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Review

Separation of inorganic phosphorus-containing anions by capillary electrophoresis

Tianlin Wang[a], Sam F.Y. Li[b,*]

[a]*Department of Chemistry, National University of Singapore, Singapore 119260, Singapore*

[b]*Department of Chemistry and Institute of Materials and Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore*

Abstract

This article provides a review of separation of inorganic phosphorus-containing anions by capillary electrophoresis including capillary isotachophoresis, capillary zone electrophoresis in free solution and capillary gel electrophoresis. Method development and method evaluation on analytical performance are described. Applications are surveyed. Much attention is focused in the review on the selectivity and detectability of each capillary electrophoretic technique. Features of capillary electrophoretic methods, compared with chromatographic methods, are summarized in the view of analytical separation of inorganic phosphorus-containing anions. Light is given on problems and potentials of the capillary electrophoretic techniques in the separation of inorganic phosphorus-containing anions.

Keywords: Reviews; Isotachophoresis; Capillary zone electrophoresis; Capillary gel electrophoresis; Capillary isotachophoresis; Phosphates; Inorganic anions; Phosphorus-containing anions; Condensed phosphates

Contents

1. Introduction

Phosphorus chemistry is an essential part in study of life processes and environment [1]. Phosphorus chemistry is dominated by oxyphosphorus compounds all of which contain phosphorus-oxygen linkages. Most of these are usually known as phosphates. Compounds containing discrete PO_4^{3-} anions

*Corresponding author. Tel.: +65-772-2681, Fax: +65-779-1691.

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are known as orthophosphates. Such anions may, however, link together by sharing oxygen atoms in common, and these compounds are known as condensed phosphates. Condensed phosphates of one-dimensional chain are termed linear polyphosphates although some of them are actually condensed by only a few or several tens of orthophosphates. Condensed phosphates of rings are named cyclic metaphosphates. Inorganic phosphates are the most important of industrial phosphorus chemicals. Phosphates are used in, just naming a few, synthetic detergents, fertilizers and food additives.

It is usually difficult to analyze complicate samples of inorganic phosphorus-containing anions. Chromatographic methods, such as paper chromatography and ion chromatography, are ones of the most common and useful methods in such analysis. Paper chromatography was found to be very useful in the analysis of condensed phosphates, particularly for separating components of mixtures of condensed phosphates, prior to chemical analysis [1–3]. Using two different solvents for elution, metaphosphates and linear polyphosphates may be separated on the same chromatogram by the technique of two-dimensional paper chromatography. After separation, the paper spots can be cut out and individually subjected to chemical analysis. Paper chromatographic techniques are relatively simple, cheap to set up, and widely used, but precision and accuracy in quantitative analysis are generally inferior to ion chromatography. Separation processes are slow and full separation of the components of a mixture can take as much as 24 h. Two-dimensional thin-layer chromatography could also give good separation of inorganic phosphorus-containing anions of less than four P atoms [4]. Advantage of separation of inorganic phosphorus-containing anions using thin-layer chromatography is its greater speed than paper chromatography.

Ion chromatography (IC) is currently the workhorse for the analysis of inorganic anions. However, separation of inorganic phosphorus-containing anions is not an easy task [5–10]. Orthophosphate shows medium affinity toward stationary phase of anion exchangers, but condensed phosphates exhibit very high affinity, especially the ones of high degree in polymerization. Gradient elution is generally required in the IC separation of inorganic phosphates to improve resolution and reduce separation time. It is still not uncommon to take hours to complete separation and column equilibrium for one injection of a sample of inorganic phosphates. As mobile phase of high elution strength and high acid strength is employed for the separation of inorganic phosphates, conductivity detection of the analytes is difficult owing to high acid concentration in the mobile phase. Thus, inorganic phosphates are usually detected via post-column derivatization with ferric nitrate in acidic solution and measurement of the UV absorption in the wavelength region between 310 nm and 330 nm [10]. Long separation time and complicate detection set-up may be drawbacks of IC in analysis of inorganic phosphates. Recently, some progresses were made in the separation of condensed phosphates by minibore IC with suppressed conductivity detection and separation time for polyphosphates of average chain lengths up to about 25 was shortened to less than 30 min. [11,12].

