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Note

Ion chromatography of polyphosphonates with direct refractive index detection

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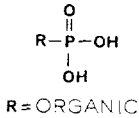
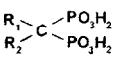
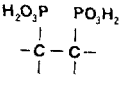
Indirect refractive index detection has been used widely for the chromatography of ions[1–3]. In this paper, we report the use of refractive index for the direct detection of polyphosphonates with a sensitivity for picograms to nanograms per injection or ng/ml (ppb) or μg/ml (ppm) concentration levels in the analyzed sample. Polyphosphonates are organic derivatives of phosphorous acid (Fig. 1). Among them, geminal diphosphonates are of biological interest since they have been shown to be effective for treating bone diseases through regulation of calcium metabolism within the body[4]. Other polyphosphonates have found usage as detergents and scale inhibitors in many aspects of industrial water treatment[5]. For the purpose of product quality control and chemical assays, methods have been sought for the specific detection of these species. As an example, ^{31}P nuclear magnetic resonance has been used for quantification of specific polyphosphonate compounds[6]. Previous studies have shown that ion chromatography can provide rapid separation and detection of polyphosphonate mixtures[6–9]. In all reports to date, the detection of polyphosphonates has been afforded by post-column reaction in which Fe^{3+} is used as a detection reagent by forming UV-absorbing species with the polyphosphonates. Such detection is unavoidable only for polyphosphonates in complex matrices. Detergent formulations or biological fluids can be named as examples. However, in numerous cases the relatively complicated post-column visualization has been used only because of the lack of a simpler approach. Reaction mixtures obtained during the manufacturing of polyphosphonates, drinking and industrial water, as well as various plating so-



R = ORGANIC GROUP



GEMINAL



VICINAL

Fig. 1. Structures of polyphosphonates.

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lutions, are just a few examples where the selectivity of the post-column derivatization is not required. For these and other samples, the post-column devices for the chromatographic analysis of phosphonates can now be replaced by sensitive refractive index detection.

EXPERIMENTAL

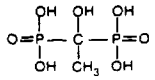
The separation and detection of polyphosphonic compounds was studied using five polyphosphonates commercially available from Monsanto Corp. Fig. 2 shows the structures and the nomenclature for these compounds.

Gold-plating solution used to demonstrate practical application of the developed method was obtained from Rockwell International, Golden, CO, U.S.A.

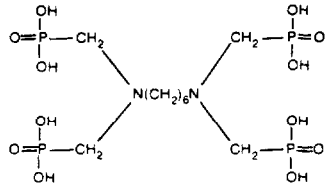
Eluents (12 and 15 m*M*) were prepared from Ultrex nitric acid (J. T. Baker) by dilution with deionized water from a Milli-Q Purification System (Millipore). Prior to use, the eluents were filtered through 0.45-μm membrane filters.

The ion chromatographic system consisted of a Model 590 programmable sol-

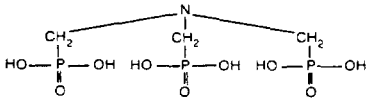
2010



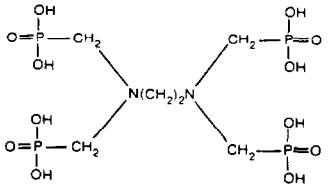
2054



2006



2041



2060

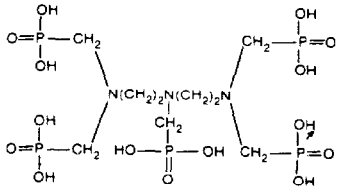


Fig. 2. Sequestering agents, Monsanto series of phosphonates (Dequest).

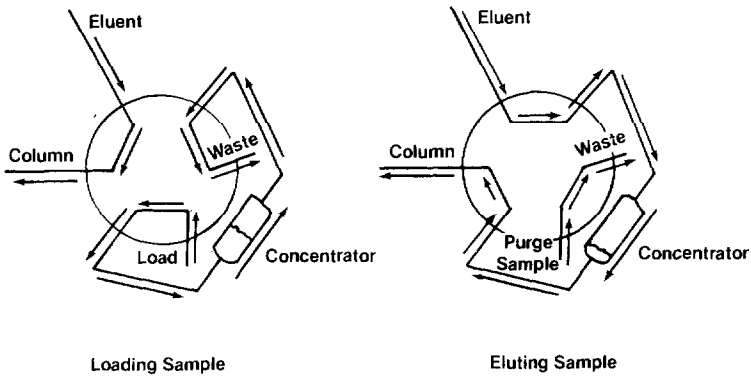


Fig. 3. Backflush technique. Use of a six-port valve to load and elute the sample.

vent delivery system, a Model 710B WISP automatic injector, and a Model 410 refractive index detector, as well as a Model 840 data acquisition and evaluation system, all from Waters–Millipore. The separations were carried out on a resin-based anion-exchange IC Pak A column, 10 μm particle size, 4 mm × 4.6 mm I.D. (Waters–Millipore). Chromatographic conditions are given in the captions to the chromatograms.

