

Electrochemistry combined on-line with atomic mass spectrometry and related techniques for trace-metal analysis and electrode-reaction studies

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Electrochemistry (EC) combined on-line with atomic mass spectrometry (MS) and related techniques (e.g., inductively coupled plasma atomic emission spectrometry, ICP-AES) affords an avenue for analysis of metals present at ultratrace levels and the effective elimination of matrix effects detrimental to atomic MS and spectrometric techniques. In addition, electrode reactions involving inorganic species can be conveniently studied, and analyte accumulated and released from adsorbates or electroactive thin films can be accurately quantified.

This review summarizes recent advances based on EC coupled with atomic MS and related techniques for trace-metal analysis and studies of electrode processes. Particular emphasis is placed on EC combined with ICP-MS (EC-ICP-MS) and electrospray-MS (EC-ES-MS). I describe criteria for selecting the suitable EC flow-cell designs and the MS sample-introduction systems or interfaces. The versatility of this hyphenated technique is well reflected in the different systems studied and the possibility of electrolytic and non-electrolytic accumulation of trace analytes for subsequent sensitive MS detections.

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1. Introduction

With the advent of various types of mass spectrometers and associated sample-introduction systems, electrochemistry (EC) combined on-line with mass spectrometry (MS) [1,2] (also referred to as EC-MS [3]) has become a powerful hyphenated technique for detecting electrogenerated products, particularly those of organic and biological nature. MS yields information (e.g., molecular weights, isotope abundances, and structures of fragments gen-

erated in the gas phase) that is not typically acquirable by voltammetric methods; it provides an attractive means for unraveling complicated electrode reactions [2,4-6]. In addition, MS detection possesses the mass-to-charge (m/z) specificity and is immune to interferences inherent in voltammetric methods (e.g., charging currents, overlapping potential peaks, and certain concomitants present in the solvent or sample). Because of these unique features, MS has been historically utilized:

- (1) to identify species produced *via* various chemical reactions following redox reactions of the analyte(s);
- (2) to study electrode kinetics (i.e. measuring intermediate lifetimes); and,
- (3) to characterize adsorbates, the surface behaviors of which are affected by applied potentials.

Interestingly, the potential use of EC as a tool for sample clean-up and analyte preconcentration for subsequent MS quantification has not been fully exploited. The lack of attention partially stems from the fact that chromatographic or other techniques (e.g., flow-injection separation by sorption columns [7]) have traditionally been employed for sample pretreatment and matrix elimination. Coupling EC on-line with MS also requires the analyst to be well versed in

both voltammetric and MS instrumentation. One of the major challenges therefore lies in making the solution-based EC technique(s) compatible with MS detection in the gas phase, through the clever design of the EC cell and the judicious choice of a suitable sample-introduction system.

Despite the aforementioned challenges, the advantages of using EC for effective matrix elimination and enhanced analyte detection are apparent in that

- (1) the EC instrumentation is cost-effective;
- (2) there are commercially available a variety of flow cells, the flow dynamics and electrochemical performances of which have been well characterized [8,9]; and,
- (3) analyte accumulation, medium exchange, and analyte release in the cell [10] are similar to those in the sorption columns, but arise from different mechanisms (redox reactions instead of physicochemical processes).

Thus, EC offers an alternative route for circumventing certain problems associated with MS or related atomic spectrometric techniques. These unique capabilities are demonstrated by several groups [11–19], but particularly that of Van Berkel [5,20–25], through their systematic optimization of the flow cells and sample-introduction systems and the applications of EC–MS to the analysis of metals in solution, electroactive films, and biological adsorbates.

The electrolytic preconcentration and medium-exchange procedures associated with stripping analysis have long been realized to be attractive routes to preconcentrate analytes in dilute samples for analytical spectrometric measurements. The first work can be dated back to the paper by Fairless and Bard [26], who deposited copper onto carbon rods prior to flameless atomic absorption analysis (AAS). Between 1972 and the mid-1980s, electrodeposition of metals from dilute sample solutions was shown to be amenable for the subsequent analysis by a number of techniques, such as AAS [26–31], direct arc with spectrographic analysis [32], neutron activation [33,34], and inductively coupled plasma–atomic emission spectrometry (ICP–AES) [35–38].

However, the research activities related to combining EC with atomic spectrometric techniques remained dormant for a long period of time, possibly for the following reasons:

- (1) first, most of studies were performed off-line, which tends to prolong the sample throughput and introduces unwanted complications or interferences; and,
- (2) second, during the same period of time, the improved performances of stripping analysis (e.g., stripping analysis by differential pulse voltammetry [39] and at ultramicroelectrodes [40]) and the emergence of other sensitive

atomic spectroscopic techniques (e.g., ICP–MS) [41] made such a hybrid technique less attractive.

The activities revived in the 1990s when Pretty et al. [11–14,42] and Van Berkel and co-workers [20,21,23] showed that stripping voltammetry, when coupled on-line with ICP–MS, could further decrease the already remarkable detection levels of ICP–MS. More importantly, matrix effects detrimental to ICP–MS analysis can also be efficiently eliminated. Some of this progress was reviewed in 1996 [43]. Since then, the scope of the research area based on EC–MS for enhanced elemental analysis has expanded greatly, especially to the studies of electroactive thin films [16,17,24], sample clean-ups for other types of MS [e.g., electrospray–MS (ES–MS)] [21,24], and the exploration of adsorptive stripping analysis for EC–MS measurements of non-electrolytically accumulated metals [22]. This article will therefore focus on reviewing the recent trend of on-line combination of EC with ICP–MS, ES–MS, and other related techniques for enhanced elemental analysis.

