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Review

Developments in sample preparation and separation techniques for the determination of inorganic ions by ion chromatography and capillary electrophoresis

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Abstract

A review is presented of sample preparation and separation techniques for the determination of inorganic ions by ion chromatography (IC) and capillary electrophoresis (CE). Emphasis has been placed on those sample treatment methods which are specific to inorganic analysis, and the developments in separation methods which are discussed are those which enhance the capabilities of IC and CE to handle complex sample matrices. Topics discussed include solid-phase extraction for sample clean-up and preconcentration, dialytic methods, combustion methods, matrix-elimination IC, electrostatic IC, electrically polarised ion-exchange resins, electromigration sample preparation in CE, chromatographic sample preparation for CE, use of high-ionic strength background electrolytes, buffering of background electrolytes in CE, use of capillary electrochromatography for inorganic determinations, and methods for the manipulation of separation selectivity in both IC and CE. Finally, some possible future trends are discussed.

Keywords: Reviews; Sample preparation; Inorganic ions

Contents

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1. Introduction and scope of this review

Separation science methods have become highly developed tools for the determination of inorganic species. Ion chromatography (IC), introduced in 1975 by Small and co-workers [1], provided the first viable analytical method for the simultaneous determination of inorganic anions at trace levels. Whilst IC could also be used successfully for the determination of cations, there were several suitable alternative analytical techniques (mainly spectroscopic in nature) for these species so the development of IC was driven chiefly by the need for improved methods for anion determination. A great deal of research effort and commercial development has been directed towards the development of IC and the technique can now be considered to be mature. This is reflected in the very wide range of sample types to which IC has been applied and the resultant variety in sample handling procedures which have been designed to support IC analyses. In contrast to IC, capillary electrophoresis (CE) of inorganic species is a relatively new technique, having been introduced in 1990 [2]. Much of the published work in this field relates to the study of fundamental separation processes, so that applications of CE to samples is less developed than is the case for IC.

This review describes some of the more important sample handling procedures which are applicable to IC and CE. The coverage of these procedures is not intended to be comprehensive but rather to outline to the reader those developments which are of particular relevance to the analytical techniques concerned. Since the degree of sample preparation in an analysis is dependent to some extent on the efficiency and selectivity of the separation method, some discussion of recent developments in the separation methods themselves is also included, with an emphasis on those developments which extend the applicability of the separation methods to more complex samples. Again, the discussion of these developments is not intended to be comprehensive. Readers seeking more detailed discussion are referred to reference texts on IC [3–8] and CE [9–13].

2. Ion chromatography

The term ‘ion chromatography’ does not refer to a specific technique defined by the nature of the stationary and mobile phases, but rather to a group of related liquid chromatographic methods that are applicable to a particular group of analytes. These analytes include inorganic anions and cations, as well as low-molecular-mass organic acids and bases. For the purposes of this discussion it is necessary to confine this definition somewhat, and this review will concentrate on the most common application areas of IC, namely the separation of inorganic anions and cations by ion exchange. The separation of organometallic species will not be discussed and only limited attention will be given to the separation of metal chelates. Ion chromatographs, whether operated in the suppressed or non-suppressed mode,

are almost always fitted with a conductivity detector, which is often supplemented with a UV–Vis absorbance detector. In this review it will be assumed that the sample preparation methods outlined in Section 2.1 are intended for use with such a mainstream instrument, with any newer developments in separation techniques being discussed separately in Section 2.2.

2.1. Sample preparation for IC

2.1.1. Introduction

The most challenging samples in IC are those in which the analyte is present at low concentration in a sample matrix of high ionic strength or of extreme pH. Examples would include the determination of trace ions in brines, concentrated acids or concentrated alkalis. The reason why these samples are problematic is that the dominant matrix ion often exerts an ion-exchange displacing effect, leading to band broadening and poor separation, or the extreme pH of the sample causes profound disturbances to the critical acid–base equilibria existing in the eluent.

Perhaps the most widely used approach in the case of a high-ionic strength sample is to minimise the amount of sample injected onto the column so that the dominant matrix ion no longer exerts a deleterious effect on the separation, and to employ a selective detection method. The sample load can be reduced either by diluting the sample or through the use of a small sample volume. Fig. 1 shows an example of this approach applied to the determination of free and complexed cyanide species in a processing liquor taken from a gold cyanidation plant [14]. The important analytical parameter is the ratio of cyanide to copper and this is obtained by first separating the metallo-cyanide species using reversed-phase ion-interaction chromatography, and then applying post-column reaction to visualise the free cyanide and the labile cyanide bound to the copper(I). The ratio of the areas of the free cyanide and copper(I) peaks in the second chromatogram of Fig. 1 can be used to determine the CN:Cu in the sample and, ultimately, to optimise the gold extraction process. This approach has been developed for on-line process control of gold extraction in remote mine sites.

The above approach has obvious limitations in that reduction in the amount of the dominant matrix ion injected onto the column also leads to a reduction in the amount of analyte injected. The sensitivity of the detection method will, therefore, determine the ap-

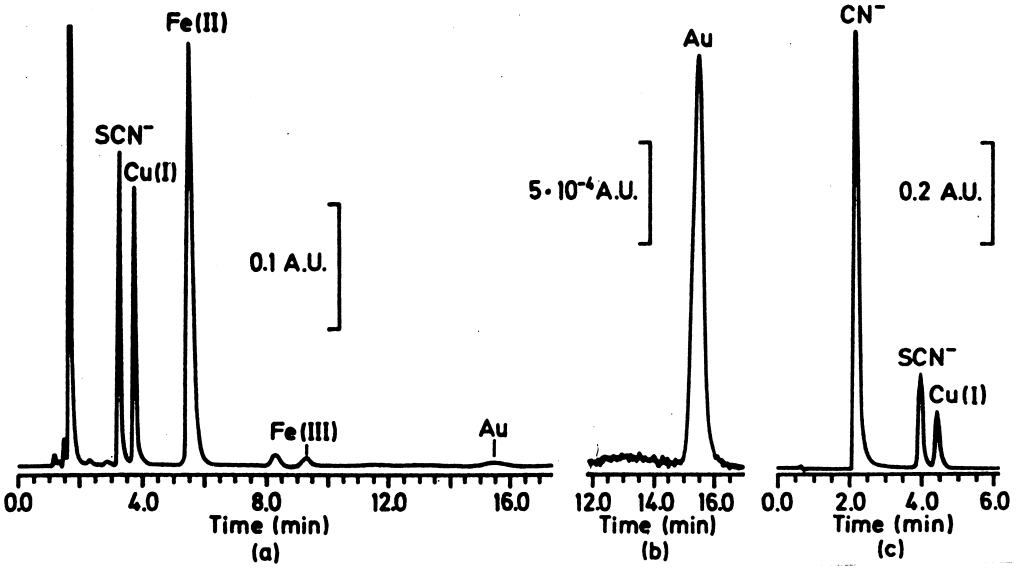

Fig. 1. Chromatogram obtained from a leach liquor. (a) Direct UV detection; (b) UV detection after post-column reaction. Reproduced with permission from Ref. [14].

plicability of this approach. Many samples will, therefore, require the use of alternative methods and some of these are discussed in Section 2.2.2 below.

2.1.2. Manipulation of separation selectivity

When a desired separation is limited by interference from a dominant matrix ion, variation of the separation selectivity may be employed as a means to improve separation. In IC, the separation is most often accomplished by ion-exchange chromatography, where the separation selectivity results chiefly from the electrostatic interactions of the analyte ions with the fixed ions on the stationary phase, with some secondary selectivity effects arising from other factors such as the size and polarisability of the analyte ion, its degree of adsorption onto the unfunctionalised portions of the stationary phase, and the nature of the fixed group on the stationary phase. The ability to manipulate separation selectivity is, therefore, rather limited and is usually accomplished by the development of new stationary phases in which specific functional groups are bound to polymers having specific adsorption properties. Success with this approach requires access to a range of stationary phases having different selectivity.

Some selectivity differences arise from changes in the composition of the eluent, especially for analyte ions of different charge. However, it is often impractical to empirically optimise the eluent composition because of the time required to equilibrate the stationary phase with each new eluent composition. Considerable interest has, therefore, been directed towards the development of suitable mathematical retention models which allow prediction of retention times for a wide range of eluent compositions, and hence computer-assisted optimisation of the eluent composition. Several mathematical retention models of varying complexity have been developed and these have been compared in a recent series of articles [15–17] by determining their predictive capabilities using a common data set of retention data obtained for a wide range of analyte anions using several stationary phases for both suppressed and non-suppressed IC. This comparison shows that the more complex models give better predictive capabilities but are more difficult to implement because they require significant input parameters. The most practical approach to retention modelling appears to be the use of an semi-empirical method whereby retention data are measured for eluent compositions at the extremes of the desired search area and an appropriate algorithm is then used to interpolate retention data at intermediate eluent compositions. Commercial software (such as DryLab, from LC Resources, Walnut Creek, CA, USA) is suitable for this purpose. Artificial neural networks (ANNs) have been shown to have great potential for the prediction of IC retention data on the basis of training the ANN using a small set of experimental retention data [18], and it is probable that this approach will find more widespread application in the future.

2.1.3. Solid-phase extraction (SPE) for sample preconcentration and clean-up (Table 1)

The most popular method of trace enrichment in IC involves the use of a separate pre-column designed to trap trace levels of solutes from a large volume of sample. This method is simple and convenient to apply, and has the major advantage of ease of automation. Further, high enrichment factors are achieved and the technique is less prone to sample contamination effects than other methods. The general procedure for trace enrichment with a preconcentration column is as follows. An accurately known volume of the sample is pumped through a small ion-exchange pre-column (or a reversed-phase pre-column coated with an ion-interaction reagent), using a syringe, or in the case of an automated system, with a HPLC pump. Analyte ions are trapped selectively on the concentrator column and then eluted onto an ion-exchange analytical column for separation and subsequent detection. The procedure is effective when the trapping and elution steps are quantitative, or at the very least, are reproducible.

There are two general hardware configurations for automation of the trace enrichment procedure using concentrator columns. These are a single-valve configuration; and a two-valve configuration. The former is the simpler and consists of a single six-port, high-pressure, switching valve and two pumps. A measured volume of the sample is pumped onto the concentrator column with the effluent directed to waste. The pump itself can be used for large volumes of sample, or an injector can be placed in line for smaller volumes and a suitable sample loading

Table 1
Some recent applications of preconcentration

Sample	Species determined	Concentration column	Type	Recovery (%)	Detection limit	Refs.
River water mineral water	Transition metals	Iminodiacetate resin	Chelating resin	80–100	0.01–0.1 ppb	[22]
Semi-conductor pure water	Anions	Dionex TAC-LP1	Anion exchange	N/A	<50 ppt	[114]
Beverages, Mine waste water	8-Hydroxyquinoline complexes of Cu(II), Al(III), Fe(III)	Nucleosil C_{18}	Reversed phase	N/A	5–40 ppb	[19]
Water	Organic lead and mercury species	Nucleosil C_{18}	Reversed phase	75–90	N/A	[115]
Sea water	Zinc, copper, nickel, cobalt and manganese	Iminodiacetate resin	Chelating resin	N/A	0.1–0.5 ng	[21]
Natural waters	Plasmocorinth B complexes of metals	LiChrospher 100 RP-18	IIR reversed-phase coated with TBA	72–95	15–150 ppb	[20]
Ozonated water	Bromate	Dionex Ion Pac AG 10	Anion exchange	90-100	0.3 – 5 ppb	[24]
Tap water	Benzene and naphthalene sulfonic acid derivatives	LiChrospher 100 RP-18	IIR reversed-phase coated with CTA	80	0.3 –8 ppb	[116]
Water	Triorganotin compounds	Baker C_8, C_{18}, and phenyl Amberlite XAD-2 and XAD-4	Reversed phase and anion exchange	20–100	2 ppb	[117]

mobile phase. The loading mobile phase must allow the analytes to adsorb quantitatively onto the preconcentrator column. Rotation of the valve allows the eluent to be pumped through the concentrator column in the reverse direction in which the sample was loaded (backflushing). The trapped analyte ions are eluted from the concentrator column, and onto the analytical column. The valve is then rotated again and the eluent carries the solute ions through the analytical column in the usual way.

The second approach is somewhat more flexible. Two high-pressure switching valves and a single programmable pump with a low-pressure solvent selection valve are configured as in Fig. 2a. Again, a measured volume of the sample is loaded onto the concentrator column at a precise flow-rate, with the effluent directed to waste (Fig. 2b). A wash step can then be introduced without losing bound analytes by switching the low-pressure solvent select valve to the eluent flow path for a precisely measured time (Fig. 2c). This partially re-equilibrates the concentrator column with the eluent to help minimise baseline disturbances. The valves are then switched to backflush the analyte ions from the concentrator column and onto the analytical column (Fig. 2d). This two-valve configuration offers the clear advantage of unlimited and precise control over the volumes of eluent for the washing and backflushing steps, allowing the possibility of tailoring the preconcentration procedure for different samples.