Preconcentration of dilute polyphosphonate solutions was achieved by loading the sample through an anion concentrator cartridge placed in a holding device. The sample containing the polyphosphonates was pumped through the concentrator cartridge utilizing a single piston pump. The solutes trapped in the concentrator were then eluted in the reverse direction with the mobile phase and subsequently separated on the analytical column. This "backflushing" routine was made possible by integrating a six-port rotary high-pressure switching valve into the flow path of the ion chromatographic system as shown in Fig. 3.

Execution of loading and elution of each sample was automated by linking of

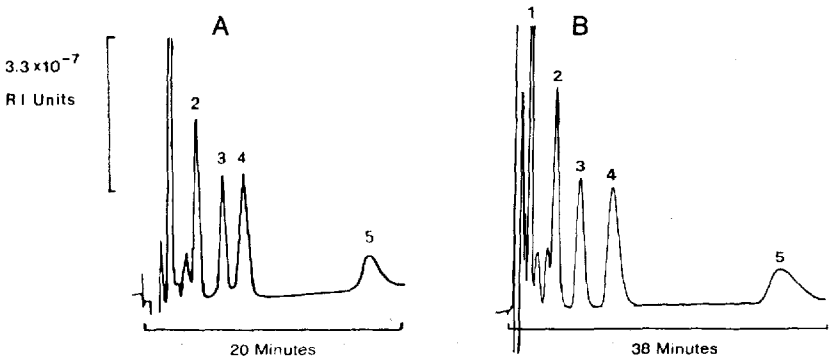


Fig. 4. Separation of polyphosphonates at two different strengths of the mobile phase: (A) 15 mM nitric acid; (B) 12 mM nitric acid. Conditions: column, Waters IC Pak A; flow-rate, 1.2 ml/min; detection, Waters M410 refractive index, sensitivity 1024, scale factor 8. Injection volume: 200 μl. Peaks: 1 = Dequest 2010 (76.8 ppm); 2 = Dequest 2054 (30.4 ppm); 3 = Dequest 2006 (38.0 ppm); 4 = Dequest 2041 (45.0 ppm); 5 = Dequest 2060 (44.1 ppm).

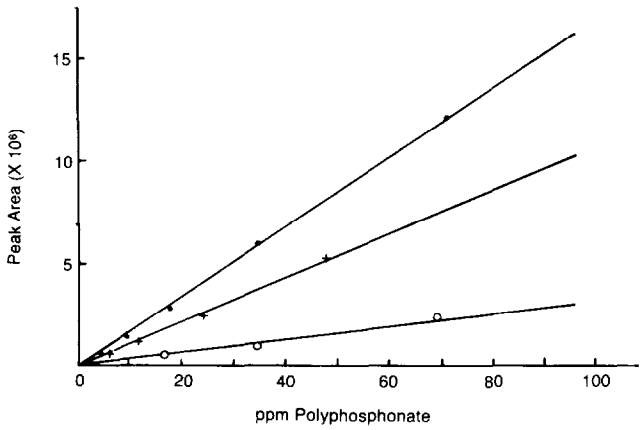


Fig. 5. Linearity of detector response for polyphosphonates. ●, Dequest 2054; +, Dequest 2006; ○, Dequest 2041. Same chromatographic conditions as in Fig. 4B.

the microprocessor control in the Model 590 pump to the single-piston trace enrichment pump and to the pneumatically driven six-port valve. Details of the trace-enrichment procedure are listed in the legends to Figs. 6 and 7.

RESULTS AND DISCUSSION

In the chromatographic separations of strongly acidic solutes such as the polyphosphonates, the pH of the eluent, as well as the concentration of the displacing anion, determines the retention time of the solute. To assure a reasonable run time, the valence of the displacing anions is to be matched to that of the analyte. In this particular case, the pH should be sufficiently low (*i.e.*, pH 2.2) to maintain the polyphosphonates in a monovalent state. For instance, Dequest 2010 (hydroxyethylidene-1,1′-diphosphonic acid) has the first pK_a at pH 1.9 (ref. 10), its average valence state is −0.5 and is as such quickly eluted. Fig. 4 demonstrates the influence of the pH of the eluent on the retention behavior of polyphosphonates. To test the significance of non-ionic interactions of polyphosphonate solutes with the polymethylmeth-

