



High-speed ion chromatographic separation of cations at elevated temperature

Jenny Chong, Panos Hatsis¹, Charles A. Lucy*

Department of Chemistry, Gunning/Lemieux Chemistry Centre, University of Alberta, Edmonton, Alberta T6G 2G2, Canada

Abstract

The application of temperatures up to 90 °C for high-speed cation separations by ion chromatography is investigated. A Dionex CS12A column (150×3 mm I.D.) and suppressed conductivity detection are used for the separation of Li^+ , Na^+ , NH_4^+ , K^+ , Rb^+ , Cs^+ , Mg^{2+} , Ca^{2+} , and Sr^{2+} . Elevated temperatures reduce the viscosity of the eluent, which allows the use of flow-rates up to 1.3 ml/min, which are significantly higher than that typically used (0.5 ml/min). Further, separation efficiencies improved with temperature, even at high flow-rates. However, elevated temperatures decrease the retention of all cations, with the decrease being most pronounced for the strongly retained cations. This limits the optimal column temperature to 60 °C. Nevertheless at 60 °C, the separation of nine cations is accomplished in under 5 min, compared to 12 min under conventional conditions, i.e., 60% reduction in analysis time.

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1. Introduction

Ion chromatography (IC) is a powerful technique for the separation, identification, and quantification of organic and inorganic ions. As a consequence, IC is widely used in the environmental, electronics, petrochemical, power, food and beverage, and pharmaceutical industries [1–5]. However, typical IC run times are 5 to 20 min, which places a restriction on sample throughput in the laboratory. Consequently, the ability to perform faster IC separations is particularly attractive.

A major hurdle associated with high-speed separations in IC is the pressure limit of the column. Most IC columns are limited to pressures at or below 4000 p.s.i. (1 p.s.i.=6894.76 Pa). Thus, there is a limit as to how high a flow-rate can be used. In addition, loss in efficiency at the higher flow-rates results in decreased resolution. This pressure limitation of the column and band broadening at high flow-rates make it difficult to achieve fast separations in IC/high-performance liquid chromatography (HPLC). However, these problems have been circumvented in a number of ways. Connolly and Paull separated the common anions in less than 2.5 min using a 3 cm long column packed with 3 μm particles [6–8]. Hatsis and Lucy exploited the high permeability of monolithic columns to perform a 15 s ion-pair separation of eight anions using a flow-rate of 16 ml/min [9]. A third approach has been to use elevated column temperature. Such

*Corresponding author. Tel.: +1-780-492-0315; fax: +1-780-492-8231.

E-mail address: charles.lucy@ualberta.ca (C.A. Lucy).

¹Current address: Institute for Marine Biosciences, National Research Council Canada, 1411 Oxford St., Halifax, Nova Scotia, B3H 321, Canada.

increases in column temperature result in a decrease in the solvent viscosity, and thus a decrease in the column backpressure. This permits the use of higher flow-rates, giving an increase in separation speed. Further, the efficiency is significantly improved at elevated temperatures due to enhanced mass-transfer of the solute [10,11]. Much of the recent studies with in high temperature has resulted from the commercial availability of thermally stable packings based on zirconia [12,13]. These columns have been used at temperatures as high as 370 °C [14]. Using reversed-phase liquid chromatography (RPLC) zirconia packings at 150 °C, Yan et al. achieved a 50-fold reduction in separation times of hydrophobic analytes relative to ambient temperature separations [11].

In this work, the use of temperature for high-speed IC separations of cations using a conventional (Dionex CS12A) IC column is systematically investigated. Previously, Rey studied the use of column temperatures as high as 70 °C for cation separations on a Dionex CS16 column [15]. Hatsis and Lucy studied the effects of increased temperature on the ion chromatographic separations of cations [16]. However, they focused on the selectivity changes caused by elevated temperatures, and did not exploit the opportunities that elevated temperatures offered in terms of separation time. The present work demonstrates that the separation time for common cations can be reduced by 60% by use of elevated column temperatures.