Capillary electrophoresis (CE) has been shown to be complementary to IC in the aspect of the separation of inorganic anions [13]. On the one hand, CE is known to be generally superior to IC in terms of separation efficiency, separation speed, and sample and regent consumption. On the other hand, CE may be only comparable or inferior to IC in terms of reproducibility and concentration detection limit. In the following we present a brief review on the separation of inorganic phosphorus-containing anions by CE. No doubt orthophosphate is the most important one of inorganic phosphorus-containing anions. However, the separation of only orthophosphate from other non-phosphorus anions will not be included in this review because such separation has been covered in published reviews [14] and will surely be reviewed again in some articles of this special issue. We will mainly focus our attention on the separation of other inorganic phosphorus-containing anions. A linear polyphosphate is denoted by using a subscript of the number of its P atoms, for example tripolyphosphate as P_3. A subscript ''m'' is used to indicate a cyclic metaphosphate. Trimetaphosphate is denoted as P_{3m}. Lower oxo-acids of phosphorus and their anions are denoted using Blaser and Worms nomenclature [1,15]. An example is 3/P-O-3/P for pyrophopshorous acid. For simplicity, charges are omitted in the representation of inorganic

phosphorus-containing anions. But readers should be aware of charge dependence of inorganic phosphorus-containing anions on pH.

2. Separation of inorganic phosphorus-containing anions by capillary isotachophoresis (cITP)

2.1. Methods

Isotachophoresis has been discussed in details and depth in terms of principle, instrumentation and applications in excellent monographs [16,17]. Separation principle is based on differences in effective mobilities of ionic analytes.

cITP was the earliest mode of CE which was employed to separate inorganic phosphorus-containing anions. The reason was that those anions could be detected by some universal detectors, such as thermal detector, potential detector and conductivity detector available in cITP. Beckers and Everaerts [18] studied the qualitative separation of anions including P_1 and P_2 using cITP with thermal detection. The leading electrolyte was a mixture of imidazole and hydrochloric acid at pH 7.05 and terminator of vitamin C. Disadvantages of such a thermal detector were low sensitivity and slow response. Detection of inorganic phosphorus-containing anions in cITP was commonly accomplished with a potential detector. Bocek et al. [19] separated P_1, P_2 and P_3 with leading electrolyte of 0.005 *M* HCl and 0.01 *M* histidine at pH 6 and terminator of 0.01 glutamic acid. Mikkers et al. [20] determined P_2 and P_3 by cITP with creatinine as the counter ion at pH 4.5. Polonsky et al. [21] studied the hydrolytic degradation of some condensed phosphates at 20–80°C and pH 4–7 by cITP. The activation parameters (energy, free energy and entropy) were calculated. Lucansky et al. [22] determined linear polyphosphates from P_1 to P_4 by cITP. The effect of hydrolysis of phosphates on the analytical results was discussed. The separation system used included Cl^- as anion and β-analine, creatinine, or histidine in the leading electrolyte to create pH 4, 5, or 6, respectively. The terminating electrolyte was a solution of glutamic acid. Optimum pH range for the separation of the four phosphates was 4–5. Components were determined by either measuring individual zone lengths or determining the ratio of each zone length to the zone length of a reference substance to correct for nonideality. Yagi et al. [23] performed the separation and quantification for various short chain (n=1–3) phosphorus oxoacids by cITP. Several linear-, cyclic, and lower oxoacids of phosphorus of up to four P atoms were separated at pH 5.5 with a 0.01 mol/l hydrochloric acid–histidine–0.1% Triton X-100 mixture as the leading electrolyte and a 0.01 mol/l hexanoic acid as the terminating electrolyte (see Fig. 1). A capillary of 10 cm×500 μm I.D., and a potential gradient detector were used. The potential unit (PU) value represents the ratio of the potential gradient difference between the sample ion and the leading ion to that between the terminating ion and the leading ion $(P_S-P_L)/(P_T-P_L)$. It is an indicator in qualitative analysis increased in the order of $P_{3m}<P_{4m}<P_3<P_2<1/P<3/P<P_1$. The calibration curves were linear in the range of 0.5–3.5 μg for phosphorus oxoacids, but the calibration curve was nonlinear above 3.5 μg because the phosphorus oxoanions with similar PU values formed the mixed zones. Relative standard deviations (R.S.D.s) (n=8) for the measured phosphorus oxoacids were less than 2% in