The hardware configurations are now well developed for trace enrichment procedures, so the emphasis in recent years has been placed on the nature of the concentrator columns and the sample loading conditions. Many types of packing materials are available commercially for concentrator columns including reversed-phase packings functionalised with C_{18}, C_8, CN, etc, chelating resins, and both anion- and cation-exchange resins. A recent example of utilising reversed-phase concentrator columns was for the analysis of trace levels of copper(II), aluminium(III) and iron(III) [22]. These metals were complexed with 8-hydroxyquinoline, with introduction of the sample to the concentrator column being performed using a sample loading mobile phase of varying mixtures of acetonitrile and water. A number of commercially available functionalised packing materials with different particle sizes (10–53 μm) were investigated and it was found that for these types of neutral metal complexes, a C_{18} functional group and small particle size (10 μm) provided the best recoveries and subsequent ana-

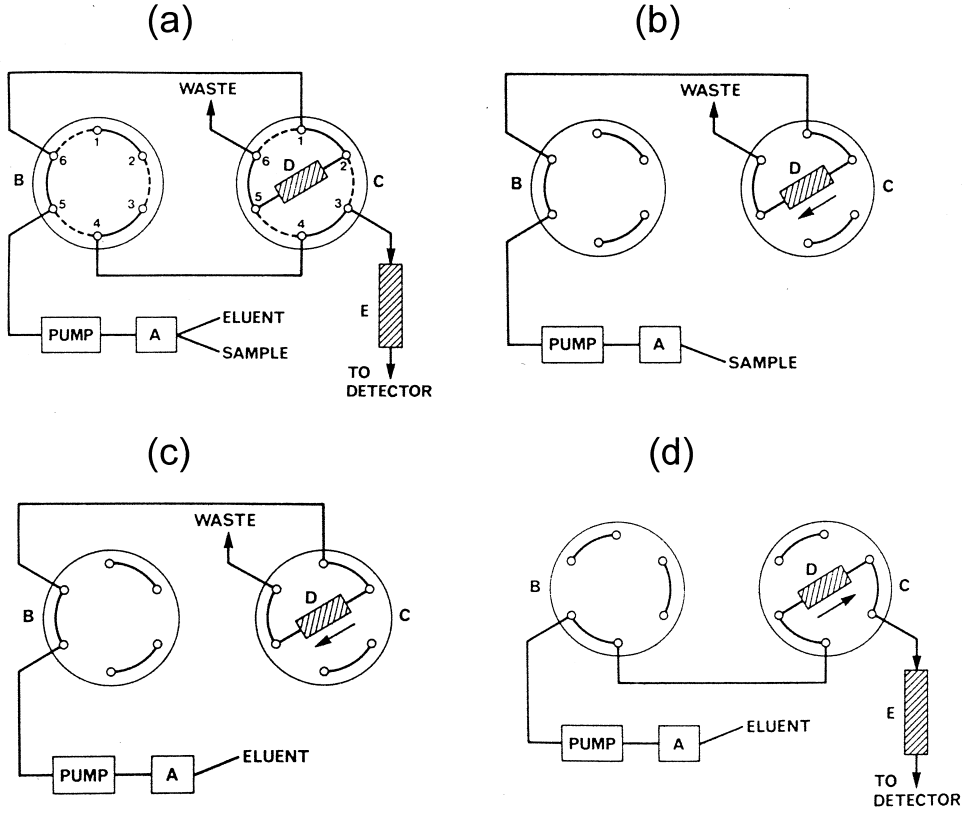

Fig. 2. (a) Apparatus for sample preconcentration using a single pump, a low-pressure solvent selection valve (A), two-high pressure switching valves (B, C), and a concentrator column (D). (E) The analytical column, (b) sample loading, (c) concentrator column washing, (d) sample stripping. Reproduced with permission from Ref. [3].

lytical separation performances when loaded onto the concentrator column with a loading mobile phase of 90:10 acetonitrile–water. Limits of detection were 5 ppb for Al(III), and 40 ppb for Cu(II) and Fe(III).

An advantage of using reversed-phase packing materials is that they be modified with suitable ion-interaction reagents (IIR) in order to retain ionic analytes. For example, Sarzanini et al. [116] coated a C_{18} pre-column with tetrabutylammonium hydroxide as the IIR to successfully concentrate Plasmocorinth B (a disulfonated azo dye) complexes of Co(III), Cu(II), Fe(III), Ga(III), In(III), Ni(II), V(V) and Zr(IV). The metal ions were complexed with Plasmocorinth B prior to loading a 100-ml sample volume directly onto the pre-coated concentrator column with the aid of a pump. Generally, greater than 94% recoveries were obtained with detection limits in the range of 15–150 ppb.

Preconcentration of some transition metals is also possible using chelating resins. Caprioli and Torcini [19] utilised an iminodiacetate chelating resin to selectively trap copper(II), nickel(II), zinc(II), and cobalt(II) in a seawater matrix. In such a sample, the high ionic strength renders the use of ion-exchange resins for preconcentration impractical. The use of the chelating resin not only served to preconcentrate the metal ions, but also eliminated analytical problems associated with the high ionic strength of the matrix. After loading 100 ml of the sample seawater solution, the pre-column was washed with 0.1 *M* ammonium nitrate, before elution of the bound metal ions onto the analytical column with 6 m*M* pyridine-2,6-dicarboxylic acid. Sub ppb detection limits were achieved. Motellier and Pitsch [115] also utilised an iminodiacetate resin for the determination of transition metals and found that the sample pH was of

particular importance for good recovery of the metal ions. pH values less than 2.8 resulted in partial uptake of the metals by the chelating column, while high pH values led to slower desorption kinetics. Post-column detection with pyridylazoresorcinol (PAR) resulted in detection limits of approximately 0.1 ppb.

Preconcentration of anions is usually achieved by employing a suitable anion-exchange resin. However, most analyses of trace amounts of anions have been restricted to samples that have a low ionic strength [23]. The preconcentration of a trace analyte in the presence of high levels of interfering ions typically leads to overloading of the concentrator column and poor recoveries of the target analytes. Several methods have been devised to deal with samples of this type, normally by coupling the preconcentration procedure to a suitable matrix elimination procedure. One approach which is suitable when the levels of interferences are only moderate involves the on-line retention of the interferences on a suitable pre-column, and is typified by the determination of bromate in ozonated drinking water [24,25]. Relatively high levels of chloride, which overloaded the anion concentrator column, were removed on-line by utilising an 'On-guard Ag' (Dionex) cartridge (containing a cation-exchanger in the silver form) which trapped chloride anions and allowed bromate to pass through to the anion concentrator column unhindered. One drawback of this approach was that silver leaching from the On-guard Ag cartridge resulted in deterioration of the analytical column. This was overcome by utilising a Dionex MetPac CC-1 metal trap column. The detection limit for bromate was approximately 1 ppb, an order of magnitude lower than direct injection methods.

When the levels of interferences are high, it is impractical to retain them on-line because the required capacity of the pre-column would be very high. Instead, concentrator columns may be used to selectivity trap target anions with the interfering matrix ions being directed to waste. One such example was for the analysis of sulfite in a variety of foods [26,27], wherein sulfite anions were bound to a Dionex AS-2 anion-exchange cartridge, with the bulk of the matrix eluted to waste. The bound sulfite analyte was then eluted to the analytical column for analysis. Any strongly retained compounds remaining on the concentrator column were removed with a wash step consisting of concentrated eluent.

An on-line device for the automation of SPE procedures for treating acidic or basic samples has been reported recently [28]. This device (shown in Fig. 3) is termed a 'sample concentrator and neutraliser (SCAN) processor' (Alltech Associates, Deer-

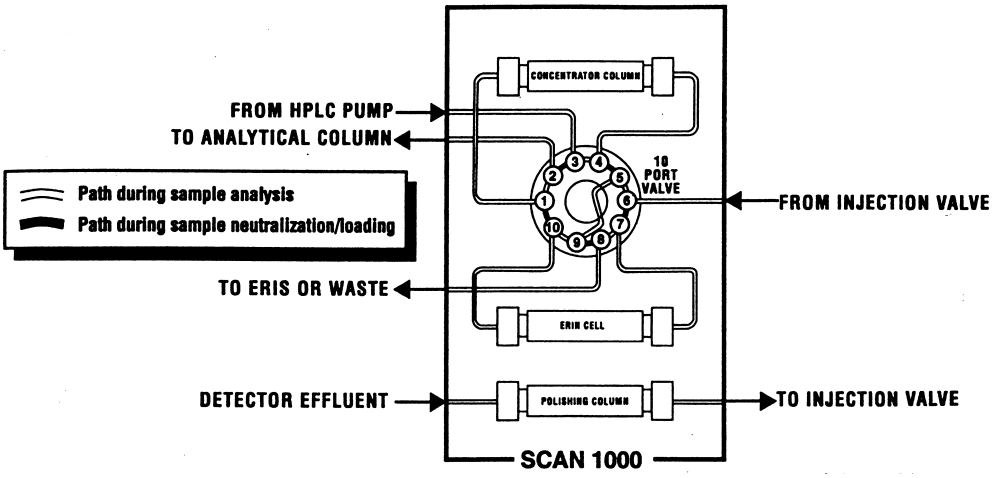

Fig. 3. The valve configuration for the SCAN 1000 sample processor. The shaded portion of the valve diagram represents the liquid flowpath during sample neutralisation/concentration. The unshaded portion shows the liquid flowpath during sample analysis. Reproduced with permission from Ref. [23].

field, IL, USA) and as the name suggests, is designed for the on-line neutralisation of acidic or basic samples and also the simultaneous preconcentration of the analyte anions. The main components of the system are an ion-exchange concentrator column and an electrochemically regenerated ion neutraliser (ERIN) column. The ERIN column operates on the principle of an electrically polarised ion-exchange resin (discussed later in Section 2.2.3), wherein an electrolysis reaction is used to generate the hydroxide or hydronium ions necessary to regenerate the anion- or cation-exchange resin in the cell. The effluent from the detector is recirculated through the system and carries the injected sample through the ERIN cell where neutralisation takes place, and thence to the concentrator column where the analyte anions are retained. Rotation of the valve results in the analytes being eluted from the concentrator column to the analytical column.

A recent innovation in the field of SPE has been the introduction of a disk format rather than a packed bed column. The SPE discs have been used widely for extracting environmental pollutants from aqueous solutions [29–32] and offer some significant advantages over conventional packed bed columns. These include large flow area, low bed masses and low void volumes (10–50 μl) [33]. Furthermore, the discs are not subject to channelling problems associated with conventional concentrator columns. So far, SPE discs have been applied to off-line extraction of phthalates and adipates [34], and the elimination of matrix interferences [35,36] but have not as yet been applied to any on-line preconcentration procedures for IC. It is envisaged that the use of discs will become more prevalent in the future, as the range of packing materials is extended and the advantages of a disc format become accepted more widely.

2.1.4. Sample clean-up using dialytic methods

Dialysis involves the diffusion of species across a membrane and the technique can broken into two classes, passive dialysis (in which molecules of a certain molecular mass are transferred across a membrane), and active (Donnan) dialysis (in which ions of a specified charge are transferred across a membrane). Active dialysis is employed most commonly in IC and is useful for the clean-up of sample solutions at extreme pH. For example, highly alkaline samples often pose problems for analysis of anions by IC, including distorted peaks, severe baseline disturbances, system peaks and reduced column life. A typical dialytic apparatus consists of a length of cation-exchange membrane fibre immersed in a suitable hydrogen ion-donating medium. The membrane is usually functionalised with sulfonic acid groups to impart cation-exchange characteristics and Donnan dialysis occurs between the sample solution on one side of the membrane and an acidic solution on the other side. The sample can be introduced by means of a syringe or pump and the effluent either collected or transferred directly to the injection loop of an IC instrument. As the sample is passed through the fibre, sodium ions in the sample are exchanged for hydrogen ions from the hydrogen ion-donating medium. Analyte anions are prevented from passing out of the fibre due to the repulsion of the cation-exchange (negatively charged) membrane.

Laksana and Haddad [37] have investigated a range of organic and inorganic acids as candidates for the acid-donating medium. The ability to neutralise the sample improved with increasing concentration of the hydrogen ion-donating medium, but the organic sulfonic acids showed superior performance to the inorganic acids in terms of minimal incursion of the acid anion into the sample solution. Octanesulfonic and camphorsulfonic acid gave best results but could only be used up to a concentration of 0.3 *M* if incursion of the acid anion was to be prevented. Clean-up devices of this nature have a finite life governed by the volume and concentration of the hydrogen-donating solution and the total neutralisation capacity can be expressed as the volume of sample of known concentration that can be treated. This capacity can be increased greatly when the hydrogen ion-donating solution is replaced by a slurry of high-capacity cation-exchange resin (in the hydrogen form) and a dilute solution of octanesulfonic acid. The resin provides a very large-capacity reservoir of hydrogen ions, whilst the octanesulfonic acid acts as a carrier to move the hydrogen ions to the membrane surface. Incursion of the acid anion into the sample is prevented due to the use of the bulky octanesulfonate anion.

Further refinement to active dialysis methods can be achieved by applying electric fields with membranes, known as electrodialysis. A schematic for an

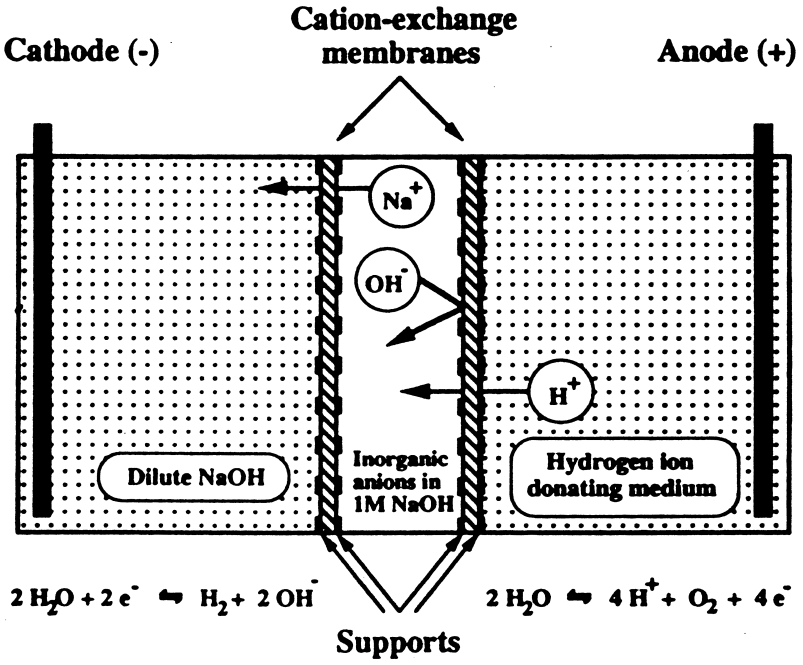

Fig. 4. Schematic diagram of the electrodialysis process. Reproduced with permission from Ref. [38]

electrodialytic process is shown in Fig. 4. Two sheets of cation-exchange membrane are arranged in a stack to form a three-compartment cell comprising separate chambers for anode, cathode and sample. The anode chamber contains a hydrogen ion-donating medium, the cathode chamber contains dilute NaOH to act as a receiver, and the sample chamber is filled with an alkaline sample containing target anions. Application of a d.c. electric field causes cations, particularly highly mobile Na^+, to move from the sample chamber to the cathode chamber. At the same time hydrogen ions flow from the anode chamber into the sample chamber. Anions are blocked from moving between the chambers by the cation-exchange membrane. The net effect of the process is to neutralise the sample. During electrodialysis, hydrogen ions are continually produced at the anode, so the hydrogen ion-donating medium is not depleted as the sample is neutralised.

