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DETERMINATION OF INORGANIC ANIONS BY HIGH-PERFORMANCE LIQUID CHROMATOGRAPHY

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CONTENTS

1. INTRODUCTION

Chromatographic techniques, and in particular ion-exchange methods, have long been used for the analysis of inorganic ions using diverse monitoring techniques such as conductivity, polarography and spectrophotometry. A major advance in this field occurred in 1975, when Small *et al.*[1] described a novel system for the chromatographic determination of inorganic ions, in which a specially developed pellic-

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ular resin was used to effect the separation and a second ion-exchange column to reduce the background conductivity of the eluent in order to improve the detection limits for the eluted analyte ions. This system, which is described in detail later, illustrated the enormous potential of chromatography for inorganic ion analysis and deservedly received considerable research attention for some years. An important side effect of this development was to stimulate greatly research into alternative chromatographic methods suitable for inorganic ions, and over the past 7 years a considerable volume of material has been published. It is the purpose of this paper to review these alternative methods, and therefore those articles which employ the same or a similar technique to that used by Small *et al.* will be discussed only briefly in order to provide a basis for comparison with other methods.

Further to the above specific restriction, this review will be confined to a discussion of methods that are chiefly applicable to anion analysis, because until very recently these methods have far outnumbered those for cation analysis. The preponderance of research into chromatographic methods for anions strongly reflects the paucity of alternative analytical procedures. This situation does not apply to cations, for which a number of excellent rapid and sensitive spectroscopic techniques (such as atomic-absorption spectrometry and inductively coupled plasma atomic-emission spectrometry) and electrochemical methods (such as polarography and anodic-stripping voltammetry) are available. Moreover, many of these are multi-element techniques and so duplicate one of the chief attractions of chromatography for inorganic cation analysis. Despite this, much of the experience gained from the intensive development of chromatographic approaches to inorganic anion analysis has recently been applied successfully to inorganic cations[1–5]. At this stage, however, it is fair to say that these chromatographic methods for cations are generally inferior to the existing spectroscopic and electrochemical methods mentioned above.

In contrast, the use of chromatography for anion analysis has proved so successful that chromatographic methods are among the best available and have been applied to a wide range of inorganic species (Table 1). This success can be attributed to concurrent advances in separation technology and detection methods, and in this review these two aspects will be described separately.

2. SEPARATION METHODS

2.1. Introduction

The separation methods applicable to inorganic anion analysis can be broadly classified according to the scheme shown in Fig. 1. Two major approaches may be identified: ion-exchange using fixed-site exchange resins of various composition and ion-interaction methods using a variety of columns as substrates to support dynamically exchanged or "permanently" bonded ionic functionalities. In addition, a small number of alternative approaches have been reported, the use of amino columns being of most significance.

2.2. Ion-exchange methods

2.2.1. Suppressed systems

It is convenient to subdivide ion-exchange methods for inorganic anion analy-

TABLE 1

INORGANIC ANIONS DETERMINED BY HIGH PERFORMANCE LIQUID CHROMATOGRAPHY

The identification codes are used in Tables 4 and 6.

Anion	*Code*	*Anion*	*Code*
Azide	1	Nitrite	19
Bromate	2	Oxalate	20
Bromide	3	Pentathionate	21
Carbonate	4	Perchlorate	22
Chlorate	5	Periodate	23
Chloride	6	Permanganate	24
Chromate	7	Persulphate	25
Cyanate	8	Phosphate	26
Cyanide	9	Silicate	27
Dichromate	10	Sulphate	28
Hexacyanoferrate(III)	11	Sulphide	29
Hexacyanoferrate(II)	12	Sulphite	30
Fluoride	13	Tetrathionate	31
Germanate	14	Thiocyanate	32
Iodate	15	Thiosulphate	33
Iodide	16	Trithionate	34
Molybdate	17		
Nitrate	18		

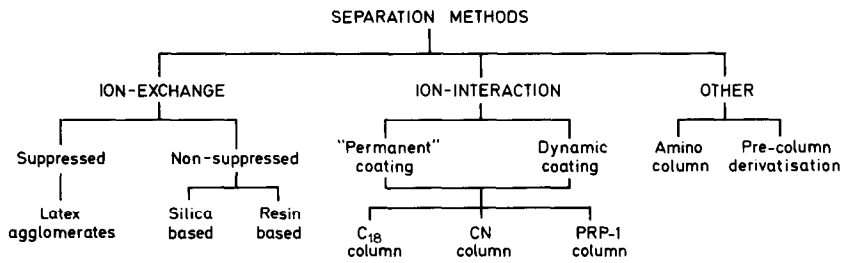


Fig. 1. Schematic representation of separation methods used for inorganic anions.

sis into two groups: those which use a suppressor column and those which do not. The first group includes those methods which are predominantly based on the system originally described by Small *et al.*[1] in 1975 and are generally described by the term "ion chromatography". Here a low-capacity anion-exchange column (called the "separator" column) is used to separate the sample anions and a second column, which consists of some form of strong cation exchanger, is used to reduce the conductivity of the eluent. This second column is generally referred to as the "suppressor" or "stripper" column and, for the purposes of this review, methods that rely on the use of a suppressor column will be described as suppressed systems in order to differentiate them from alternative methods.

The use of suppressed systems for ion chromatography has been the subject of a number of reviews[6–16] and compilations of applications are also available[17–19].

The widespread success of suppressed systems has resulted directly from the novel ion exchanger used in the separator column, together with the innovative use of the suppressor column to improve detectability of eluted ions.

The separator column is packed with a specially developed material consisting of an aminated latex agglomerated on to an ion-exchange substrate. This material contains a core of styrene–divinylbenzene copolymer (S/DVB) beads (20–30 μm diameter) which have surface sulphonic acid groups. These groups serve to hold (via electrostatic attraction) a monolayer of small (0.1–0.5 μm diameter) latex particles that have been converted into an anion-exchange material by amination. The resulting agglomerated particle is stable, resistant to pH changes and, in comparison with conventional microporous ion exchangers, has improved efficiency as a result of reduced mass transfer effects arising from the pellicular configuration of the material[20].

The suppressor column is either packed with a conventional strong cation exchanger or alternatively consists of an ion-exchange membrane formed into hollow fibres through which the eluent passes[21–23]. After traversing the suppressor column, the eluent ions are protonated to produce essentially non-ionized weak acids that have minimal conductivity. In this way, the background conductivity of the eluent is dramatically reduced and eluting sample anions are more easily detected. Full details of the chemistry involved in this process may be found in the above-mentioned reviews of suppressed ion chromatography. A typical separation is shown in Fig. 2, and more complete retention data are provided in Table 2.

This form of chromatography has been extensively studied, and interferences and other adverse effects have been well documented[24–26]. The method has recently been applied to microbore[27,28] (Fig. 3) and gradient elution[29] techniques, and a retention model applicable to eluents containing more than one active species has

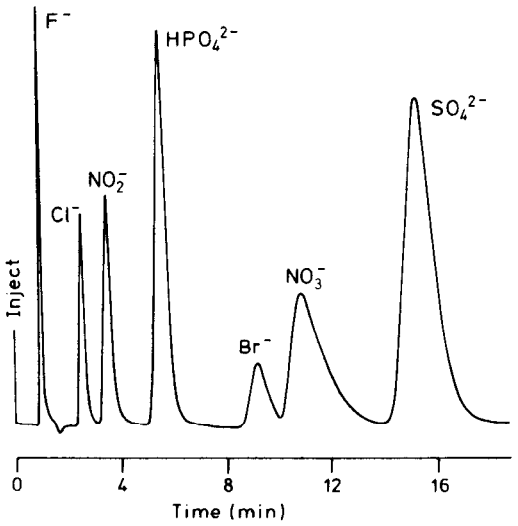


Fig. 2. Separation of some inorganic anions using a latex agglomerate separator column, together with a packed suppressor column. Separator column: 250 × 4.6 mm I.D. packed with 20–30 μm agglomerated material. Suppressor column: 10 × 4.6 mm I.D. packed with 20–40 μm Dionex DC-X8 totally sulphonated resin. Eluent: 3.0 m*M* HCO_3^-–2.4 m*M* CO_3^{2-}. Flow-rate: 3.5 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 3–50 ppm. (From ref. 6, with permission.)

TABLE 2

RETENTION TIMES OF SOME INORGANIC ANIONS ON A LATEX AGGLOMERATE COLUMN

Dionex anion separator column (250 × 4.0 mm I.D.) with anion suppressor. Eluent: 3 m*M* $NaHCO_3$–2.4 m*M* Na_2CO_3 at 2.3 ml/min. (Data from ref. 116.)

Anion	*Retention time (min)*	*Anion*	*Retention time (min)*
F^-	2.4	PO_4^{3-}	8.4
S^{2-}	2.4	AsO_4^{3-}	12.2
IO_3^-	2.6	Br^-	13.0
ClO_2^-	3.0	SO_3^{2-}	13.4
$NH_2SO_3^-$	3.8	N_3^-	14.1
BrO_3^-	4.3	NO_3^-	15.2
Cl^-	4.6	ClO_3^-	15.2
NO_2^-	5.9	SO_4^{2-}	22.8
HPO_3^{2-}	6.7	SeO_4^{2-}	27.2
SeO_3^{2-}	6.9		

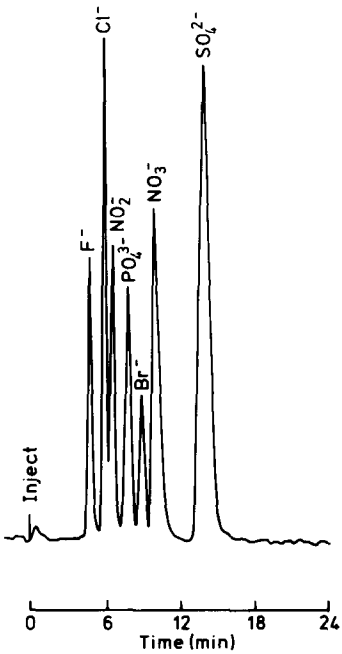


Fig. 3. Separation obtained using suppressed ion chromatography with a microbore separator column and a hollow-fibre suppressor. Separator column: 47 cm × 190 μm I.D. YEW AX-1 resin. Suppressor column: 0.2 mm I.D. Nafion tubing surrounded by 0.05 *M* dodecylbenzenesulphonic acid. Eluent: 4 m*M* Na_2CO_3–4 m*M* $NaHCO_3$ (pH 10.2). Flow-rate: 1.9 μl/min. Splitting ratio 70:1. Injection volume: 20 μl. Temperature: 40°C. Conductivity detection. Solute concentration: 0.07–0.56 ppm. (From ref. 28, with permission.)

also been described[30]. The cost effectiveness of suppressed ion chromatography in comparison with ion-selective electrodes has also been established[31,32].

Other developments that are of special significance to this review include the use of pre-concentration[33,34] and sample cleanup[35,36] techniques to extend the method to incorporate very dilute or complex samples. In addition, it has been demonstrated[37] that conventional types of pellicular materials with relatively high ion-exchange capacities can also provide excellent separations in the suppressed mode, provided that eluents of suitable pH are employed (Fig. 4).

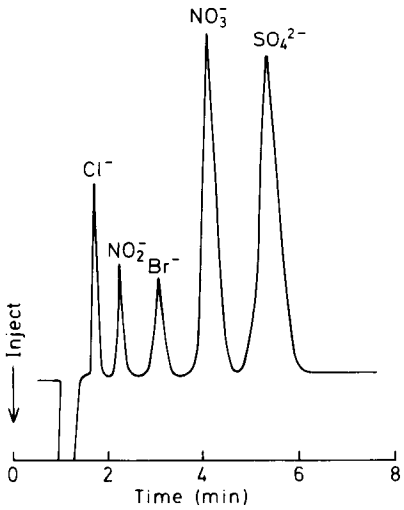


Fig. 4. Suppressed ion chromatography using a pellicular methacrylate ion-exchange column. Separator column: 200 × 4.5 mm I.D. Zipax-SAX. Suppressor column: Bio-Rad AG 50W-X12. Eluent: 2 m*M* disodium adipate (pH 7). Flow-rate: 2.5 ml/min. Injection volume: 50 μl. Conductivity detection. Solute concentrations: 2–20 ppm. (From ref. 37, with permission.)

From a chromatographic viewpoint, suppressed systems suffer from a number of drawbacks, most of which arise from the suppressor column itself. Band broadening of sample peaks resulting from the additional dead volume introduced by the suppressor column may be identified as the major drawback, although this detriment is less evident when hollow-fibre suppressor columns are used[22]. This is illustrated in Fig. 5, which shows a comparison between a packed suppressor and a hollow-fibre suppressor. Nevertheless, band broadening on the suppressor column exacerbates the relatively low efficiency of the separator column (usually about 6000 theoretical plates per metre). In addition, packed suppressors require periodic regeneration to restore their ion-exchange capacity and the eluents applicable to suppressed ion chromatography are restricted to those which undergo suitable protonation or other[38] reactions in the suppressor column. These deficiencies have provided an impetus for the development of chromatographic methods for inorganic anion analysis that do not require use of a suppressor column.

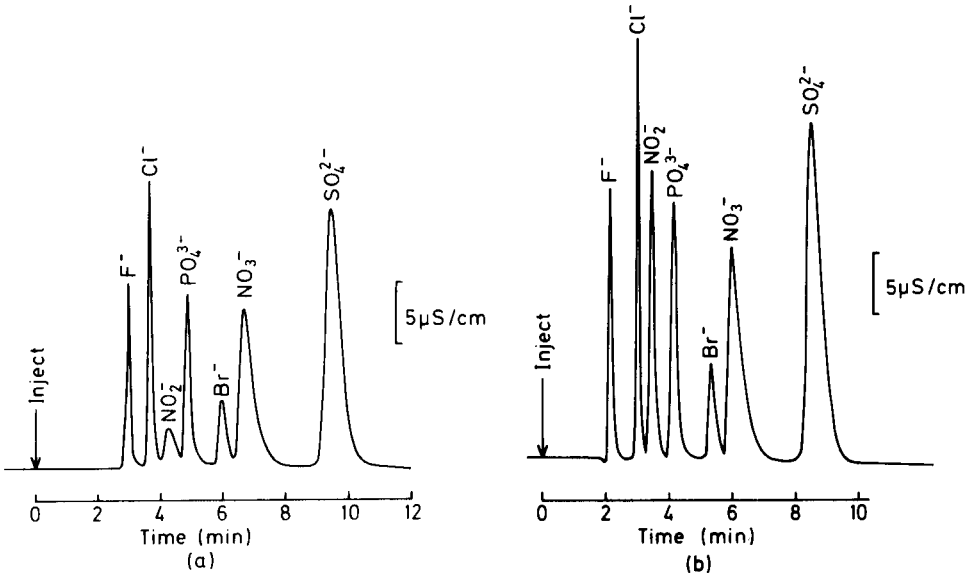


Fig. 5. Suppressed ion chromatography using (a) a conventional packed suppressor column and (b) a hollow fibre suppressor. Separator column: 250 × 4.6 mm I.D. latex agglomerate. Suppressor column: (a) 100 × 9 mm I.D. strong cation-exchange resin; (b) 0.4 mm I.D. Du Pont Nafion Type 811X surrounded by 0.05 *M* dodecylbenzenesulphonic acid. Eluent: 4 m*M* Na_2CO_3–4 m*M* $NaHCO_3$. Flow-rate: 2 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 5–40 ppm. (From ref. 23, with permission.)