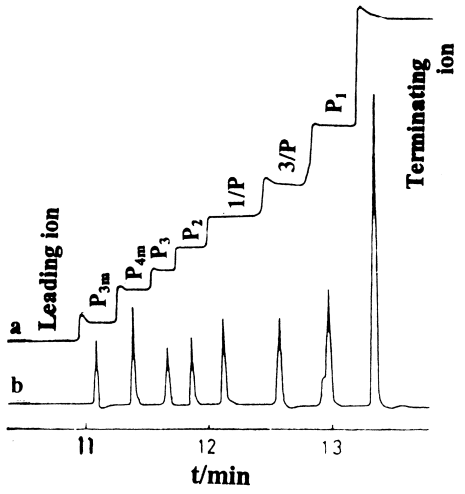

Fig. 1. Isotachopherogram of various phosphorus oxoacids. (a) Potential gradient; (b) differential potential gradient. A Shimadzu Capillary Tube Isotachophoresis Analyzer IP-2A was used with a main capillary column (100 mm×0.5 mm I.D.) for the separation (reproduced with permission from Ref. [23]).

terms of zone length except for P_3 which was measured with a R.S.D. of about 5%. Separation time was approximately 15 min. Separation of long chain length polyphosphates ($n \geq 4$) was difficult since the potential unit were too close. Motooka et al. [24] used the same cITP procedure for the determination of average chain length of linear polyphosphates. They found in the presence of the leading solution of a 0.01 mol/l hydrochloric acid–histidine–0.1% Triton X-100 mixture of pH 5.5, corrected average chain length of about 7 to be a critical chain length on the boundary between rigid and flexible forms. Motooka et al. [25] performed another study on the separation and quantification of a series of cyclic condensed phosphates of P_{3m}, P_{4m}, P_{6m} and P_{8m}. They noted that the leading electrolyte of 0.01 *M* histidine hydrochloride–histidine–0.1% Triton X-100 previously used could not separate P_{6m} and P_{8m}. But the addition of alkaline earth metal cations improved the separation. Nariai et al. [26] separated P_1, P_2, 3/P, 3/P-O-3/P and 3/P-O-5/P at pH 5.5 with 0.01 *M* histidine hydrochloride–0.1% Triton X-100 mixture as the leading electrolyte and 0.01 *M* hexanoic acid as the terminating electrolyte and detected them using potential gradient detector. Fukushi and Hiiro [27] similarly separated P_1, P_2 and P_3 at pH 4.0 with 0.01 *M* histidine hydrochloride–0.075% Triton X-100 mixture as the leading electrolyte and 0.01 *M* hexanoic acid as the terminating electrolyte and detected them using potential gradient detection. Hirokawa et al. [28] evaluated the ion-pair formation constants of phosphorus oxo-acids with histidine and pointed out that the separation of P_{3m} and P_{4m} with a histidine-buffered electrolyte system reported by Yagi et al. [23] was a result of the interaction of the sample ions with the counter ions to form ion pairs leading to a decrease in the effective mobility of the sample ions. Weetman et al. [29] separated monofluorophosphate (MFP), fluoride and P_1 by cITP. A leading electrolyte of 5 m*M* hydrochloric acid adjusted to pH 4.2 with 6-amino-*n*-hexanoic acid and containing hydroxypropyl methylcellulose was used with a terminating electrolyte of 5 m*M* succinic acid. Shida et al. [30] recently used the same conditions to separate various phosphorus oxoacid anions of P_1, 3/P, 1/P, P_2 and P_3, and investigated their adsorption on titanium-oxide treated with alginate.