2. Principle and instrumentation

Fig. 1 illustrates the basic principle behind EC–MS for metal analysis at ultratrace levels. Samples are introduced through an injector into the EC flow cell. Metals of interest are accumulated onto the electrode either electrolytically (e.g., reduced and deposited) or non-electrolytically (e.g., complexed with a ligand and subsequently adsorbed as a complex [44]). If the analytes are present in a medium that causes interferences to the MS operation or detection, the cell content can be washed out to ‘waste’. The MS detection is accomplished by altering the electrode potential to strip (desorb) the accumulated metals (metal complexes), followed by diverting the solution out of the flow cell to the MS sample-introduction system. In some cases, a solution in which the stripping or desorbing processes are more rapid and complete, can be introduced to the cell. Once the analyte (complex) is released into the solution, the sample plug can then be directed to the mass spectrometer. The potential can be either stepped or scanned over different redox waves, while the voltammograms and mass intensity-potential diagrams are recorded simultaneously. Thus far, the bulk of the published studies are based on anodic stripping voltammetry (ASV) at thin mercury film (TMF)-covered porous or disk carbon electrodes [11–15,20,21,23,42].

Compared to the instrumentation of EC–MS for studying electrode reactions of pharmaceutically and biologically important species [1], the set-up of EC–MS for enhanced elemental analysis and matrix elimination is simpler in that generally there is no need for a chromatographic column. The absence of the

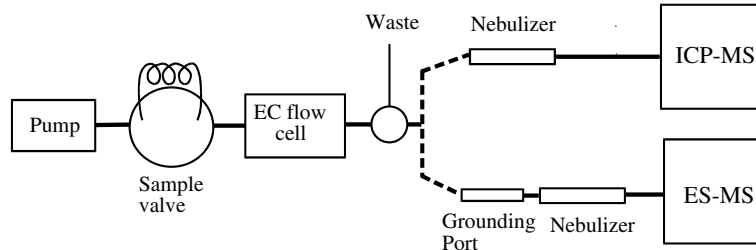


Figure 1. Schematic set-up of EC combined on-line with ICP-MS or ES-MS, the two major types of MS reviewed in this article, for matrix-free detection of metal analytes in solution, adsorbates, and electroactive thin films.

chromatographic column affords the opportunity to conduct the analyses at a slower flow rate and the possibility of using flow cells that are otherwise unsuitable (see below). As a result, sample consumption and analysis time can be dramatically decreased. However, avoiding the chromatographic components seriously limits metal-speciation studies (determination of different charge states and chemical forms of an element) by the combination of EC and ICP-MS, since ICP-MS can quantify only the total amount of an element and EC renders possibilities of differentiating certain electroactive forms of a few elements only.

3. Electrochemical flow cells and MS sample-introduction systems

Thus far, three types of EC flow cells (*viz.* flow-by, flow-through, and flow-onto) have been positioned upstream of the atomic MS or other spectrometers. The choice of

the flow cell and the corresponding sample-introduction system is critical to achieving the maximal intensity of analyte signal (enhancement) and the desired matrix elimination. Typically, compromised experimental conditions are selected upon considering the analyte conversion (deposition) efficiency, the signal-enhancement factor, the wash-out time, the stability of the adsorbate(s), and the compatibility of the solvent system and flow rate with the MS sample-introduction system. Specifically, the conversion efficiency increases with the ratio of working electrode area/cell volume ratio. While the signal enhancement is directly proportional to the conversion efficiency, it is worth noting that the actual signal amplification is also affected by the internal EC cell volume and the volume of the tubing interconnecting the cell to the MS interface. When the adsorbates at the electrode are not hydrodynamically stable (in the case of ASV, the TMF electrode can be eroded by a fast-flowing solution stream), the flow rate of the solution sometimes needs to be decreased. This may compromise the MS

Table 1. Selection criteria of various types of EC cells and the corresponding nebulizers/sample-introduction systems of MS

| | Flow-by | Flow-through | Flow-onto |
|--|---|--|--|
| Conversion efficiency | Low at high flow rates Greater at slower flow rates | High | Low |
| Internal cell volume | Can be as small as a few microlitres | Large | Varies |
| Hydrodynamic stability of adsorbates/films | Improved at a slow flow rate | Relatively poor and worsens at high flow rates | Poor at high flow rates generally employed |
| Wash-out time | Short | Long at a slow flow rate Short at a high flow rate | Short |
| Recommended or commonly used nebulizers/interfaces | MCN, DIN, and DIHEN nebulizers for ICP-MS ^a at slow flow rates Pneumatic nebulizer with a spray chamber for ICP-MS at high flow rates | Pneumatic nebulizer with a spray chamber for ICP-MS at high flow rates Unfavorable for ES-MS ^b | Pneumatic nebulizer with a spray chamber for ICP-MS Unfavorable for ES-MS |

^aMCN, DIN, and DIHEN denote microconcentric nebulizer, direct injection nebulizer, and direct-injection high-efficiency nebulizer, respectively.

^bA grounding connector or port is usually used to isolate the high electric field of the ES-MS interface from the EC cell.

sensitivity, since the quantity of samples and quality of the droplets in the aerosols may be decreased or affected. Sometimes, the solvent system that is optimal for sample accumulation/release might not be ideal for MS operation. The objective would then be to vary the solvent or electrolyte ingredient systematically, so that the final composition of the solution can be tolerated by both EC and MS. Table 1 summarizes and contrasts the three types of flow cells in terms of the aforementioned performance criteria.