2. Experimental

2.1. Apparatus

A Dionex AGP-1 (Dionex, Sunnyvale, CA, USA) dual-piston pump was used for eluent flow. A Spectra Physics AS3500 (Thermo Finnigan, Mississauga, Canada) autosampler was used to inject 20 μ l of sample by means of a Rheodyne 9010 injection valve (Rheodyne, Cotati, CA, USA) under the “full loop” mode. Separations were achieved with a Dionex CS12A cation-exchange column (150 \times 3 mm I.D.). Detection of the cations was via a Dionex CDM-3 conductivity detector with a Dionex CSRS-Ultra (2 mm) suppressor. The connecting

tubing was 0.005 in. I.D. (1 in.=2.54 cm) polyether ether ketone (PEEK; Upchurch Scientific, Oak Harbor, WA, USA). Data was collected at 5 Hz through a Dionex AI-450 data acquisition system linked to a Pentium II microcomputer equipped with Dionex Peak Net 5.0 software. Fifty centimeters of connecting tubing was added after the conductivity cell to provide sufficient backpressure to prevent formation of air bubbles in the cell.

The use of a suppressor at elevated flow-rates and temperatures necessitated additional modifications to the chromatographic system. The 2 mm CSRS suppressors can only tolerate flow-rates up to 0.75 ml/min. Thus, the flow was split to maintain a constant flow of 0.5 ml/min through the suppressor. A T-adaptor (1 μ l dead volume, Upchurch Scientific) was placed between the column and suppressor. Capillary tubing (Polymicro Technologies, Phoenix, AZ, USA) was connected to the third outlet of the T-adaptor to act as a flow constrictor, and thus control the flow through the suppressor. Four to twenty centimeters of 75 μ m I.D. capillary was used for flow-rates of 0.6–1.2 ml/min, and 14 cm of 100 μ m I.D. capillary was used for a flow-rate of 1.3 ml/min. In addition, the suppressor was unable to withstand temperatures above 30 °C [15]. Thus, the eluent was cooled to room temperature before entering the suppressor, as described below.

An Eppendorf CH-30 column heater and an Eppendorf TC-50 control module (Alltech Associates, Deerfield, IL, USA) were used to pre-heat the eluent and control the column temperature. The eluent was preheated using a 30 cm long piece of connecting tubing (0.005 in. I.D. PEEK, Upchurch Scientific) wrapped around the mobile phase preheater. The effluent from the column was cooled before entering the suppressor by passage through 10 cm of PTFE tubing (0.007 in. I.D., Alltech) immersed in a beaker of room temperature water. The efficiencies achieved with the oven in place were the same at the 95% confidence level [17] as those observed at room temperature (23 °C) without the column oven and extra connecting tubing.

2.2. Reagents

All sample and eluent solutions were prepared using distilled deionized water (Nanopure Water

System, Barnstead, Chicago, IL, USA). Eluents were prepared using 99.5%+ methanesulfonic acid (MSA) purchased from Aldrich (Milwaukee, WI, USA). The eluent was degassed by a continual purge with helium. All chemicals were reagent grade or better. Stock solutions ($10^{-2} M$) of the cation samples were prepared and sample solutions ($10^{-5} M$) of the desired cations were prepared by dilution. Sodium (BDH, Toronto, Canada), ammonium (BDH), rubidium (Fisher, Nepean, Canada), cesium (Fisher), calcium (Anachemia, Toronto, Canada), strontium (Fisher), and magnesium (BDH) cations were obtained by dissolving their chloride salts. Lithium (Fisher) and potassium (Fisher) were used in the form of their nitrate salts.

2.3. Procedure

The effect of temperature on retention can be described by the simplified integrated van't Hoff equation [18–20]:

$$\ln k = \frac{-B}{T} + A \quad (1)$$

where k is the retention factor, T is the temperature (K), and A and B are constants for a particular analyte, eluent and column. Plots of $\ln k$ vs. $1/T$ were fit to the van't Hoff equation using Microsoft Excel 97 software (Microsoft, Seattle, WA, USA). The water dip was used for the void time. Plate heights for the van Deemter curves were calculated from the second moment found by fitting the peaks to an exponentially modified Gaussian curve using MATLAB Release 12 (Mathworks) [21]. The resulting data was fit to the van Deemter relationship using GraphPad Prism 3.02 (GraphPad Software, San Diego, CA, USA).