Electrodialysis has been employed for the off-line analysis of strongly alkaline samples containing trace amounts of common inorganic anions [34]. Several commercially available membranes were investigated for their performance and most gave greater than 80% recoveries for strong acid anions, but in all cases the recovery of fluoride was poor. This was attributed to partial protonation of fluoride to form neutral hydrofluoric acid which could then diffuse through the membrane and out of the sample reservoir. The membrane that gave the best overall performance was Asahi CMV (Asahi Glass, Japan). Again, the best hydrogen ion-donating media were found to be 2:1 (w/v) slurries of large organic sulfonic acids (toluene sulfonic acid, octane sulfonic acid, or camphor sulfonic acid) with Bio-Rad AG 50W-X8 (200–400 mesh, H^+ form) resin. Under these conditions, 1 *M* NaOH sample solutions could be neutralised in about 10 min without loss of strong acid anions or incursion of the acid-donating medium anion. However the device was unsuitable for the electrodialysis of samples in which the target analytes were a weak acid, such as fluoride and nitrite, due to loss of these ions from the sample.

The cell design shown in Fig. 4 can be modified to allow on-line electrodialysis and direct injection onto an IC instrument if a small volume, flow-through sample reservoir is used. Such a flow-through device has been reported in which the volume of the sample

compartment is 300 μl and membranes of large surface area are employed [39]. When a Neosepta CMS membrane was used, the recovery of fluoride was improved dramatically when compared to the static device. This was attributed to the production of hydrofluoric acid occurring in the sample at the point of exit from the cell, so the loss of fluoride due to diffusion did not occur. However, the recovery of nitrite was still poor. The on-line device was applied to the analysis of fluoride in forage vegetation samples. The samples were prepared by NaOH fusion, and the prepared alkaline sample was injected directly. The results obtained by IC compared favourably with those obtained from a colorimetric method.

Electrodialysis has also been used to neutralise highly acidic solutions prior to determination of magnesium(II) and calcium(II) [40]. The authors utilised an electrodialysis device consisting of a Tosoh TASN-80 anion-selective membrane tube (40 cm×1 mm I.D.). The rest of the device was similar in nature to the previous examples, except that NaOH was used for the cathode chamber (to donate OH^- ions) and an acidic medium acted as the receiver. The device was capable of neutralising 1 *M* acid solutions within 10 min without loss of target analytes.

2.1.5. Sample preparation using combustion

Combustion techniques are extremely useful for preparation of samples in which heteroatoms can be converted to ionic species suitable for determination by IC. Combustion is, therefore, used frequently for the determination of heteroatoms in the microanalysis of organic chemicals, as well as for the analysis of oils and fuels. Normally the sample is combusted in oxygen, during which some non-metallic elements are converted into gaseous compounds which are collected in a suitable absorbing solution for analysis by IC.

Several experimental configurations are possible, including the Schoeniger flask, the Parr oxygen bomb, and furnace methods. The Schoeniger flask consists of a pyrex or quartz vessel containing an absorber solution and a small amount of sample (0.1 g) in a paper cup. The sample is then ignited manually or electrically and the gaseous products are collected in the absorber solution. A typical application is the analysis of chlorine, bromine and phosphorus in organic compounds [41] using a solution of 30% (w/w) H_2O_2 as the absorber. In the case of phosphorus determination, it is necessary after combustion to boil the collected solutions to facilitate hydrolysis reactions to convert the less oxygenated oxyanions of phosphorus to orthophosphate in order to simplify the analysis [42]. Larger samples (up to 1g) may be combusted in a Parr bomb combustion apparatus using a high pressure of oxygen. Typical applications of combustion bombs include elemental analysis of chemical wastes [43,44], halogens and sulfur in oil and solid organic chemicals [45,46]. Furnace methods are applicable to more intractable samples, such as rocks and ores.

Due to the nature of the apparatus used, combustion techniques are most often employed off-line. However, Andrew and co-workers [47] have reported an on-line combustion IC technique for the determination of sub-ppm levels of sulfur and chlorine in liquid hydrocarbon samples. A twin-tube furnace is used and the schematic layout of the apparatus is shown in Fig. 5. The oxygen to be used in the combustion is first purified by passage through the furnace and then through three scrubber solutions. The sample is injected into a helium stream, before being mixed with oxygen and combusted in the furnace. The gaseous products are then trapped in a bubbler and the absorbing solution passed through a concentrator column for enrichment prior to IC analysis. Recoveries of chlorine and sulfur from a range of liquid hydrocarbons was close to 100% and good agreement was obtained between results obtained by the combustion-IC method and microcoulometry.

2.2. Developments in IC separation methods

In cases where manipulation of separation selectivity or the application of sample treatment procedures do not provide the desired separation, it may be necessary to employ a different separation technique. In the following section, developments in IC separation methods which enhance the ability of the technique to accommodate difficult samples are discussed.

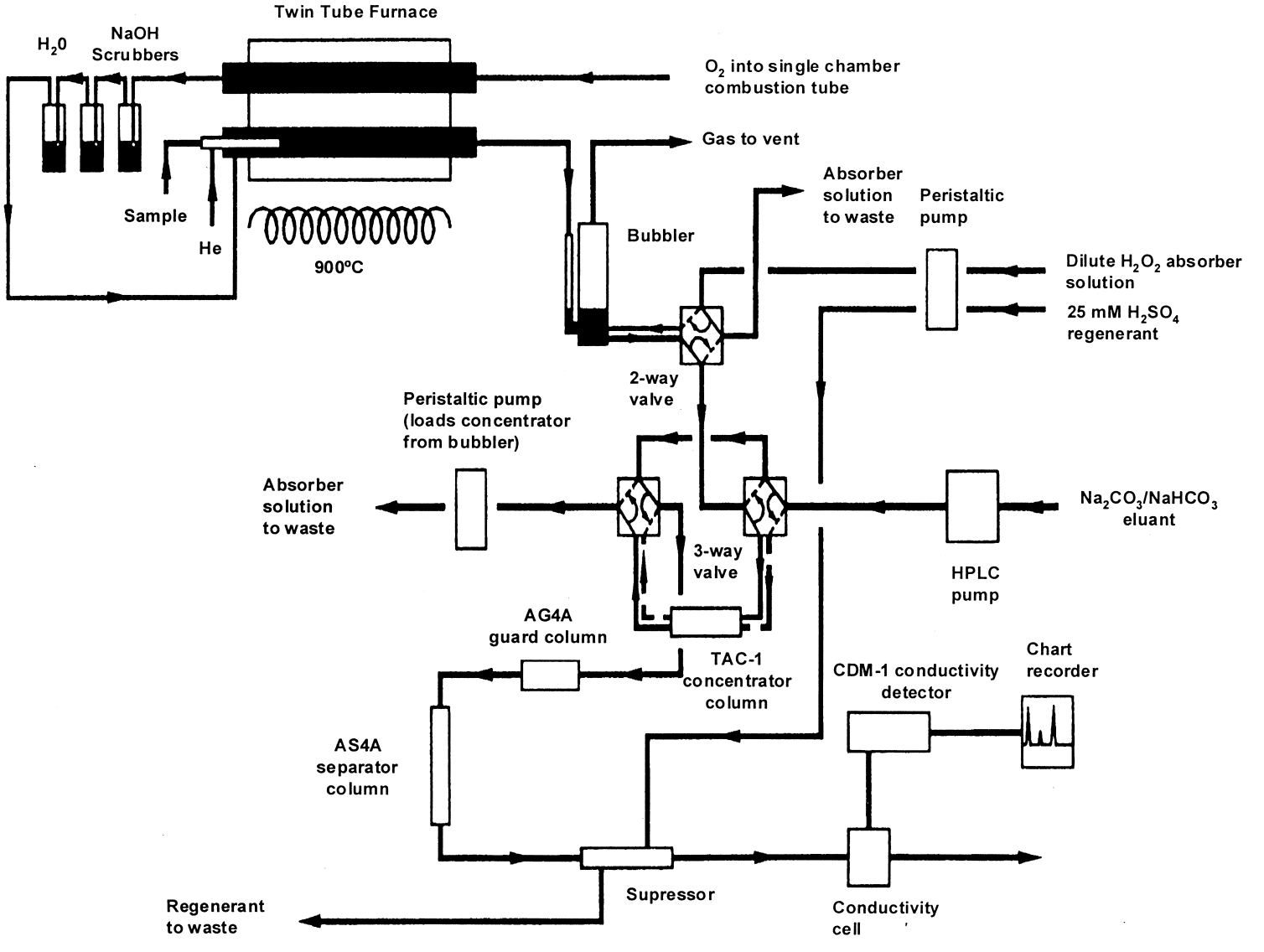

Fig. 5. Schematic diagram of the combustion-IC apparatus. Reproduced with permission from Ref. [43].

2.2.1. Matrix elimination IC

A novel solution to the problem of performing IC separations on high ionic strength samples, such as brines, has been to use the dominant matrix ion as eluent. The principle of this method is that the exchange sites on the stationary phase are equilibrated with the dominant matrix ion before introduction of the sample itself, which prevents additional binding of the dominant matrix ions from the sample and, therefore, diminishes band-broadening effects [48,49]. This approach is termed 'matrix elimination IC' because the dominant matrix ion passes through the column unretained.

Matrix elimination IC has been applied to a range of sample types, but is used most frequently for the analysis of brines. Here, a relatively high concentration of sodium chloride is used as the eluent and the sample is injected without dilution. Fig. 6 demonstrates the utility of this approach by comparing the separation of the same group of anions in a water matrix and in a matrix comprising 20 000 ppm chloride. Retention times and peak shapes are virtually identical for the two chromatograms, showing that the band-broadening resulting from self-elution effects caused by the dominant matrix ion in the sample have been almost eliminated. Matrix elimination IC has been applied also to samples containing high levels of sulfate, using sodium sulfate as the eluent.

2.2.2. New separation methods

When a conventional IC separation method encounters interference problems which cannot be resolved by either systematic optimisation of the eluent composition or by using a specialty ion-exchange stationary phase, use of an alternative separation mode may be desirable.

One example of a very difficult separation which can be resolved in this way is the determination of ionic species in acid rain. Here, the acidic anions, chloride, nitrate and sulfate, must be determined in the presence of monovalent and divalent cations, such as sodium, ammonium, potassium, calcium and magnesium. Although a range of approaches to this separation have been proposed, such as the use of two parallel separation systems or the use of a coupled anion/cation IC system, Tanaka and co-workers [50–52] have developed an elegant method which uses a weak acid (carboxylate) cation-exchange column coupled with a solution of a weak

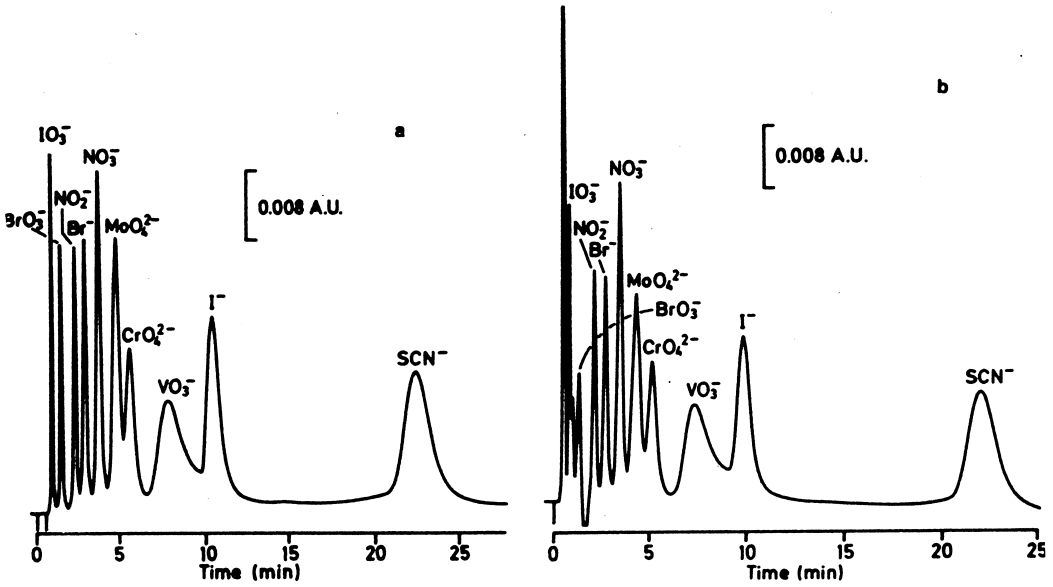

Fig. 6. Separation of 10 anions in (a) water and (b) 20 000 ppm chloride. A Waters IC Pak A column was used and the eluent was 15 m*M* sodium chloride containing 5 m*M* phosphate buffer at pH 6.5, 1.2 ml/min, U.V. detection at 210 nm, 10 – 50 ppm of each anion [48].

carboxylic acid (such as tartrate) as eluent and employing conductivity detection. Under these conditions, the cation-exchange column operates in the ion-exclusion mode for the separation of the anions and in the cation-exchange mode for the separation of the cations, with hydronium ion acting as the competing cation. Fig. 7 shows a typical separation obtained. This system has been incorporated into an automatic acid rain analyser in which a rainfall event triggers a collection of sample and subsequent analysis, whilst a meteorological satellite provides data on the source of the rain sample. The system operates unattended and is in routine use for monitoring of acid rain in Nagoya, Japan.