For many years, the flow-through cell was the design of choice for EC-MS [2,3], given its high analyte-conversion efficiency. For EC-MS studies of electrode-reaction mechanisms and kinetics, the conversion efficiency is indeed the most important criterion. Since a column is sometimes used in conjunction with the EC cell and MS, the high solution flow, which is generally favorable for the separation step, can also sweep the reaction products rapidly out of the porous electrode to the MS. Therefore, the relatively large cell volume would not cause significant peak tailing or sample dispersion. However, for the purpose of analyte preconcentration, the thin-layer flow-by cell design is far superior, because this type of cell has smaller internal volumes and can be readily connected to the flow-injection device and MS sample-introduction system with microbore tubings. Furthermore, flow-by cells tend to have greater analyte deposition (conversion) efficiency when operated at a slow flow rate (the dwell or electrolysis time in the thin-layer cell is longer). The effort along this line is therefore directed at the adoption of a sample-introduction system (e.g., nebulizer) that performs well at a slow flow rate.

4. Signal enhancement and elimination of matrix effects

The three types of flow cells listed in Table 1 have all been coupled on-line with ICP-MS, ES-MS, and other related atomic spectrometric techniques (e.g., ICP-AES). It was shown that a flow-through cell incorporating a TMF predeposited onto a reticulated vitreous carbon (RVC) electrode [19] yielded a much greater signal-enhancement factor than the flow-onto wall-jet electrode [18]. Pretty et al. [11-14,42], in a series of studies, demonstrated that the flow-through cell can eliminate the detrimental spectroscopic (polyatomic) and non-spectroscopic ICP-MS interferences while achieving signal enhancements.

I previously reviewed representative studies [43]. Since that review, the thin-layer flow-by cell has emerged as the most attractive cell type for signal-enhancement and matrix-elimination purposes for both EC-ICP-MS [15,20,21] and EC-ES-MS [21,24]. Such compatibility is attributable to the fact that ES-MS typically operates at a low flow rate (<100 $\mu\text{L}/\text{min}$), and

ICP-MS can also be performed at a slow flow rate by incorporating nebulizers, such as the microconcentric nebulizer (MCN), the direct injection nebulizer (DIN) [45], and the direct injection high-efficiency nebulizer (DIHEN) [46,47]. These novel nebulizers for ICP-MS offer high sampling efficiencies for ICP-MS. Compared to the work by Pretty et al., studies reported by Van Berkel and co-workers [20-22] and Zhou and co-workers [15,23] demonstrated that the signal enhancement based on the thin-layer cell design is greater, but the preconcentration time is dramatically shortened. Using Ag deposition onto a glass-carbon electrode as a test case, Van Berkel and co-workers [20] found that the enhancement factor for Ag using a thin-layer cell modified from a commercial unit was 400 times greater than that obtained by continuous nebulization with a MCN. Such an analysis requires only 2-3 mL of sample and deposition times less than 30 min (50 times for a 20-mL Cd^{2+} solution when a flow-through cell was employed [42]). A serendipitous discovery led the same researchers to use an anodized glassy carbon electrode to accumulate and subsequently release uranium for the ICP-MS detection [21]. Excellent accuracy and recoveries were achieved from the analysis of a certified sample. The signal enhancement resulted from using a DIHEN is particularly noteworthy [15]. Fig. 2 displays the time-resolved ICP-MS signal of Cd^{2+} upon EC preconcentration at a TMF electrode, together with the signal observed by continuous nebulization with the DIHEN. These data suggested that as little as 1.3 pg of Cd^{2+} was needed for an enhancement factor of 11.

Ugo et al. [48] preconcentrated mercury in process and lagoon waters onto Au coils for subsequent ICP-MS analysis. Though the work was performed off-line, the feasibility of using solid electrodes for accumulating analytes from real samples is evident.

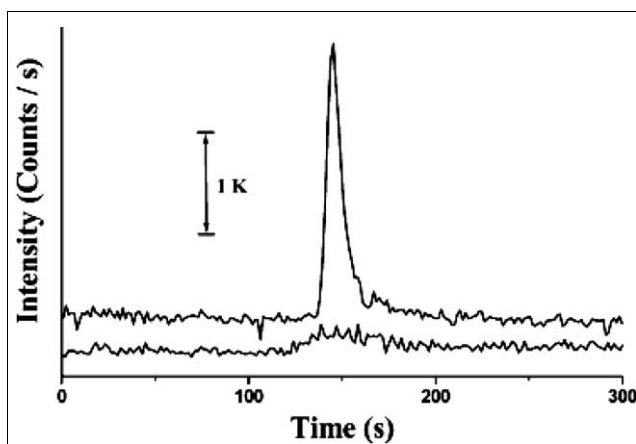


Figure 2. Time-resolved ICP-MS signal to Cd preconcentrated from a 5 ppt Cd^{2+} solution at a TMF electrode and subsequently stripped into a 0.1% HNO_3 solution (top trace). The bottom trace corresponds to the ICP-MS signal from continuous nebulization of a 5 ppt Cd^{2+} solution with a DIHEN. (From [15].)