3. Results and discussion

3.1. Effect of temperature on retention

The effect of temperature on ion chromatographic separations can be complex. Both exothermic (decreasing retention with temperature) and endothermic (increasing retention with temperature) enthalpies of retention have been observed for anion-exchange

separations [18]. However, the low thermal stability of anion-exchange resins limits their use to temperatures below 60 °C. Above this temperature nucleophilic substitution of hydroxide on the benzylic carbon, and to a lesser extent the methyl carbon, results in decreased strong base capacity and a decrease in retention at high pH (e.g., when using hydroxide eluents) [22].

In contrast, cation-exchange resins exhibit exceptional thermal stability. For example, sulfonated cation-exchange resins are formed by reaction of the polystyrene resin with concentrated sulfuric acid at 100 °C [20]. Thus, a greater temperature range can be explored with these resins, thereby enabling higher flow-rates to be used. Further, previous studies between 27 and 60 °C indicated that retention in cation-exchange separations usually decreases with an increase in temperature [16]. This further augments the enhanced separation times that could be achieved by increasing the column temperature.

The effect of temperature on the retention of cations was studied herein between 27 and 90 °C. The resulting van't Hoff plots (Eq. (1)) are shown in Fig. 1. The linear regression data associated with these plots are summarized in Table 1. Linear van't Hoff plots were observed in previous studies of anion- [18] and cation- [16] exchange chromatography conducted over the temperature range of 27–60 °C. However, studies over more extended temperature ranges reported non-linear behavior in van't Hoff plots for ion-exchange chromatography [23]

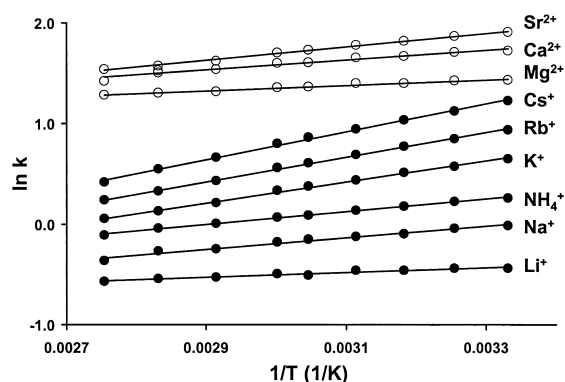


Fig. 1. van't Hoff plots of cations. Experimental conditions: Dionex CS12A column, 17 mM MSA at 0.5 ml/min, 20 μ l injection, temperature range from 27 to 90 °C, 50 μ M analyte concentration.

Table 1
van't Hoff temperature dependencies for cation-exchange retention

Cation	Slope	P-Value	r^2
Li ⁺	240±30	0.007	0.862
Na ⁺	530±20	0.000	0.994
NH ₄ ⁺	640±10	0.000	0.997
K ⁺	1050±20	0.000	0.997
Rb ⁺	1230±10	0.000	0.999
Cs ⁺	1410±20	0.000	0.995
Mg ²⁺	220±10	0.001	0.944
Ca ²⁺	520±30	0.000	0.939
Sr ²⁺	670±20	0.000	0.994

Experimental conditions: Dionex CS12A column, 17 mM MSA eluent temperature range from 27 to 90 °C; flow of 0.5 ml/min, 20 µl injection, 50 µM analyte concentration.

and RPLC [19]. Over the temperature range of 27–90 °C, the van't Hoff plots of all nine cations studied in this work are linear, as indicated by the small *P*-values (less than 0.05) in Table 1. This means there is adequate correlation of the data to the simplified van't Hoff equation (Eq. (1)) to support the use of a linear relationship at the 95% confidence level. The slopes of these van't Hoff plots are positive showing that retention decreases with increasing temperature, which is consistent with previous studies [16]. The decrease in retention might be due in part to reduced ionization of the carboxylate groups of the stationary phase at elevated temperature. This would lead to an effective capacity reduction of the stationary phase, and a decrease in retention. Thus, as is the case in RPLC [11,19], increasing column temperature in cation-exchange chromatography yields a decrease in retention and thereby an increase in separation speed.