2.2. Applications

Bocek et al. [19] determined P_1 and P_2 in liquid artificial fertilizers by cITP. Mikkers et al. [20] determined P_2 and P_3 for industrial use. The R.S.D. was $<2\%$. Results of cITP were compared with an ion-exchange method using fraction collection and subsequent spectrophotometric determination. Lucansky et al. [22] obtained analytical results for a mixture of P_1, P_2 and P_3, and for an NH_4^+ polyphosphate solution of liquid fertilizer. Their results obtained using cITP were compared with results of ion-exchange chromatography. Yagi et al. [23] determined P_1, P_2 and P_3 in the ground tripolyphosphates. Weetman et al. [29] determined MFP, fluoride and P_1 by cITP as the direct and simultaneous determination of them is a great advantage in the study of interaction of monofluorophosphate with saliva. Calibration curves for all the three analytes had good linearity over a wide concentration range ($n=10$; $r=0.9997$; 0.5–50 m*M*).The three ions were well separated with the analysis time less than 25 min. For sample preparation only dilution was needed. Shida et al. [30] determined P_1, P_2, P_3, 3/P and 1/P with R.S.D. less than 5% ($n=5$) using cITP. Capillaries used in cITP were usually made of PTFE which is rather inert to allow direct injection of aggressive samples.

3. Separation of inorganic phosphorus-containing anions by capillary zone electrophoresis (CZE)

3.1. Methods

CZE in free solution is the basic and simple mode of CE. Ions are separated into zones on the basis of differences in their effective mobilities. The principle, instrumentation and applications of CZE are discussed in details in many books [31–33].

Hjerten [34] attempted CZE in free solution for the analysis of inorganic ions as early as in 1967. Jorgenson and Lukacs [35,36] demonstrated high separation efficiency and short separation time, and brought CZE into great attention at the beginning of 1980s. It was about ten years later that CZE became a valuable technique for the separation of poor or

non-UV absorbing inorganic ions [37–41]. One reason for such a delay was due to the lack of sensitive detection method for those ions. Inorganic phosphorus-containing anions were rather inactive to common spectrometric and electrochemical detectors operated in CZE. These analytes hardly show any UV absorption, fluorescence or redox activity. Although suppressed conductivity detection has been reported as a universal detector for ions, this approach is not yet much exploited [42]. Potentiometric detector and non-suppress conductivity detector are not as effective and sensitive to inorganic phosphorus-containing anions in CZE as in cITP because the responses of those detectors are often dominated by the carrier electrolytes. Furthermore, separation process in CZE leads generally to dilution of a sample. Only after indirect UV detection was applied to the detection of ionic species in CZE [43], especially introduction of chromate as UV chromophore in carrier electrolyte [40,41], interest in separating inorganic anions by CZE increased rapidly.

In spite of the fact that Jones and Jandik [44] could demonstrate high peak capacity and rapid analysis time in the CZE separation of more than 30 inorganic and organic anions with chromate electrolyte and cationic surfactant of electroosmotic flow (EOF) modifier at pH 8.0, they did not obtained baseline separation of P_1 and 3/P. It has been noted that orthophosphate tends to generate a tailing peak of irreproducible peak area in chromate-based background electrolyte [45–47]. Such a tailing peak was also observed by Wang and Li [48] in chromate-based electrolyte which was adjusted to acidic pH. Mobility of chromate is much greater than that of orthophosphate [48,49]. In general, an asymmetric peak for an analyte is resulted when the mobility of the analyte mismatches with that of co-ion of background electrolyte [50,51].