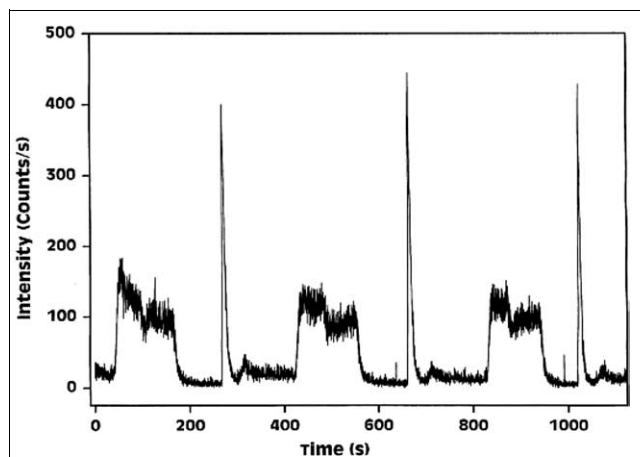


Figure 3. Adsorptive stripping peaks (the three sharp peaks) for three replicate runs of 100 ppt U(VI) with a combination of electrochemical and chemical stripping processes. U(VI) was first complexed with propyl gallate and adsorbed onto a TMF electrode at -0.15 V (vs. Ag/AgCl) for 60 s, followed by stripping in a 1% HNO_3 solution upon stepping the potential to -1.2 V. The steps in the middle of the three flat-topped peaks correspond to the accumulation of U–PG complex at the TMF electrode at -0.15 V. (Reprinted from [22], with permission.)

Zhou et al. [23] were the first to couple adsorptive stripping voltammetry on-line with ICP–MS to analyze uranium ligated by cupferron. However, reductive desorption did not appear to effectively release the uranium–cupferron complex into the solution. It is also ambiguous whether or not the uranium signal originated from the metal complex eroded from the Hg electrode by the relatively high flow rate. Duckworth and co-workers [21] amended this approach by complexing uranium with propyl gallate (PG) and releasing the resultant uranium–PG complex with simultaneous chemical (changing solution from 0.1 M NH_4NO_3 to 1% HNO_3) and electrochemical (stepping potential in the negative-going direction) stripping processes. As can be seen from Fig. 3, the reproducibility of the method is quite good. Furthermore, the MS analysis enables these researchers to monitor the analyte accumulation, chemical stripping of the metal–ligand complex, and diversion of the stripped complex to the ICP–MS in real-time. Such a capability is advantageous, since the adsorption/desorption processes and the performance of the EC cell can all be studied and evaluated in a convenient manner.

5. Metal speciation

Unless coupled with chromatographic methods or performed with pretreated samples, ICP–MS or related atomic spectrometric techniques (e.g., ICP–AES) cannot identify different chemical forms or valence states of an element [41]. Placing an EC flow cell before the ICP

sample-introduction system affords an alternative avenue for selectively determining targeted chemical forms and/or charge states of an element. Pretty et al. [12,14] took advantage of electrolytic deposition processes to accumulate certain ionic forms of several environmentally and biologically important metals. As a result of this approach, As(III), Se(IV), Cr(VI), and V(V) were determined by EC–ICP–MS without matrix interferences. For example, Cr(VI), which is recognized as a possible carcinogenic agent, was measured without interference by ArC^+ (a polyatomic interference) and could potentially be accumulated onto the electrode in the presence of Cr(III) [14].

Recently, ES–MS has also been shown to be a viable technique for trace-metal analysis [49]. ES–MS could be complementary to ICP–MS for elemental analysis, because gas-phase ions from both elemental and molecular forms can be observed [49].

However, the limitations of ES–MS for metal analysis are its relatively low sensitivity, relatively narrow dynamic range, and incompatibility with aqueous solutions (especially those containing high levels of electrolytes) [49]. By interfacing the same thin-layer flow-by cell with an ion-trap ES–MS, Pretty and Van Berkel [25] showed that Cu^{2+} can be deposited from a NaCl solution and stripped into a $\text{CH}_3\text{OH}/\text{H}_2\text{O}$ mixture (a solvent system more favorable to ES–MS operation).

Although the work demonstrates nicely the possibility of using EC sample pretreatment/preconcentration to overcome problems associated with ES–MS assays for metals, compared to EC–ICP–MS, much work remains to be done to make EC–ES–MS a hybrid technique for metal quantification in real samples (many of them contain high salt contents) or digested samples (e.g., high acidity). One possibility is the combination of EC with other types of mass spectrometers. For example, quadrupole and triple quadrupole mass spectrometers possess wider dynamic ranges and are less subject to ion suppressions. Coupling EC with quadrupole mass spectrometers has shown some potential for trace-metal analysis [50].

6. Studies of electrode reactions

After the systematic evaluation of the EC flow cells and optimization of both analyte accumulation/release and MS-operation conditions [13,15,18–23,42], EC–MS for enhanced elemental analysis and the concurrent matrix elimination has been firmly established. As a consequence, attention has most recently shifted to using EC–MS for studies of electrode reactions involving metals in adsorbates, counterions within electroactive thin films, and quantification of metals in biomolecules. Traditionally, in a flow-through cell, the high surface area of the porous electrode leads to a high current background.

Voltammograms are difficult to acquire together with m/z intensity–potential diagrams. However, Baca et al.