TABLE I

DETECTION LIMITS BY DIRECT INJECTION

Dequest	*Detection limits (100 µl injection volume)*		
	ppm	*ng*	*nmol*
2010	2.4	480	2.3
2054	2.8	560	1.1
2006	3.0	600	2.0
2041	7.1	1420	4.7
2060	15.2	3040	5.3

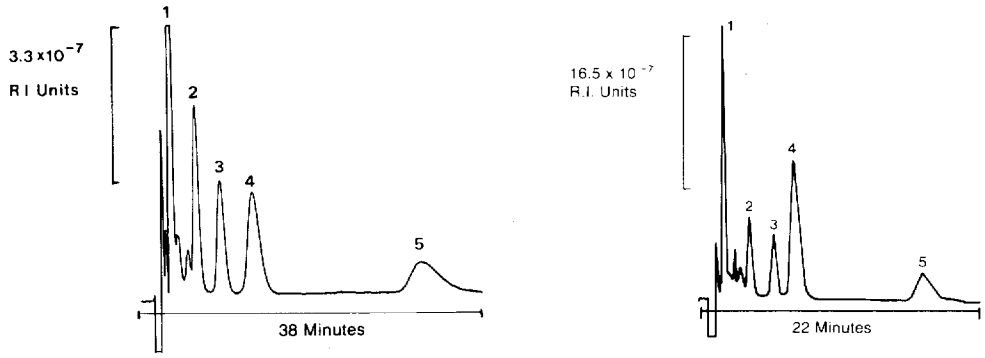


Fig. 6. Analysis of low concentrations of polyphosphonates using trace enrichment at a low flow-rate and with a weak eluent. Conditions: trace enriched volume, 20 ml; trace enrichment flow-rate, 1.55 ml/min. Other conditions same as in Fig. 4B. Peaks: 1 = Dequest 2010 (768 ppb); 2 = Dequest 2054 (304 ppb); 3 = Dequest 2006 (380 ppb); 4 = Dequest 2041 (450 ppb); 5 = Dequest 2060 (441 ppb).

Fig. 7. Preconcentration of polyphosphonates using higher flow-rate and stronger mobile phase. Conditions: trace enrichment volume, 25 ml; trace enrichment flow-rate: 2.9 ml/min. Other conditions same as in Fig. 4A. Peaks: 1 = Dequest 2010; 2 = Dequest 2054; 3 = Dequest 2006; 4 = Dequest 2041; 5 = Dequest 2060. Concentrations of all five polyphosphonates were 400 ppb.

acrylate resin backbone of the ion exchanger, 5% acetonitrile had been added to the mobile phase. No change in the peak shapes or retention times was observed, allowing the conclusion that such interactions do not contribute significantly to the separation mechanism. The response of the refractive index detector was linear up to 100 ppm (20 μg) of polyphosphonate (Fig. 5). The limit of linearity was imposed by the capacity of the analytical column, not by the detector itself. In a related study[11], where a larger capacity column was used, the linearity was extended to 400 ppm (80 μg) of polyphosphonates.

The correlation coefficient of each calibration curve was in excess of 0.9995.

TABLE II

RECOVERY OF POLYPHOSPHONATES AT 1.55 ml/min FLOW-RATE IN THE TRACE ENRICHMENT STEP (WEAKER ELUENT)

Refer to Figs. 4B and 6 for conditions. Direct injections: amounts indicated in Fig. 4B. Trace enrichment: amounts given in Fig. 6. The same absolute amounts of analytes were injected in both direct injection and trace enrichment experiments. Average recovery (%) $= \frac{\text{mean peak height trace enrichment}}{\text{mean peak height direct injection}} \cdot 100$

Dequest	*Peak heights (cm)*						
	Direct injection			*Trace enrichment*			*Average recovery (%)*
	Exper. 1	*Exper. 2*	*Mean*	*Exper. 1*	*Exper. 2*	*Mean*	
2054	13.15	13.20	13.18	10.80	11.00	10.90	82.7
2006	7.90	7.90	7.90	6.80	6.80	6.80	86.1
2041	7.30	7.30	7.30	6.10	6.00	6.05	82.9
2060	2.10	2.15	2.13	1.80	1.80	1.80	84.5

TABLE III

RECOVERY OF POLYPHOSPHONATES AT 2.9 ml/min FLOW-RATE IN THE TRACE ENRICHMENT (STRONGER ELUENT)

Polyphosphonates (100 ppm) were directly injected. For trace enrichment, the 100 ppm standard solutions were diluted in the ratio of 1:250. Direct injected and trace enriched volumes were 100 μl and 25 ml, respectively.