Electrostatic ion chromatography (EIC), developed recently by Hu and co-workers [53–56], is a separation method for inorganic anions which has

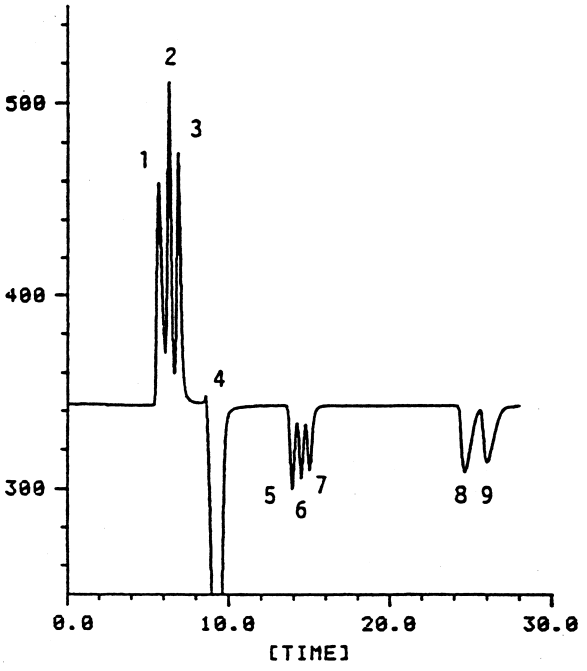

Fig. 7. Simultaneous IEC/CEC chromatogram of common anions and cations on a TSKgel OA-PAK column by elution with a 5 m*M* tartaric acid/7.5% methanol/water. Eluent background conductivity: 537 mS cm^{-1}. Peaks: (1) SO_4^{2-}; (2) Cl^-; (3) NO_3^-; (4) eluent-dip; (5) Na^+; (6) NH_4^+; (7) K^+; (8) Mg^{2+}; (9) Ca^{2+}. Chromatographic conditions: eluent flow-rate, 1.2 ml/min; column temp., 26°C; detector sensitivity, 100 mS cm^{-1}; injection volume, 0.1 ml; injected sample, mixture of 0.1 m*M* HNO_3, KCl, NH_4NO_3, $(NH_4)_2SO_4$, $CaCl_2$, and $MgCl_2$. Reproduced with permission from Ref. [51].

separation selectivity different to that of conventional ion-exchange. In EIC, the stationary phase is formed by coating an octadecyl reversed-phase material with a hydrophobic zwitterionic surfactant, such as 3-(*N*, *N*-dimethylmyristylammonio)propanesulfonate (Zwittergent-3-14) or 3-[(3-cholamidopropyl)dimethylammonio]-1-propanesulfonate (CHAPS), both of which are characterised by a hydrophobic tail and a cation-exchange and an anion-exchange functionality separated by three methylene groups. The resultant coated material acts as a zwitterionic stationary phase in which the two functional groups are situated sufficiently closely that they exert simultaneous electrostatic attraction and repulsion effects on analyte ions. The combined effects of the above result in the achievement of an effective distribution of both the analyte cations and anions from the electrical fields (stationary phase) to the bulk solution (mobile phase) without need for a displacing ion. Separations can, therefore, be performed using water as eluent and analyte ions are eluted as pairs of ions (that is, each analyte anion is accompanied by an analyte cation), with the retention time being determined by the nature and charge of the anion and the cation. When a mixture of analyte salts is injected, ion-pairs comprising all possible combinations of the analyte cations and anions are produced, with the distribution of cations and anions between the ion-pairs being dependent on a priority order determined by the molal energies (ΔG) of the cation and anion in the ion-pair. A particular anion may, therefore, be eluted as multiple peaks, being present as an ion-pair with a range of different cations. The separation selectivity is illustrated in Fig. 8 (upper trace), from which it can be seen that the elution order differs substantially from that evident in IC.

Although the use of water as eluent is of great advantage to the achievement of high conductivity detection sensitivity, the fact that the analyte ions are eluted as ion-pairs having a composition dependent on the nature and concentration of the sample has obvious drawbacks in analytical applications since the chromatogram would be dependent on the sample composition. A recent development in EIC has overcome this problem. It has been reported that the addition of a low concentration of an electrolyte to the eluent resulted in all analyte anions being eluted as single peaks consisting of an ion-pair of the

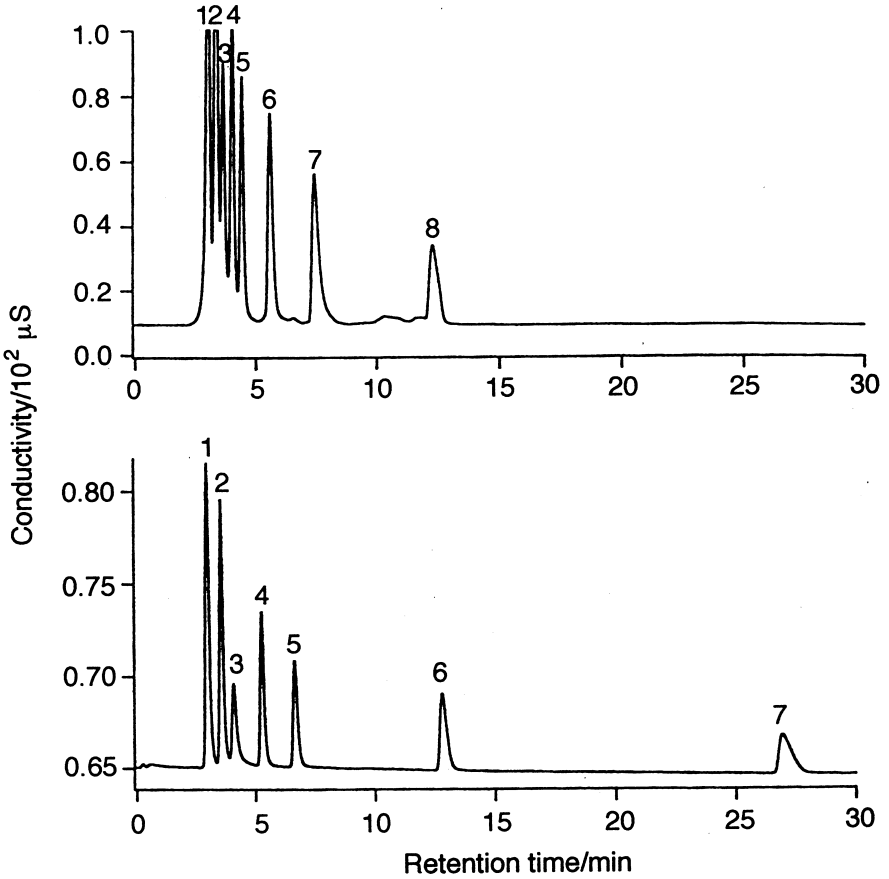

Fig. 8. EIC chromatograms of inorganic anions using water (upper trace) or 10 m*M* $NaHCO_3$ (lower trace) as eluent. Column, ODS modified with C14N3S; flow-rate, 1.0 ml/min; detection, suppressed conductivity; sample, 100 μl of a solution containing 1.0 m*M* (upper trace) or 0.1 m*M* (lower trace) of each anion. The peak due to thiocyanate in the lower trace was eluted at a retention time of 378 min. Peak identities: (1) sulfate; (2) chloride; (3) nitrite; (4) bromide; (5) nitrate; (6) chlorate; (7) iodide; and (8) thiocyanate. Reproduced with permission from Ref. [57].

analyte anion with the eluent cation [53]. That is, the cations in the sample did not influence the final chromatogram. Use of sodium bicarbonate as the eluent permitted the EIC separation to be performed in conjunction with a conventional IC suppressor. In this way, the high detection sensitivity obtained with water eluents was maintained, as was the unique separation selectivity of EIC. Fig. 8 (lower trace) shows a separation of inorganic anions performed by suppressed EIC using sodium bicarbonate as mobile phase.

In evaluating the effects of adding an electrolyte to the mobile phase in EIC, it was observed that the first addition of electrolyte caused substantial changes in retention times, but subsequent higher concentrations of electrolyte caused little further change. For example, the chromatogram obtained with 10 m*M* $NaHCO_3$ as mobile phase was almost the same as that obtained using 200 m*M* $NaHCO_3$. This behaviour is quite different from that occurring in conventional ion exchange and demonstrates further that EIC operates under a different mechanism to that of ion exchange. The tolerance of the separation to changes in the electrolyte concentration in the mobile phase suggests that this form of EIC should be applicable to the determination of trace

anions in samples of high ionic strength. This application has been investigated and UV-absorbing analyte anions have been determined successfully in seawater using a dilute synthetic seawater as the mobile phase [58]. This approach is clearly similar in concept to matrix elimination IC which was discussed earlier.

2.2.3. Electrically polarised ion-exchange resins

Hydroxide eluents in IC have hitherto found only limited use because of the difficulty in avoiding carbonate contamination in preparing and using eluents of this type. The ready absorption of carbon dioxide to form carbonate means that the true eluent composition is rarely known accurately, and poor reproducibility of the retention times results. Electrolytic generation of hydroxide eluents has been recently developed wherein water is used as the feed to the electrolysis cell and potassium counter ions are added from an external supply via a cation-exchange membrane to give a very pure solution of potassium hydroxide [59]. Carbonate contamination does not occur to any appreciable extent since the eluent does not come into contact with the atmosphere. Variation of the current flowing through the electrolysis cell can be used to control the strength of the eluent and gradients can be generated by applying a predetermined current–time profile to an electrolysis cell supplied with a constant stream of water as feed. In this way, an isocratic pump can be used in a gradient-IC system. The ability to use hydroxide eluents in a reliable manner has meant that samples containing high levels of hydroxide present less of a separation problem because the anion-exchange sites on the column are already equilibrated with hydroxide, so there is less perturbation caused by the introduction of a high pH sample than would occur for eluents of different composition. This process of electrolytic eluent generation has been commercialised as the Dionex EG40 Eluent Generator, which can also be used to electrolytically produce methanesulfonic acid eluents for the separation of cations.

The use of electrically generated eluents has sparked an increase in interest in the use of electric fields in ion-exchange separations, particularly the use of polarised ion-exchange beds. This has formed the basis of some major developments in IC which have broadened the range of samples to which the technique may be applied. Small and co-workers have designed so called ‘ion-reflux devices’ in which an electrical field is applied longitudinally along a packed-bed cation-exchange column in the potassium form using porous flow-through metal electrodes, with water being passed through the column [60]. The electrolysis reaction occurring at the anode produces hydronium ions which, when carried by the flowing water stream, displace potassium ions from the resin, which then combine with hydroxide produced by the electrolysis reaction at the cathode to produce a potassium hydroxide eluent. In an alternative configuration, the flowing water phase passes not through the packed-bed, but over a cation-exchange membrane which is in contact with the ion-exchange bed. This is illustrated in Fig. 9, which shows that the potassium hydroxide produced in the eluent generator is passed through an injector and a separator column (where analyte ions are separated), and the effluent from the separator column is then returned to the ion-reflux device where the potassium hydroxide eluent is suppressed to water, thereby allowing sensitive conductimetric detection of the analyte anions. In this way, the ion-reflux device serves the dual purposes of eluent generation and eluent suppression. Such a system opens the possibility of an eluent recycling system in which IC is performed simply by circulating water through the ion-reflux device.

In practice, eluent recycling can be achieved by using two electrically polarised resin beds, arranged as in Fig. 10 [57]. Here, the resin beds are of identical size and each is fitted with a pair of porous metal electrodes. At the start of the separation, each bed is roughly half in the hydronium form and half in the potassium form. The upper bed is electrically polarised and functions as the eluent generator, whilst the lower bed is electrically passive and functions as the suppressor. At the end of the chromatographic run, the upper bed has become partially depleted in potassium ions, whilst the lower bed has become partially depleted in hydronium ions. If the roles and positions of the two beds are now reversed, and their orientations to the direction of flow of water are also reversed, the system has been re-established to its condition before the in-

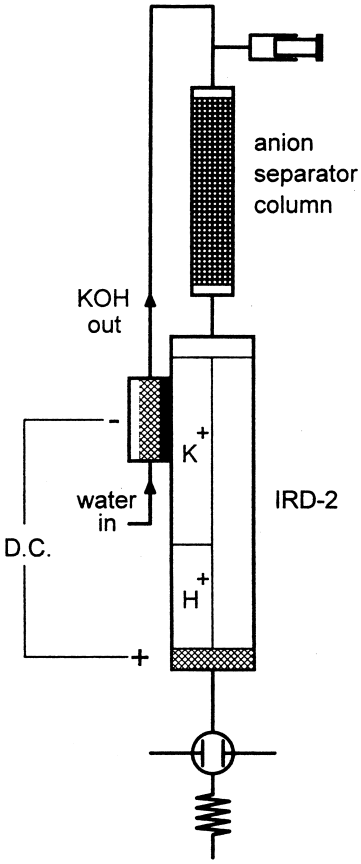

Fig. 9. An IRD-2 in an IC system. The solid black rectangle represents the cation-exchange membrane separating the resin bed from the cathode compartment. Reproduced with permission from Ref. [56].

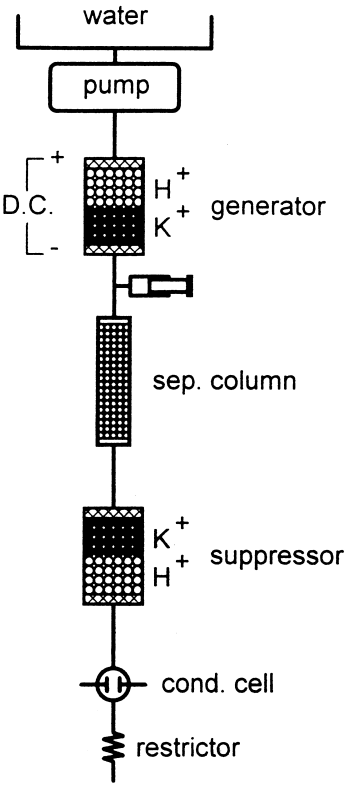

Fig. 10. The basis of eluent recycling. Reproduced with permission from Ref. [61]

jection of sample. This reversal can be accomplished with the aid of appropriately configured switching valves [57]. Injection of a new sample can then proceed and the whole cycle can be repeated. If the ion-exchange beds have sufficient capacity, several samples may be analysed before the roles of the beds are reversed.

Electrically polarised ion-exchange resins have also been used to maintain continuous operation of an IC system using solid-phase suppressors [62]. In this case, two small ion-exchange beds (in the hydronium form) fitted with electrodes are used (Fig. 11). A sodium hydroxide eluent (not produced by electrolysis) is supplied to the separator column and is then suppressed by passage through one of the resin beds which is not electrically polarised. The effluent (water) is passed to the second bed (which is electrically polarised) and the electrolysis reaction brings the resin completely to the hydronium form. The two beds are then reversed, so that the bed which was formerly used as the suppressor (and therefore contains some sodium from the eluent) now becomes electrically polarised and is regenerated, whilst the other, fully regenerated bed now becomes the suppressor. In this way, a fresh suppressor is used for each injection and potential problems caused by using a partially regenerated suppressor are avoided. In addition, the ion-exchange beds used are physically very small, so that band-broadening effects do not occur. This system has been commercialised by Alltech Associates as the 'Electrically Regenerated Ion Suppressor (ERIS)' method.