Stover and Keffer [52] presented the separation of P_1, P_2 and P_3 using CZE with a phthalate buffer of pH 4.2 inside a fused-silica capillary of 75 μm I.D. Dodecyltrimethylammonium bromide was added to the buffer to ensure anodic EOF and rapid separations. The separation was accomplished in 5 min with polarity of power supply reversed and the detection was made at 250 nm in indirect detection mode. Effective charges of P_1, P_2 and P_3 at pH 4.2 were calculated from pK_a data. Approximately equal corrected slopes but different intercepts were observed when calibration curves of normalized peak area vs. equivalent concentration were drawn for P_1, P_2 and P_3. They inferred that the reasons for low detection sensitivities of P_2 and P_3 might include interaction with surfactant and or on-line hydrolysis. R.S.D. ($n=3$) in terms of peak area was 8, 4 and 10% for P_1 at 10 μg/ml, P_2 at 50 μg/ml, and P_3 at 100 μg/ml concentration levels, respectively. At higher concentrations of the analytes precision of peak area was improved and at lower concentrations was worsened. R.S.D. in terms of migration time was in a range of 1.8–3.3%. Problems encountered were significant baseline shifts and relatively poor reproducibility, especially for P_3, in terms of peak area.

Two groups of researchers performed studies on use of ribonucleotides as carrier electrolyte in CZE for the separation and detection of phosphates [48,53,54]. An advantage of using ribonucleotide-based carrier electrolytes is that nucleotides contains a phosphate group in their structure and any irreversible interaction between analytes of phosphates and the wall of fused-silica capillaries [55–57] could be minimized through favourable competition of the carrier electrolytes of high concentration. Shamsi and Danielson [53] studied the separation and detection of polyphosphates (from P_1 to P_4) together with polyphosphonates in adenosine-5′-monophosphate (AMP)-based carrier electrolytes in a pH range of 6.8–8.3 inside a capillary of 50 μm I.D. Their results showed that only P_1 could be transported by the cathodic EOF to the detector located at the cathode side in a buffer composing of 5 m*M* AMP and 100 m*M* H_3BO_3 with pH adjusted to 7.1 if no modifier had been added to the buffer. P_1, P_2 and P_3 were separated with excellent resolution when magnesium ion was added to the AMP-based carrier electrolyte but baseline deterioration was observed. Even in the presence of Mg^{2+}, complete separation of P_3 from P_4 could not be achieved. DR (dynamic reserve being defined as ratio of detector response of carrier electrolyte to noise level [58]) was determined to be 612 for AMP, which was the highest among the four most common ribonucleoside monophosphates. TR (transfer ratio being defined as the number of molecules of background signal generating co-ion in carrier electrolyte to be displaced per analyte ion [58]) was determined to be in increasing order of

$1/P<P_1<P_2$ in a range of 0.51 to 1.5 at pH 6.8 and 7.8. Detection limits for the four analytes were found in a range of 2–5 μ*M* which were comparable with the detection limits of IC for the same analytes [59]. Theoretically calculated detection limits for the above inorganic phosphorus-containing anions were compared with the experimentally determined ones. The two sets of values agreed well with each other. Wang and Li [48,54] developed CZE methods for the separation of P_1, P_2, P_3, P_{3m} and MFP using adenosine-5′-triphosphate (ATP)-based carrier electrolytes in an acidic pH range. All of the analytes were well separated at pH about 3.5 (see Fig. 2). Mobility changes with pH were measured experimentally and compared with theoretical calculation using data in literature. Effect of sample injection volume on separation efficiency and reproducibility of peak area was examined. Separation efficiency of more than $1.2 \cdot 10^5$ theoretical plate number was achieved when sample of 1.0 nl was injected. It was found that sample injection volume about 4.0 nl was a good compromise between separation efficiency and reproducibility of peak area with the manual CE system. In the ATP-based carrier electrolyte Joule heating put a severe limit on the choice of capillary I.D., carrier electrolyte concentration and field strength for the separation. Good results were obtained under conditions of 50 μm I.D. capillary, 5 m*M* ATP and 250 V/cm. Conditions of larger capillary I.D., higher concentration of ATP and greater field strength deteriorated baseline stability, detection limit and reproducibilities of migration time and peak area. DR of $2.8 \cdot 10^3$ was observed in their experiments. The detection limits for the analytes were in a range of 1.0 –5.6 μ*M*. The value of DR reported by Wang and Li [54] was much greater than the one obtained by Shamsi and Danielson [53], but detection limits for the analytes reported were similar probably because the greater DR reported by Wang and Li [54] was compensated for by a loss in TR.