Dequest	*Peak height: mean (cm) ± R.S.D. (%) (n = 4)*		*Average recovery (%)*
	Direct injection	*Trace enrichment*	
2054	3.22 ± 0.9	2.74 ± 1.7	85.1
2006	2.52 ± 3.8	2.16 ± 2.2	85.7
2041	5.64 ± 2.0	4.70 ± 1.2	83.3
2060	1.05 ± 0.0	0.89 ± 2.8	84.8

Points in the plot were obtained from replicate determinations for Dequest 2054 and 2041. In the case of Dequest 2006, three determinations for each of the points have been carried out. The average precision for these triplicate runs was ±0.9%, ranging from 3.4% for the smallest peak areas to 0.04% for the largest peak areas.

The detection limits (two times the noise expressed in concentration units) by direct injection, without any preconcentration of the sample are shown in Table I.

Solutions containing concentrations lower than the above detection limits can be analyzed after preconcentration (Figs. 6 and 7, see also Experimental). A recovery study involving four of the five polyphosphonates was performed at two different flow-rates, in the trace enrichment step and at two differing concentrations of the mobile phase.

As can be seen comparing the respective recovery rates (Tables II and III) no significant improvements are achieved by choosing a lower trace enrichment flow-

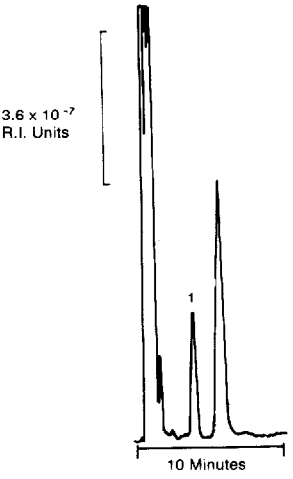


Fig. 8. Dequest 2006 in a gold-plating bath. Conditions: 100 μl of 1:1000 diluted sample, other conditions same as in Fig. 4A. 1 = Dequest 2006 (96.4 ppm).

rate and a lower concentration of the nitric acid eluent. This observation is valid only in the tested range of flow-rates of 1.55–2.9 ml/min and for the concentrations of nitric acid between 12 and 15 m*M*.

Using the experimental conditions shown in Fig. 7, *i.e.* higher trace enrichment flow-rate and stronger eluent resulting in shorter duration of analysis, four repetitive runs were carried out to assess the reproducibility of the method. The relative standard deviations (R.S.D.) observed were in the range of 1.7 to 2.8%.

To demonstrate the practical usefulness of the studied method, the concentration of Dequest 2006 in a gold plating bath was analyzed (Fig. 8). The polyphosphonate is added to the plating solution to improve its coulombic efficiency. The optimal range of concentrations is usually of the order of 5–10%. These levels are well above the direct injection detection limit for the Dequest 2006 as given in Table I.

The concentration of the polyphosphonate determined by direct injection (no trace enrichment is required) using the external standard quantitation is given in the legend to Fig. 8.

CONCLUSION

This study shows that the direct refractive index detection may be advantageously employed to monitor large, non-chromophoric inorganic ions that are eluted by a low-molecular-weight inorganic eluent. The sensitivity thus obtained is due to the large difference in the refractive indices of the solute and eluent and is directly related to the respective molecular weights and densities[12].

REFERENCES

1 J. S. Fritz, D. T. Gjerde and C. Pohlandt, *Ion Chromatography*, Hüthig, Heidelberg, New York, 1982.
2 P. R. Hadded and P. Jandik, in J. Tarter (Editor), *Ion Chromatography*, Marcel Dekker, New York, 1986, p. 87.
3 P. R. Haddad and A. L. Heckenberg, *J. Chromatogr.*, 252 (1982) 177.
4 M. D. Francis and R. L. Center, *J. Chem. Educ.*, 55 (1978) 760.
5 R. Weintritt and N. Cowan, *Water Formed Scale Deposits*, Gulf Publishing Co., Houston, 1976, pp. 273–275.
6 A. W. Fitchett and A. Woodruff, *I.C, Liq. Chromatogr. HPLC Mag.*, 1 (1983) 48.
7 F. Pacholec, D. T. Rossi, L. D. Ray and S. Vazapolas, *LC, Liq. Chromatogr. HPLC Mag.*, 3 (1985) 1068.
8 S. H. Edelmuth and D. J. Pietrzyk, *ACS National Meeting, Chicago, September 1985.*
9 T. Imanari, S. Tanabe, T. Toida and T. Kawanishi, *J. Chromatogr.*, 250 (1982) 55.
10 T. Fonong, D. J. Burton and D. J. Pietrzyk, *Anal. Chem.*, 55 (1983) 1089.
11 D. Wong, unpublished results.
12 D. J. Pasto and C. R. Johnson, *Organic Structure Determination*, Prentice Hall, Engelwood Cliffs, NJ, 1969, p. 68.