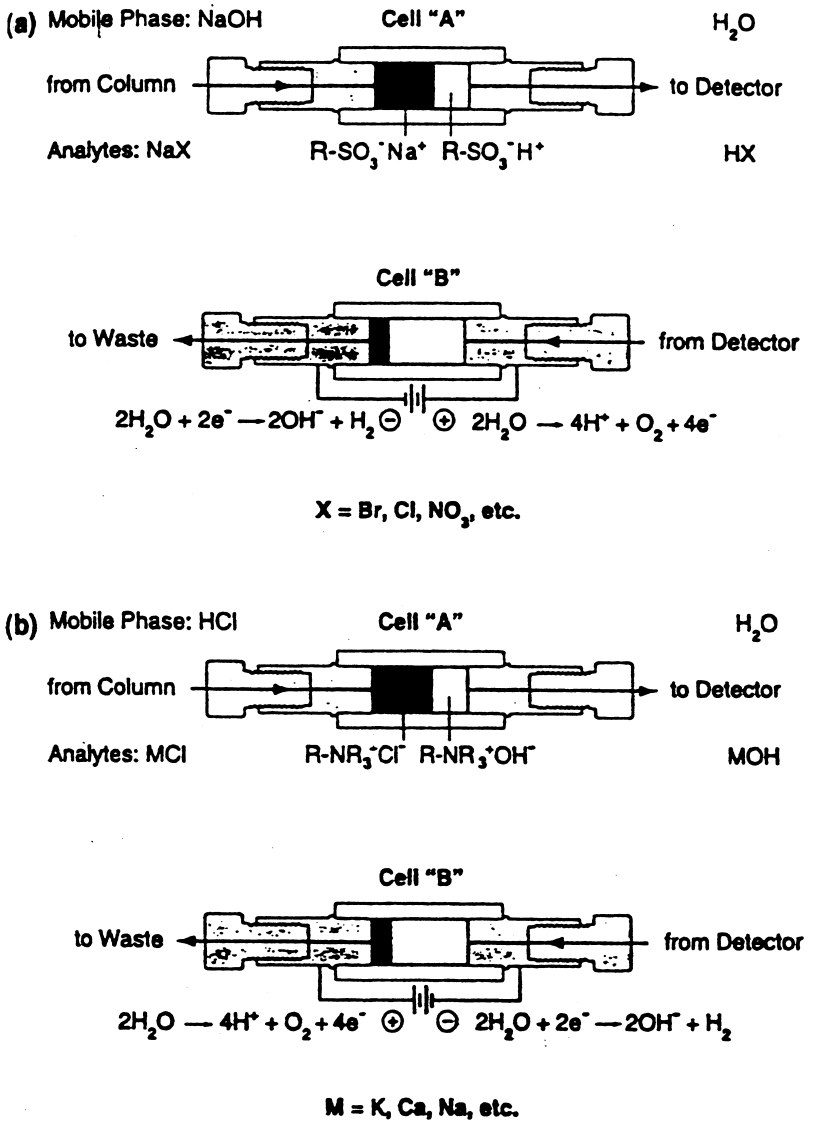

Fig. 11. Suppression and electrochemical regeneration during (a) anion analysis and (b) cation analysis. Cell 'A' suppresses the eluent while cell 'B' is electrochemically regenerated. Reproduced with permission from Ref. [58].

3. Capillary electrophoresis (CE) for inorganic analysis

Most of the applications of CE to the determination of inorganic species involve the injection of free ions and their separation by conventional free zone capillary electrophoresis using a fused-silica capillary, an in-line UV–Vis absorbance detector, and using hydrostatic injection. Detection is frequently accomplished by indirect absorbance techniques. The separation of inorganic anions and cations will be discussed below, but once again, the separation of organometallic species or metal chelates will not be included. As was the case for IC, it will be assumed in the ensuing discussion that the sample preparation methods outlined in Section 3.1

are intended for use with a conventional instrument, with any newer developments in separation techniques being discussed separately in Section 3.2.

3.1. Sample preparation for CE

3.1.1. Introduction

It is interesting to note that the samples which presented the most difficulty in IC are also difficult to analyse by CE. These samples are those containing a high-ionic strength matrix, whether this be caused by high concentrations of an electrolyte or by elevated acidity or basicity. These types of samples cause problems in CE in several ways. First, the high ionic strength imparts a low electrical resistance, which interferes with the sample stacking process leading to loss of the very high separation efficiency usually encountered in CE. Analyte peaks often become very broad and of poor shape. Second, the electroosmotic flow (EOF) in the capillary can be altered by the influence of the sample matrix, especially as a result of changes in the degree of ionisation of silanol groups on the wall of the capillary. Third, the detector baseline is usually perturbed when the pH of the sample differs greatly from that of the background electrolyte (BGE). This particular aspect is discussed in more detail in Section 3.2.1.

There are some fundamental differences in the tolerance of IC and CE to high-ionic strength matrices. In IC it was a feasible option to dilute the sample (to negate the deleterious effects of the matrix) and to then rely on the high sensitivity of conductivity detection to establish a suitable analysis. In CE this is not an attractive approach because the detection sensitivity of indirect absorbance detection is not very high. On the other hand, high levels of acids and bases are often more easily accommodated in CE than IC. The reason for this is that hydronium and hydroxide ions each have very high electrophoretic mobilities in comparison to inorganic anions and cations, so it is possible to arrange the experimental conditions such that these species migrate rapidly through the capillary and are eliminated prior to the arrival of the analyte ions at the detector. If the BGE is designed to be relatively insensitive to pH changes and data collection is delayed until the interferences have passed, a relatively clean electropherogram often results. However, the success of this approach is limited to specific applications and the ensuing discussion will elaborate on a wider range of techniques for sample handling and separation which broaden the applicability of CE to the determination of inorganic species.

3.1.2. Manipulation of separation selectivity in CE

The opportunities for varying the separation selectivity in CE are rather limited in comparison to IC, and this is especially true for the separation of inorganic anions. Some of the more useful approaches to the manipulation of separation selectivity for inorganic analytes are discussed below, but the interested reader is referred to two recent reviews dealing with this subject [63,64]. The discussion will be limited to those approaches which enhance the tolerance of the separation to complex matrix compositions.

Selectivity effects in CE arise from three main sources, namely chemical parameters, instrumental parameters, and from the capillary itself. Of these, the chemical effects are by far the most significant and are caused by changes to the nature of the analyte (e.g. through solvation, complexation or ion-pairing effects), or by specific chemical interactions between the analyte and the BGE. The effective mobilities of inorganic anions have been found to be dependent on the nature and concentration of an organic solvent added to the BGE. These effects have been attributed to changes in the solvation volume or pK_a of the analyte, which in turn alter the charge:mass ratio of the analyte [65,66]. The type and concentrations of organic solvents used vary widely and the choice depends on the effect of the solvent on detection, baseline noise, miscibility with the BGE, etc. However, aliphatic alcohols, acetonitrile and tetrahydrofuran are used commonly.

To rapidly separate inorganic anions by CE, cationic surfactants (or EOF ‘modifiers’) are usually included in the BGE to reverse the EOF flow so that it moves in the same direction as the migrating anions. The presence of the surfactant offers a further opportunity for the manipulation of selectivity and this aspect has been reviewed recently [67]. Typical EOF modifiers are hydrophobic quaternary ammonium salts, such as tetradecyltrimethyl-

ammonium bromide (TTAB), dodecyltrimethylammonium bromide (DTAB), and cetyltrimethylammonium bromide (CTAB). The effect of the length of alkyl chain on the surfactant on separation selectivity of inorganic anions has been studied by Buchberger and Haddad [68], who showed that analyte ions which were prone to ion-pairing effects (such as thiocyanate and iodide) gave decreased relative migration times with increasing size of the alkyl chain. The concentration of the cationic surfactant in the BGE can influence the selectivity by a similar mechanism, with ion-pairing being favoured at higher concentrations of surfactant. In using this parameter to manipulate selectivity, care must be taken not to exceed the critical micelle concentration of the surfactant since chromatographic partitioning effects with the micelle might also play a part in the separation. Ion-pairing effects are pronounced for polarisable or lipophilic anions, but other anions also show selectivity changes of this type. The reversal of migration order between nitrite and sulfate with increasing surfactant concentration has been indicated as being due to a greater ion-association between the sulfate and the surfactant and the same argument has been used for the selectivity change between chloride and bromide at ≥0.6 m*M* CTAB or ≥0.5 m*M* TTAB [69].

A further means to manipulate selectivity is to mix two or more surfactants together and to seek a selectivity in the mixed surfactant system that differs from that obtained using the two component surfactants individually as the EOF modifier. This approach has been reported for binary mixtures of DTAB and TTAB [70,71]. Selectivity changes were evident for chloride, nitrite and fluoride as a function of total surfactant concentration and the molar ratios of the surfactants. Binary mixtures of cationic surfactants were used to simultaneously separate over 10 anions in Bayer liquor in 4 min [71]. This is illustrated in Fig. 12, in which a standard mixture separated using BGEs with single 2.6 m*M* DTAB (Fig. 12a) and 2.6 m*M* TTAB (Fig. 12b) suffered from poor resolution of bromate and nitrite from their respective adjacent anions. By using a BGE containing a binary mixture of 2.6 m*M* each of DTAB and TTAB, the problems noted above were eliminated (Fig. 12c). Finally, it should be noted that there are some practical limitations to the use of surfactants in manipulating anion selectivity. CTAB and TTAB are disadvantaged by limited solubility and formation of insoluble ion-associates with some BGE components. The useful pH range can also be limited due to precipitation effects.

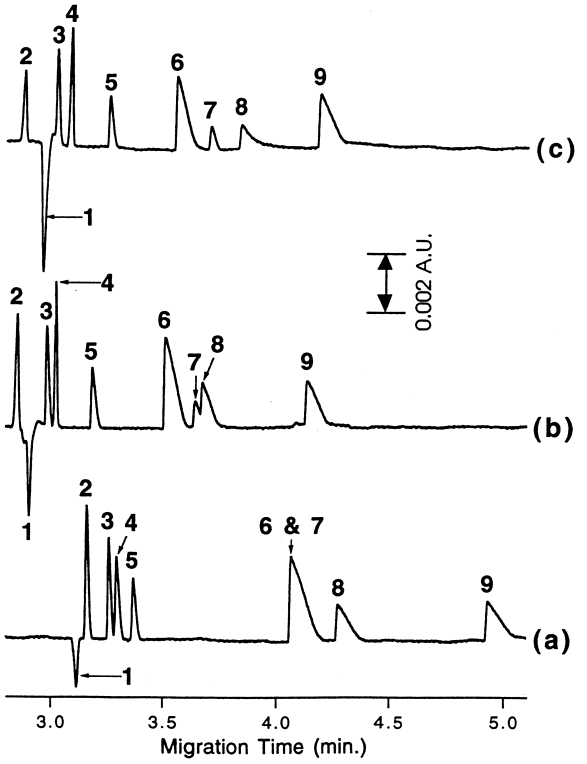

Fig. 12. Comparison of separations using DTAB and TTAB singly and as binary mixtures. Conditions: (a) 2.6 m*M* DTAB, 5 m*M* chromate and pH 9.1 (sampling was in the hydrostatic mode (10 cm for 30 s) and indirect UV at 254 nm was used for detection; other conditions were as in Fig. 5); (b) 2.6 m*M* TTAB (other conditions as in (a)). (c) BGE had 2.6 m*M* TTAB and 2.6 m*M* DTAB. Other conditions were as in (a). Anions: (1) system (bromide); (2) chloride; (3) nitrite; (4) sulfate; (5) nitrate; (6) fluoride; (7) bromate; (8) phosphate; and (9) carbonate. Reproduced with permission from Ref. [64].

The separation selectivity in CE arises from the differences in the electrophoretic mobilities of the analytes. Whilst the mobilities of metal cations as hydrated ions range from about 40×10^{-9} m^2 V^{-1} s^{-1} (Li^+) to about 80×10^{-9} m^2 V^{-1} s^{-1} (Rb^+), the values for individual members of the main groups of metal ions, such as lanthanides or transition metals, are often very similar so that a separation of these species would demand extremely high (or even

unattainable) efficiencies. The solution to this dilemma is the use of auxiliary ligands which introduce secondary equilibria into the separation through the formation of complexes with the metal ions, thereby leading to the achievement of substantial changes in selectivity. For an analyte species present in several forms which are in equilibrium with rapid kinetics of interchange between the forms, the effective mobility of the analyte is defined as the weighted average of all the mobilities of each of the forms. Metal ions are separated either as partial or fully complexed species with the auxiliary ligand.