Previous work has shown that the selectivity of cation-exchange separations can be altered through a change in column temperature [16]. Selectivity changes were most pronounced between cations of differing charge. This is most evident in Fig. 2 where there is a significant improvement in the separation between Cs⁺ and Mg²⁺ upon increasing the column temperature from 27 to 60 °C. However, for cations of the same charge, the more strongly retained cations show a greater van't Hoff plot slope. That is, a greater decrease in retention at elevated temperature is seen for more strongly retained cations. Thus, as the temperature is increased, the more strongly

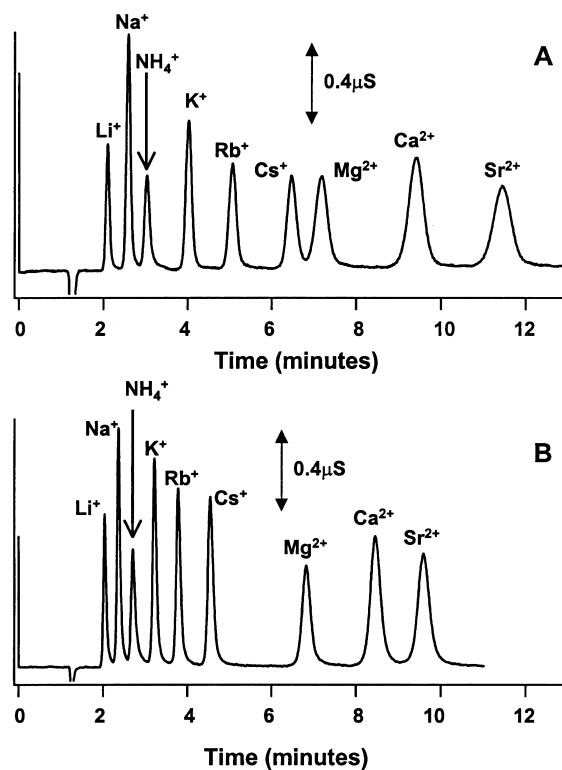


Fig. 2. Separation of nine cations at (A) 27 °C, (B) 60 °C. Experimental conditions: Dionex CS12A column, 17 mM MSA at 0.5 ml/min, 20 µl injection, 50 µM analyte concentration.

retained cations within a group will elute closer to the more weakly retained species. This differs from the behavior observed in RPLC, where the van't Hoff plots are generally parallel [19,24], i.e., temperature does not have a significant effect on selectivity in the RPLC of small molecules even over temperature ranges as wide as 30 to 130 °C [19].

Fig. 2 compares separations of the nine cations at 27 and 60 °C, with the same flow-rate and eluent strength. There is a 15% increase in the separation speed due to the decreased retention. However as can be seen in Fig. 2, the peaks of the monovalent cations begin to converge as the temperature is increased from 27 to 60 °C, and similarly for the divalent cations. At temperatures higher than 60 °C, baseline resolution is lost (separation not shown). The loss of resolution results from a number of factors. Firstly, retention decreases as the temperature is increased. This results in many of the

univalent cations eluting near the dead volume of the column. The eluent strength can be reduced to compensate for the reduced retention at elevated temperatures [25]. However, increasing the retention negates some of the advantages to be gained by using higher column temperatures. Nevertheless, adjustment of the eluent strength is explored in Section 3.4. Secondly, extra-column band broadening can severely impact the efficiency of weakly retained analytes [26]. Finally, the retention factors of the cations converge at high temperature. This is most evident for the alkaline earth metals in Fig. 1. For these reasons, 60 °C was chosen as the optimum temperature for further studies.

3.2. Effect of temperature on viscosity and column backpressure

At elevated temperatures there is a decrease in eluent viscosity and a concomitant decrease in column backpressure. From 27 to 60 °C there is a 45% decrease in viscosity, from 0.86 to 0.47 cP [27]. At a flow-rate of 0.5 ml/min there is a 33% decrease in pressure, from 1660 to 1100 p.s.i. (Fig. 2). The reduction in backpressure is somewhat moderated by the extra column components, which remain at room temperature. If the contribution of the extra-column components is removed (approximately 300 p.s.i.), then there is a 41% drop in column backpressure at 60 °C, which is in close agreement to theory. Nonetheless, the drop in column backpressure allows an increase in flow-rate, and ultimately, will lead to an increase in separation speed.