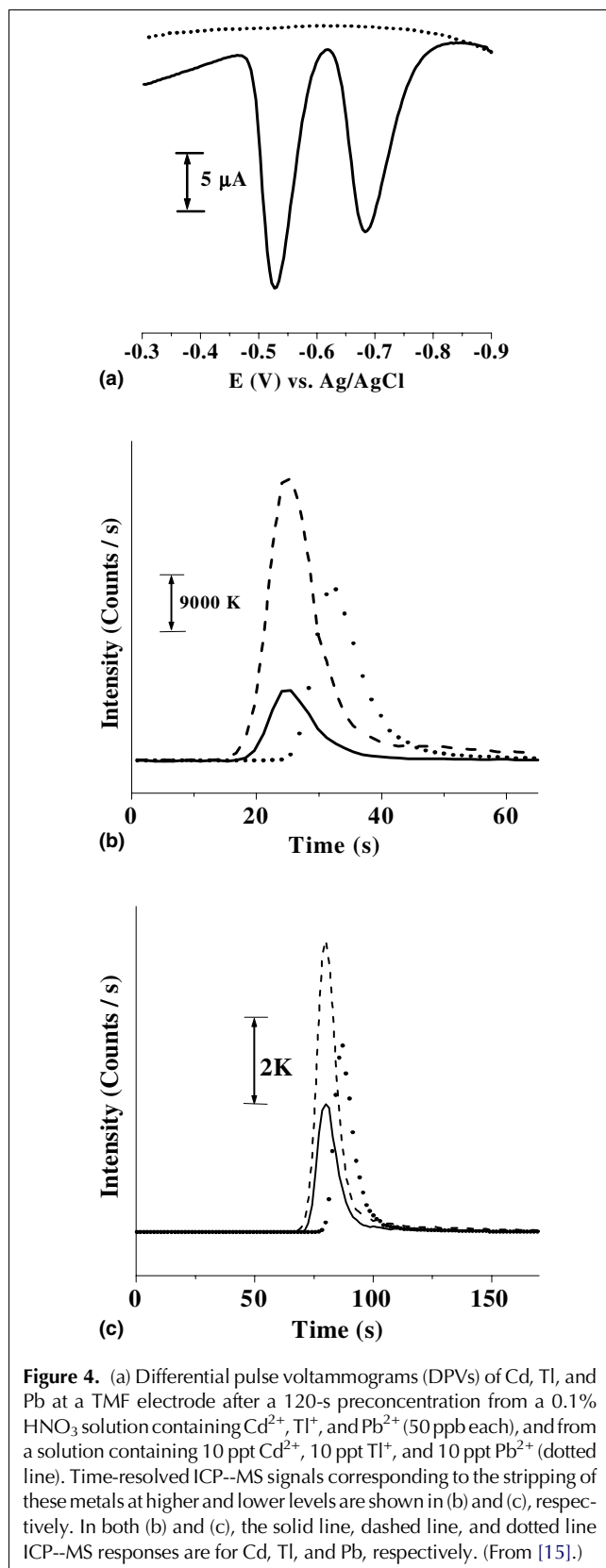


Figure 4. (a) Differential pulse voltammograms (DPVs) of Cd, Tl, and Pb at a TMF electrode after a 120-s preconcentration from a 0.1% HNO_3 solution containing Cd^{2+} , Tl^+ , and Pb^{2+} (50 ppb each), and from a solution containing 10 ppt Cd^{2+} , 10 ppt Tl^+ , and 10 ppt Pb^{2+} (dotted line). Time-resolved ICP-MS signals corresponding to the stripping of these metals at higher and lower levels are shown in (b) and (c), respectively. In both (b) and (c), the solid line, dashed line, and dotted line ICP-MS responses are for Cd, Tl, and Pb, respectively. (From [15].)

[15] showed that it was possible to obtain stripping voltammograms in a thin-layer flow-by cell. Fig. 4 displays DPVs of several amalgam-forming metals and the