2.2.2. Non-suppressed systems

2.2.2.1. High-capacity ion-exchange materials. Most commercially available silica or resin-based anion exchangers have relatively high ion-exchange capacities, usually in excess of 1 mequiv./g. These materials have not found widespread use in the chromatography of inorganic anions, chiefly because their high ion-exchange capacities necessitate the use of eluents with considerable ionic strength for the successful elution of sample anions. This in turn prevents the use of conductivity detection unless a frequently regenerated suppressor column is used. As a result, these readily available and efficient high-capacity materials have been applied only when detection methods other than conductivity were used.

This may be illustrated by the determination of inorganic phosphates and polyphosphates using conventional resin-based ion exchangers, with electrochemical[39] or post-column reaction detection[40–42] (Fig. 6). Similarly, nitrate and nitrite ions may be separated on microparticulate[43–45] or pellicular[46] silica, polymeric[47] or cellulose[48] ion exchangers, using direct UV absorbance or amperometric detection. The recent development of indirect detection methods, particularly those using refractive index measurements[49–51], has provided a suitable alternative to conductivity detection that will permit the much wider use of high-capacity ion exchangers. These detection methods are discussed later.

2.2.2.2. Low-capacity resin-based ion-exchange materials. In a major attempt to design an ion-exchange material specifically for the chromatography of inorganic anions, Fritz and co-workers[52,53] synthesized a range of low ion-exchange capacity

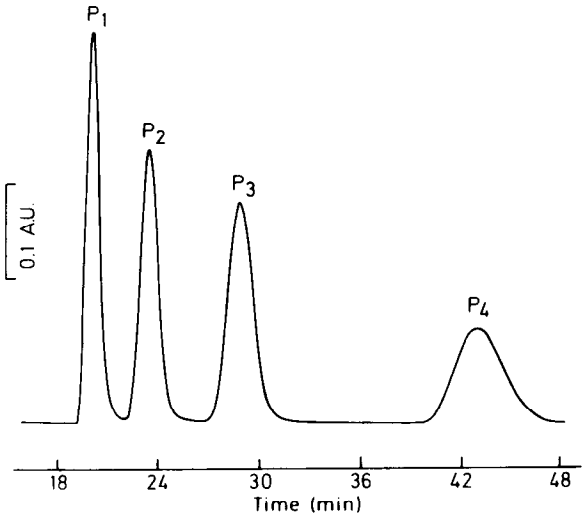


Fig. 6. Separation of orthophosphate (P_1), diphosphate (P_2), triphosphate (P_3) and tetraphosphate (P_4). Column: 500 × 2.6 mm I.D. TSK-GEL-IEX-220SA anion exchanger. Eluent: 0.23 *M* KCl (pH 10). Flow-rate: 1.0 ml/min. Injection volume: 100 µl. Detection by post-column reaction to form heteropoly blue complex with absorbance measured at 830 nm. Solute concentrations: *ca.* 40 nmol each (as P). (From ref. 40, with permission.)

(0.007–0.07 mequiv./g) macroporous ion exchangers. The rationale used was that by maintaining the ion-exchange capacity at a very low level, elution of sample ions would be possible with eluents of very low ionic strength. When very dilute (*ca.* 0.1 m*M*) solutions of aromatic acids such as benzoic or phthalic acid were used, the background conductivity of the eluent was sufficiently low that no suppressor column was necessary for conductivity detection to be used. Indeed, published data[54] indicate that the conductivity of a 0.2 m*M* benzoic acid solution at pH 7.0 is actually less than that of the 3 m*M* carbonate–hydrogen carbonate eluent generally used in suppressed ion chromatography, after this latter eluent has been passed through the suppressor column. The effect of variation of the ion-exchange capacity of the resin has been studied[55] and it was found that the distribution ratios of anions decreased with decreasing resin capacity, but the selectivity coefficients remained essentially constant over the range of capacities 0.04–1.46 mequiv./g. Computer simulation of the factors affecting ion-exchange chromatography with conductivity detection[56] has confirmed that the use of low-capacity ion exchangers is essential for sensitive detection.

The resins prepared by Fritz and co-workers were synthesized using macroreticular cross-linked polystyrene beads (XAD-1, supplied by Rohm and Haas, Philadelphia, PA, U.S.A.) as the substrate. These beads were ground and sieved, before being chloromethylated, usually by reaction with chloromethyl methyl ether, methylene chloride and nitromethane, with zinc chloride as catalyst. The reaction time was varied to control the degree of chloromethylation. The treated resin was then aminated with trimethylamine in methanol to produce a material with excellent chemical and physical stability and favourable flow properties.

Several eluents have been studied for use with this surface-aminated resin, including benzoate, biphthalate and sulphobenzoate[52,57]. These eluents were selected for their suitability for conductivity detection and all are effective ion-exchange displacement ions with minimal conductivity. With these eluents, the separation of common inorganic anions such as fluoride, chloride, bromide, nitrite, nitrate, iodide, sulphate, thiocyanate and thiosulphate have been achieved; however, at best only five of these species could be resolved from each other in a single run. Fig. 7 illustrates a typical separation and more complete retention data are given in Table 3. Data from published chromatograms indicate that these resins are of fairly low efficiency (*ca.* 1000–2000 theoretical plates per metre). Resins of this type are not commercially available, but detailed information on their preparation and selectivity characteristics has been published[52,53,55] in order to permit chromatographers to synthesize their own resins if required.

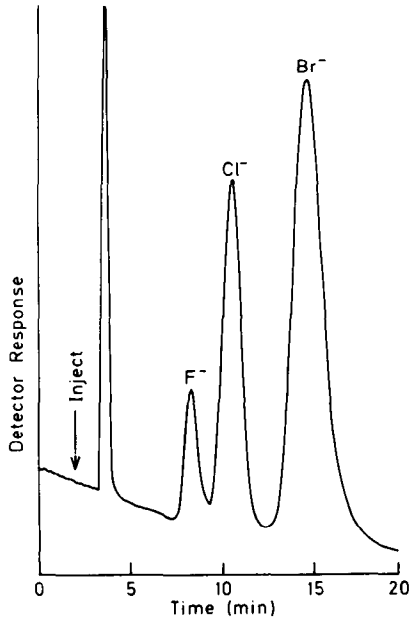


Fig. 7. Typical separation obtained with a low-capacity resin-based anion exchanger. Column: 1000 × 2 mm I.D. XAD-1 resin treated to show an anion-exchange capacity of 0.04 mequiv./g. Eluent: 0.65 m*M* potassium benzoate at pH 4.6. Flow-rate: 2 ml/min. Injection volume: 50 μl. Conductivity detection. Solute concentrations: 4.8–26.0 ppm. (From ref. 52, with permission.)

In summary, surface-aminated macroporous ion-exchange resins do not provide adequate efficiency for most applications and have been used only when high resolution was not required[58,59]. Despite this, the work of Fritz and co-workers has demonstrated the utility of low-capacity ion exchangers when used in the non-suppressed mode. Moreover, these resins have the advantage that they can be used over the entire pH range.

In view of this, considerable recent efforts have been directed towards the design of new high-efficiency resin-based ion exchangers with low ion-exchange capa-

cities[60–62] and several manufacturers are currently producing columns of this type. One particularly promising resin is TSK GEL 620 (Toyo Soda, Tokyo, Japan), which is a porous polymeric resin of small particle size (9 ± 1 μm) and low ion-exchange capacity (30 μequiv./g). This material has been shown to give excellent resolution of up to seven common inorganic anions in a single chromatographic run (Fig. 8), using a variety of eluents such as gluconate in borate buffer[61,63], phthalate or potassium hydroxide[64]. The measured efficiency of this material when packed into a 50 × 4.6 mm I.D. column is approximately 20,000 theoretical plates per metre (for nitrate ion), which illustrates its potential for non-suppressed ion-exchange chromatography.

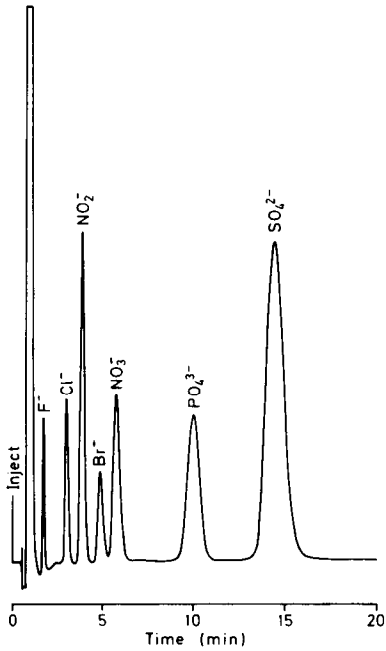
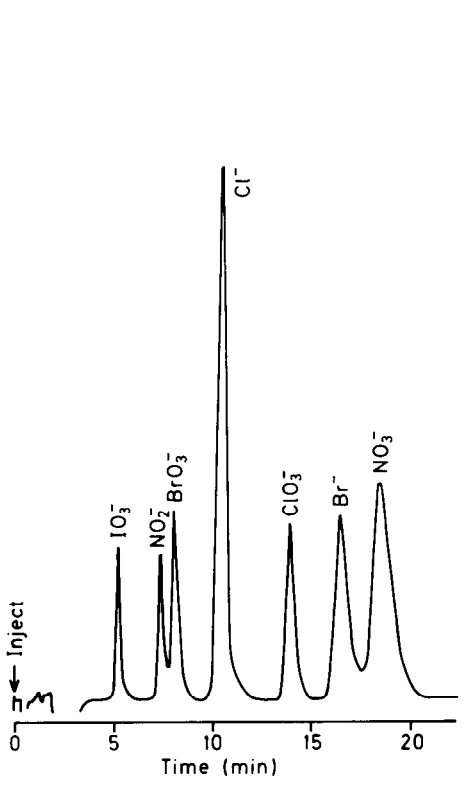


Fig. 8. Separation of inorganic anions on TSK GEL 620 anion-exchange material. Column: 50 × 4.6 mm I.D. TSK-GEL IEX-620 anion exchanger. Eluent: 1.3 m*M* $Na_2B_4O_7$–5.8 m*M* H_3BO_3–1.4 m*M* potassium gluconate at pH 8.5 in water–acetonitrile (88:12). Flow-rate: 1.2 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 5–40 ppm.

2.2.2.3. Low-capacity silica-based ion-exchange materials. Concurrent with the development of the resin-based ion exchangers discussed in the previous section, silica-based materials were also developed for the chromatography of inorganic anions. Once again, the fundamental aim was to produce a low-capacity ion exchanger, which, when used with eluents of low background conductivity, would be suitable for conductivity detection without the need for a suppressor column. The materials developed were low-capacity (0.1–0.3 mequiv/g) anion exchangers produced by bonding quaternary amino functionalities on to microparticulate silica (6–10 μm)[65,66]. As before, eluents were selected with a view to their suitability for conductivity detection and aromatic acids such as phthalic, benzoic and salicylic acids proved most useful. The most favoured eluent was *o*-phthalic acid (1–10 m*M*) with pH adjustment within the approximate range 3.5–6.0 being used to vary the ionic strength (and hence the elution characteristics) of the eluent[67].

Low-capacity silica-based anion exchangers are marketed for non-suppressed ion chromatography by a number of suppliers, including Vydac (The Separations Group, Hesparia, CA, U.S.A.), Wescan (Santa Clara, CA, U.S.A.) and Toyo Soda (Tokyo, Japan). These columns show relatively high efficiencies (typically 16,000 theoretical plates per metre for the Vydac and Wescan columns and 25,000 theoretical plates per metre for the Toyo Soda columns[68]), but the choice of eluent is clearly restricted and this approach has the further disadvantages of a small linear range of sample loadings and a restricted working pH range (2–6.5) owing to the use of a silica-based material. Figs. 9 and 10 illustrate some typical separations and Table 3 lists more complete retention data.

The commercial availability of these columns has led to the development of a considerable number of specialized applications[69–71], particularly the analysis of natural waters and rain waters[72–74]. When clean samples such as waters are analysed, it



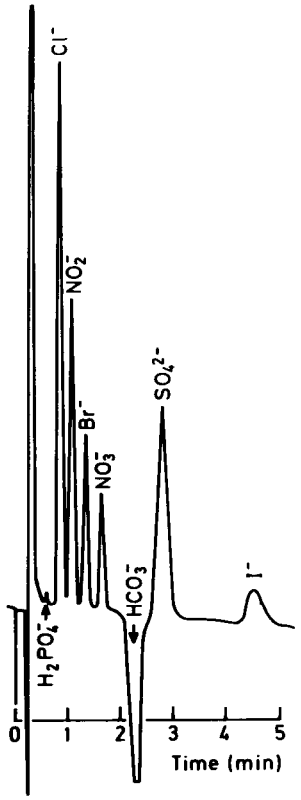


Fig. 9. Typical separation obtained with a low-capacity silica-based anion exchanger. Column: 50 × 4 mm I.D. TSK-GEL IEX-520 anion exchanger. Eluent: 1 m*M* tartaric acid (pH 3.2). Flow-rate: 1.5 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 10 ppm. (From ref. 68, with permission.)

Fig. 10. Rapid separation of inorganic anions using a low-capacity silica-based anion exchanger. Column: Wescan anion HS column, 100 × 4.6 mm I.D. Eluent: 4 m*M* potassium hydrogen phthalate (pH 3.9). Flow-rate: 4 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: not specified. (From ref. 72, with permission.)