Utilisation of the partial complexation of the analyte metal ion with a weakly complexing ligand was first demonstrated in CE by Foret et al. [72] and further studies on methods for manipulating the separation selectivity of these systems followed. Typical ligands have been 2-hydroxyisobutyric acid (HIBA), tartrate, lactate or even crown ethers. Fig. 13 shows how this approach enables the simultaneous separation of several classes of metal ions (in this case, alkali metals, alkaline earths, transition metals and lanthanides) [11]. A different situation occurs when utilising auxiliary complexing ligands forming strong complexes with the metal ions. Since most of the metal ion is complexed under all BGE conditions, selectivity is not as easy to manipulate as in the case of weakly complexing ligands. Apart from minor factors influencing the selectivity, such as solvation changes in various media, there are only very few means to bring about a change in the charge/mass value of the analytes (and consequently a substantial change in selectivity). Typical ligands forming strong metal complexes used for the separation of metal ions by CE include cyanide [73], 8-hydroxyquinoline-5-sulfonic acid (HQSA) [74],

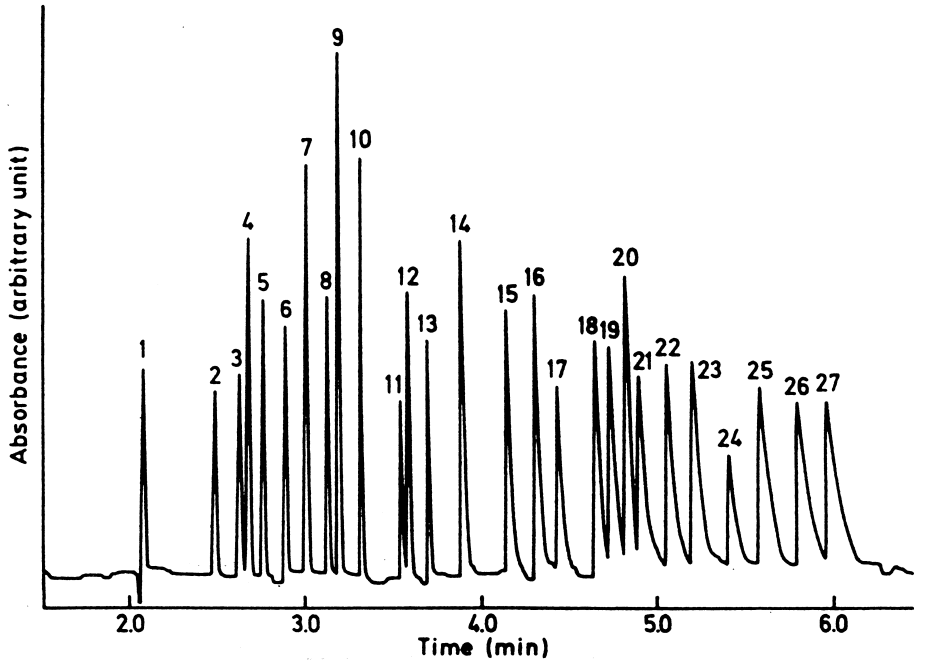

Fig. 13. Separation of 27 alkali, alkaline earth, transition and rare earth metal ions in a single run using lactate as auxiliary ligand. Capillary, fused-silica 75 μm I.D., 0.600 m length, 0.527 m to detector; BGE, 15 m*M* lactic acid, 8 m*M* 4-methylbenzylamine, 5% methanol, pH 4.25; separation voltage, 30 kV; detection, 214 nm; injection, hydrostatic (30 s); sample, 1–5 ppm of each metal. Peak identification: (1) K^+; (2) Ba^{2+}; (3) Sr^{2+}; (4) Na^+; (5) Ca^{2+}; (6) Mg^{2+}; (7) Mn^{2+}; (8) Cd^{2+}; (9) Li^+; (10) Co^{2+}; (11) Pb^{2+}; (12) Ni^{2+}; (13) Zn^{2+}; (14) La^{3+}; (15) Ce^{3+}; (16) Pr^{3+}; (17) Nd^{3+}; (18) Sm^{3+}; (19) Gd^{3+}; (20) Cu^{2+}; (21) Tb^{3+}; (22) Dy^{3+}; (23) Ho^{3+}; (24) Er^{3+}; (25) Tm^{3+}; (26) Yb^{3+}; (27) Lu^{3+}. Reproduced with permission from Ref. [11].

Table 2
Equilibria utilised for governing the separation selectivity of cations (from Ref. [63])

Complexation mode	Source of separation selectivity	Examples of ligands
Partial	Complexation with the auxiliary ligand	HIBA, lactate, etc.
Total	Influence of the metal on the pK_a of ligand group	PAR [118]
	Dissociation of bound water molecules to mixed hydroxo–ligand–metal complexes)	EDTA, CDTA and analogues [80]
	Ion-association (e.g. with TBA^+ or hexamethonium bromide)	CN^- [69]
	IEEKC (ion-exchange electrokinetic chromatography), e.g. with poly(diallyldimethylammonium chloride)	EDTA [119]

and aminopolycarboxylic acid ligands such as EDTA and CDTA [75,76].

Some generalised conclusions can be drawn about the mechanisms which govern selectivity in separations of metal ions using auxiliary ligand and these are summarised in Table 2. Significant selectivity changes can be achieved by employment of complexation equilibria in the partial complexation mode. In the total complexation mode, however, it is usually not possible to govern the selectivity with changes in ligand concentration since almost all of the metal is usually complexed, and other mechanisms have to be utilised.

3.1.3. General sample treatment

Real samples often require the application of simple procedures such as sample extraction, filtration to remove particular matter, or dilution, prior to the CE step and an on-line or at-line combination of such procedure(s) with CE is desirable. Arce et al. [77] used an FIA setup for on-line filtration of water samples prior to the CE analysis (Fig. 14). They also constructed a pump-driven unit for extraction and filtration of soil samples combined with CE in an at-line mode (automated sample transfer between the pre-CE sample preparation step and the CE) [78]. The method was precise and four times faster

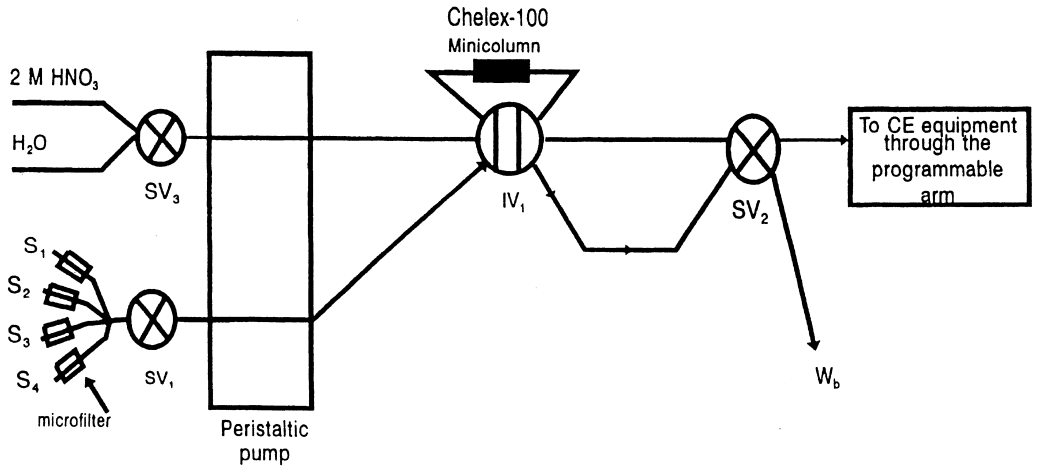

Fig. 14. Single FI system used for sample preparation/introduction in the CE system. IV, injection valve; SV, selecting valve; W, waste. Reproduced with permission from Ref. [73].

compared to conventional methods of sample preparation off-line. Although such sample preparation steps may be regarded as less sophisticated than those to be discussed later, the importance of automated sample preparation for CE is undisputed and is likely to grow in the future.

3.1.4. Electromigration sample preparation techniques

Electromigration injection and stacking/transient isotachophoresis (ITP) are sample handling methods which are relatively easy to combine with CE as they are implemented in the same capillary as for the CE separation step. Electromigration injection appears to be a straightforward procedure but is known to suffer severe matrix-dependence effects [79] and therefore its use for real samples is very limited. Although several authors have reported its use for analyte preconcentration in inorganic analysis [63,80], the robustness of such methods for samples of varying composition is questionable. Stacking of analyte ions in a hydrostatically injected large sample plug is another method mostly used for sample preconcentration and is again performed in the CE separation capillary. While there have been numerous papers and the reader is referred to some excellent reviews on this topic [81–85], applications in inorganic analysis are mostly in the area of preconcentration of dilute samples (typically water) having much lower conductivity than the electrolyte by exploiting the field amplification effect (e.g. Refs. [59,76]).

A somewhat specialised area of sample stacking is those methods utilising an on-capillary derivatisation reaction between the analyte(s) and a reagent either contained within the electrolyte or injected in a plug next to the sample plug, with the derivatised analyte(s) forming a sharp zone at the start of the CE separation [86]. In inorganic analysis, this approach can be applied to determination of metal ions as complexes formed on-capillary between oppositely migrating metal cations and ligand anions converging and reacting at the boundary between the injected sample plug and the BGE [59]). Reagan et al. [87] demonstrated this approach for four divalent metal complexes with PAR in which a plug of 1 m*M* PAR was first injected into the capillary and then electromigration injection from a sample without added ligand was performed (illustrated schematically in Fig. 15). This method with an optimised stacking procedure offered detection limits in the range of 10 n*M*. Macka et al. [88] utilised stacking by on-capillary complexation for the determination of Ba(II) and Sr(II) in waters using on-capillary complexation with sulfonazo(III) and for on-capillary complexation and stacking of lanthanides and U(VI) using a BGE containing citrate and arsenazo(III) [89]. In the latter case, the peak shapes for lanthanides were the same for 100- and 10-s hydrostatic injections (Fig. 16) but the peak of the kinetically inert U(VI) complex was split, which illustrates the problems encountered in CE of metal ions and complexes due to the kinetics of complex formation and dissociation [59]). Finally, Haumann and Baechman [90] developed an interesting two-step on-capillary complexation method. At the start of the run, first a zone of EDTA was injected as a 1 m*M* plug from the injection cathodic side, then metal cations were introduced at the detector side (anodic) and were separated in a partial complexation mode with tartrate present in the BGE, and finally the zones of the metal cations came into contact with the EDTA

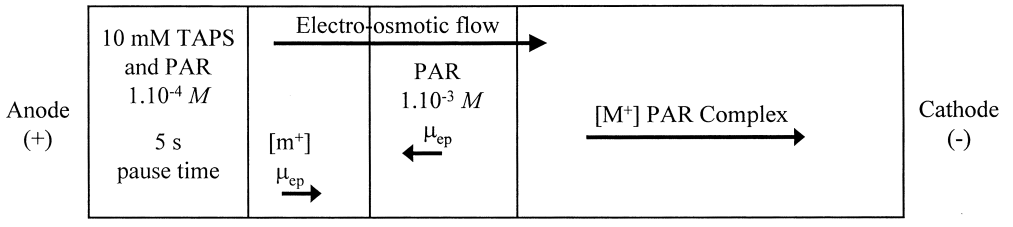

Fig. 15. Schematic diagram of stacking with on-capillary complexation; μ_{ep} is the electrophoretic mobility. Reproduced with permission from Ref. [81].

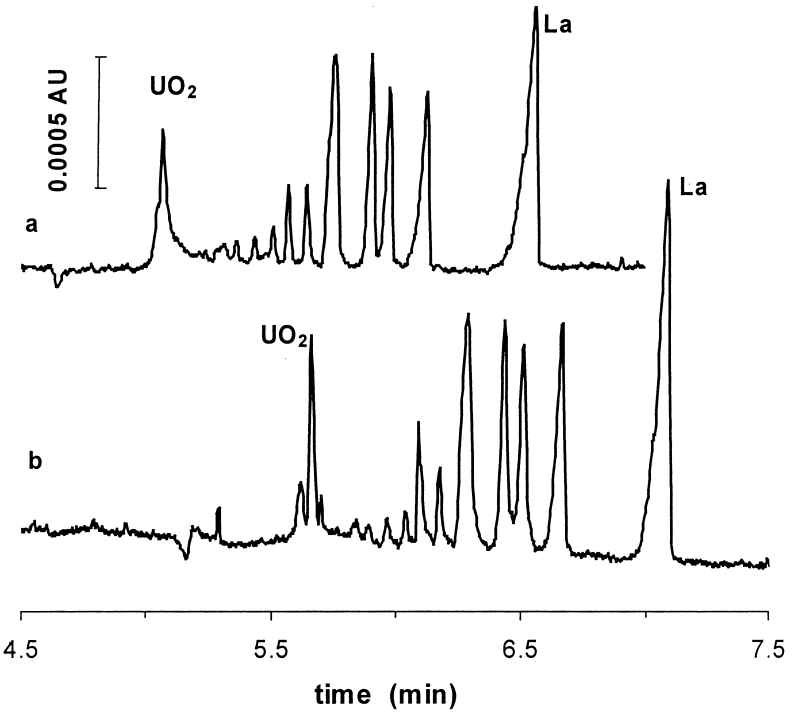

Fig. 16. Electropherograms of separations of U(VI) and 14 lanthanides using a 10-s injection of a standard solution containing 10 μ*M* of each metal (except 20 μ*M* for Tm(III), Yb(III) and Lu(III)) and a 100-s injection of that standard solution 10× diluted. Capillary, FS 0.6000×0.520 m, pre-run dynamically modified with CW20M; injection, hydrostatic (10 s, 100 mm) of a standard solution containing 10 μ*M* of each metal. BGE: 0.025 m*M* A(III) in 15 m*M* citric acid and 20 m*M* Tris (pH 4.3); separation voltage, −30 kV (30 μA); separation voltage, −30 kV (39 μA); temperature, 25°C; detection, LED 654 nm; injection of a standard solution containing 10 μ*M* of each metal (except 20 μ*M* for Tm(III), Yb(III) and Lu(III)) in 10 m*M* HNO_3. Reproduced with permission from Ref. [83].

zone and formed stable EDTA complexes which then migrated to the detector.

Capillary isotachophoresis (CITP) has been coupled with CE by Blatny et al. [91] who determined Fe(III) in water after pre-capillary complexation with EDTA. The purpose of the CITP step was to enable a large sample volume to be used and to permit a sharp zone of Fe(III) to be formed and transferred to the CE capillary for separation. This work serves as a good example of problems which can be encountered when stacking large sample volumes, as elevated blank levels due to impurities in reagents adversely influenced the detection limit (10 ppb). A general remark on the applicability of CITP-CE for sample cleanup is that the mobility of the analyte(s) should differ from the matrix ion(s) to be removed, and for such cases some new applications in inorganic analysis can be expected.

3.1.5. Chromatographic sample preparation

Off-line methods of sample cleanup and preconcentration for CE have been reported. Kuban et al. ([92]) used a supported liquid membrane with a cationic ion-pairing reagent to create a liquid anion-exchanger for preconcentration of negatively charged metallo-cyanide complexes. Enrichment factors between 50 and 600 were achieved. Fritz et al. [93] have discussed the use of ion-exchange and chelating resins to preconcentrate metal ions prior to CE determination. They pointed to the limited usefulness of non-selective ion-exchange methods in contrast to the selective preconcentration of heavy metals using chelating (iminodiacetate or dithiocarbamate) resins, or formation of metal chelates with an excess of the reagent, followed by adsorption of the chelate on a hydrophobic column.