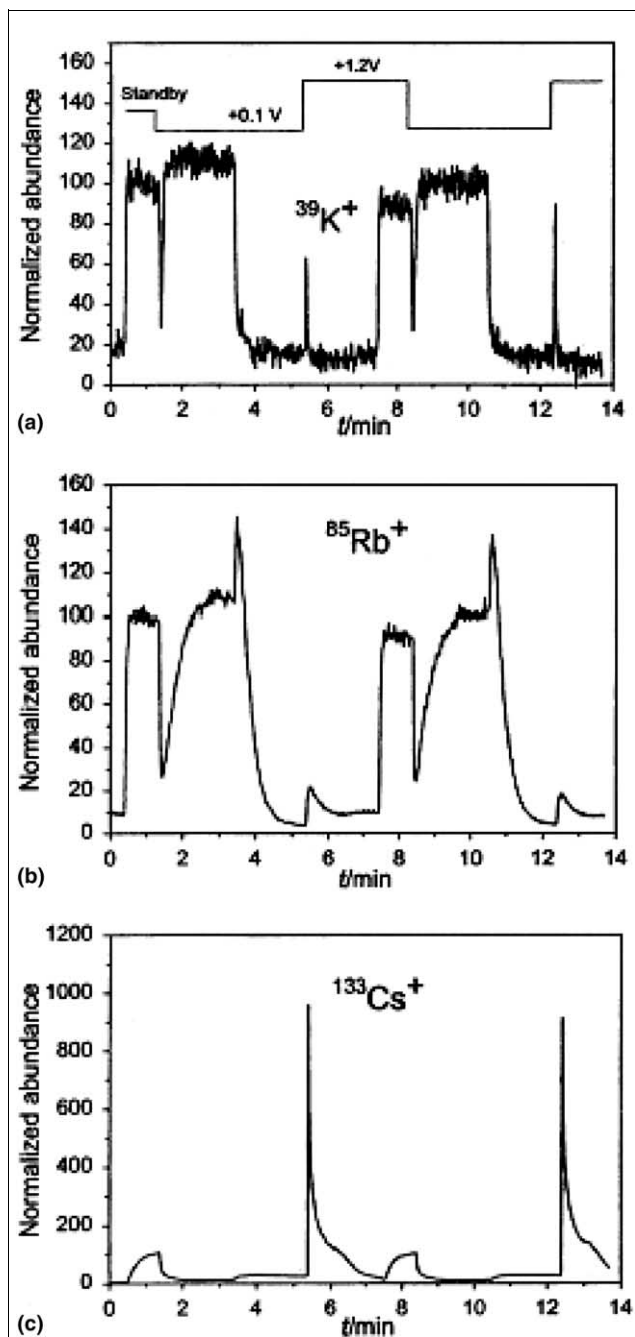


Figure 5. Time-resolved ES-MS signals of (a) $^{39}\text{K}^+$; (b) $^{85}\text{Rb}^+$; and (c) $^{133}\text{Cs}^+$ accumulated into, and subsequently released from, a nickel hexacyanoferrate (NiHCNFe) film. The NiHCNFe film, prepared in a 0.5 M NaCl solution, releases Na^+ upon oxidation and takes up other alkali-metal ions (particularly Cs^+) during reduction. The injected analyte solution in contact with the NiHCNFe film contained 2 μM KCl , 2 μM RbCl , and 2 μM CsCl . During the stand-by phase of the potential modulation sequence (shown in (a)), no potential was applied and all ions simply flew through the cell to the ES-MS. At -0.1 V, only small amounts of K^+ and Rb^+ were taken up by the film, while Cs^+ was preferentially accumulated into the film. At 1.2 V, Cs^+ release accompanying the film reduction resulted in a signal enhancement of 10 times, whereas the K^+ and Rb^+ peaks are smaller than the signals when the cell was at open circuit. (Reproduced from [24], with permission.)

corresponding ICP–MS responses of the eluted metal peaks. Acquiring both the voltammogram and m/z -potential diagram enables an analyst to gain insights about the electrode reactions.

In Fig. 4, the comparison between the curves in (b) to the DPV of Cd(Hg), Tl(Hg) and Pb(Hg) reveals that the temporal sequence of the eluted metal peaks correlates well with the oxidation potentials of the metal analytes [15]. When the potentials of the oxidation peaks are close or overlapped (e.g., Tl⁺ at -0.530 V and Cd²⁺ at -0.548 V), the m/z specificity of MS helps distinguish the individual analytes. The superior sensitivity of ICP–MS allows analytes to be measured at levels that are not accessible by voltammetric means (e.g., compare the dashed DPV in Fig. 4(a) to the curves in (c)).

In a separate study, Kertesz et al. [24] demonstrated that ES–MS could also be linked to a flow-by cell for studying metal uptake and release processes occurring within an electroactive thin film. The multi-element detection capability of MS facilitated the simultaneous measurements of the ingress of several alkali metals into a nickel hexacyanoferrate (NiHCNFe) thin film (Fig. 5). These researchers confirmed that Cs⁺ was indeed preferentially accumulated by the NiHCNFe film under the influence of the applied potential. Particularly note-worthy is that continuous monitoring of the ingress into and egress out of the NiHCNFe film provides the possibility of measuring metal-uptake capacity and isotopic distributions of metal ions within an electroactive thin film. Understanding the isotopic dis-