TABLE 3

RETENTION TIMES OF SOME INORGANIC ANIONS ON SILICA AND RESIN-BASED LOW-CAPACITY ION-EXCHANGE COLUMNS

(A) 0.007 mequiv./g XAD-1 polymeric ion-exchange column (500 × 3.0 mm I.D.) with 0.1 m*M* phthalate at pH 6.25 as eluent. The flow-rate was 2.0 ml/min and conductivity detection was used. (Data calculated from ref. 53 using t_0 = 1.5 min.) (B) Vydac 302 IC silica-based ion-exchange column (250 × 4.6 mm I.D.) with 5.0 m*M* phthalate at pH 4.0 as eluent. The flow-rate was 2.0 ml/min and indirect refractive index detection was used.

Anion	*Retention time (min)*	
	A	*B*
F^-	2.90	–***
CH_3COO^-	2.90*	2.10
$H_2PO_4^-$	3.24*	3.15
CN^-	–**	3.40
BrO_3^-	–**	3.60
HCO_3^-	3.30*	–***
Cl^-	2.96	3.82
NO_2^-	3.10	4.40
Br^-	3.38	5.00
ClO_3^-	–**	5.05
NO_3^-	3.40	5.72
I^-	4.42	11.5
CrO_4^{2-}	6.70	–***
SCN^-	7.04	22.4
ClO_4^-	8.46	27.0
SO_4^{2-}	9.04	13.6
SO_3^{2-}	9.14	13.6
$C_2O_4^{2-}$	9.60	14.6
$S_2O_3^{2-}$	14.4	21.6

* Negative peak.
** No data available.
*** No peak observed.

is possible to use injection volumes as large as 2 ml[72,74,75] without causing excessive broadening of eluted peak profiles. This results from a pre-concentration effect occurring at the top of the analytical column as the sample is injected. The sample ions thus move as a compact band down the column and, provided they do not coelute with the necessarily large solvent peak, they appear as sharp peaks. This procedure obviates use of a concentrator column, but is applicable only to very clean, dilute samples.

The injection (or solvent) peak produced in this form of chromatography results from a combination of factors, including dilution of the eluent and subsequent perturbation of the eluent buffer equilibria by the injection volume, together with conductivity changes caused by cations in the sample that coelute with the injection peak. For more conventional injection volumes of 100 μl, the injection peak has been shown to be a measure of the total ionic content of the injected sample and careful quantitation of the injection peak can assist in the determination of ions with long retention times[76]. In this work, the concentration of a strongly retained ion is deter-

mined from quantitative data for the injection peak and all sample ions, with the exception of the most retained ion.

The behaviour of cationic species during anion analysis by non-suppressed chromatography with conductivity detection has also been studied[77]. The presence of certain cations such as copper, lead or zinc ions was shown to affect the stability and performance of the column, and through interaction with the column material these ions could be partially retained and could coelute with the anions of interest. This resulted in the appearance of spurious peaks or possible incorrect assignment of peaks.

In summary, the low-capacity silica-based ion exchangers suffer from the same eluent restrictions applicable to their resin-based counterparts, but have slightly higher efficiencies. The main drawback of the silica columns is that their operating pH range is very limited and this in turn restricts both the range of samples to which they can be applied and the types of eluents that can be used. The results of this latter restriction is that the elution order of common anions is generally the same, regardless of the type of column or eluent selected. A summary of the experimental conditions used for all of the non-suppressed separation methods discussed above is given in Table 4.

2.3. Ion-interaction methods

2.3.1. Principles

Ion-interaction chromatography (also called ion-pair chromatography), in which an ionic, hydrophobic reagent is added to the mobile phase of a reversed-phase chromatographic system in order to increase the retention of an oppositely charged ionic solute, has become well established as a successful technique[78]. This method is widely used for organic ions and has the advantage that a number of mobile phase parameters can be manipulated in order to control the retention of the organic solute ion. These parameters include the organic modifier content, the concentration and type of the ion-interaction reagent and the addition of competing ionic species such as sodium sulphate. With the ability to tailor the mobile phase composition to suit the particular solute ion being studied, it is not surprising that a considerable amount of research has been directed towards the application of this technique to the separation of inorganic anions.

The greatest asset of ion-interaction chromatography in this particular application is the flexibility it offers for adjustment of the ion-exchange capacity of the column. This parameter is governed by the amount of ion-interaction reagent that is adsorbed on to the hydrophobic stationary phase, and this in turn is regulated chiefly by the nature of the ion-interaction reagent used and the concentration of organic modifier in the mobile phase. In principle, any desired ion-exchange capacity can be produced, provided that the procedure used for coating the stationary phase with ion-interaction reagent is reproducible and the resulting column has stable properties. A further advantage of this approach is the potential for attainment of high efficiencies. The efficiencies obtained with the fixed site ion-exchangers discussed earlier do not approach those regularly attained for organic compounds on microparticulate reversed-phase columns, even for the silica-based ion exchangers. Ion-interaction chromatography using high-efficiency reversed-phase packings therefore

TABLE 4

SUMMARY OF EXPERIMENTAL CONDITIONS USED IN SOME NON-SUPPRESSED ION-EXCHANGE METHODS USING A VARIETY OF COLUMN TYPES AND DETECTORS

The anions are identified by the codes given in Table 1.

Anions studied	*Column*	*Eluent**	*Detection***	*Ref.*
14, 26, 27	Anion exchange	0.4 *M* NaOH or 0.4 *M* NaOH–Na_2SO_4	CPC	39
Phosphates and polyphosphates	TSK GEL IEX 220SA or Bio-Rad AG 1-X8	0.12–0.32 *M* NaCl containing 5 m*M* EDTA	PCR with molybdate	40, 42
Condensed polyphosphates	Hitachi 2630 ion exchanger	NaCl gradient containing 5 m*M* EDTA	PCR with molybdate	41
18, 19	Partisil-10 SAX	0.005 *M* KH_2PO_4–Na_2HPO_4 (pH 6.4)	UV at 205 nm	43
18, 19	Partisil-10 SAX	45–50 m*M* phosphate buffer (pH 2.9–3.0)	UV at 210 nm	44
18	Partisil-10 SAX	1 m*M* KHP	IUV at 265 nm	45
18	Zipax SAX	0.05 *M* KH_2PO_4	UV at 210 nm	46
18	Dowex 1-X8	5 m*M* $HClO_4$	AMP	47
18	Cellulose anion exchanger	0.03 *M* K_2SO_4 and 0.01 *M* Tris buffer (pH 7)	UV at 210	48
3, 5, 6, 16, 18, 19, 26, 28	Nucleosil 5 or 10 SB	0.03 *M* salicylate (pH 4.0) or 0.075 *M* *p*-hydroxybenzoate (pH 5.6) or 0.05 *M* KHP (pH 3.9)	IRI	49, 51
2, 3, 16, 18, 19, 32	Permaphase AAX	Dil. $CuSO_4$	UV at 210 nm	117
28	Nucleosil 5 SB	0.25 m*M* trimesate and 2 m*M* sulphobenzoate (pH 5.5)	IUV at 258 nm	123
2, 3, 5, 6, 13, 15, 16, 22, 26, 28	Sephadex QAE A25 or Partisil SAX	0.05 *M* $NaNO_3$ or 0.04 *M* KI or 0.05 *M* KIO_3	IUV	125
3, 6, 7, 9, 13, 16, 18, 26, 28, 29, 32, 33	Permutit Zeo-Karb 225 (Cd form)	0.0025 *M* $(CH_3COO_2)Cd$	POT	134
3, 6, 9, 13, 16	Aminex A25	0.20 *M* $NaNO_3$	CPC	139
3, 4, 6, 7, 13, 16, 18, 19, 26, 28, 32, 33	0.007–1.46 mequiv./g resin-based ion exchanger	2–6.5 × 10^{-4} *M* benzoate or 5 · 10^{-4} *M* KHP (pH 4.4) or 5 · 10^{-4} *M* sulphobenzoate (pH 5.8)	C	52, 53, 55, 57
7	As above	2 × 10^{-4} *M* KHP (pH 6.25)	C	58
6, 28	As above	2 × 10^{-4} *M* benzoate (pH 6.2)	C	59

7, 17, 18	Phenyl-modified Kel-F	0.05 *M* citrate (pH 8.3)–methanol (95:5, v/v)	UV	62
3, 4, 13, 18, 19, 26, 28	TSK GEL 620	1.3 m*M* gluconic acid in borate buffer (pH 8.5)	C	61, 63
6, 13, 18, 19, 28	TSK GEL 620 SA	2 m*M* KOH	C	64
2, 3, 5, 6, 15, 16, 18, 19, 28, 32	TSK GEL IEX 520	1 m*M* citrate (pH 5.2) or 1 m*M* tartrate (pH 3.2)	C	68
19, 30, 32, 33	TSK GEL IEX 520	0.5 *M* phosphate buffer (pH 7.5) containing 0.5 *M* $NaNO_3$	AMP	71
2–7, 9, 11–13, 15, 16, 18, 19, 26, 28–30, 33	TSK GEL IEX 520	0.1 *M* $NaNO_3$ or 0.05 *M* $NaNO_3$ in 0.05 *M* acetate buffer	PCR using $Fe(ClO_4)_3$	145
1–6, 8, 13, 15, 18, 19, 26, 28, 30	Surface-agglomerated pellicular ion exchanger	1 m*M* phthalate (pH 7–10) or 10^{-4} *M* sulphobenzoate (pH 8) or 10^{-2} *M* trimesate (pH 8)	IUV	121
9, 29	Dionex anion	0.008 *M* NaOH	AMP	138
3, 6, 16, 18, 19, 26, 28	Vydac 302 IC	5 m*M* KHP (pH 4.0)	IUV, IRI, C	50, 124
3, 6, 9, 13, 16, 18, 19, 26, 28, 33	Vydac 302 IC	0.5–5 m*M* KHP (pH 4.6–5.4) (other isomers of phthalic acid also studied)	C	65–67
1	Vydac 302 IC	10 m*M* KHP (pH 3.5)	C	70
3, 4, 16, 18, 19, 26, 28	Wescan 269-001 or 269-013	4 m*M* KHP (pH 3.9)	C	72, 73
6, 18, 28	Wescan 269-001	2 m*M* KHP (pH 4.5)	C	74
2, 3, 5, 6, 15, 16, 18, 26, 28	Vydac 302 IC	5 m*M* KHP (pH 4.6)	C and IUV	122
18, 19	Vydac 302 IC	7 m*M* chloromethanesulphonate (pH 5.0)	UV at 210 nm	118
3, 6, 16, 18, 19	Wescan 269-001	2–10 m*M* methanesulphonate (pH 5)	UV at 214 nm	119
3, 6, 16, 32	Vydac 302 IC	1 m*M* salicylic acid (pH 4.12)	POT	135
3, 6, 9, 11–13, 16, 29, 32, 33	Hitachi 2613 cation exchanger	0.5 *M* CH_3COONa (pH 9.4) or 0.5 *M* Na_2SO_4 (pH 11.9) or 0.5 *M* $NaClO_4$ (pH 11.7)	CPC	140, 141

* Abbreviation used: EDTA = ethylenediaminetetraacetate; KHP = potassium hydrogen phthalate.

** Abbreviations used: AMP = amperometry; C = conductivity; CPC = controlled-potential coulometry; IRI = indirect refractive index; IUV = indirect UV absorbance; PCR = post-column reaction; POT = potentiometry.

offers perhaps the highest efficiencies attainable for inorganic anions and may also contribute advantageous selectivity effects derived from the existence of slight hydrophobic interactions (in addition to ion-exchange interactions) for some ions.

2.3.2. Columns

Three different types of column have been examined as supports for the ion-interaction reagent. These are silica-based reversed-phase columns[79–85], neutral S/DVB copolymer columns[84–88] and normal-phase cyano columns[90,91]. Figs. 11–13 illustrate some typical separations obtained with these columns, and more complete retention data are given in Table 5. Two distinct approaches for coating the column with ion-interaction reagent may be identified, dynamic coating and "permanent" coating. In the first approach an ion-interaction reagent of relatively low hydrophobicity (such as a tetramethyl- or tetrabutylammonium salt) is used initially to condition the column and is maintained in the mobile phase for all subsequent chromatography. In the "permanent" coating method, a much more hydrophobic ion-interaction reagent (such as a cetyltrimethylammonium salt) is used for initial column conditioning, after which it is removed from the mobile phase and is replaced in the

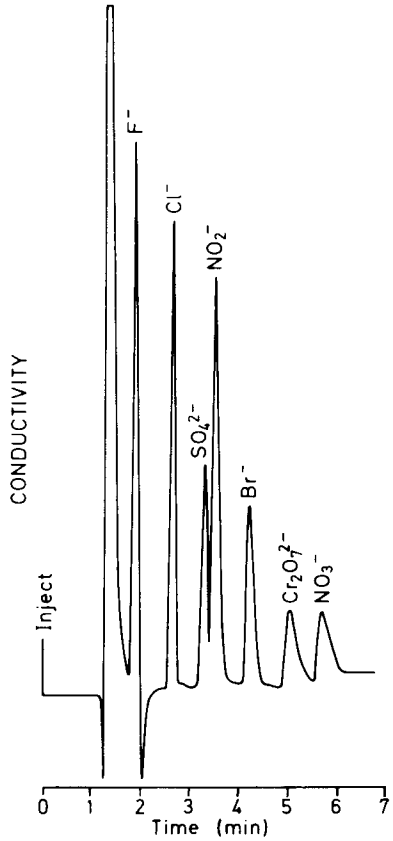


Fig. 11. Separation of some inorganic anions by ion-interaction chromatography using a reversed-phase column. Column: 10 μm LiChrosorb RP-18, 250 × 4.6 mm I.D. Eluent: 2 m*M* tetrabutylammonium hydroxide and 0.05 *M* phosphate buffer (pH 6.7). Flow-rate: 2.0 ml/min. Injection volume: 20 μl. Conductivity detection. Solute concentrations: 1000 ppm. (From ref. 79, with permission.)