To compare the separation speed that is achievable at elevated temperatures, the separation of nine cations was performed under flow conditions corresponding to a constant backpressure of 2400 p.s.i. The column is rated to 4000 p.s.i. [28]. However, it was considered that 2400 p.s.i. represented a pressure at which the IC could be operated routinely. Fig. 3A shows the cation separation at 27 °C. A flow-rate of 0.90 ml/min yielded an analysis time of 8 min. In contrast, at 60 °C a flow-rate of 1.30 ml/min was attained giving an analysis time of 5 min (Fig. 3B). Comparing Fig. 3A and B, the elution time decreased from 8 to 5 min when the temperature was increased from 27 to 60 °C. This is a 35% decrease in analysis time based solely on the increased flow-rate allowed

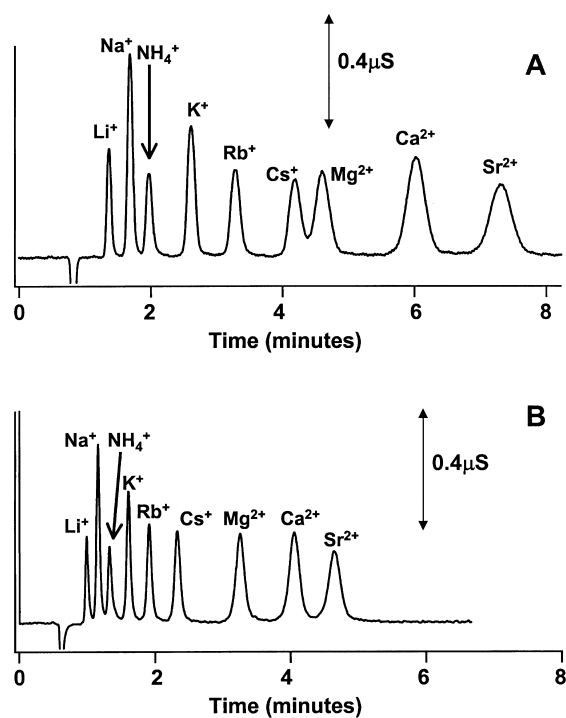


Fig. 3. High-speed separation of nine cations (A) 27 °C and 0.9 ml/min (2410 p.s.i.), (B) 60 °C and 1.3 ml/min (2420 p.s.i.). Experimental conditions: Dionex CS12A column, 17 mM MSA, 20 μ l injection, 50 μ M analyte concentration.

by the reduced viscosity. In comparing a run under conventional conditions (Fig. 2A) to one at 1.30 ml/min and 60 °C (Fig. 3B), there is a 60% increase in speed due to the combined effects of elevated temperatures on retention time and viscosity.

3.3. Band broadening

Previous work showed an improvement in efficiency at elevated temperatures at a constant flow-rate [16]. However, increases in flow-rate decrease the column efficiency due to the finite rate of mass transfer between the mobile and stationary phases. Therefore, the effect of elevated temperatures on efficiency at varying flow-rates was studied.

The effect of flow-rate on efficiency can be modeled with the van Deemter equation [29]:

$$H = A + \frac{B}{u} + Cu \quad (2)$$

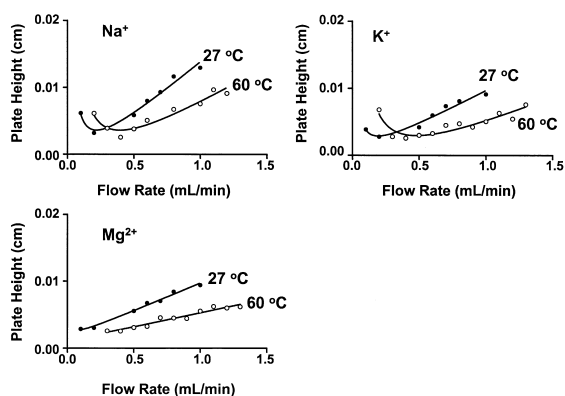


Fig. 4. van Deemter plots of Na^+ , K^+ , and Mg^{2+} at 27 and 60 °C. Experimental conditions: Dionex CS12A column, 17 mM MSA eluent, 20 μl injection, 50 μM analyte concentration. Separated under flow-rates from 0.10 to 1.30 ml/min.