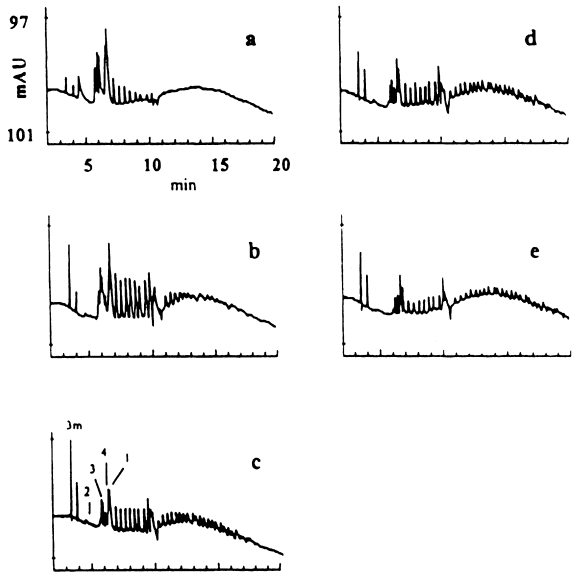

Fig. 2. Separation of sodium polyphosphates with average chain lengths of (a) 5.6, (b) 11.4, (c) 17, (d) 22 and (e) 44. Sample concentrations are (a) 0.2 mg/ml, and (b–e) 0.5 mg/ml. Commercially available separation buffer; 2.25 m*M* pyromellitic aicd, 1.6 m*M* triethanolamine, 0.75 m*M* hexamethonium hydroxide, 6.5 m*M* NaOH, pH 7.7. (c) Shows verified peak identities where the number is chain length (number of phosphorus atoms) with ''m'' indicating *meta* species. Absorbance and time axes for (b–e) same as (a). CE was performed on a SpectroPhoresis 500 instrument (Thermo Separation Products) equipped with a 44 cm (36 cm effective length)×75 μm I.D. fused-silica capillary. Separation were run at −20 kV and 25°C using indirect UV detection at 254 nm (reproduced with permission from Ref. [60]).

Polyphosphates of chain length ≥4 display nearly equal free solution electrophoretic mobilities [24]. Separation of long chain polyphosphates by an electrophoretic technique is more challenging. Stover performed a study on polyphosphate separation using pyromellitic acid as UV-absorbing co-ion and organic ammonium cation as EOF modifier in carrier electrolyte (see Fig. 2) [60]. Model samples were sodium polyphosphates with average chain lengths (*n*) of 5.6, 11.4, 17, 22 and 44. A tentative conclusion on the separation mechanism was that the separation involves ion-pairing between the cationic EOF modifier, such as hexamethonium ion, and the polyphosphates. Similar interactions between polycations with small anions were reported earlier for ''ion-exchange'' electrophoretic separation of aromatic sulfonates by Terabe and Isemura [61].

3.2. Applications

The CZE methods have been applied to the analysis of a variety of samples. The applications of the method range from food processing to quality control of healthcare products and from semicon-

ductor manufacture to environmental concern. Carpio et al. [62] separated MFP and P_1 in a sample of borophosphosilicate thin film, but the peak assignments were somewhat questionable. A sample of P_1 and P_2 from a potato bath of commercial food process was analyzed by Stover and Keffer [52] using phthalate-based carrier buffer. The CZE results were reported and compared with the IC results. Resultant precision for analysis of P_2 was lower than 3% in terms of R.S.D., but precision for P_1 of low concentration was very poor, i.e., about 16% in terms of R.S.D. ($n=3$). Shamsi and Danielson [53] separated anions in either toothpaste or soap without quantification. Interest in separation of toothpaste lies in co-existence of fluoride, MFP and polyphosphates in toothpaste. Fluoride has a very low retention but MFP and polyphosphates have medium to high retention when determined by IC. Fluoride is often eluted very close to the ''dips'' in IC due to its low affinity to anion-exchangers. Some difficulties can arise in quantification of fluoride, especially in the case of presence of carbonate or bicarbonate. On the other hand, elution of MFP and polyphosphates requires the use of eluents of high elution strength.