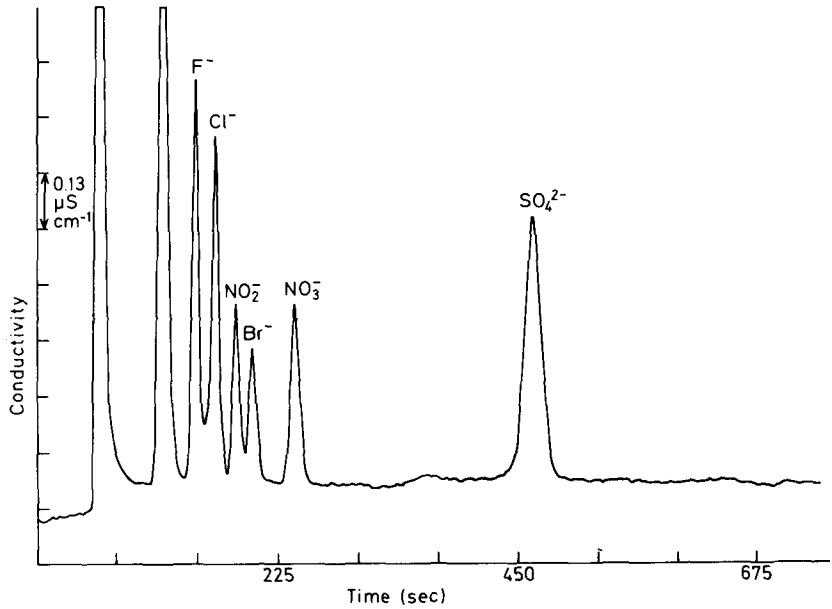


Fig. 12. Separation of inorganic anions by ion-interaction chromatography using a PRP-1 column. Column: PRP-1, 150 × 4.1 mm I.D. Eluent: 0.75 m*M* tetrabutylammonium salicylate in acetonitrile–water (7:93) (pH 6.3.). Flow-rate: 1 ml/min. Injection volume: 20 μl. Conductivity detection. Solute concentrations: 0.5–1.0 ppm. (From ref. 87, with permission.)

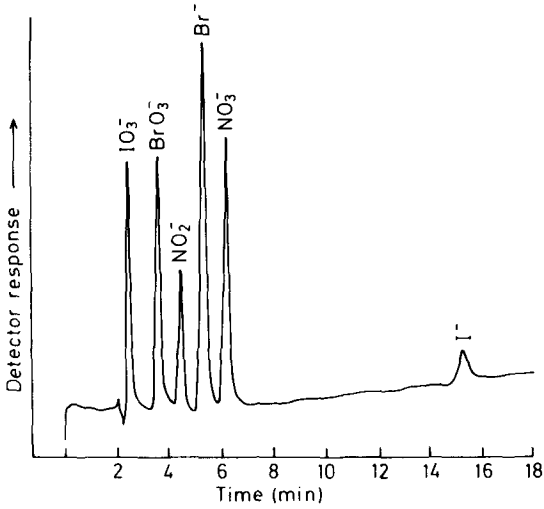


Fig. 13. Separation of inorganic anions by ion-interaction chromatography using a CN column. Column: Polygosil-60-D-10 CN, 250 × 4.6 mm I.D. Eluent: acetonitrile–buffer (25:75), the buffer consisting of 0.1 *M* Na_2HPO_4–0.1 *M* KH_2PO_4 containing 0.1% (w/v) hexadecyltrimethylammonium chloride. Flow-rate: 1.5 ml/min. Detection by UV absorbance at 205 nm. Solute concentrations: not specified. (From ref. 91, with permission.)

TABLE 5

RETENTION TIMES OF SOME INORGANIC ANIONS OBTAINED WITH ION-INTERACTION METHODS USING VARIOUS COLUMN TYPES

*C_{18} column***		*C_{18} column****		*CN column*****		*PRP-1 column*§*	
Anion	*Retention time (min)*	*Anion*	*Retention time (min)*	*Anion*	*Retention time (min)*	*Anion*	*Retention time (min)*
IO_3^-	3.04	IO_3^-	1.4	IO_3^-	1.94	F^-	3.48
IO_4^-	3.08	PO_4^{3-}	1.7	BrO_3^-	2.94	Cl^-	4.72
Br^-	4.40	Cl^-	2.6	HS^-	2.99	BrO_3^-	4.78
BrO_3^-	4.58	BrO_3^-	3.0	NO_2^-	3.40	NO_2^-	4.95
NO_2^-	4.75	NO_2^-	3.8	HSO_3^-	3.52	Br^-	5.08
MnO_4^-	4.88	NO_3^-	5.6	N_3^-	4.09	NO_3^-	5.60
OCN^-	4.88	ClO_3^-	8.8	NO_3^-	4.71	I^-	7.08
$S_2O_8^{2-}$	6.64	SO_4^{2-}	11.0	Br^-	5.99	SCN^-	8.73
NO_3^-	6.73	$C_2O_4^{2-}$	13.6	$S_2O_3^{2-}$	7.96	IO_4^-	16.1
I^-	8.84	I^-	16.8	I^-	11.2	ClO_4^-	18.3
SCN^-	20.3	$S_2O_3^{2-}$	31.0				
$C_2O_4^{2-}$	35.2	SCN^-	47.6				

* Column: Partisil ODS-3. Eluent: 0.01 *M* octylamine adjusted to pH 6.2 with H_3PO_4, at a flow-rate of 2 ml/min. (Data from ref. 80.)

** Column: end-capped C_{18}, 50 × 4.6 mm I.D. Eluent: 4 m*M* citric acid and 1 m*M* cetrimide in methanol–water (30:70) at a flow-rate of 1 ml/min. (Data from ref. 83.)

*** Column: Chromopack Sil 60-D10-CN, 250 × 4.6 mm I.D. Eluent: 0.1% cetrimide in methanol–0.1 *M* phosphate buffer (40:60) at a flow-rate of 1.5 ml/min. (Data from ref. 90.)

§ Column: PRP-1, 150 × 4.1 mm I.D. Eluent: acetonitrile–1 m*M* tetrapentylammonium fluoride (35:65) at a flow-rate of 1 ml/min. (Data calculated from ref. 88, using t_0 = 1.3 min).

eluent by a less hydrophobic ion (usually a tetramethylammonium salt). The amount of adsorbed ion-interaction reagent "permanently" bonded to the column (and hence the ion-exchange capacity) may be readily determined by removing the adsorbed reagent with an organic modifier, followed by spectrophotometric analysis of the collected eluate.

2.3.3. Mechanism

Although the mechanism of ion-interaction chromatography of organic ions is still the subject of some dispute[92–94], most workers have generally agreed that a dynamic ion-exchange mechanism operates when inorganic ions are used as solutes[79,80,84,86–89,95]. This is probably due to the fact that the absence of significant hydrophobic effects for most inorganic ions makes the interpretation of the retention mechanism more simple than is the case for organic ions. For inorganic anions, two major equilibria are considered to contribute towards the retention of these ions on a reversed-phase column when an eluent containing a tetraalkylammonium salt ($R_4N^+A^-$) is used. The first equilibrium describes the retention of R_4N^+ on the column surface, which leads to the formation of a double layer. The R_4N^+ occupies the primary layer, producing a positive charge at the stationary phase surface, while the coanion (A^-) of the salt occupies a diffuse secondary layer[95]. The second equi-

librium describes the selectivity of one anion over another in the secondary layer. Evidence to support this double layer model has largely been based on results that indicate that the effects of changing the nature and concentration of the coanion (A^-) are essentially identical between ion-interaction and conventional ion-exchange chromatography[80,88].

2.3.4. Mobile phase parameters

Experimentally controllable parameters used to govern the retention characteristics of inorganic anions are the type and concentration of the ion-interaction reagent, the choice of coanion, the type and concentration of the organic modifier used in the eluent, the ionic strength (which is adjusted by adding salts of the same or different coanion) and the type of column used to support the ion-interaction reagent. The last of these parameters exerts the least influence and the choice between column types is generally based on considerations of efficiency and applicable pH range. Several workers[84–86] have compared silica-based reversed-phase columns (various C_{18}) with S/DVB copolymer columns[96] (generally Hamilton PRP-1) as supports in the ion-interaction chromatography of inorganic anions. They have concluded that the polymeric column has a lower efficiency (20,000[87] *versus* 30,000 plates per metre[84] for an octadecylsilyl column), but shows stronger adsorption of some ion-interaction reagents.

2.3.4.1. Type of ion-interaction reagent. An extensive range of ion-interaction reagents has been investigated, including tetramethyl-[82], tetraethyl-[86], tetrabutyl-[79,81,84,86], tetrapentyl-[88,89] and cetyltrimethylammonium[90,91] salts, and octylamine[80] for dynamic coating of columns. More hydrophobic ion-interaction reagents such as trioctylmethyl-[86], tetraoctyl-[86] or tridodecylmethylammonium[86] salts and cetylpyridinium salts[84,87] have been employed with the "permanent" coating method. The particular reagent employed does not appear to be a critical factor, and is generally selected to provide an adequate surface coverage under the mobile phase conditions used. However, when PRP-1 packing is used as the support for "permanent" bonding, the preferred ion-interaction reagent is cetylpyridinium chloride[84], as the structure of this reagent more closely resembles that of the PRP-1 packing than do quaternary alkylammonium salts.

One notable characteristic of the use of high-molecular-weight ion-interaction reagents in the "permanent" coating method is an initial, rapid improvement in column efficiency that occurs when the eluent composition is altered after completion of the "permanent" coating procedure[84,86]. This change has been attributed to reorientation of the bulky ion-interaction reagent molecules in response to the introduction of a more aqueous eluent, which results in more efficient mass transfer. After this initial change in efficiency has occurred, HETP values and capacity factors remain stable for the passage of up to 40 l of mobile phase[84]. The reproducibility of column coating using the "permanent" coating method has been shown to be excellent, with retention times obtained for repeated coatings of the same column, and also for different columns, agreeing to within 2%[84].

2.3.4.2. Elution characteristics. The eluting power of the mobile phase can be varied in a number of ways. One approach is to add an anionic component (such as a salt or buffer) to the mobile phase, which then competes with solute anions for the cationic sites of the adsorbed ion-interaction reagent. In this way, the roles of the

ion-interaction reagent and competing anion are separate and are independently controllable. Thus a mobile phase containing tetrabutylammonium hydroxide (TBA^+OH^-) as the ion-interaction reagent and phosphate buffer as the competing anion has proved successful for the separation of Main Group inorganic anions on an octadecylsilyl column[79] (Fig. 11). An alternative approach is to utilize the coanion of the ion-interaction reagent as the competing anion; here the ion-interaction reagent serves the dual roles of coating the column surface to create ion-exchange sites and also to provide competing anions necessary to elute sample anions. This function of the coanion of the ion-interaction reagent has not been widely recognized[88]. Thus retention times obtained with TBA^+OH^- will be considerably longer than those obtained with the same concentration of TBA^+Cl^- because of the greater ion-exchange displacing ability of chloride, in accordance with established ion-exchange selectivities[97].

A further factor must be considered when selecting the coanion of the ion-interaction reagent, namely the compatability of the coanion with the detection mode used. For example, when conductivity detection is employed, it is desirable to minimize the background conductivity of the eluent or, on the other hand, it may be essential for the eluent to be either UV transparent or strongly UV absorbing to facilitate a particular mode of detection. Eluents such as phosphates or hydroxides of tetraalkylammonium ions have high conductivity and will give a mixture of both positive and negative peaks with conductivity detection and the high background conductivity will adversely affect detection limits. Consequently, use of salicylate (SAL^-) as the coanion of the tetraalkylammonium species is much more suited to conductivity detection because it can provide the necessary eluting strength and also has a low background conductivity. Thus TBA^+SAL^- has been used for the dynamic coating method with PRP-1 columns[84,87] (Fig. 12), while TBA^+benzoate$^-$ and TBA^+-phthalate$^-$ were also successful for this approach[87]. Similarly, tetramethylammonium salicylate (TMA^+SAL^-) was an effective eluent for PRP-1 columns with a "permanent" coating of cetylpyridinium ions[84,87].

A recent study has been devoted to the selection and application of an eluent suitable for UV absorbance, electrochemical, refractive index and conductivity detection of inorganic anions separated on an octadecylsilyl column[83]. The eluent was required to meet several criteria, including the ability to function as an ion-interaction reagent, to contain a multivalent competing anion for rapid elution of sample ions, to be slightly UV absorbing at 220 nm, to have a low background conductivity and to have some buffering capacity. The eluent selected was cetyltrimethylammonium bromide and citric acid at pH 5.5, and this example clearly illustrates the extreme versatility of the ion-interaction method.

The percentage of organic modifier in the eluent is a further important factor in the ion-interaction chromatography of inorganic anions. First, adjustment of the percentage of modifier is the most convenient method for regulating the amount of ion-interaction reagent adsorbed on the stationary phase in both the dynamic and "permanent" coating procedures. Second, studies have shown that small amounts ($> 5\%$) of acetonitrile or tetrahydrofuran[84,87] were required for maximum efficiency, whereas methanol or ethanol tended to produce broader peaks than observed for acetonitrile-based eluents[88]. The poor chromatography in purely aqueous solvents has been attributed in part to poor wetting of the support surface (PRP-1) by the

eluent[88]. In support of this hypothesis is the fact that higher concentrations of acetonitrile (beyond that necessary to initially increase efficiency) did not have any further appreciable effect. A summary of the experimental conditions used in all of the ion-interaction separation methods discussed above is given in Table 6.

2.4. Other separation methods

In addition to the separation methods already described, a number of alternative approaches have also been reported, although it is valid to say that these approaches lack the wide applicability of ion-exchange or ion-interaction methods.

Some inorganic anions may be determined by pre-column derivatization reactions, followed by chromatography on conventional reversed-phase columns. For example, nitrite ion reacts with diamines (such as 2,3-diaminonaphthalene) to form triazole derivatives that can be chromatographed on an octadecylsilyl column with ethanol–water as the mobile phase[98]. Nitrate ion may be determined in a similar manner after reduction to nitrite. An alternative method for nitrite involves reaction with hydralazine at pH 1.1 to form tetrazolo-5,1-phthalazine, which can be separated from the reaction mixture on an octadecylsilyl column using acetonitrile–phosphate buffer as eluent[99]. A further method for nitrite (and nitrate) involves reaction with excess of phenol to form *o*-nitrophenol, with subsequent reversed-phase separation[100].

Silica-based columns with a bonded amino functionality have proved successful for the separation and determination of nitrate and bromide in foodstuffs, using phosphate buffer as the eluent[101]. This method has been further extended to other inorganic anions[102] (Fig. 14), but only UV-absorbing species were studied and it is therefore difficult to establish accurately the full potential of this approach. Notwithstanding this, the method clearly exhibits the efficiency expected from a silica-

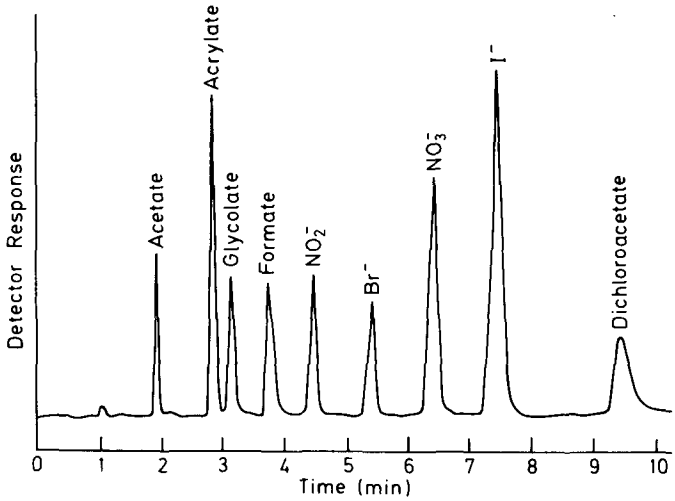


Fig. 14. Separation of some inorganic anions on an amino column. Column: Zorbax NH_2, 250 × 4.6 mm I.D. Eluent: 0.03 *M* H_3PO_4 adjusted to pH 3.2 with NaOH. Flow-rate: 2.0 ml/min. Injection volume: 20 μl. Detection by UV absorbance at 205 nm. Solute concentrations: 25–100 ppm. (From ref. 102, with permission.)

