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Pressure-assisted capillary electrophoresis for cation separations using a sequential injection analysis manifold and contactless conductivity detection

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ABSTRACT

Pressure assisted capillary electrophoresis in capillaries with internal diameters of 10 μm was found possible without significant penalty in terms of separation efficiency and sensitivity when using contactless conductivity detection. A sequential injection analysis manifold consisting of a syringe pump and valves was used to impose a hydrodynamic flow in the separation of some inorganic as well as organic cations. It is demonstrated that the approach may be used to optimize analysis time by superimposing a hydrodynamic flow parallel to the electrokinetic motion. It is also possible to improve the separation by using the forced flow to maintain the analytes in the capillary, and thus the separation field, for longer times. The use of the syringe pump allows flexible and precise control of the pressure, so that it is possible to impose pressure steps during the separation. The use of this was demonstrated for the speeding up of late peaks, or forcing repeated passage of the sample plug through the capillary in order to increase separation.

1. Introduction

In capillary electrophoresis the performance in terms of separation efficiency, detection limits, and analysis time is generally optimized by varying the injected amount, the separation voltage applied and the capillary length. These parameters are interdependent, in that the injected amount affects both, separation and sensitivity, and separation voltage and capillary length determine field strength as well as residence time of the analytes. The product of the latter parameters is largely responsible for separation efficiency. Of the three variable parameters, only the injection volume and separation volume can be optimized via automated, electronic control; the adjustment of the capillary length requires mechanical manipulations by the operator and possible reconditioning. A potentially further useful parameter is the superimposition of a hydrodynamic flow in order to modify the residence time, either for improved separation or for faster analysis. However, pressurization has not generally been employed as the imposition of a hydrodynamic flow tends to lead to extra bandbroadening (see Section 2). Reports on pressure assisted capillary electrophoresis (PACE) have therefore been largely limited to counterbalancing the electroosmotic flow in order to increase the residence time and hence separation [1–3], and to special applications such as CE coupled to a mass spectrometer via electrospray ionization and capillary electrochromatography [4–12].

On the other hand, band broadening due to the effect of the laminarity of a hydrodynamic flow can be reduced by using capillaries of very small diameters (see Section 2). While the commonly employed UV-absorption method is not well suited for detection in very narrow capillaries due to its direct dependence on the optical pathlength, Zemann and co-workers [13] showed that capacitively coupled contactless conductivity detection (C^4D) may be used for capillaries with internal diameters as small as 10 μm. A later report by Wuersig et al. [14] furthermore indicated that good sensitivity should be possible with C^4D in such slender channels. The increasingly popular method relies on two tubular electrodes placed on the outside of the separation capillary, and is thus very simple and robust and in principle suitable for the determination of any ion. More details can be found in recent reviews [15–17] as well as in fundamental studies [18–21].

The coupling of sequential-injection analysis (SIA) based on a syringe pump and a multi-position valve with CE is a relatively new approach which provides simultaneous detection capability to SIA. On the other hand it is also an attractive and versatile means to miniaturization, automation and extension of CE. Conventional instruments rely on the more complex application of gas pressure or vacuum to effect injection or flushing of capillaries. Some SIA–CE systems with optical detection have been reported by several research groups [22–27] and Wuersig et al. used an SIA–CE-C^4D system to achieve fast separation of inorganic ions in approximately 10 s [14]. Recently, Mai et al. demonstrated the use of an automated

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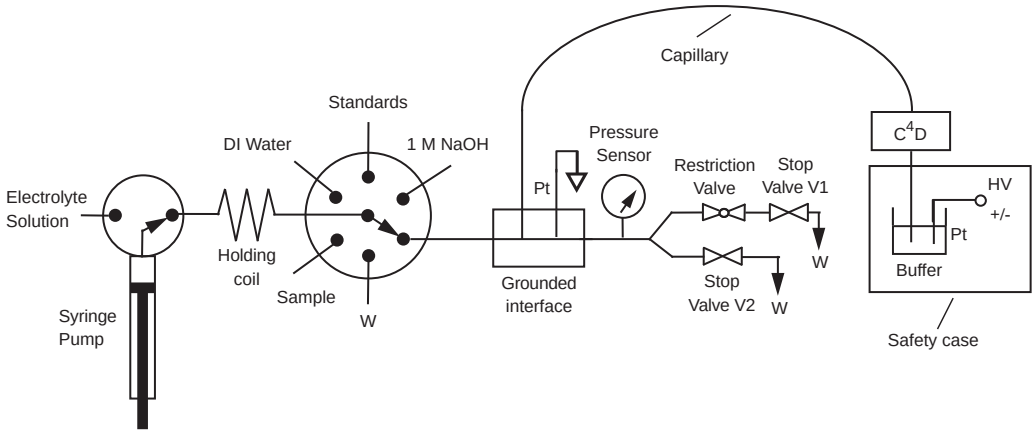

Fig. 1. Schematic drawing of the SIA–CE-C^{4}D-system for pressure-assisted capillary electrophoresis. C^{4}D: contactless conductivity detector; HV: high-voltage power supply; W: waste.