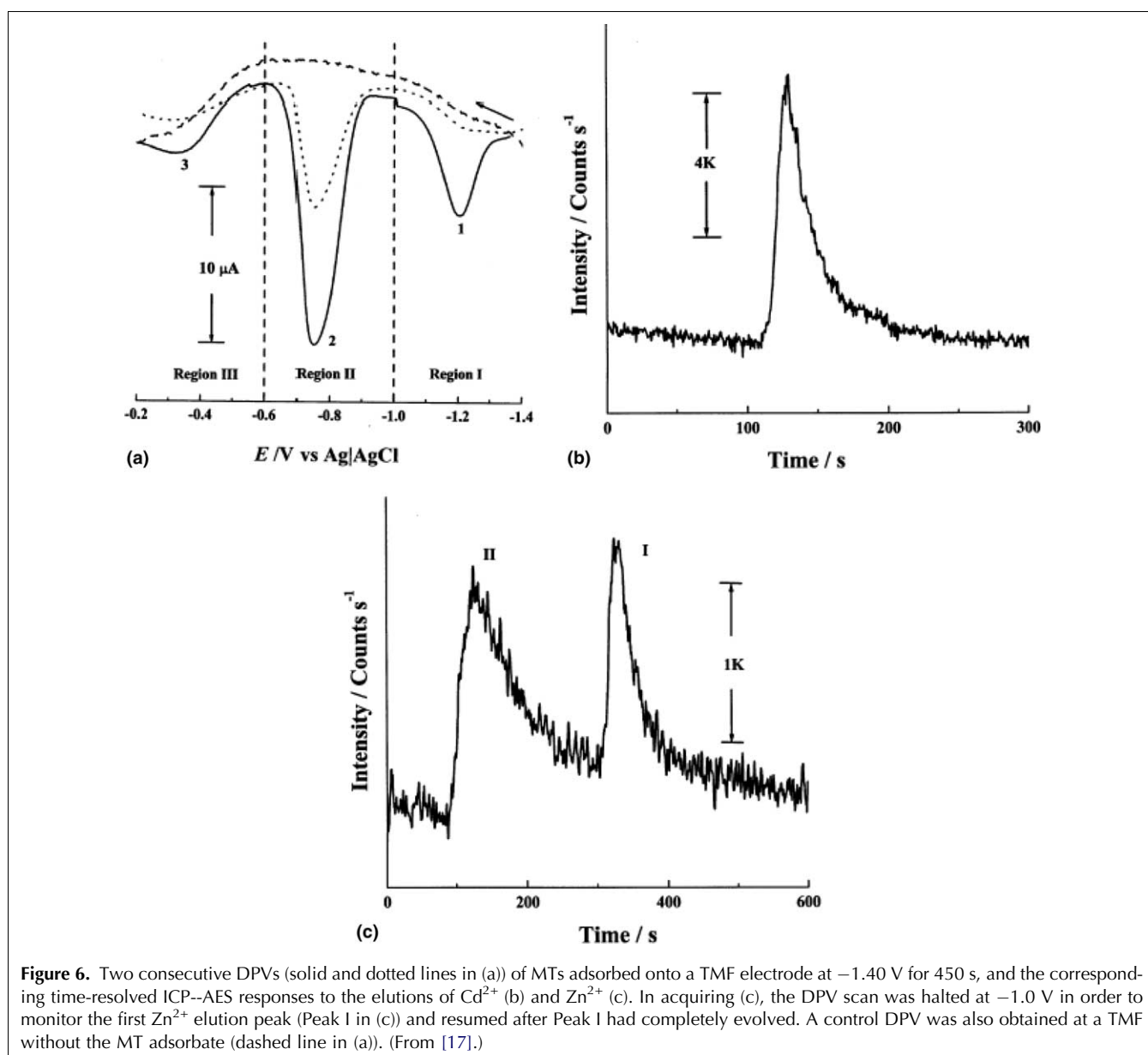


Figure 6. Two consecutive DPVs (solid and dotted lines in (a)) of MTs adsorbed onto a TMF electrode at -1.40 V for 450 s, and the corresponding time-resolved ICP–AES responses to the elutions of Cd²⁺ (b) and Zn²⁺ (c). In acquiring (c), the DPV scan was halted at -1.0 V in order to monitor the first Zn²⁺ elution peak (Peak I in (c)) and resumed after Peak I had completely evolved. A control DPV was also obtained at a TMF without the MT adsorbate (dashed line in (a)). (From [17].)

tribution of metal ions within a film is important in screening and evaluation of materials for remediation of metals present in nuclear wastes (e.g., ^{133}Cs vs. ^{137}Cs).

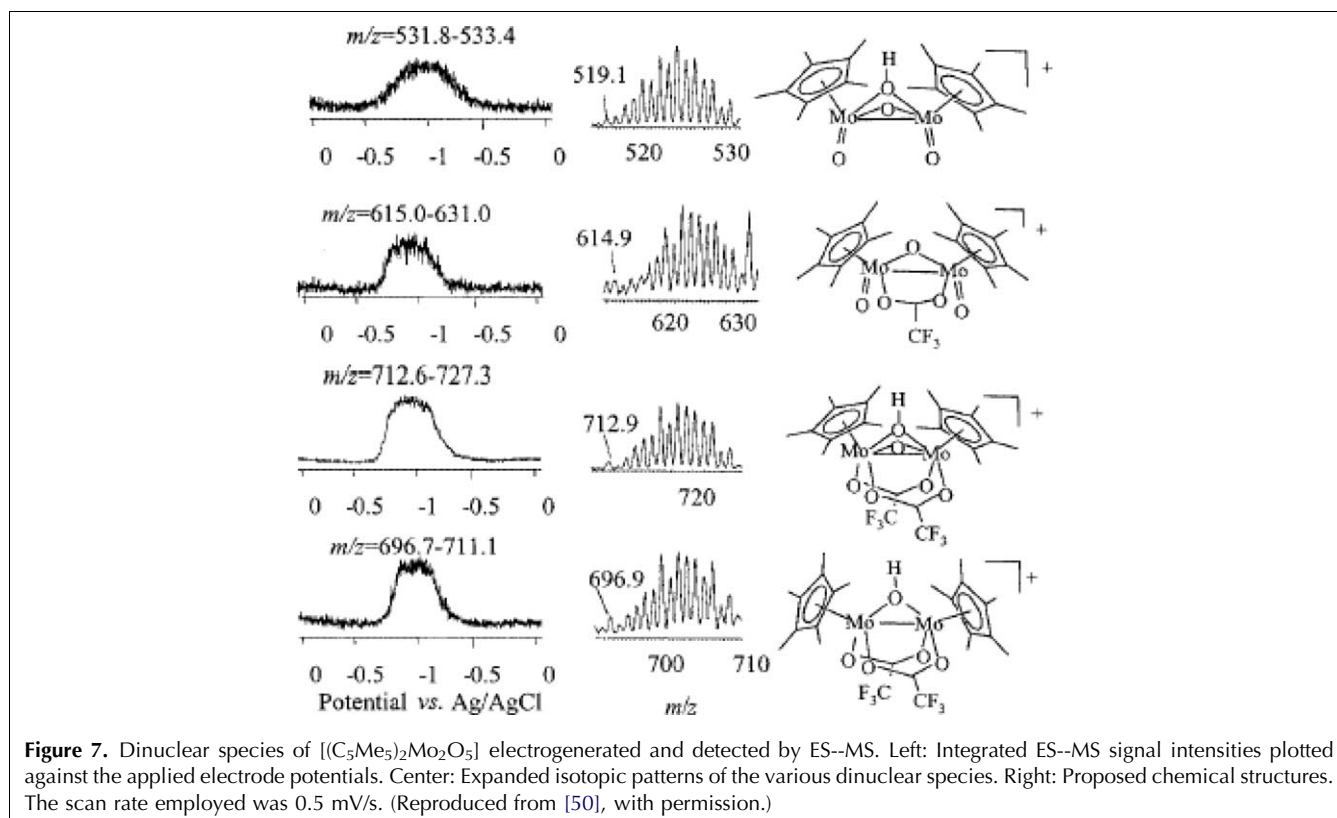
The tandem use of EC with other types of atomic spectrometric techniques is also possible. Briseno et al. [16] used EC-ICP-AES to quantify several metal-containing and anionic dopants present in polypyrrole films. They corroborated their results with those measured by an electrochemical quartz crystal microbalance (EQCM) [16]. EC-ICP-AES complements EQCM, which is a more commonly used method for quantifying dopants in conductive polymer thin films. Ambiguities arising from solvent incorporation and competitive doping processes were clarified.