TABLE 6

SUMMARY OF EXPERIMENTAL CONDITIONS USED IN SOME ION-INTERACTION METHODS WITH VARIOUS DETECTORS

The anions are identified by the codes given in Table 1.

Anions studied	*Column*	*Eluent**	*Detector***	*Ref.*
3, 6, 10, 13, 18, 19, 28	LiChrosorb RP-18	2 m*M* TBA^+ OH^- in 0.05 *M* phosphate buffer (pH 6.7)	C	79
2, 3, 8, 15, 16, 18–20, 23–25, 32	C_{18} (various)	0.01 *M* *n*-octylamine salts (pH 6–6.5)	UV at 205–214 nm	80
Arsenic anions	C_{18} (various)	0.005 *M* TBA^+ OH^-	RI or ICPAES	81
18, 19	μBondapak C_{18}	5 m*M* TMA^+ phosphate	UV at 214 nm	82
2, 5, 6, 15, 16, 18–20, 26, 28, 32, 33	C_{18}	4 m*M* citric acid and 1 m*M* cetrimide in methanol–water (30:70)	C, UV, IUV, AMP	83
3, 15, 16, 18, 19	Various C_8 and C_{18}	1 m*M* N-methyloctylammonium *p*-toluenesulphonate	C and IUV	126
2, 3, 5, 6, 13, 15, 16, 18, 19, 22, 23, 28, 30	Supelco LC18 DB	4 m*M* naphthylmethyl-TBA^+ OH^- and 0.25 m*M* sodium hexanesulphonate in 10 m*M* acetate buffer (pH 4.75)	UV	128
1–3, 15, 16, 18, 19, 21, 29–31, 33, 34	Chrompack Sil60-D 10 CN	0.1% cetrimide in methanol–0.1 *M* phosphate buffer (40:60 or 55:45)	UV at 210–220 nm	90
2, 3, 15, 16, 18, 19	Polygosil 60-D-10 CN	0.1% cetrimide in 0.1 *M* phosphate buffer–acetonitrile (75:25)	UV at 205 nm	91
3, 6, 13, 18, 19, 26, 28	PRP-1 coated with cetylpyridinium ions	0.5 m*M* TMA^+ SAL^- in 7% acetonitrile	C	84, 87
3, 6, 13, 18, 19, 26, 28	PRP-1 and various C_{18} types	0.5 m*M* TBA^+ SAL^-	C	84, 87
15, 16, 18, 19, 33	PRP-1 and various C_{18} types	TEA^+, TBA^+, $TDMA^+$, TOA^+ and $TDMA^+$ salts in methanol–water	C	86
2, 3, 6, 9, 13, 15, 16, 18–20, 22, 24, 28–30, 31	PRP-1	0.5–1.0 *M* TPA^+ F^- in 17.5–35% acetonitrile–water	C, UV, RI	88
18, 19	PRP-1	1 m*M* TPA^+ F^- in 33% acetonitrile–water	UV or C	89

* Abbreviations used: TMA = tetramethylammonium; TEA = tetraethylammonium; TBA = tetrabutylammonium; TPA = tetrapentylammonium; TOMA = trioctylmethylammonium; TOA = tetraoctylammonium; TDMA = tridodecylammonium; SAL = salicylate.

** Abbreviations as in Table 2, plus RI = refractive index; ICPAES = inductively coupled plasma atomic-emission spectroscopy.

based column but would undoubtedly also suffer from pH restrictions. Further chromatographic approaches that have been applied to inorganic anions include the use of silica-coated polyamide crown resin for halide separation with water as the eluent[103] and the separation of phosphorous oxopolyanions by Donnan exclusion chromatography[104].

3. DETECTION METHODS

3.1. Introduction

Together with the need to develop adequate separation methods, the advancement of chromatographic methods for inorganic anions was hampered by a lack of suitably sensitive detection methods. This situation has altered over recent years with the development of sensitive and widely applicable detection methods, including conductivity, UV absorbance, indirect absorbance and refractive index procedures, electrochemical techniques and post-column reactions. In addition, some specific methods such as the spectroscopic detection of phosphorus and sulphur species[105] and arsenic anions[81] have also been reported.

In most instances, the detection method is inextricably linked to the separation method used, as the eluent is usually chosen with both the separation and detection methods in mind. The following discussion aims to highlight the requirements and advantages of commonly used detection methods, so that the reader may determine the suitability of these for the separation methods discussed earlier.

3.2. Conductivity detection

The advantages of conductivity detection for inorganic anion analysis have long been recognized[1] and include sensitivity, range of applicability, low cost and simplicity of operation. The chief problem is that eluents for ion-exchange or ion-interaction chromatography must necessarily contain ionic species, which may provide an excessively high background, resulting in poor detectability for eluted ions. Conductivity detection operates on the principle that the elution of a sample anion is accompanied by a corresponding decrease in the concentration of the competing anion in the eluent, in order to maintain electroneutrality. It is therefore the difference in the equivalent conductivities of the sample ion and the eluent competing ion that is generally monitored, and this leads to the possibility of two distinct strategies for maximizing the conductivity response signal.

The first and most widely employed strategy is either to negate the conductivity of the remaining eluent competing ions by a chemical reaction (and so enhance the detectability of the solute ions), or to use weakly conducting competing ions. The first of these possibilities is, of course, extensively applied through the use of suppressor columns[1,21–23] and the second possibility is exemplified by the use of aromatic acid eluents with low-capacity fixed-site ion exchangers[52,53,65,66] and both dynamically and "permanently" coated reversed-phase columns[84,87]. It should be noted here that the range of chemical reactions suitable for suppressing eluent conductivity is potentially very broad and has included thermal decarboxylation[38] and proton exchange, leading to the formation of poorly conducting zwitterionic species[106]. The latter approach is illustrated in Fig. 15.

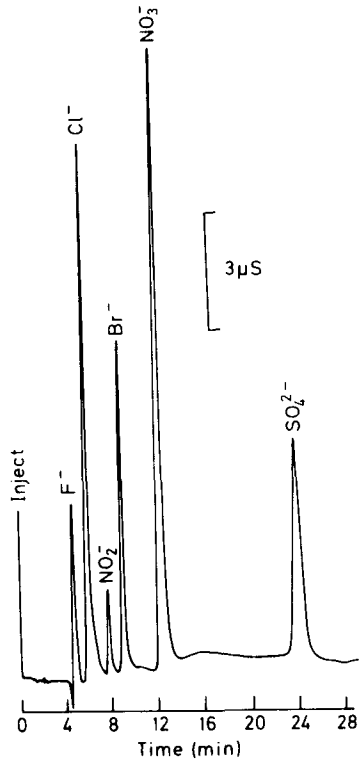


Fig. 15. Suppressed ion chromatography involving formation of poorly conducting zwitterions in the suppressor column. Separator column: μBondapak C_{18}, 250 × 4.6 mm I.D. Suppressor column: Dionex anion suppressor (Type 030829). Eluent: 10 m*M* tetrabutylammonium hydroxide and 11 m*M* 2-(N-morpholino)ethanesulphonic acid. Flow-rate: 2 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 10–30 ppm. (From ref. 106, with permission.)

The second strategy for conductivity detection is to use a highly conducting competing anion in the eluent and to monitor the decrease in conductivity that accompanies the elution of a solute anion. This approach is of limited utility for the detection of inorganic anions, most of which are highly conducting, but potassium hydroxide has been successfully employed for the separation and conductimetric detection of fluoride, chloride, bromide, nitrite, nitrate and sulphate, using a resin-based low-capacity ion exchanger[64] (Fig. 16). The limitation here was that hydroxide acted as a weak eluent and high concentrations were necessary to elute sulphate ion.

The design of conductivity detectors suitable for the chromatography of inorganic ions has been the subject of some study and the general requirements are a small cell volume (to minimize dispersion effects), high sensitivity, wide range of linearity, rapid response and acceptable stability. Most conductivity detectors function according to the Wheatstone bridge principle and the applied alternating voltage produces a considerable current through the cell, which leads to heat dissipation, resulting in a noisy, drifting baseline. The cell current can be reduced by correct cell design[79] and further improvements in response time, accuracy and linear range are possible with suitable electronic modifications, such as use of the bipolar pulse technique[107,108]. This involves the application of two successive constant-voltage pulses

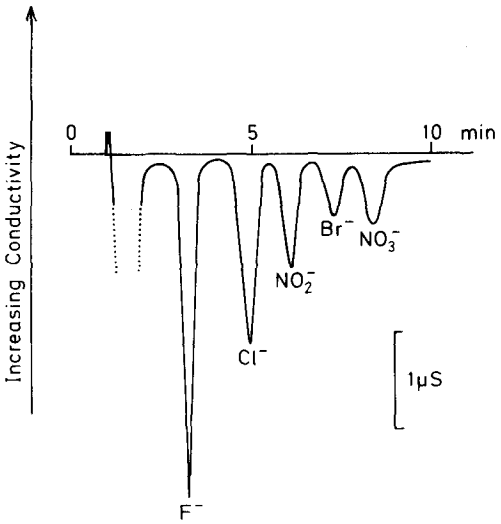


Fig. 16. Conductivity detection in non-suppressed ion chromatography using an eluent with high background conductivity. Column: TSK GEL 620 SA, 50 × 4 mm I.D. Eluent: 2 m*M* KOH. Flow-rate: 1 ml/min. Injection volume: 100 μl. Conductivity detection. Solute concentrations: 5 ppm. (From ref. 64, with permission.)

of opposite polarity to the conductance cell and measurement of the current flowing in the cell at the end of the second pulse. In this way, capacitance effects are overcome and electronic nulling of the background conductance of the eluent is also possible. Other developments with conductivity detectors include the introduction of logarithmic response to increase the dynamic range (to about six orders of magnitude[109]) and the design of a cell in which the electrodes are not in galvanic contact with the solution to be measured[110]. The principal advantage of this latter innovation is that polarization, corrosion and other side effects that may change the measuring electrode surface condition, and also the cell constant, are eliminated. Further refinements to conductivity detectors have also been reported[111–113].

Thermal stability of conductivity detectors is a problem that has been recognized by a number of workers[10,67,79,84,87,114]. As the temperature coefficient of conductivity measurements is approximately 2%/°C[6], it is clear that very close temperature control is essential in order to minimize baseline noise and to maximize sensitivity, especially when non-suppressed eluents are used. The extreme temperature sensitivity of conductivity detection can be revealed by the detector signal produced by placing a hand on the column or steel tubing[114]. To minimize such temperature effects, it is necessary to take the unusual precaution of thoroughly insulating all components of the chromatographic system, including the injector, pre-column, analytical column, detector cell and all related tubing[84,114]. This treatment has been observed to reduce baseline noise by a factor of seven[84].

Detection limits achieved with conductivity detection may be typified by the values for nitrate ion of 500 ppb* for non-suppressed detection[67] and 100 ppb for suppressed detection[10].

* Throughout this article, the American billion (10^9) is meant.

3.3. *UV-Absorbance detection*

Perhaps the most straightforward method for the detection of inorganic anions is to monitor their UV absorbance. A considerable number of anions show appreciable absorbance in the range 195–220 nm[115], for example, nitrate, nitrite, bromide, bromate, iodide, iodate, periodate, thiocyanate and thiosulphate. Table 7 lists the detection limits and suitable wavelengths for some of these UV-absorbing inorganic anions. The important anions chloride, fluoride, sulphate, phosphate, perchlorate and cyanide do not show significant absorbance of UV radiation in the above wavelength range. Some degree of detection selectivity therefore exists, and this can often be used to advantage in the determination of UV-absorbing anions in samples that contain high levels of UV-transparent ions, such as chloride.

TABLE 7

UV ABSORBANCE DETECTION LIMITS FOR SOME INORGANIC ANIONS, OBTAINED USING LATEX AGGLOMERATE COLUMNS WITH DIFFERENT ELUENTS

Eluents: (A) 10 m*M* HCl; (B) 3 m*M* $NaHCO_3$–2.4 m*M* Na_2CO_3; (C) 6 m*M* Na_2CO_3. (Data from ref. 116.)

Anion	*Detection limit (ppm)*	*Wavelength (nm)*	*Eluent*
AsO_3^{3-}	1.2	200	A
AsO_4^{3-}	1.5	200	A
Br^-	0.1	195	B
BrO_3^-	0.16	195	B
Cl^-	2	192	B
ClO_3^-	4	195	B
I^-	0.15	195	C
IO_3^-	0.08	195	B
N_3^-	0.3	195	B
NO_3^-	0.1	195	B
NO_3^-	0.1	195	B
S^{2-}	0.4	200	A
SCN^-	0.2	195	C
$SeCN^-$	0.4	195	C
SeO_3^{2-}	0.5	195	B
SeO_4^{2-}	15	195	B

Direct UV absorbance detection has found considerable usage in inorganic anion analysis[27,80,90,91,102,116], with particular emphasis on the determination of nitrite and nitrate[48,82,101,117,118]. An obvious restriction on the eluent composition is that all components must be essentially non-absorbing in the desired wavelength range. For this reason, eluents such as phosphate buffer[82,90,91,101,102], chloride[80], sulphate[48,80,117], carbonate buffer[27,116], citrate[83] and alkylsulphonates[118,119] have been used. The molar absorptivities of the inorganic ions listed in Table 7 are not great (e.g., 9000 l mol^{-1} cm^{-1} at 210 nm for nitrate in water) and they are diminished even further in the eluents used. For this reason, great care should be exercized in the selection of both the nature and concentration of components used in the eluent. This can be illustrated by two methods for inorganic anion analysis using ion-interaction chromatography in which the molar absorptivity of bromide was increased by

a factor of ten when the eluent was altered by replacing methanol with a lower proportion of acetonitrile[90,91]. The variability of detection limits obtained using direct UV absorbance detection in the range 195–220 nm is indicated by the following limits of detection for nitrate ion in different eluents: 100 ppb in carbonate buffer[116], 150 ppb in citrate–cetrimide eluent[83], 20 ppb in sulphate eluent[48], 3–200 ppb in phosphate–cetrimide eluent[90,91], 100 ppb in phosphate–tetramethylammonium eluent[82] and 50–300 ppb in phosphate eluent[101,102].