where H is the plate height, u is the linear velocity of the mobile phase, and A , B , and C are constants associated with eddy diffusion, longitudinal diffusion, and resistance to mass transfer between the stationary and mobile phase, respectively. For simplicity the plate height is plotted directly versus flow-rate. The van Deemter plots for Na^+ , K^+ , and Mg^{2+} at 27 and 60 °C are shown in Fig. 4. Flow-rates below 0.1 ml/min were not studied due to the long analysis times (50 min), poor reproducibility and high background noise. The lines in Fig. 4 are the fit of the data to the van Deemter equation (Eq. (2)) with the corresponding C -terms summarized in Table 2.

The key conclusion that can be drawn from Fig. 4 and Table 2 is that the C -term is lower at 60 °C

Table 2
van Deemter parameters for Na^+ , K^+ and Mg^{2+} at 27 and 60 °C

Temperature (°C)	Cation	C -Term	r^2
27	Na^+	0.017 ± 0.002	0.969
	K^+	0.010 ± 0.001	0.959
	Mg^{2+}	0.0083 ± 0.0008	0.988
60	Na^+	0.012 ± 0.002	0.928
	K^+	0.006 ± 0.001	0.893
	Mg^{2+}	0.0042 ± 0.0009	0.942

Experimental conditions: Dionex CS12A column, 17 mM MSA eluent, 20 μl injection, separated under flow-rates from 0.10 to 1.30 ml/min, 50 μM analyte concentration.

compared to 27 °C. The decrease in the C -term is due to a decrease in retention and an increase in mass transfer of the solute in the mobile phase and stationary phase, with the later being of more significance [10,11]. The increase in mass-transfer is due to the decrease in viscosity of the mobile phase, which based on the Stokes–Einstein relationship improves diffusion. This will give a lower plate height, and thus, a higher efficiency. Furthermore, the optimum linear velocity is shifted to higher values. In other words, as with RPLC, there is a considerable advantage in performing IC separations at elevated temperatures [11].

However, the van Deemter equation does not explicitly include thermal-mismatch band broadening. Thermal-mismatch band broadening occurs if the eluent entering the column is not at the same temperature as the column [11,30]. This leads to temperature gradients within the column which cause differences in retention and eluent viscosity across the column. Thompson et al. demonstrated that thermal-mismatch band broadening manifests itself in the C -term of the van Deemter equation [31]. Therefore, thermal-mismatch band broadening is an extremely important consideration in achieving high temperature, high-speed separations [11,31]. In particular thermal-mismatch band broadening might be particularly important in this work because of the use of an air bath rather than a liquid bath for heating [11,30] and the low thermal conductivity of PEEK compared to stainless steel [27].

However, it does not appear that thermal-mismatch band broadening was a significant contribution to the C -terms observed in Table 2. Traditional mass transfer terms within the C -term are inversely dependent upon the diffusion coefficient. The diffusion coefficients of the cations studied in this work roughly double between 27 and 60 °C [27]. Thus, the C -term at 60 °C should be approximately half what it is at 27 °C. (The effect of retention is ignored, since diffusion and particle size are the major determinants of the C -term [32]). The C -terms given in Table 2 for K^+ and Mg^{2+} at 60 °C are indeed half of what they are at 27 °C, while that of Na^+ about only one third lower. In contrast, thermal-mismatch band broadening causes an increase in the C -term as the column temperature increases, and can cause the overall C -term to be larger at elevated temperatures

than at ambient [31]. This is obviously not the behavior observed in Fig. 4. Furthermore, the efficiency at elevated temperature is better than at room temperature, which serves as direct experimental evidence that thermal mismatch is not a significant contributor to band broadening under the conditions used in this work.