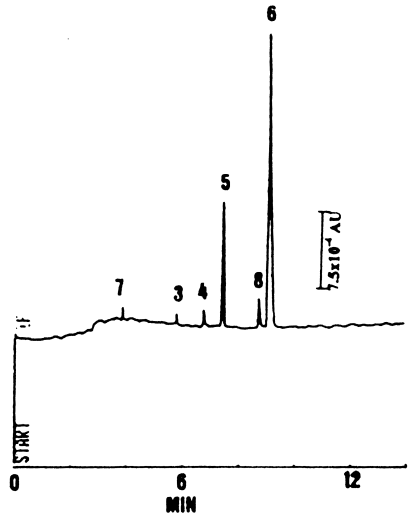

Fig. 3. A typical electropherogram obtained with a sample of commercial toothpaste. Carrier electrolytes: 5 m*M* ATP–0.02 m*M* CTAB at pH 3.6. Capillary: 50.0 cm (40.0 cm effective length)× 50 μm I.D. Voltage: −12.5 kV. Injection: 40 s at 3.0 cm. Detection: at 260 nm. Peaks: 3=P_2; 4=F^-; 5=MFP; 6=P_1; 7=SO_4^{2-}; 8=unidentified. (Reproduced with permission from Ref. [54]).

Unfortunately, fluoride and MFP could not be separated by CZE using their carrier electrolyte of neutral pH. Wang and Li [48] determined builder of phosphates in detergent by CZE. Precision of analysis for P_1, P_2 and P_3 was in a range of 3.2–5.9% in terms of R.S.D. ($n=3$). They also determined anions related to anticaries in toothpaste under milder experimental conditions [54]. A typical electropherogram is given in Fig. 3. The precision for fluoride, MFP, P_1 and P_2 were in a range of 2.4–4.0% in terms of R.S.D. ($n=3$). The CZE results were compared with those obtained by IC or ion selective electrode (ISE). The method developed for the separation of long chain polyphosphate by Stover [60] has a potential use in the rapid characterization of complex polyphosphate mixture, but study on detection response to polyphosphates of different charges and chain lengths is needed.

4. Separation of inorganic phosphorus-containing anions by capillary gel electrophoresis (CGE)

4.1. Method

CGE is known to be a capillary electrophoretic separation mode of unique selectivity on the basis of difference in sizes of analyte molecules [63–66].

Linear gels without cross-linking (i.e., entangled polymer solutions) can be employed to provide size sieving selectivity and avoid the problems of bubble formation in in situ preparing cross-linked gels inside capillaries in spite of somewhat inferior separation efficiencies [67,68]. Wang and Li [69] reported the separation of condensed phosphates by CGE with indirect UV detection. The linear gel was prepared by polymerization of 12% (w/v) acrylamide solution containing 5 m*M* pyromellitic acid and 20 m*M* Tris (pH=7.2). More than 30 components were separated and detected in a polyphosphoric sample using the CGE method (see Fig. 4). In Fig. 4, peak orders of identified components indicated that the separation of the linear polyphosphates is not only based on size but also the charge-to-size ratios which still play a significant role in the migration behaviour of P_1 and P_3. To quantify each component and characterize condensed phosphate samples, further study is