3.4. Indirect detection methods

The use of eluents containing aromatic acid anions as competing anions in ion-exchange methods using low-capacity columns with conductivity detection has resulted in the development of an innovative alternative detection mode. These aromatic acid anions were selected as eluents for conductivity detection because of their low equivalent conductivities[52,57], but these anions also show high UV absorbance and have a considerable refractive index in aqueous solution. As the elution of a solute anion in an ion-exchange process is accompanied by a localized deficiency of the competing anion in the eluent, then if the competing anion is derived from an aromatic acid with the above-mentioned properties, the background absorbance or refractive index of the eluent will change when a solute anion elutes. This provides the basis for a non-specific method whereby inorganic anions may be indirectly detected. This method is also known as "vacancy" detection[120] as it is a deficiency of eluent anions that is being monitored, or is alternatively named "indirect photometric chromatography"[121].

Indirect detection has been applied using both UV absorbance[50,120–124] and refractive index[49–51,120,124] measurements with ion-exchange systems and Fig. 17 illustrates these two detection methods. The criteria to be considered when selecting the eluent in the indirect UV absorbance method have been systematically evaluated[121], but a similar evaluation for the indirect refractive index method has not yet been reported. For indirect UV absorbance detection, both chemical and photometric considerations must be applied to selection of the eluent. The eluent anion must necessarily have sufficient displacing power to elute solute anions within a reasonable time, or loss of sensitivity due to band broadening effects can be expected. In addition, a knowledge of the effect of pH changes on the ionization and absorbance properties of the eluent anion is critical to the success of the method[123]. Eluents used for indirect UV absorbance detection include phthalate[50,121,122,124], nitrate[125], sulphobenzoate[121,123], iodide[121] and benzenetricarboxylate[121].

Photometric factors are also of prime importance in view of the fact that photometric error is minimal only within the approximate absorbance range 0.2–0.8. In most instances, the eluent concentration is fixed by the ion-exchange capacity of the column, together with the displacing power of the eluent anion, yet at the same time the above limits of absorbance must be adhered to in order to minimize the photometric error. This situation may be resolved by selection of an appropriate wavelength of detection, which is adjusted so that the background absorbance of the eluent is less than 0.8. In this way, indirect UV absorbance detection may be employed with columns having a wide range of ion-exchange capacities and using eluents of relatively high concentration. This flexibility is, of course, not offered by conductivity detection.

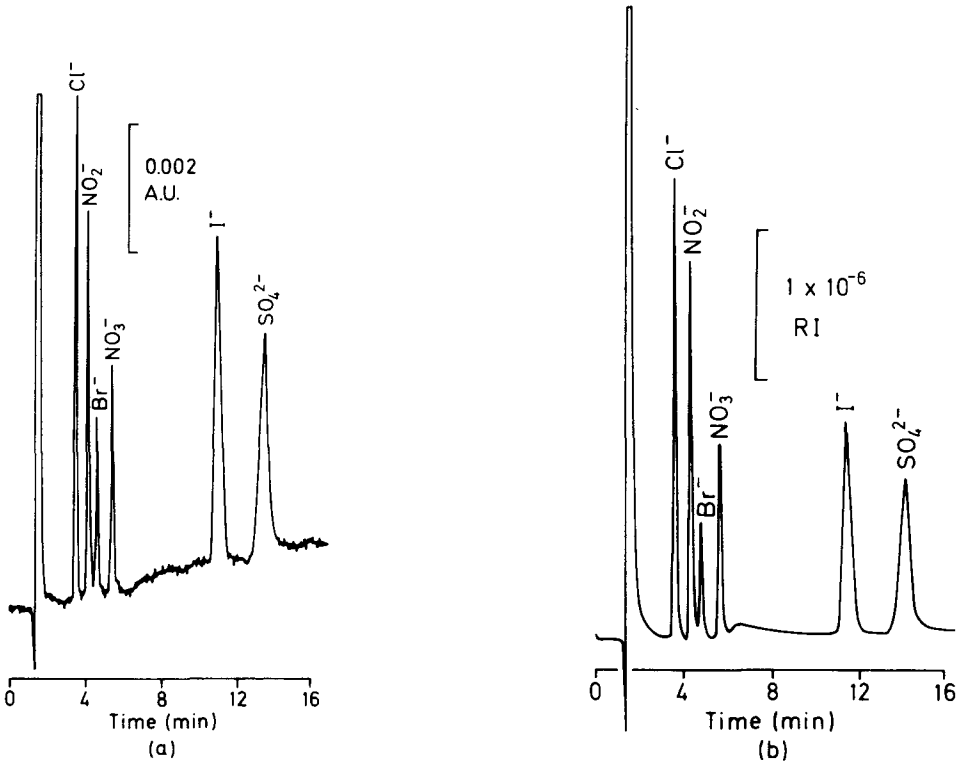


Fig. 17. (a) Indirect UV-absorbance and (b) refractive index (RI) detection of inorganic anions. Column: Vydac 302 IC, 250 × 4.6 mm I.D. Eluent: 6.0 m*M* potassium hydrogen phthalate (pH 4.0). Flow-rate: 2.0 ml/min. Injection volume: 100 μl. Detection by UV absorbance at 285 nm or by refractive index measurement. Solute concentrations: 2.5–7.5 ppm.

A further factor that must also be considered is the effect of wavelength on detection sensitivity. As the molar absorptivity of the eluent anion is increased through wavelength changes, the sensitivity of detection improves owing to the increased absorbance changes occurring for the same concentration change of the eluent anion. In this regard, maximum sensitivity is achieved at the wavelength of maximum absorption of the eluent anion, but baseline noise, photometric error and the ability of the detector electronically to offset background absorbance levels must also be considered. With respect to these considerations, it is clear that the results obtained with indirect UV absorbance detection will be strongly dependent on the performance characteristics of the detector used[124].

Indirect refractive index detection is subject to fewer restrictions than indirect UV absorbance detection. The background refractive index of the eluent is theoretically not restricted, as measurements are conventionally made by comparison of the column effluent with a sample of eluent contained in a reference cell. Sensitivity is limited only by the performance of the detector used, which does, however, impose a practical limitation in that most commercially available refractive index detectors are designed for the detection of large concentrations of solute and are generally not optimized for high-sensitivity applications. The possibility therefore exists for a refractive index detector to be designed for this particular application. Eluents used for

indirect refractive index detection of inorganic anions include phthalate[49,50,120,124], salicylate[49,51], *p*-hydroxybenzoate[49] and sulphobenzoate[49], and columns of both low[50,124] and high[49,51,120] ion-exchange capacities have been employed.

The principle of indirect detection may be readily extended to include ion-interaction in addition to ion-exchange chromatography. To apply this, all that is needed is that the competing anion in the eluent (which must also contain a suitable ion-interaction reagent) should have appropriate UV absorbance or refractive index properties. The competing anion in the eluent may be added separately to the ion-interaction reagent or may be the coanion of the ion-interaction reagent. An example of the first of the above possibilities is the use of citrate (as competing anion) with cetrimide (as ion-interaction reagent)[83] and the second possibility is illustrated by the use of N-methyloctylammonium *p*-toluenesulphonate[126] as an ion-interaction reagent with a competing coanion (Fig. 18). Several other competing coanions have also been studied[126] and an alternative ion-interaction method using a UV-absorbing ion-interaction reagent cation with non-specific UV detection of anions through the formation of induced peaks[127] has also been described[128].

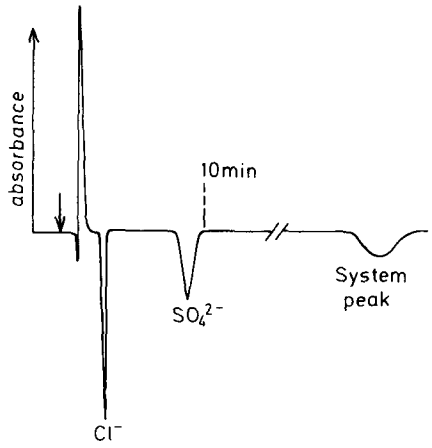


Fig. 18. Ion-interaction separation of chloride and sulphate, using indirect UV-absorbance detection. Column: Zorbax C8, 200 × 4.6 mm I.D. Eluent: 1 m*M* N-methyloctylammonium *p*-toluenesulphonate. Flow-rate: 1.6 ml/min. Injection volume: 20 μl. Detection by UV absorbance at 254 nm. Solute concentrations: 10^{-3} *M*. (From ref. 126, with permission.)

An unusual feature of the chromatograms obtained with indirect detection in both the ion-exchange and ion-interaction modes is the appearance of a slowly eluting peak that is not directly attributable to any injected anion[50,120,123,124,126,128]. This peak, which is generally called a "system" peak[129], can be large, depending on the experimental parameters being used and can represent a major interference to later eluting solute anions. The size of the system peak depends on the type and concentration of the solute ion injected, the nature and pH of the eluent and also the injection volume[130] (Fig. 19), but a convincing explanation of its origin has not appeared in the literature. Indirect refractive index detection appears to be more prone to problems with system peaks than does the indirect UV absorbance method[123,131].

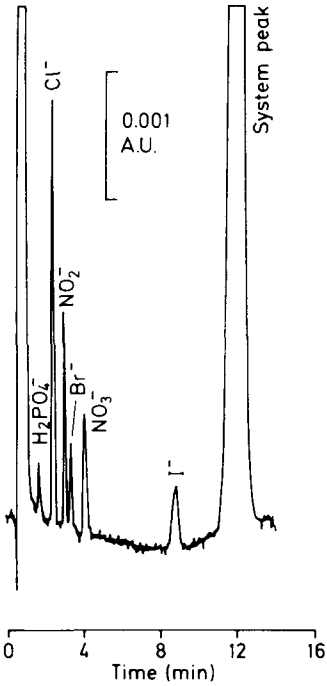


Fig. 19. Illustration of the "system" peak observed with indirect UV absorbance detection when a large injection is used. Column: Vydac 302 IC, 200 × 3.0 mm I.D. Eluent: 2.5 m*M* potassium hydrogen phthalate at pH 4.0. Flow-rate: 2.0 ml/min. Injection volume: 250 μl. Detection by UV absorbance at 285 nm. Solute concentrations: 100–400 ppb.

The indirect detection methods have been shown to be more sensitive than non-suppressed conductivity detection using the same eluents[49,50,122,123,126], but are generally less sensitive than suppressed conductivity detection[123]. Notwithstanding this, a significant advantage of the indirect detection methods is their ready applicability to conventional liquid chromatographic instrumentation, which results in a considerable expansion of the utility of this instrumentation. Typical detection limits are 100 ppb for chloride and 300 ppb for nitrate[122], but improvements result when large injection volumes (up to 2 ml) are used[75].

3.5. Electrochemical detection

Electrochemical detection of inorganic anions by potentiometry, amperometry (including polarography) or coulometry is generally restricted in its applicability, but can exhibit greater sensitivity than other methods. The selectivity of electrochemical detection is particularly advantageous in those situations where separation is inadequate or interferences are a problem. Sometimes an electrochemical detector is used in tandem with a non-selective detector, such as a conductivity detector, in order to aid peak identification and interpretation of chromatograms[83].

Potentiometric detection, chiefly using ion-selective electrodes, has been applied by a number of workers[132–136] and the main requirements are the construction

of a suitably small flow cell in which the electrode contacts the column effluent and the design of electrode systems that show sufficient sensitivity and speed of response. Halide ions are particularly suited to potentiometric detection using an indicator electrode constructed from silver wire coated with a silver salt[134] and this has been applied to the detection of thiocyanate and halides in ion-exchange chromatography[135,136]. The best results were achieved when silver salicylate was used to coat the silver wire and salicylate was also used as the eluent, as this combination produced a faster response and a more stable baseline than was obtained with other alternatives[135].

Amperometric techniques are generally applied to the detection of those anions which readily undergo oxidation reactions in aqueous media at relatively low potentials. Reduction reactions are usually not preferred because of the requirement to remove dissolved oxygen, but the cathodic detection of nitrate ion using a copperized cadmium flow-through electrode has been reported[47]. Anions that are suited to oxidative detection include nitrite, oxalate, thiosulphate, thiocyanate, sulphide and cyanide. Methods for the detection of these species have been described using a variety of indicator electrodes and flow-cell designs[71,83,137,138].

Controlled-potential coulometry may also be used for the detection of anions, either by direct reaction of electroactive species at a constant-potential working electrode, or by using a post-column reaction between the sample anions and a selective reagent that produces electroactive species. The first of these methods, called primary controlled potential coulometry, has been applied to the detection of fluoride, chloride, bromide, iodide and cyanide, using a silver working electrode[139]. The second method is called secondary controlled potential coulometry and may be illustrated by the detection of a large number of inorganic ions by post-column reaction with quinone[139,140]. Under controlled potential coulometric conditions, this reagent is very sensitive to the presence of acids, so if the eluting anions are passed through a suppressor column (and so emerge in their protonated forms) prior to addition of quinone, then they are readily detected[141].

Both primary and secondary controlled potential coulometry offer some unique advantages for the detection of inorganic anions. The well defined nature of the redox reactions that are occurring at the electrode permit direct quantitation of the species of interest from peak area measurements, and the preparation of a calibration graph is not always necessary[139]. In addition, the method has a high sensitivity and small variations in flow-rate or eluent temperature have little effect on baseline stability. Moreover, the sensitivity of the method is at least equivalent to that of conductivity detection[139]. The detection limits attainable by the electrochemical techniques discussed in this section are indicated by the following: <1 ppm for bromide ion using potentiometric detection[135], 15 ppb for thiocyanate ion using amperometric detection[71] and 100 ppb for fluoride ion using coulometric detection[139].

3.6. Post-column reaction detection

In addition to the post-column reaction methods already discussed, some other similar procedures have been reported for the detection of inorganic anions, particularly phosphates and polyphosphates[40–42,142,143]. For the detection of phosphates,

the post-column reactor was based on the formation of heteropoly blue complex (see Fig. 6) by reaction of the phosphates with molybdenum reagents, using either air-segmented[142] or unsegmented[144] flow systems. This approach is particularly valuable because the routine use of an ionic complexing agent (such as EDTA) in the mobile phase to prevent hydrolysis of the polyphosphates during ion-exchange separation means that conventional detection methods, such as conductivity, are not suitable.