Although there are many examples of chromato-

graphic sample treatment procedures coupled on-line with IC, this is not the case for CE. The preconcentration of heavy metals loaded onto a Chelex resin column shown in Fig. 14 before being eluted with an acid and automatically transferred into the CE is a rare example [73]. Given the recent research activity in the area of in-line (where a plug of adsorbent is inserted in the CE capillary) or on-line (where the effluent from a chromatographic column is sampled into the CE capillary) coupling of chromatographic sample cleanup and preconcentration techniques [85,94–96], new developments in the area of inorganic analysis can be expected.

3.1.6. Sample preparation using dialysis

Dialysis and electrodialysis have been used extensively as an on-line sample preparation for IC, and for both high- and low-molecular-mass organic analytes, dialysis has also been used in on-line combination with CE. The dialysis methods used with CE range from microdialysis (including in vivo) [97,98] over-sampling into a CE capillary through a permeable membrane in a flow-through sampling jacket introduced by Bao and Dasgupta [99], to electrodialysis devices [100–102]. Kuban and Karlberg [103] presented an example of a dialysis/FIA sample cleanup system on-line coupled to a CE (Fig. 17). A number of anions were analysed in a variety of samples with complex matrixes, such as milk, juice, slurries or liquors from the pulp and paper industry. Despite the limited attention devoted hitherto to dialysis and electrodialysis combined on-line with CE, these approaches have good potential for application to inorganic analysis and developments in this area can be anticipated.

3.2. Developments in CE separation methods

As for IC, this section discusses some of the developments in CE separation methods which enhance the ability of the technique to accommodate difficult samples of the types described earlier.

3.2.1. High-ionic strength BGEs

Samples of high ionic strength are problematic in CE due to the loss of sample stacking effects caused by the low electrical resistance of the sample plug, resulting in broadening of peaks and poor separation.

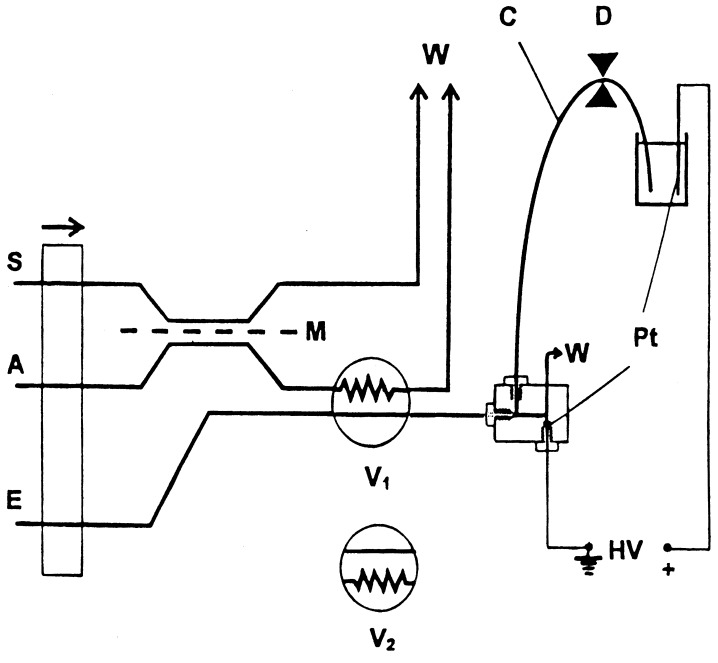

Fig. 17. Schematic diagram of the FIA–CE system used for on-line sample dialysis: (S) sample, (A) acceptor stream, (E) electrode, (M) dialysis membrane, (D) UV detector. Reproduced with permission from Ref. [97].

In IC one of the approaches used for separating samples of high ionic strength was to use the dominant sample ion as the eluent ion, thereby pre-equilibrating the stationary phase functional groups with the dominant sample ion and, therefore, preventing further adsorption of this ion when the sample is injected. This technique, known as matrix-elimination IC, was discussed earlier in Section 2.2.1.

An analogous approach in CE would be to use the dominant matrix ion as a BGE component, but to ensure sample stacking, the BGE would need to be of high ionic strength. It is commonly thought that even a moderately high ionic concentration in the BGE would be impractical due to Joule heating effects, leading to poor peak shapes. However, recent studies [104] have shown that a BGE containing up to 5 *M* sodium chloride can be used for the determination of UV-absorbing inorganic anions in a sample containing up to 0.5 *M* of a salt. In these studies, progressively higher concentrations of sodium chloride were added to a BGE buffered with borate and it was found that a sample made up in water gave good peaks for the constituent analyte anions when the BGE contained 220 m*M* NaCl (Fig. 18). Under these conditions the full power of the instrument was applied, leading to an internal temperature inside the capillary of 49°C, which was insufficient to cause band dispersion through heating effects. Further increases in the concentration of NaCl in the BGE caused no increase in temperature because the separation current was reduced automatically. It was also noted that the addition of salt to the BGE resulted in suppression of the electroosmotic flow, so that anion separations could be undertaken without the need to add a surfactant EOF modifier to the BGE.

When applied to the determination of anions in seawater (which is approximately 0.5 *M* in NaCl), a BGE of 1.5 *M* NaCl provided good sample stacking and acceptable peak shapes for an undiluted sample of seawater. In the general application of high salts BGEs, it was recommended that the BGE be maintained at a salt concentration three times higher than

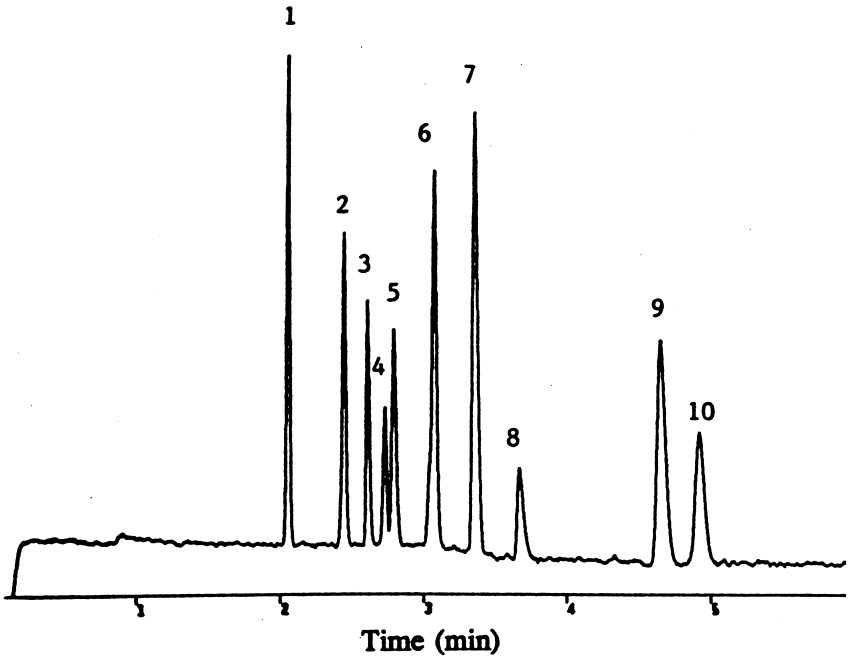

Fig. 18. CE separation of 10 inorganic anions. Capillary, 50 μm I.D., 33 cm length; carrier electrolyte, 10 m*M* borate, 220 m*M* NaCl, pH 8.5 adjusted by NaOH; sampling time, 40 s; voltage, −10 kV; wavelength for detection, 214 nm. Peaks: (1) Br^- (10 ppm); (2) NO_2^- (20 ppm); (3) $S_2O_3^-$ (80 ppm); (4) NO_3^- (2 ppm); (5) N_3^- (40 ppm); (6) $Fe(CN)_6^{4-}$ (20 ppm); (7) MoO_4^{2-} (40 ppm); (8) WO_4^{2-} (40 ppm); (9), CrO_x^{3-} (40 ppm); (10) ReO_4^- (40 ppm). Reproduced with permission from Ref. [98].

that of the sample in order to preserve sample stacking.

3.2.2. Buffering of BGEs

It is noteworthy that many of the BGEs used in early published separations of inorganic species by CE were unbuffered. This characteristic meant that the separations developed were often very intolerant of even minor changes in sample composition. Moreover, electrolysis effects occurring at the separation electrodes caused large changes in pH in both the inlet and outlet electrolyte vials, and these pH changes were shown to enter the capillary through both electromigration and pH effects. Macka et al. [105] have shown that pH changes of >2.5 pH units could be introduced into the separation capillary within 3 min of applying the separation voltage, depending on the relative positions of the capillary and the electrode in the inlet BGE vial. When the tip of the capillary was positioned above the end of the electrode, the pH of an unbuffered BGE changed rapidly during the separation, but this effect was very much diminished when the tip of the capillary was positioned at least 1 mm below the end of the electrode. The importance of buffering of the BGE can be illustrated by reference to Fig. 19, which shows the separations obtained with an unbuffered chromate BGE (the most commonly employed BGE for the determination of inorganic anions) and the same BGE buffered with Tris when the sample contained 50 m*M* NaOH [100].

In view of the fact that most inorganic anions and cations do not absorb appreciably in the UV region, indirect absorbance detection is used widely. In this detection mode, a UV-absorbing co-ion (called the probe) is added to the BGE and detection is effected by the absorbance change caused when the migrating band of analyte ions displace the probe ions from the BGE in accordance with the Kohlraush Regulating Function. This detection mode places particular demands on the approach used to buffer the BGE since the addition of any buffer ions having the same

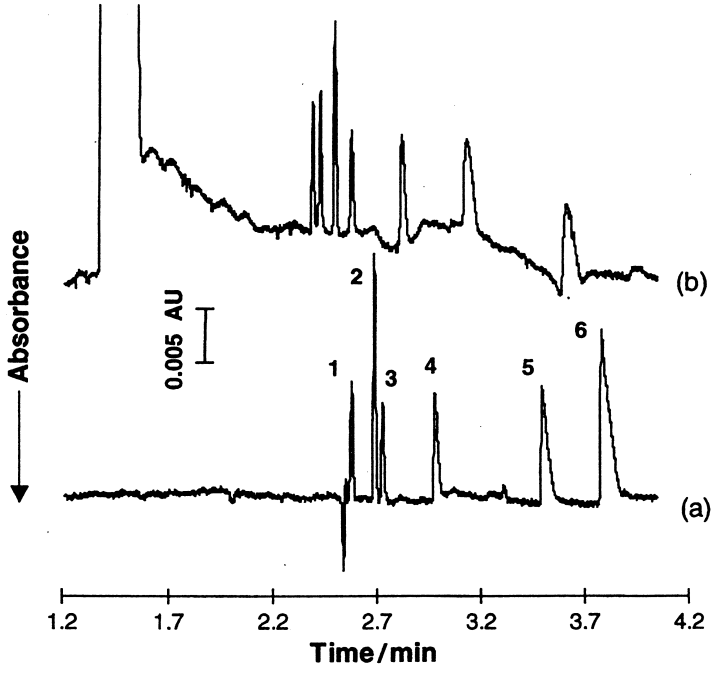

Fig. 19. Electropherograms obtained with buffered (a), and unbuffered (b) chromate electrolytes after injection of solutes in an alkaline matrix. Conditions: separation voltage, −20 kV; indirect detection at 254 nm; hydrostatic injection at 10 cm for 10 s; temperature, 25°C; sample, 0.1 m*M* of each anion in 50 m*M* sodium hydroxide. Key: (1) chloride; (2) sulfate; (3) nitrate; (4) chlorate; (5) phosphate; (6) carbonate. Reproduced with permission from Ref. [106].

charge as the probe can establish competitive displacement processes with the analyte ions, leading to loss of detection sensitivity. System peaks may also be produced in these circumstances.

There are two main approaches to buffering of BGEs for indirect detection which minimise the loss of detection sensitivity and the appearance of system peaks. Firstly, the probe itself or its counter-ion can be used to provide buffering, for example use of phthalate as the probe or the use of Tris as the counter-cation for chromate BGE (see Fig. 19). The disadvantage of this approach is that the concentration of the probe is normally kept low, so the probe or its counter-ion normally cannot alone provide sufficient buffering. Secondly, an ampholyte could be used as a buffer, provided that it exists in a zwitterionic form with zero overall charge. In this form it will not act as a competing co-ion nor will it increase the conductivity of an electrolyte. The buffering capacity of an ampholyte depends on how close together the pK_a values of its buffering groups are to the isoelectric point, and there are few ampholytes which are effective buffers. However, Doble et al. have demonstrated the use of lysine and glutamic acid as ampholytic buffers for inorganic separations [107].

3.2.3. New CE preparation methods

It is instructive to examine the separation selectivities achieved by IC and CE under standard conditions, as revealed by the elution or migration order of common analytes. In the case of IC, anions are eluted in the following order of retention times: $F^- < Cl^- < NO_2^- < Br^- < NO_3^- < PO_4^{3-} < SO_4^{2-} < I^-$. However, the migration times of these species in co-EOF CE are $Br^- < Cl^- < SO_4^{2-} < NO_2^- < I^- < NO_3^- < F^- < PO_4^{3-}$ and in counter-EOF CE are $F^- < PO_4^{3-} < NO_3^- < I^- < NO_2^- < SO_4^{2-} < Cl^- < Br^-$. These sequences show that the selectivities of each of the three techniques are quite different. A similar pattern emerges when the same comparison is made for inorganic cations for which the IC retention times follow the order $Li^+ < Na^+ < NH_4^+ < K^+ < Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+}$, whilst migration times for co-EOF CE are $NH_4^+ < K^+ < Ba^{2+} < Sr^{2+} < Ca^{2+} < Na^+ < Mg^{2+} < Li^+$ and for counter-EOF CE are $Li^+ < Mg^{2+} < Na^+ < Ca^{2+} < Sr^{2+} < Ba^{2+} < K^+ < NH_4^+$. Complementary selectivities are again apparent.

These selectivities suggest that a mixed-mode separation system in which the movement of analytes is influenced both by electromigration effects and ion-exchange interactions might provide a means to manipulate selectivity in order to solve existing separation problems. Such a mixed-mode separation system can be created by adding an ion-exchange stationary phase (or pseudo-stationary phase) to a conventional CE capillary.