SIA–CE-C^{4}D system for long-term unattended on-site monitoring [28]. Herein, the investigation of the use of an SIA-manifold for pressurization of a CE-C^{4}D system in order to superimpose a hydrodynamic flow for the optimization of separation and/or analysis time of cations is reported.

2. Theoretical aspects

Studies of the effect of an imposed laminar flow on dispersion and thus on electrophoretic efficiency have been reported [29–31]. Grushka [31] expressed the dependence of the theoretical plate height (H) on the hydrodynamic flow velocity (v_p) as follows:

$$H = \frac{2D}{v_{tot}} + \frac{d^2 v_p^2}{24 D v_{tot}} \quad (1)$$

D is the diffusion coefficient and d is the inner capillary diameter. v_{tot} is the total average velocity of the analyte ion, which is given by $v_a + v_p$ when the hydrodynamic and electrophoretic flows are in the same direction (v_a, velocity of the analyte ion) and by $v_p - v_a$ if they are in the reverse direction. For cation separations v_a is given by v_e (electrophoretic velocity of the analyte ion) + v_{EOF} (electroosmotic flow velocity). The first term in the equation relates to longitudinal diffusion while the second term is due to the parabolic flow profile induced by the laminar flow. For parallel-pressure induced CE where $v_{tot} = v_p + v_a$, an increase in v_p results in a larger value of v_{tot}, leading to a smaller value of $2D/v_{tot}$ but an increased value of $d^2 v_p^2/24 D v_{tot}$.

Eq. (1), however, does not include a further consideration. In an unrelated study by Liu et al. [32] (and in works cited therein) it was found both theoretically and experimentally that a significant contribution to band broadening may also be due to thermal effects caused by Joule heating due to the application of the separation voltage. The contribution of Joule heating to the plate height in CE is displayed in the second term of the following equation (a modified version of the equation given by Liu et al. [32], which does not take into account any possible hydrodynamic flow):

$$H = \frac{2D}{v_a} + \frac{\tau^2 \lambda^2 v_e^2}{k^2 D}\left(K_1 \frac{E^4 d^6}{v_a} + K_2 \frac{E^6 d^8}{LD}\right) \quad (2)$$

E is the electric field strength, L the effective length of a capillary, λ the specific conductance of the solution, k the thermal conductivity of the buffer, τ the thermal coefficient of the solute mobility, and K_1 and K_2 are experimental coefficients. Mayrhofer et al. [13] indeed attributed an improvement of plate numbers found in CE-C^{4}D for capillaries with increasingly smaller internal diameters to a reduced effect of Joule heating.

According to these equations both effects are thus strongly dependent on the internal size of the capillaries, and a reduction of the diameter can be expected to lead to an improvement of resolution (corresponding to a low H) even in the absence of hydrodynamic flow.

3. Experimental

3.1. Chemicals and materials

All chemicals were of analytical or reagent grade and purchased from Fluka (Buchs, Switzerland) or Merck (Darmstadt, Germany) except for 2-amino-1-butanol and 1-amino-2-propanol which were obtained from Lancaster (Morecambe, England). Stock solutions of 5 mM were used for the preparation of the standards and those of the inorganic cations were prepared from the respective chloride salts. The separation buffer consisted of 12 mM L-histidine adjusted to pH 4 with acetic acid in all cases, unless otherwise stated. Before use, the capillary was preconditioned with 1 M NaOH for 10 min and deionised water for 10 min prior to flushing with electrolyte solution (for 1 h). Deionised water purified with a system from Millipore (Bedford, MA, USA) was used for the preparation of all solutions. The sample of red wine was purchased from a local shop and was prepared by filtering through a 0.02 μm PTFE membrane filter (Chromafil O-20/15 MS, Macherey-Nagel, Oensingen, Switzerland), then diluted with deionised water followed by ultra-sonicating for 10 min for degassing. The dilution was carried out immediately prior to use.

3.2. Instrumentation

A simplified diagram of the instrument is given in Fig. 1. The SIA section consists of a syringe pump (Cavro XLP 6000) fitted with a 1 mL syringe and a 6-port channel selection valve (Cavro Smart Valve) (both purchased from Tecan, Crailsheim, Germany). To connect the SIA manifold to the CE part, a purpose made interface based on two consecutive T-junctions was used. Details on this interface have been given previously [33]. The micro graduated needle valve (restriction valve) and the isolation valves used for pressurization were obtained from Upchurch Scientific (P-470, Oak Harbor, WA, USA) and from NResearch (HP225T021, Gümligen, Switzerland), respectively. A dual polarity high voltage power supply (Spellman CZE2000, Pulborough, UK) with ±30 kV maximum output voltage and polyimide coated fused silica capillaries of 365 μm OD (from Polymicro, Phoenix, AZ, USA) were used for all CE experiments. One end of the capillary was connected to the grounded SIA–CE interface, the other end was placed in a vial