An interesting post-column reaction method has recently been described for common inorganic anions[145], based on the formation of coloured complexes by reaction of many anions with iron(III) in perchlorate media[146–148]. The anions are separated on a TSK GEL IEX 520 silica-based anion exchanger, using nitrate ion and acetate buffer as the competing anions in the eluent, with iron(III) perchlorate being added to the column effluent. This approach is applicable to the separation and detection of thiocyanate, cyanide, sulphate, chloride, iodide, nitrite, thiosulphate and phosphate, and detection at 340 nm provides limits of detection of as low as approximately 2 ppm (for thiocyanate)[145]. Fig. 20 shows a typical chromatogram obtained using this detection method.

A post-column method for reduction of eluent conductivity in ion-interaction chromatography has been proposed[86], but no evaluation of the merits of this method has been reported. A hydrophobic quaternary salt in the hydroxide form is used as

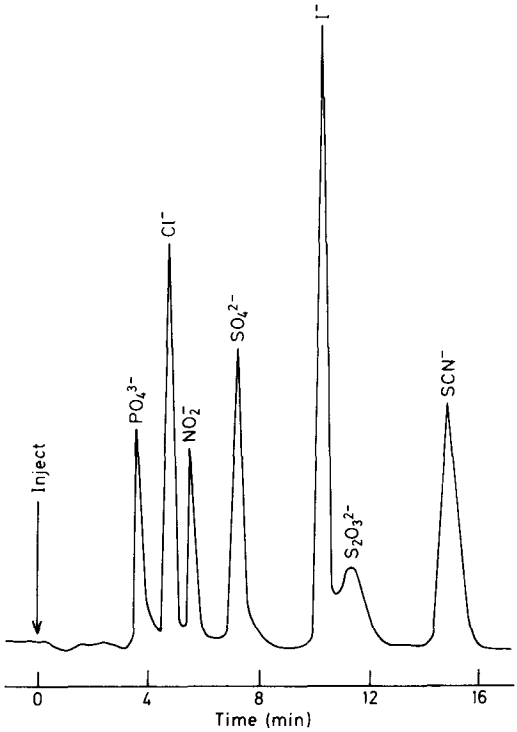


Fig. 20. Detection of inorganic anions by UV absorbance following post-column reaction with iron(III). Column: TSK-GEL IEX-520 QAE (silica-type pellicular anion exchanger), 150 × 4 mm I.D. Eluent: 0.5 *M* acetate buffer (pH 5.48) containing 0.05 *M* $NaNO_3$. Flow-rate: 0.8 ml/min. Detection by absorbance at 340 nm, following post-column reaction with 0.8 *M* $HClO_4$ containing 0.05 *M* $Fe(ClO_4)_3$. Solute concentrations: not specified. (From ref. 145, with permission.)

the eluent and a weak organic acid is added at the column exit. The products from the reaction of the acid and the quaternary salt will be water and a hydrophobic ion pair with a conductivity considerably lower than that of the unreacted eluent. Initial studies using tetrabutylammonium hydroxide as the eluent and phthalic acid as the post-column addition reagent indicated that sensitivities for eluted inorganic anions could be improved by a factor of up to 100[86].

4. SAMPLE TREATMENT

4.1. Introduction

To complete this review, the important area of sample treatment procedures will be briefly discussed. These procedures may be divided into sample cleanup methods and pre-concentration methods, and a large amount of valuable research in both of these areas has been directed towards the suppressed ion-exchange separation systems[6–19]. The results obtained, however, are equally pertinent to the other separation and detection methods described here.

4.2. Sample cleanup

The necessity for suitable sample cleanup procedures is exemplified by the difficulties encountered in the analysis of trace level anions in strongly alkaline solutions. Direct injection of even well diluted solutions is impractical as solutions of high pH destroy the equilibria that exist between eluent species concentrations in the mobile phase and on the column in both suppressed[19] and non-suppressed[52,53] methods. In the latter instance, positive and negative system peaks result from such an injection[130]. Neutralization of the sample with strong acid is also not feasible owing to the consequent introduction of large amounts of the acid anion that could possible interfere with the low level anions of interest. One solution to this problem is to pass the alkaline sample through a strong cation-exchange column in the hydrogen form, during which the sodium ion is removed from the sample and it is effectively neutralized[36].

In a similar manner, specially prepared cleanup columns have been used to separate chloride and bromide from complex sample matrices prior to ion chromatographic determination[35]. Here an ion exchanger loaded with silver ions was employed to trap the halide ions, which were later recovered by elution with ammonia solution. Inorganic anions may also be readily separated from organic sample matrices by passing the samples through a C_{18} Sep-Pak (Waters Assoc., Milford, MA, U.S.A.)[36,118,149]. Provided the capacity of the Sep-Pak is not exceeded, excellent sample cleanup can be achieved.

4.3. Sample pre-concentration

The detection limits attained with all of the detection methods discussed above are such that some samples, such as condenser waters and some natural waters, require pre-concentration prior to analysis. In a few instances, chemical amplification reactions may be employed[150], but the use of some type of ion-exchange pre-con-

centration device is generally more applicable. Usually this device consists of an ion-exchange pre-column[33], through which a carefully measured amount of sample is passed and the pre-column effluent is directed to waste. The sample anions accumulate on the pre-column, which is then inserted prior to the analytical column and eluted with the desired mobile phase. Problems with this approach are possible overloading of the concentrator column by a major (and perhaps unimportant) ionic component of the sample and the broad peaks that result from injection of a fairly diffuse band of solute on to the analytical column. In addition, the considerable volume of sample solution retained in the interstitial cavities of the concentrator column can cause major baseline disturbances in the detector output, with resulting interference for early eluting solute ions[34]. Despite these limitations, the use of concentrator columns is at present the most convenient method for sample pre-concentration, and these columns have been packed with either fixed-site anion exchangers[33,34] or reversed-phase materials that have been "permanently" coated with a hydrophobic ion-interaction reagent[87]. An example of the results obtained with the latter type of pre-concentration column is given in Fig. 21.

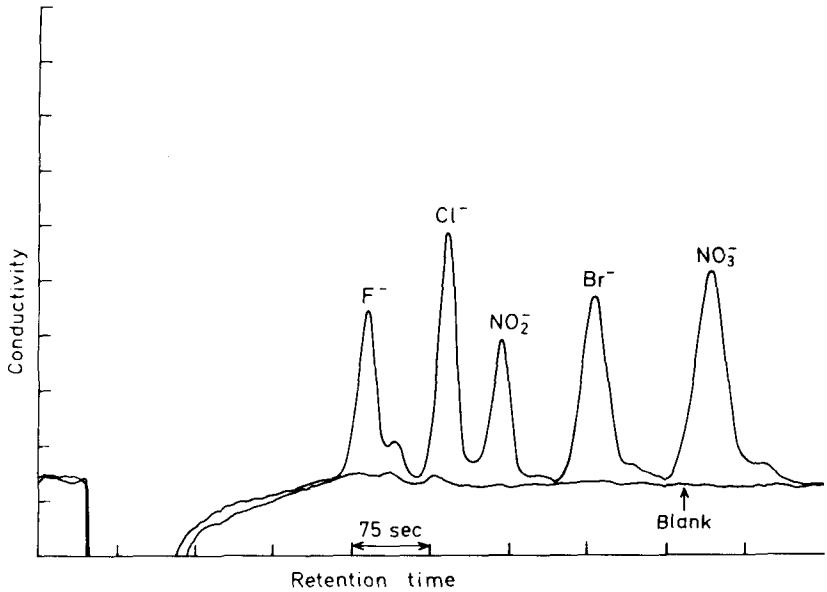


Fig. 21. Pre-concentration of inorganic anions on a PRP-1 column "permanently" coated with a hydrophobic ion-interaction reagent. Separator column: PRP-1, 150 × 4.1 mm I.D., coated with *ca.* 45 mg of cetylpyridinium chloride. Concentrator column: C_{18} cartridge with a "permanent" coating of cetylpyridinium chloride. Eluent: 0.5 m*M* tetramethylammonium salicylate. Flow-rate: 1 ml/min. Injection volume: 2 ml of sample was passed through the concentrator column. Conductivity detection. Solute concentrations: 50–150 ppb. (From ref. 87, with permission.)

An alternative approach has been reported by Cox and co-workers[151–160] and others[161,162]. Here, the sample anions are concentrated into a small volume of static or flowing electrolyte through a Donnan dialysis mechanism. In addition to significant enrichment factors, the method provides for matrix normalization by ensuring that the concentrated sample ions are always contained in the same matrix receiver solution, irrespective of the original composition of the sample. The chief drawback

of this method for the concentration of anions is the required high ionic strength of the receiver electrolyte, with the resulting large concentration of at least one anion, which may result in interferences. This approach has been successfully applied to the ion chromatographic determination of cations[162], but successful anion analysis using this method has not been reported.

5. CONCLUSIONS

A wide range of elegant separation and detection methods have been developed for the determination of inorganic anions and there is clearly the opportunity for further developments. Comparison of the various approaches has been attempted by a number of workers, both for separation[120,163] and detection[50,83,116] techniques and certain advantages of particular methods have been indicated. Nevertheless, no single technique emerges as the universal method of choice and selection of the most suitable method for a particular application must be based on such considerations as sample type, analyte concentrations, resolution required, speed, cost, precision, ease of operation and suitability for automation. It has been the intention of this review to provide some insight into these factors.

6. ACKNOWLEDGEMENTS

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REFERENCES

1 H. Small, T. S. Stevens and W. C. Bauman, *Anal. Chem.*, 47 (1975) 1801.
2 J. S. Fritz, D. T. Gjerde and R. M. Becker, *Anal. Chem.*, 52 (1980) 1519.
3 C. Pohlandt and J. S. Fritz, *J. Chromatogr.*, 176 (1979) 189.
4 R. M. Cassidy and S. Elchuk, *J. Chromatogr. Sci.*, 18 (1980) 217.
5 R. M. Cassidy and S. Elchuk, *J. Chromatogr. Sci.*, 19 (1981) 503.
6 C. A. Pohl and E. L. Johnson, *J. Chromatogr. Sci.*, 18 (1980) 442.
7 F. C. Smith and R. C. Chang, *CRC Crit. Rev. Anal. Chem.*, 9 (1980) 197.
8 H. Small, *Anal. Chem.*, 55 (1983) 235A.
9 J. D. Mulik and E. Sawicki, *Environ. Sci. Technol.*, 13 (1979) 804.
10 J. S. Fritz, D. T. Gjerde and C. Pohlandt, *Ion Chromatography*, Hüthig, New York, 1982.
11 R. Wetzel, *Environ. Sci. Technol.*, 13 (1979) 1214.
12 R. Wetzel, *Ind. Res. Dev.*, April (1982) 92.
13 J. C. MacDonald, *Amer. Lab.*, 11 (1979) 45.
14 H. Small, in E. Sawicki, J. D. Mulik and E. Wittgenstein (Editors), *Ion Chromatographic Analysis of Environmental Pollutants*, Vol. 1, Ann Arbor Sci. Publ., Ann Arbor, MI, 1978, p. 11.
15 A. J. Muir, *Sci. Technol.*, 16 (1978) 19.
16 R. G. Warren, *Food Technol. Aust.*, 33 (1981) 300.
17 H. Small, *Trace Anal.*, 1 (1981) 267.
18 A. J. Lipski and C. J. Vairo, *Can. Res.*, 13 (1980) 45.
19 E. Sawicki, J. D. Mulik and E. Wittgenstein (Editors), *Ion Chromatographic Analysis of Environmental Pollutants*, Vols. 1 and 2, Ann. Arbor Sci. Publ., Ann Arbor, MI, 1978.
20 T. S. Stevens and M. A. Langhorst, *Anal. Chem.*, 54 (1982) 950.
21 T. S. Stevens, J. C. Davis and H. Small, *Anal. Chem.*, 53 (1981) 1488.