Another potential determinant of efficiency for the high-temperature, high-speed separations studied in this work is extra-column band broadening. It is desirable to keep the flow-rate through the suppressor as high as possible to minimize its contribution to the overall band broadening. However, the maximum flow-rate of the suppressor is 0.75 ml/min. Fig. 5 shows two high-speed separations of cations obtained under the same conditions (1.3 ml/min) except for the split ratio. In Fig. 5A the split ratio is 2.6 corresponding to a flow of 0.5 ml/min through the suppressor, and in Fig. 5B the split ratio is 13

corresponding to 0.1 ml/min through the suppressor. Clearly the separation obtained with the higher split ratio shows considerable band broadening. Therefore, in this work, the flow-rate through the suppressor was fixed at 0.5 ml/min, which was comfortably below the suppressor's flow limit, but at the same time, was high enough so that the split ratio was always as low as possible. It should also be mentioned that the CSRS electrolytic suppressor used in this work requires a different current setting at different suppressor flow-rates to maintain optimal performance [28]. Maintaining a constant flow-rate through the suppressor eliminated this problem.

3.4. Effect of eluent strength

Of the nine cations studied above, only Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+} are commonly present and thus are of greatest interest in industry. The high-speed separation of these six cations at 60 °C and 1.30 ml/min (Fig. 3B) shows a large gap between the potassium and magnesium peaks. If the size of this gap is reduced, the speed of the separation of these six cations could be further increased. Increasing the eluent strength will decrease the retention of all cations. However, the magnitude of the change in retention is a function of the analyte charge [33]. Thus when the eluent strength is increased divalent cations should experience twice the decrease in retention compared to monovalent cations. This should result in closer elution between the monovalent and divalent cations, without sacrificing resolution between cations of the same charge.

Fig. 6 shows the $\log k$ vs. $\log [\text{MSA}]$ plot for the six common cations, and Table 3 shows a summary of these plots. A linear model adequately describes the data for the six cations at the 95% confidence level. The slope of these plots is negative with $\log k$ decreasing with $\log [\text{MSA}]$; i.e., retention decreases with increased eluent strength. Further, the slopes for monovalent and divalent cations are close to the theoretical values of -1 and -2 , although some slopes differ from ideality at the 95% confidence interval. Similar deviations from theory have been noted in the past [33]. More importantly herein, Fig. 6 shows that eluent strength will not significantly affect the separation between cations of equal charge, but will strongly reduce the retention of

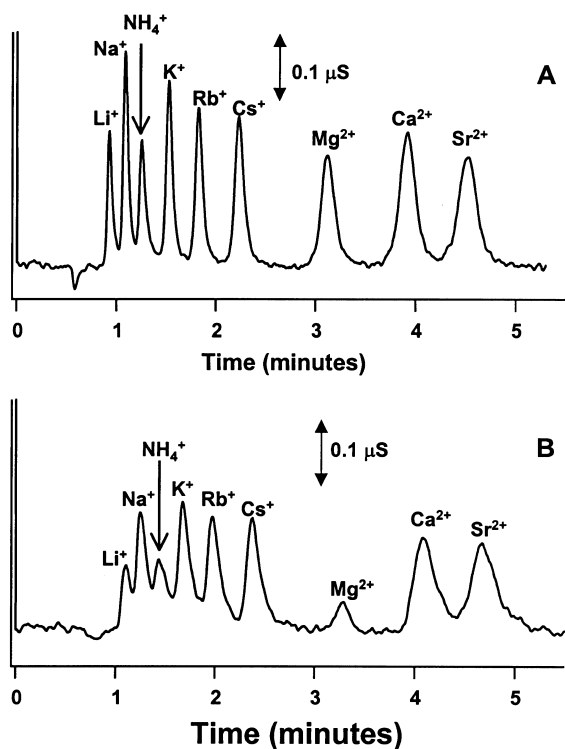


Fig. 5. Effect of split ratio on efficiency of separation: (A) split ratio=2.6, (B) split ratio=13. Experimental conditions: Dionex CS12A column, 17 mM MSA at 1.3 ml/min, 20 μl injection, 50 μM analyte concentration.