Relying on the same methodology, Baca et al. [17] showed that it was possible to study metals released by metallothionein (MT), a metalloprotein purported to play an important role in metal homeostasis, metabolism, and detoxification [51]. MT is a cysteine-rich protein that can accumulate divalent metal ions and release them under oxidoreductive conditions. Fig. 6 depicts DPVs of MT adsorbates at a TMF electrode (a) and the elution of Cd^{2+} (b) and Zn^{2+} (c) released by the MT adsorbate through breakage of the metal-thiolate bonds. For the first time, the concurrent release of Cd^{2+} and Zn^{2+} when the DPV scan passed Peak 2 in Fig. 6(a) was detected. Such a

process is normally difficult to study by voltammetry or other types of hyphenated EC methods. Thus, using atomic MS and related techniques, electrode reactions involving stable inorganic species can be assessed, expanding the compound or reaction types generally addressed by EC-MS.

In an elegant study, Gun et al. [50] used EC coupled on-line with ES-MS to study the electroreductive reactions of two molybdenum-containing organometallic complexes, $[(\text{C}_5\text{Me}_5)_2\text{Mo}_2\text{O}_5]$ and $[(\text{C}_5\text{Me}_5)_2\text{Mo}_2\text{O}_4]$, in methanol/water/trifluoroacetate solutions. Aided by MS and MS^n (MS/MS), they identified a large number of intermediates associated with the starting materials and dinuclear and trinuclear species of $[(\text{C}_5\text{Me}_5)_2\text{Mo}_2\text{O}_5]$ and $[(\text{C}_5\text{Me}_5)_2\text{Mo}_2\text{O}_4]$ electrochemically reduced. Compared to MS analysis of the starting materials dissolved in different solution media, adducts formed in the gas-phase were also pinpointed.

Fig. 7 displays the dependence of the total ion-current intensities of several dinuclear species on the applied electrode potentials, together with the expanded isotopic pattern and the proposed structures of the dinuclear species. In addition to the elucidation of the electrode-reaction mechanisms involving these organometallic complexes, the approximate reduction potentials of the starting materials and the dinuclear and trinuclear species were also determined. The results demonstrate



the powerful feature of MS and MSⁿ for unraveling complex electrode reactions.

7. Conclusions

EC combined on-line with atomic MS greatly expands the type of analytes measured and the class of electrode reactions addressed by conventional EC–MS. Each method is highly beneficial to the other in terms of circumventing the problems or limitations of its counterpart.

On one hand, using EC as an analyte-preconcentration/sample-matrix-elimination method for MS has shown several distinctive advantages that make MS even more powerful (e.g., simplicity of instrumental set-up, low sample consumption, fast assay time, high sensitivity, and flexibility in controlling analyte accumulation and release). EC can also selectively accumulate certain chemical forms or charge states of a metal, compensating the deficiency of ICP–MS for metal speciation.

On the other hand, *m/z* specificity and gas-phase ion detection by MS provide an unambiguous way of identifying and quantifying products or species involved in electrode reactions, the measurements of which might be subject to interferences inherent in voltammetric means. In this regard, EC combined with atomic MS differs from conventional EC–MS in that stable analytes are controllably released from chemically modified electrodes and quantification of targeted analytes at ultratrace levels by MS is sought. However, as mentioned above, the absence of the chromatographic components limits the possibility of conducting metal-speciation studies, a deficiency inherent in ICP–MS. As in the use of molecular MS for studies of organic and biological molecules involving metals in different forms, avoiding the separation step exacerbates the uncertainty or difficulty in elucidating complex electrode reactions. Collision-induced dissociation studies and MSⁿ capabilities of certain types of mass spectrometers can be helpful. But, in many cases, interpretations of the results with high fidelity can be tricky. Thus, it is apparent that much remains to be done to increase the capabilities of EC–MS and yield a wider range of applications.

Conceivably, in order to introduce separation devices into the system, flow cells that can produce larger quantities of electrogenerated products/stable intermediates should be explored. In this respect, flow-through type of cells might be more desirable. Moreover, electrodes should be developed with surfaces that are easier to treat and clean (e.g., a surface that is less prone to poisoning or that can be straightforwardly renewed or regenerated would be attractive).

MS interfaces that are more tolerant for the various types of sample media and electrolyte solutions commonly utilized for EC studies would also be helpful.

With the performance of different types of EC flow cells well understood and the various kinds of nebulizers and MS interfaces invented, coupling EC to MS should no longer be a formidable feat. Consequently, this field abounds with research and application opportunities, particularly in elemental speciation at ultratrace levels and studies of electrode reactions involving biologically and environmentally important molecules.

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