22 T. S. Stevens, G. L. Jewett and R. A. Bredeweg, *Anal. Chem.*, 54 (1982) 1206.
23 Y. Hanaoka, T. Murayama, S. Muramoto, T. Matsuura and A. Nanba, *J. Chromatogr.*, 239 (1982) 537.
24 M. A. O. Bynum, S. Y. Tyree, Jr. and W. E. Weiser, *Anal. Chem.*, 53 (1981) 1935.
25 D. Jenke, *Anal. Chem.*, 53 (1981) 1535.
26 W. Ishibashi, R. Kikuchi and K. Yamamoto, *Bunseki Kagaku (Jap. Anal.)*, 31 (1982) 207; *C.A.*, 97 (1982) 16246y.
27 S. Rokushika, Z. Y. Qiu, Z. L. Sun and H. Hatano, *J. Chromatogr.*, 280 (1983) 69.
28 S. Rokushika, Z. Y. Qiu and H. Hatano, *J. Chromatogr.*, 260 (1983) 81.
29 T. Sunden, M. Lindgren, A. Cedergren and D. D. Siemer, *Anal. Chem.*, 55 (1983) 2.
30 D. R. Jenke and G. K. Pagenkopf, *J. Chromatogr.*, 269 (1983) 202.
31 C. J. Jackson, C. Neuberger and M. Taylor, *Anal. Proc.*, 18 (1981) 201.
32 M. Oehme and H. Stray, *Z. Anal. Chem.*, 306 (1981) 356.
33 R. A. Wetzel, C. L. Anderson, H. Schleicher and G. D. Crook, *Anal. Chem.*, 51 (1979) 1532.
34 B. E. Andrews, *Abstr. 7th Aust. Symp. Anal. Chem., Adelaide, Aug. 1983*, p. 18.
35 D. D. Siemer, *Anal. Chem.*, 52 (1980) 1874.
36 R. A. Hill, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 6 (1983) 275.
37 M. J. van Os, J. Slanina, C. L. de Ligny, W. E. Hammers and J. Agterdenbos, *Anal. Chim. Acta*, 144 (1982) 73.
38 J. P. Ivey, *J. Chromatogr.*, 281 (1983) 314.
39 Y. Takata and G. Muto, *Bunseki Kagaku (Jap. Anal.)*, 28 (1979) 15; *C.A.*, 90 (1979) 161630d.
40 N. Yoza, K. Ito, Y. Hirai and S. Ohashi, *J. Chromatogr.*, 196 (1980) 471.
41 H. Yamaguchi, T. Nakamura, Y. Hirai and S. Ohashi, *J. Chromatogr.*, 172 (1979) 131.
42 T. Nakamura, T. Yano, A. Fujita and S. Ohashi, *J. Chromatogr.*, 130 (1977) 384.
43 A. Takahashi, *Bunseki Kagaku (Jap. Anal.)*, 29 (1980) 508; *C.A.*, 94 (1981) 89884c.
44 J. R. Thayer and R. C. Huffaker, *Anal. Biochem.*, 102 (1980) 110.
45 M. Cooke, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 6 (1983) 383.
46 H. Terada, T. Ishihara and Y. Sakabe, *Eisei Kagaku*, 26 (1980) 136; *C.A.*, 93 (1980) 184443w.
47 G. A. Sherwood and D. C. Johnson, *Anal. Chim. Acta*, 129 (1981) 101.
48 R. G. Gerritse, *J. Chromatogr.*, 171 (1979) 527.
49 F. A. Buytenhuys, *J. Chromatogr.*, 218 (1981) 57.
50 P. R. Haddad and A. L. Heckenberg, *J. Chromatogr.*, 252 (1982) 177.
51 F. A. Buytenhuys, personal communication.
52 D. T. Gjerde, J. S. Fritz and G. Schmuckler, *J. Chromatogr.*, 186 (1979) 509.
53 D. T. Gjerde, G. Schmuckler and J. S. Fritz, *J. Chromatogr.*, 187 (1980) 35.
54 J. S. Fritz, D. T. Gjerde and C. Pohlandt, *Ion Chromatography*, Hüthig, New York, 1982, p. 118.
55 D. T. Gjerde and J. S. Fritz, *J. Chromatogr.*, 176 (1979) 199.
56 H. Sato, *Bunseki Kagaku (Jap. Anal.)*, 31 (1982) 97; *C.A.*, 96 (1982) 173479y.
57 D. T. Gjerde and J. S. Fritz, *Anal. Chem.*, 53 (1981) 2324.
58 D. L. DuVal, J. S. Fritz and D. T. Gjerde, *Anal. Chem.*, 54 (1982) 830.
59 K. M. Roberts, D. T. Gjerde and J. S. Fritz, *Anal. Chem.*, 53 (1981) 1691.
60 J. R. Benson and D. Woo, *Pittsburgh Conference, 1983, Abstract 69.*
61 N. Baba, K. Koaiya, S. Watsushita and W. Unino, *Pittsburgh Conference, 1983, Abstract 68.*
62 R. W. Siergiej and N. D. Danielson, *J. Chromatogr. Sci.*, 21 (1983) 362.
63 *Manual for TSK HLC-601 Ion Chromatograph*, Toyo Soda, Tokyo, 1983, p. 3.
64 T. Okada and T. Kuwamoto, *Anal. Chem.*, 55 (1983) 1001.
65 J. E. Girard and J. A. Glatz, *Amer. Lab.*, 13 (1981) 26.
66 R. L. Stevenson and K. Harrison, *Amer. Lab.*, 13 (1981) 76.
67 J. A. Glatz and J. E. Girard, *J. Chromatogr. Sci.*, 20 (1982) 266.
68 S. Matsushita, Y. Tada, N. Baba and K. Hosako, *J. Chromatogr.*, 259 (1983) 459.
69 *Application Notes*, Wescan Instruments, Santa Clara, CA, U.S.A., 1982.
70 H. Mackie, S. J. Speciale, L. J. Throop and T. Yang, *J. Chromatogr.*, 242 (1982) 177.
71 T. Imanari, K. Ogata, S. Tanabe, T. Toida, T. Kawanishi and M. Ichikawa, *Chem. Pharm. Bull.*, 30 (1982) 374.
72 Th. Jupille, D. Burge and D. Togami, *Chromatographia*, 16 (1982) 312.
73 S. Dogan and W. Haerdi, *Chimia*, 35 (1981) 339.
74 A. E. Buchholz, C. I. Verplough and J. L. Smith, *J. Chromatogr. Sci.*, 20 (1982) 499.

75 A. L. Heckenberg and P. R. Haddad, *J. Chromatogr.*, 299 (1984) 301.
76 H. Hershcovitz, C. Yarnitzky and G. Schmuckler, *J. Chromatogr.*, 244 (1982) 217.
77 D. R. Jenke and G. K. Pagenkopf, *Anal. Chem.*, 55 (1983) 1168.
78 B. A. Bidlingmeyer, *J. Chromatogr. Sci.*, 18 (1980) 525.
79 I. Molnár, H. Knauer and D. Wilk, *J. Chromatogr.*, 201 (1980) 225.
80 N. E. Skelly, *Anal. Chem.*, 54 (1982) 712.
81 D. Bushee, I. S. Krull, R. N. Savage and S. B. Smith, Jr., *J. Liq. Chromatogr.*, 5 (1982) 463.
82 S. H. Kok, K. A. Buckle and M. Wootton, *J. Chromatogr.*, 260 (1983) 189.
83 B. B. Wheals, *J. Chromatogr.*, 262 (1983) 61.
84 R. M. Cassidy and S. Elchuk, *J. Chromatogr. Sci.*, 21 (1983) 454.
85 D. E. Burge, D. W. Togami and T. J. Jupille, *Pittsburgh Conference, 1983, Abstract 65.*
86 R. M. Cassidy and S. Elchuk, *Anal. Chem.*, 54 (1982) 1558.
87 R. M. Cassidy and S. Elchuk, *J. Chromatogr.*, 262 (1983) 311.
88 Z. Iskandarani and D. J. Pietrzyk, *Anal. Chem.*, 54 (1982) 2427.
89 Z. Iskandarani and D. J. Pietrzyk, *Anal. Chem.*, 54 (1982) 2601.
90 R. N. Reeve, *J. Chromatogr.*, 177 (1979) 393.
91 J. P. de Kleijn *Analyst. (London)*, 107 (1982) 223.
92 C. Horvath, W. Melander, I. Molnar and P. Molnar, *Anal. Chem.*, 49 (1977) 2295.
93 J. L. M. van de Venne, J. L. H. M. Hendrikx and R. S. Deelder, *J. Chromatogr.*, 167 (1978) 1.
94 B. A. Bidlingmeyer, S. N. Deming, W. P. Price, Jr., B. Sachok and M. Petrusek, *J. Chromatogr.*, 186 (1979) 419.
95 Z. Iskandarani and D. J. Pietrzyk, *Anal. Chem.*, 54 (1982) 1065.
96 D. P. Lee, *J. Chromatogr. Sci.*, 20 (1982) 203.
97 F. Helfferich, *Ion Exchange*, McGraw-Hill, New York, 1962, p. 95.
98 G. L. Wheeler and P. F. Lott, *Microchem. J.*, 19 (1974) 390.
99 H. Noda, M. Minemoto, A. Noda, K. Matsuyama, S. Iguchi and T. Kohinata, *Chem. Pharm. Bull.*, 28 (1980) 2541.
100 M. A. Alawi, *Z. Anal. Chem.*, 313 (1982) 239.
101 U. Leuenberger, R. Gauch, K. Rieder and E. Baumgartner, *J. Chromatogr.*, 202 (1980) 461.
102 H. J. Cortes, *J. Chromatogr.*, 234 (1982) 517.
103 M. Igawa, K. Saito, J. Tsukamoto and M. Tanaka, *Anal. Chem.*, 53 (1981) 1942.
104 Y. Tokunaga, H. Waki and S. Ohashi, *J. Liq. Chromatogr.*, 5 (1982) 1855.
105 B. G. Julin, H. W. Vandenborn and J. J. Kirkland, *J. Chromatogr.*, 112 (1975) 443.
106 J. P. Ivey, *J. Chromatogr.*, 287 (1984) 128.
107 D. E. Johnson and C. G. Enke, *Anal. Chem.*, 42 (1970) 329.
108 J. M. Keller, *Anal. Chem.*, 53 (1981) 344.
109 V. Svoboda and J. Maršál, *J. Chromatogr.*, 148 (1978) 111.
110 E. Pungor, F. Pal and K. Toth, *Anal. Chem.*, 55 (1983) 1728.
111 B. Evans and J. Stolz, *Pittsburgh Conference, 1982, Abstract 247.*
112 T. Jupille, D. Togami and D. Burge, *Pittsburgh Conference, 1982, Abstract 242.*
113 H. Sato, *Bunseki Kagaku (Jap. Anal.)*, 31 (1982) T23; *C.A.*, 96 (1982) 173486y.
114 D. R. Jenke and G. K. Pagenkopf, *Anal. Chem.*, 54 (1982) 2603.
115 R. P. Buck, S. Singhadeja and L. B. Rogers, *Anal. Chem.*, 26 (1954) 1240.
116 R. J. Williams, *Anal. Chem.*, 55 (1983) 851.
117 T. Kamiura and M. Tanaka, *Anal. Chim. Acta*, 110 (1979) 117.
118 P. E. Jackson, P. R. Haddad and S. Dilli, *J. Chromatogr.*, 295 (1984) 471.
119 J. P. Ivey, *J. Chromatogr.*, 267 (1983) 218.
120 J. D. Newburger and W. R. Day, *Pittsburgh Conference, 1983, Abstract 64.*
121 H. Small and T. E. Miller, Jr., *Anal. Chem.*, 54 (1982) 462.
122 R. A. Cochrane and D. E. Hillman, *J. Chromatogr.*, 241 (1982) 392.
123 C. A. Hordijk, C. P. C. M. Hagenaars and Th. E. Cappenberg, *J. Microbiol. Methods*, 2 (1984) 49.
124 P. R. Haddad and A. L. Heckenberg, *Chem. Aust.*, 50 (1983) 275.
125 A. Laurent and R. Bourdon, *Ann. Pharm. Fr.*, 36 (1978) 453.
126 M. Dreux, M. Lafosse and M. Pequignot, *Chromatographia*, 15 (1982) 653.
127 J. J. Stranahan and S. N. Deming, *Anal. Chem.*, 54 (1982) 1540.
128 W. E. Barber and P. W. Carr, *J. Chromatogr.*, 260 (1983) 89.
129 M. Denkert, L.Hackzell, G. Schill and E. Sjögren, *J. Chromatogr.*, 218 (1981) 31.

130 P. E. Jackson, P. R. Haddad and A. L. Heckenberg, unpublished results.
131 P. R. Haddad, *Waters Symposium on HPLC, Etten-Leur, The Netherlands, April 1983.*
132 F. A. Schultz and D. E. Mathis, *Anal. Chem.*, 46 (1974) 2253.
133 W. Roehse, G. Roewer, R. Boran and R. Hellmig, *Z. Chem.*, 22 (1982) 226.
134 M. C. Franks and D. L. Pullen, *Analyst (London)*, 99 (1974) 503.
135 H. Hershcovitz, C. Yarnitzky and G. Schmuckler, *J. Chromatogr.*, 252 (1982) 113.
136 V. V. Bardin, Yu. M. Ivanov and O. F. Shartukov, *Zh. Anal. Khim.*, 33 (1978) 1732.
137 E. A. Ostrovidov, L. A. Kuleshova, S. I. Mitina, R. G. Vinogradova, A. M. Vorontsov, A. S. Kanev and O. A. Rys'ev, *Zh. Anal. Khim.*, 35 (1980) 1677.
138 A. M. Bond, I. D. Heritage, G. G. Wallace and M. J. McCormick, *Anal. Chem.*, 54 (1982) 582.
139 J. E. Girard, *Anal. Chem.*, 51 (1979) 836.
140 K. Tanaka, Y. Ishihara and H. Sunahara, *Bunseki Kagaku (Jap. Anal.)*, 24 (1975) 235; *C.A.*, 83 (1975) 125624b.
141 T. Yoshinori, M. Haruo, T. Hiromichi and M. Giichi, *Bunseki Kagaku (Jap. Anal.)*, 15 (1967) 573; *C.A.*, 67 (1967) 39908k.
142 Y. Hirai, N. Yoza and S. Ohashi, *J. Liq. Chromatogr.*, 2 (1979) 677.
143 Y. Hirai, N. Yoza and S. Ohashi, *J. Chromatogr.*, 206 (1981) 501.
144 Y. Hirai, N. Yoza and S. Ohashi, *Anal. Chim. Acta*, 115 (1980) 269.
145 T. Imanari, S. Tanabe, T. Toida and T. Kawanishi, *J. Chromatogr.*, 250 (1982) 55.
146 S. Tanabe, T. Toida, T. Imanari, N. Okubo and M. Miyazaki, *Bunseki Kagaku (Jap. Anal.)*, 29 (1980) 543; *C.A.*, 94 (1981) 1705m.
147 R. Goguel, *Anal. Chem.*, 41 (1969) 1034.
148 T. Toida, K. Ogata, S. Tanabe and T. Imanari, *Bunseki Kagaku (Jap. Anal.)*, 29 (1980) 764; *C.A.*, 94 (1981) 168756r.
149 N. M. Ferguson, S. E. Lindberg and J. D. Vargo, *Int. J. Environ. Anal. Chem.*, 11 (1982) 61.
150 H. Weisz, S. Pantel and B. Moesta, *Z. Anal. Chem.*, 306 (1981) 106.
151 G. L. Lundquist, G. Washinger and J. A. Cox, *Anal. Chem.*, 47 (1975) 319.
152 J. A. Cox and K. H. Cheng, *Anal. Chem.*, 50 (1978) 601.
153 J. A. Cox and K. H. Cheng, *Anal. Lett.*, 11 (1978) 653.
154 J. A. Cox and Z. Twardowski, *Anal. Chim. Acta*, 119 (1980) 39.
155 J. A. Cox and Z. Twardowski, *Anal. Chem.*, 52 (1980) 1503.
156 J. A. Cox and J. Carnahan, *J. Appl. Spectrosc.*, 35 (1981) 447.
157 J. A. Cox, E. Olbrych and K. Brajter, *Anal. Chem.*, 53 (1981) 1308.
158 J. A. Cox, R. Gajek, G. R. Litwinski, J. Carnahan and W. Trochimczuk, *Anal. Chem.*, 54 (1982) 1153.
159 J. A. Cox and G. R. Litwinski, *Anal. Chem.*, 55 (1983) 1640.
160 J. A. Cox and J. E. DiNunzio, *Anal. Chem.*, 49 (1977) 1272.
161 W. J. Blaedel, T. J. Haupert and M. A. Evenson, *Anal. Chem.*, 41 (1969) 583.
162 J. E. DiNunzio and M. Jubara, *Anal. Chem.*, 55 (1983) 1013.
163 J. L. DiCesare and P. A. Perone, *Pittsburgh Conference, 1983, Abstract 61.*