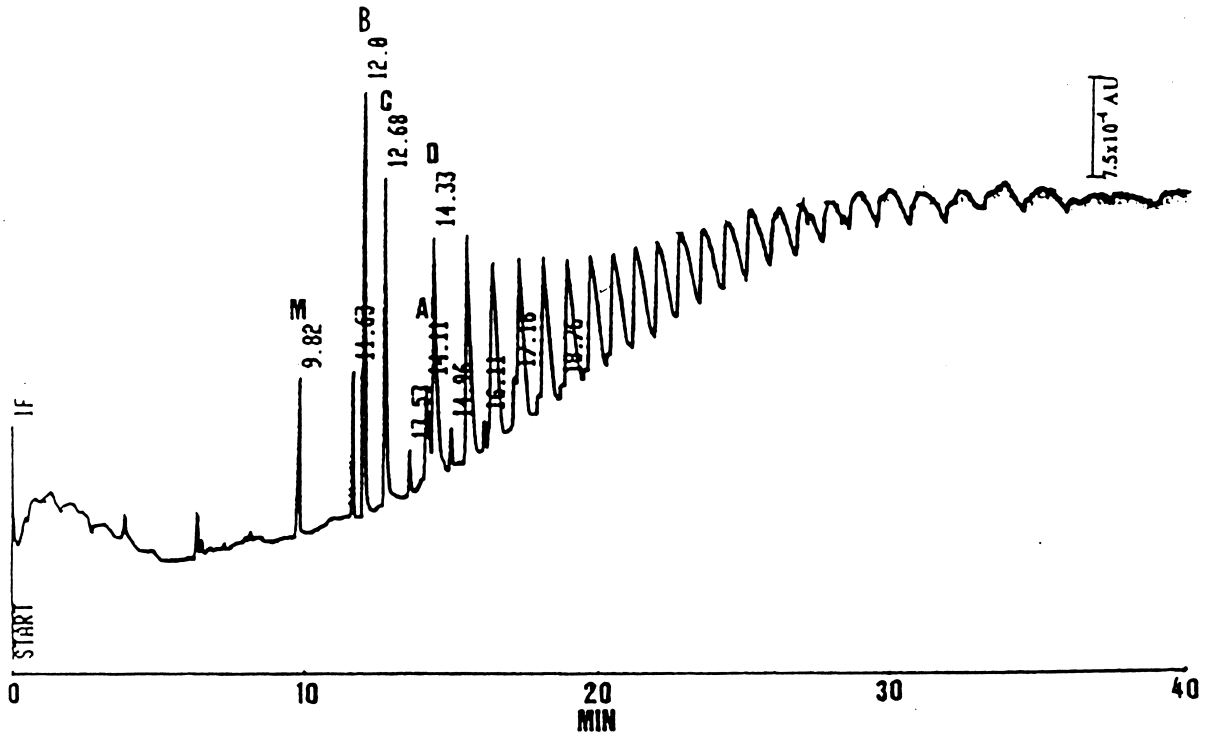

Fig. 4. Separation of polyphosphoric acid (sodium salt) in a linear polyacrylamide gel-filled capillary. The linear polyacrylamide gel was prepared by polymerisation of 12% (w/v) acrylamide solution containing 5 m*M* pyromellitic acid and 20 m*M* Tris (pH=7.2). Electrokinetic injection: −4.5 kV for 5 s. Detection: at 254 nm. Separation voltage: −8.4 kV. Capillary: 40.0 cm (31.0 cm effective length)×50 μm I.D. Peaks: A=P_1; B=P_2; C=P_3; D=P_4; M=P_{3m}. (Reproduced with permission from Ref. [69]).

needed to correct the bias generated by electrokinetic injection and to take into consideration the differences in the detection response to polyphosphates of different charges and chain lengths.

5. Conclusions

Inorganic phosphorus-containing anions with less than four P atoms in various samples can be readily analyzed by either cITP with potential gradient detection or CZE with indirect UV detection. Advantages of electrophoretic methods for the analysis of inorganic phosphorus-containing anions include short analysis time, little or no sample preparation, and low operation cost. With the introduction of separation mechanisms based on ion-exchange or size sieving effects, phosphates of chain lengths up to several tens of orthophosphates can be separated by either CZE or CGE. Quantification of individual components and separation of polyphosphates of greater chain lengths are challenging future research areas. Besides identification and quantification, capillary electrophoresis separation of inorganic phosphorus-containing anions may also provide useful information on the electrolyte solution chemistry of these ions.

Acknowledgements

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