconcentration time was 500 s. The error bars were computed from at least three replicates. The inset in (b) is a representative elution profile of Cd^{2+} after preconcentration from a 300 ppq Cd^{2+} solution.

in that the slow flow rate ensures the mechanical stability of the TMF, allowing metal species to be accumulated more effectively and reproducibly than at a solid electrode.¹⁶

Reducing the detection limits of ICPMS for Cd^{2+} and Ti^+ by ASV-DIHEN-ICPMS was therefore investigated. Upon a 340-s preconcentration, the detection limits for Cd^{2+} (0.16 ppt) and Ti^+ (0.013 ppt), judged on the basis of $3\sigma/\text{sensitivity}$,²⁹ were 27 and 68 times lower than those for Cd^{2+} (4.4 ppt) and Ti^+ (0.89 ppt), respectively. The Ti^+ detection level is also comparable to the value obtained with ASV-ICPMS using a DIN, but with a shorter preconcentration time (a preconcentration time of 900 s was employed in ref 15).

It is of great interest to develop hyphenated techniques capable of performing reliable analysis at concentration levels that would be difficult to measure otherwise. In line with this consideration, we examined the linearity and reproducibility of the ASV-DIHEN-ICPMS for measurements at or below the concentration detection limits for Cd^{2+} and Ti^+ by conventional ICPMS. Shown in Figure 4 are the corresponding calibration curves. As can be seen, linear relationships were observed at the lower end of the dynamic range of the technique, (r^2 values of 0.999 and 0.997 for Cd^{2+} and Ti^+ , respectively). The error bars shown in these calibration curves range from 3.7 to 7.5%, which are acceptable for most analytical techniques at or close to the limits of detection.²⁹ Since Van Berkel and co-workers have demonstrated that the combination of ASV

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with ICPMS via a MCN^{11,13} possesses a wide dynamic range with the linearity extending to the ppm levels, in this work the establishment of the linearity of the calibration curves above the ppt levels was not explored. From a practical point of view, the analysis of real samples by ASV-DIHEN-ICPMS would be most meaningful when used for a concentration near or below the detection limits of conventional ICPMS.

Real Sample Analysis by ASV-DIHEN-ICPMS. Another attractive feature offered by ASV combined on-line with ICPMS is the elimination of matrix effects for ICPMS (including both spectroscopic and nonspectroscopic interferences) through the "medium-exchange procedure".^{1,16} When conducted in a flow system, the medium-exchange procedure enables ICPMS analysis to be conducted in an interference-free solvent. To demonstrate the capability of ASV-DIHEN-ICPMS for the analysis of real samples and to verify the accuracy of the technique, a series of Cd²⁺ analyses were conducted on a certified open ocean seawater reference sample (CASS-4). While the certified Cd²⁺ concentration (25 ± 3 ppt) is higher than the detection limit by a conventional ICPMS, the sample contains a high salt content and, without dilution or other treatments, tends to clog the interface of the ICPMS sample introduction system, cause ion suppression and loss in sensitivity, and generate polyatomic adducts that can compromise the identification and quantification of various analytes. Utilizing the matrix-exchange procedure, we carried out the analysis without performing any sample pretreatment and dilution. The area of the Cd²⁺ elution peak generated by the injection of a CASS-4 sample was quantified using a calibration curve. The value of 26 ± 4 ppt determined by ASV-DIHEN-ICPMS was remarkably close to the certified value for Cd²⁺ of 25 ± 3 ppt. Thus, it is apparent that ASV-DIHEN-ICPMS is capable of accurately analyzing species present at ultratrace levels in relatively complicated sample matrixes.

CONCLUSIONS

This work has demonstrated that the combination of ASV with ICPMS via a DIHEN is a viable alternative to the coupling of ASV with ICPMS with other nebulizers (e.g., DIN or MCN). The slow flow rate tolerated by the DIHEN prolongs the life of the thin mercury film and the small internal volume associated with the electrochemical flow cell, and DIHEN assembly results in a

significant preconcentration effect. These features make the DIHEN particularly attractive for the incorporation of ASV based on the use of thin mercury film electrodes into the flow system of the ICPMS sample introduction system. The ability of acquiring stripping voltammograms and time-resolved ICPMS signals affords the possibility of studying electrode reactions involving trace amounts of metal release/transfer in real time. With a 340-s preconcentration, the concentration levels analyzed for Cd²⁺ and Tl⁺ are 27 and 68 times below those measurable by conventional ICPMS. Excellent linearity was obtained from the low-ppt to low-ppq levels. Through the utilization of the medium-exchange procedure inherent in the ASV technique, samples having relatively complicated matrixes can be analyzed directly at ultratrace levels. This hyphenated technique was found to be highly accurate for the analysis of Cd²⁺ in a saline matrix, which illustrates the potential of the technique for undertaking routine measurements of trace metals in seawater. The adoption of a DIHEN, in addition to the inherent advantages of DIHEN over a conventional DIN (in terms of the ease of operation and immunity to sample clogging), preserves the unique aspects of a conventional DIN for carrying out electrochemical preconcentration at a slow flow rate without sacrificing the sensitivity of time-resolved ICPMS measurements.

ACKNOWLEDGMENT

Dr. F. Song is thanked for his help. We also thank J. E. Meinhard Inc. for technical assistance. Partial support of this work by an NSF-CRUI grant (DBI-9978806), an NIH-AREA grant (GM R15-63530-01 for F.Z.), a Drefuys Teacher-Scholar award (TH-01-025 to F.Z.), and the California State University Program and Education in Biotechnology (for both F.Z. and A.Z.M.) is gratefully acknowledged. Support for the acquisition of the ICPMS was provided by a major research instrumentation award from NSF (OCE-9977564 for both A.Z.M. and F.Z.) and by funds from the College of Natural Sciences at California State University, Long Beach.

Received for review October 23, 2002. Accepted March 5, 2003.

AC026257S