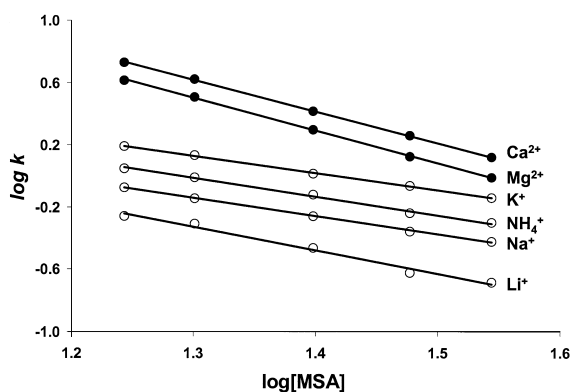


Fig. 6. Plots of $\log k$ vs. $\log[\text{MSA}]$. Experimental conditions: Dionex CS12A column, 0.5 ml/min, 60 °C, 20 μl injection, 50 μM analyte concentration. Eluent range from 17 to 35 mM MSA.

divalent ions relative to the monovalent ions. Fig. 7 shows a separation for the six cations in less than 2 min using 30 mM MSA. Thus, for the six common cations, the separation speed can be increased a further 50% by raising the eluent strength.

Although theory predicts a negligible loss in resolution, in practice, a small loss in resolution was observed (especially for Li^+ , Na^+ , and NH_4^+). This was partly due to the convergence of peaks at 60 °C (as shown by Fig. 2), the decreased retention and the greater impact of extra-column band broadening at low retention. Thompson and Carr showed that efficient high-speed, high temperature separations could be obtained through a decrease in eluent strength, while significant improvements in analysis time could still be realized through the higher flow-rates attainable at high temperatures [25]. Since

Table 3

Regression parameters for the effect of eluent strength on the retention of Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+}

Cation	Slope	P-Value	r^2
Li^+	-1.5 ± 0.3	0.000	0.987
Na^+	-1.2 ± 0.1	0.000	0.999
NH_4^+	-1.2 ± 0.2	0.000	0.995
K^+	-1.1 ± 0.1	0.000	0.998
Mg^{2+}	-2.0 ± 0.1	0.000	0.999
Ca^{2+}	-2.1 ± 0.1	0.000	0.999

Experimental conditions: Dionex CS12A column at 60 °C, 1.3 ml/min, 20 μl injection, [MSA] ranging from 17 to 35 mM. The standard deviations of the slope represent the 95% confidence intervals.

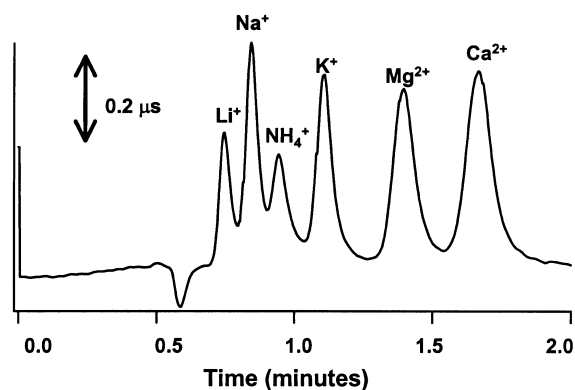


Fig. 7. High-speed separation of six common cations. Experimental conditions: Dionex CS12A column, 30 mM MSA, 1.3 ml/min, 20 μl injection, 50 μM analyte concentration.

extra-column band broadening is more pronounced for weakly retained species, a decrease in the eluent concentration would counteract the increased band broadening by increasing the retention of weakly retained analytes (e.g., Li^+ , Na^+ , and NH_4^+). However, based on Fig. 6 this approach would result in prohibitively long retention times of the divalent ions. This is not a phenomenon seen in the prior RPLC work [25]. Further, the effect of eluent strength in IC is similar for cations of the same charge. Thus, a decrease in the eluent strength does not compensate for the loss in resolution caused by convergence of the van't Hoff plots at elevated temperatures (Fig. 2). Therefore, high-speed separations employing weak acid cation exchangers (e.g., CS12A) are limited to relatively low temperatures. This again is why 60 °C was chosen as the maximum temperature in this work.

4. Conclusions

The application of elevated temperatures to the separation of cations by IC was demonstrated and resulted in a 60% improvement in analysis time. This was predominantly due to the decreased viscosity, and thus backpressure, at high temperatures. A secondary cause for the improved separation times was the decrease in cation retention at elevated temperature.

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