Capillary electrochromatography (CEC) can be performed by packing the capillary with ion-exchange particles and the relative contributions of ion-exchange and electromigration can be manipulated by varying the concentration of a competing co-ion in the BGE. Thus a low concentration of co-ion would results is a small degree of ion-exchange competition, so that ion-exchange interactions between the analyte and the stationary phase would dominate retention. On the other hand, a high concentration of competing co-ion would compete effectively with the analyte ions for the exchange sites on the stationary phase, so that the migration of the analyte ions would be largely influenced by electromigration effects (Fig. 20).

A similar approach involves using a soluble pseudo-stationary phase, which has an advantage over CEC in that the instrumental implementation is straightforward (especially the lack of a need for column packing and the construction of frits). Strong interactions can be obtained with small additions of pseudo-stationary phase to the electrolyte. Soluble polymeric pseudo-stationary phases have been shown to be ideal for influencing selectivity while still providing high-efficiency separations. Krokhin et al. [108] have used cationic polymers to introduce interactions to influence the separation of metal complexes of 4-(2-pyridylazo)resorcinol, and ion-exchange interactions of free metal ions have been reported by Buchberger et al. [109] who examined the influence of adding an ion-interaction agent (sodium dodecylsulfate (SDS)) to the electrolyte. For divalent metals having a strong interaction with SDS, it was demonstrated that the metals could be made to migrate after the EOF, indicating the influence of strong ion-pairing type interactions. Chromatographic particles can also be employed as a pseudo-stationary phase by using a suspension of the particles as the electrolyte. In the first demonstration of

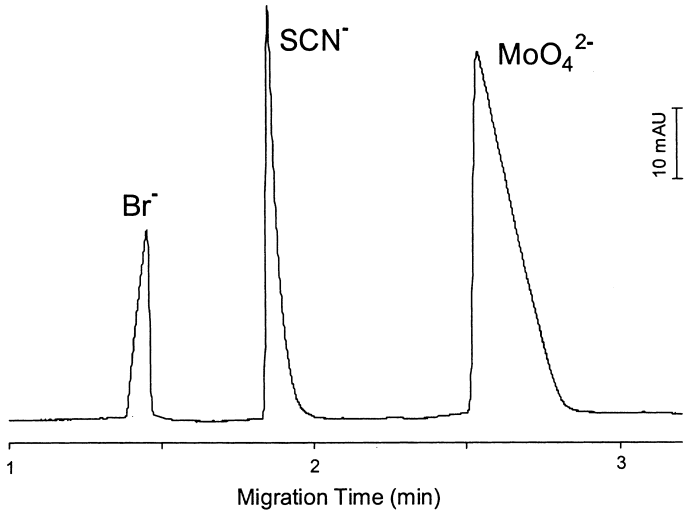

Fig. 20. CEC of inorganic anions performed using an anion-exchange stationary phase. Conditions: column, 75 μm I.D., 34.5 cm total length, 25-cm packed bed; stationary phase, 3-μm silica-based strong anion exchanger (Xtec Consultants); BGE, 10 m*M* sulfuric acid titrated to pH 8.2 with Tris; separation voltage, −25 kV; electrokinetic injection, −10 kV for 10 s; concentration of each anion, 0.2 m*M*; detection wavelength, 214 nm. Electropherogram courtesy of Emily Hilder.

this technique Bächmann et al. [110] used 1.5-μm reversed-phase particles coated with SDS to separate nine phenols. The surfactant was necessary to impart some charge and consequently electrophoretic mobility to the particles so that the analytes could be separated by their selective interactions with the stationary phase. Recently, studies have been undertaken using cation-exchange particles as a pseudo-stationary phase in capillary electrochromatography of inorganic cations [111]. The influence of these particles on the separation selectivity of alkali metals and ammonium was determined to explore the feasibility of using a combination of CE and IE separation, and methods for switching between the two separation modes, for the determination of these cations. These analytes were chosen because their elution order in IE ($Li^+ < Na^+ < NH_4^+ < K^+ < Rb^+ < Cs^+$) is the nearly the reverse of their migration order in CE conducted in the co-electroosmotic mode ($Rb^+ < Cs^+ < NH_4^+ < K^+ < Na^+ < Li^+$) [112]. A 0.015% (w/v) suspension of sulfonated polystyrene–divinylbenzene particles (particle size 225 nm) containing imidazole as an indirect detection probe was used as BGE. The negative surface charge on the particles imparts an electrophoretic mobility of -25.46×10^{-9} m^2/Vs, so that these particles will, therefore, migrate after the EOF in the co-EOF mode. Evidence of the interaction of the metal ions with the SPR will, therefore, appear as a reduction in the observed electrophoretic mobility of the analytes. Fig. 21 shows that this behaviour was observed and that the predicted changes in the migration order were also apparent. The migration order with no pseudo-stationary phase was $Cs^+ < Rb^+ < NH_4^+ < K^+ < Na^+ < Li^+$; however, at a concentration of 0.015% of the suspension, the migration order was $NH_4^+ < Rb^+ < K^+ < Cs^+ < Na^+ < Li^+$.

4. Future trends

4.1. Comparison of IC and CE

Before attempting to outline the possible future trends in IC and CE of inorganic ions, it is important to recognise the fundamental differences between the two techniques and their relative strengths and weaknesses. CE and IC have been compared by several authors [112,113], who have pointed out that the two techniques differ in their stages of development, separation efficiency, separation selectivity (as discussed in Section 3.2.3 above), analytical per-

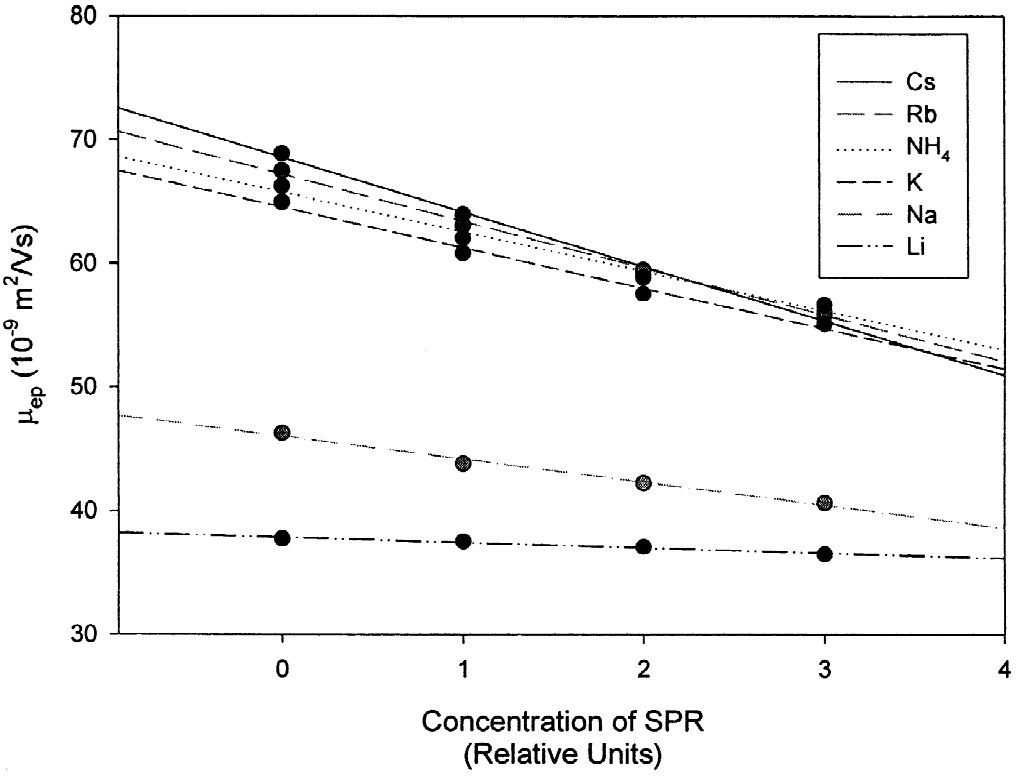

Fig. 21. Change in electrophoretic mobility for monovalent analytes caused by increasing concentration of solid-phase reagent (SPR) added to the BGE. Concentration of 3 relative units corresponds to a dilution of 1:1000 SPR added to the electrolyte. Conditions: 67.0 cm capillary (60.5 cm to detector), +25 kV, indirect absorbance detection at 214 nm, 1 s injection at 0.5 p.s.i.. Electrolyte: 5 m*M* imidazole, 10 m*M* MES, pH 6.15; sample, 2 m*M* of each metal ion. Reproduced with permission from Ref. [105].

formance characteristics, and applications. Some discussion of these aspects is pertinent as a basis for predicting future trends. It should be pointed out here that this comparison is restricted to the mainstream manifestations of each technique, namely ion-exchange separation and conductivity detection for IC, and co-EOF separation with indirect absorbance detection for CE.

It is readily apparent that IC and CE are at very different stages of development. IC has been included in a number of standard methods of analysis for regulatory purposes, whereas CE is less developed. This difference is particularly evident when one considers the range of applications to which the two techniques have been applied. IC is used for a much wider range of samples than has CE and enjoys a higher level of routine usage. It is interesting to note that the development of IC applications has continued at a high rate for the past 5 years and the number of new IC applications introduced over this period far exceeds that for CE. There is little evidence of an increase in CE applications which might be expected if it was emerging as the potential replacement for IC. However, the CE applications commonly address a sample or analyte type which is difficult to analyse using IC (e.g. the determination of fluoride in Bayer liquor shown in Fig. 12), so the two techniques are complementary in this respect.

A striking difference between the IC is the separation efficiency. If one uses the number of theoretical plates to quantify the efficiency (remembering that the concept of a theoretical plate is not strictly applicable to CE) then there is an approximate 50-fold increase in efficiency between the two techniques in routine applications (4000 plates for a 15-cm IC column and 250 000 plates for a 50-cm CE

capillary). At first glance this increase in efficiency would appear to endow CE with an enormous advantage over IC. However, it is instructive to examine the peak capacities (that is, the number of peaks which can be baseline resolved in a given time window) of each technique. To do this one must first consider the manner in which efficiency varies over the specified separation time window. In a typical IC chromatogram the efficiency of successive peaks reaches a fairly constant level for peaks with capacity factors in the range 2–10, and the peak capacity calculated for the time window of 1–20 min is approximately 32. Repeating this process for a typical electropherogram obtained for CE shows that a plot of the number of theoretical plates (N) versus analyte mobility reaches a maximum when the analyte mobility is close to that of the electrolyte. When there is a difference between the mobilities of the analyte and electrolyte, the peak shape is distorted leading to reduced values of N. The wide variation in N over the electropherogram is in direct contrast to that observed for IC and leads to the peak capacity for CE being considerably less than one would expect by consideration of the maximum value of N alone. Choosing a time window of 5 min for a co-EOF system, the peak capacity is approximately 88.

Table 3 summarises some of the analytical performance parameters of the mainstream IC and CE methods and shows that IC is considerably more sensitive than CE, but the techniques display similar sensitivities if preconcentration (for IC) or electromigration injection (for CE) are employed. It should be noted that preconcentration in IC usually also results in the achievement of some selective sample clean-up (see Section 2.1.3) which can permit it to be applied to more complex sample matrices than is the case for electromigration injection in CE. In terms of precision, relative standard deviations (RSD) of 1% or less are routinely achievable in IC, but precision is somewhat worse for CE. Two factors contribute to this. The first is that the migration time of an analyte in CE is governed not only by the electrophoretic mobility of the analyte but also by the mobility of the EOF, and the second is the small magnitude of the detection signal in CE due to the short light path used. Signal-to-noise ratios are, therefore, smaller in CE than in IC for similar analyte concentrations, leading to the possibility for increased error in measurement of peak areas.

The relative strengths and weaknesses of IC and CE are summarised in Table 4. It can be seen that the strengths of IC lie in the highly developed nature of the technique, its broad applications base, and the relative ease with which it can be applied to demanding analyses. It weaknesses relate to considerations of speed, separation efficiency and costs of consumables, which are the same areas in which the strengths of CE lie. Similarly, the weaknesses of CE are generally in the aspects where IC is strong. Table 4 demonstrates clearly the complementarity of the two techniques, which was also evident in the earlier discussion of separation selectivity and applications.

4.2. IC and CE in the next millennium

The foregoing discussion allows some insight into the future trends in IC and CE. Future developments in IC might include further advances in sample handling to extend the application of IC to more complex samples, the development of new stationary phases offering different separation selectivities to those available currently, and the increased usage of IC in hyphenated techniques. Miniaturisation and increased portability of IC instrumentation will occur and it is possible that research in building analytical instruments on microchips will include work on IC.

Table 3
Some analytical performance parameters for IC and CE (from Ref. [106])

Parameter	IC[a]	CE[b]
Detection limit (direct sample injection)	10 ppb, 50 μl	200 ppb, 30 s
Detection limit (sample preconcentration)	<1 ppb	<1 ppb
Precision	1% RSD	3-5% RSD

[a] Suppressed IC system, conductivity detection.
[b] Indirect UV detection.

Table 4
Strengths and weaknesses of IC and CE (from Ref. [106])

Technique	Strengths	Weaknesses
IC	Broad range of applications	Moderate speed
	Well-developed hardware	Moderate separation efficiency
	Many detection options	Intolerance to some sample matrices (e.g. high ionic strength)
	Reliability (good accuracy, precision)	High cost of consumables
	Accepted as standard methodology	
	Manipulation of separation selectivity is simple	
	High sensitivity	
CE	High speed	Instability and irreproducibility of migration times and peak areas
	High separation efficiency	Moderate sensitivity
	Good tolerance to sample matrices (especially high pH)	Manipulation of separation selectivity is difficult
	Low cost of consumables	Detection options are limited
		Routine applications are limited

Finally, further development of expert systems and computer-assisted optimisation packages for IC can be expected, leading to increased commercial availability of such software.

Future directions in CE will address the weaknesses listed in Table 3. Stability and ruggedness of the technique, especially for anions, will be improved through the use of stable, bonded-phase capillaries. Detection options will increase, particularly in the areas of electrochemical detection (both amperometry and potentiometry), suppressed conductivity detection, and post-column reaction detection. The hardware technology can be expected to improve and the range of applications will increase as more scientists adopt CE as a routine tool for inorganic analysis. Microchip technology for CE is already a reality and is likely to be examined as a tool for inorganic analysis. Finally, capillary electrochromatography, which can be considered to be a hybrid of IC and CE and which combines the advantages of both techniques, can be expected to be applied to the ions of interest.

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