filled with background electrolyte (BGE), in which the high voltage electrode is placed. A safety cage, which was equipped with a microswitch to interrupt the high voltage on opening, was used to isolate the high voltage assembly. Detection was carried out with a C^4D-system built in-house, details can be found elsewhere [34]. The cell currents are strongly dependent on the capillary diameter and therefore different feedback resistors were fitted to the pick-up amplifier which converts the signal to a voltage, for details see [20]. Resistors of 220 kΩ, 270 kΩ, 1 MΩ and 3.9 MΩ were fitted for capillaries of 75 μm, 50 μm, 25 μm and 10 μm, respectively. An e-corder 201 data acquisition system (eDAQ, Denistone East, NSW, Australia) was used for recording the detector signals. The fluidic pressure was monitored in-line with a sensor from Honeywell (24PCFFM6G, purchased from Distrelec, Uster, Switzerland). The programming package LabVIEW (version 8.0 for Windows XP, from National Instruments, Austin, TX, USA) was used to write the control code. Further detail on the instrument can be found in our previous publication [28].

3.3. Operation

The SIA-manifold allows automated capillary conditioning, flushing as well as hydrodynamic sample aspiration and injection. For capillary flushing both stop-valves (designated as V1 and V2 in Fig. 1) are closed while pumping solution at a low flow rate. Injection is carried out by pumping a defined sample plug past the capillary inlet in the SIA–CE interface while partially pressurizing the manifold by closing only V2. This procedure is necessary as it is not possible to create sample plugs of appropriate small size for complete injection. More details on the typical procedures can be found in the previous publication [28]. Separation is carried out by application of the high voltage of appropriate polarity from the detector end, while the injection end remains grounded at all times. This is contrary to conventional set-ups, but C^4D is not affected by this arrangement. Pressurization of the capillary during separation was achieved by closing both stop-valves while advancing the stepper motor driven syringe pump by the smallest increment possible (corresponding to 0.02 μL). To obtain constant pressure the increment was repeated at appropriate time intervals (typically 10 s) to compensate for its slow decrease due to the passing of the solution. Pressure gradients could be established by adjusting the time intervals and/or the volume increments and the use of the pressure sensor allowed a precise monitoring and adjustment. The resulting hydrodynamic flow velocities were experimentally determined by pumping a small plug of water through the capillary filled with background electrolyte (in the absence of an applied voltage) and determining the time until passage through the detector.

4. Results and discussion

4.1. Dependence of the sensitivity and separation efficiency on the internal diameter of the capillary

The first experiments concerned an investigation of the premise that C^4D is indeed compatible with narrow capillaries. Separations were carried out, initially without application of pressure, in capillaries of IDs from a standard size of 75 μm down to 10 μm. The use of smaller IDs was attempted, but was found not to be readily possible because of the excessive pressures required for flushing of the narrower capillaries. A sample plug of 0.8 cm length was injected in each case, which corresponds approximately to 2% of the effective capillary length (37 cm) as was suggested by Huang et al. [35] as optimum. Mixtures of the three cations, K^+, Na^+ and Li^+, were injected at different concentrations and the detection limits, defined as the concentrations which give peak heights corresponding to three times the baseline noise level, were determined for the different capillary diameters. As can be seen from the data of Table 1, the LODs determined are all in the low μM-range, and almost identical for the 4 diameters investigated, with the loss of sensitivity in going to the narrowest capillary being less than a factor of two for all three ions. This interesting feature of C^4D is deemed to be due to the fact that the device is a bulk detector, that is, it responds to a general solution property, rather than being analyte specific. Thus when decreasing the cell size (by reducing the capillary diameter) not only the signal for the analyte is reduced, but also the background signal. The reduction of the noise associated with the latter must lead to the observed behaviour. Clearly, the use of narrow capillaries down to 10 μm ID is possible with C^4D without incurring a significant penalty in detection limits as would be the case with optical detection.

Table 1
Detection limits for the determination of some inorganic cations with capillaries of different internal diameters. CE conditions: 12 mM His adjusted to pH 4 with acetic acid; l_{eff} = 37 cm; E = 400 V/cm.

Cation	LOD[a] (μM)			
	75 μm	50 μm	25 μm	10 μm
K^+	1.3	1.0	1.3	2.3
Na^+	1.8	1.5	1.8	3.0
Li^+	2.3	2.0	2.0	3.0

[a] Based on peak heights corresponding to 3 times the baseline noise.

The second critical aspect is the question if indeed it is possible to introduce hydrodynamic flow without serious deterioration of separation efficiency when using CE-C^4D with narrow capillaries. Thus the theoretical plate numbers (N) were determined from electropherograms obtained for the injection of 100 μM Na^+ into capillaries of different internal diameter and for superimposed hydrodynamic flow velocities in the range from 0.025 to 0.27 cm/s. Note, that for the field strength used, the velocity of sodium ions due to the electrophoretic mobility would be 0.16 cm/s and the electroosmotic flow would be 0.025 cm/s. The data is shown in Fig. 2. It is, first of all, clearly evident that the separation efficiency is strongly dependent on capillary diameter, even when no hydrodynamic flow is imposed. The application of pressure leads to a lowering of separation efficiency, but the relative deterioration in plate numbers is indeed much less pronounced for the smaller

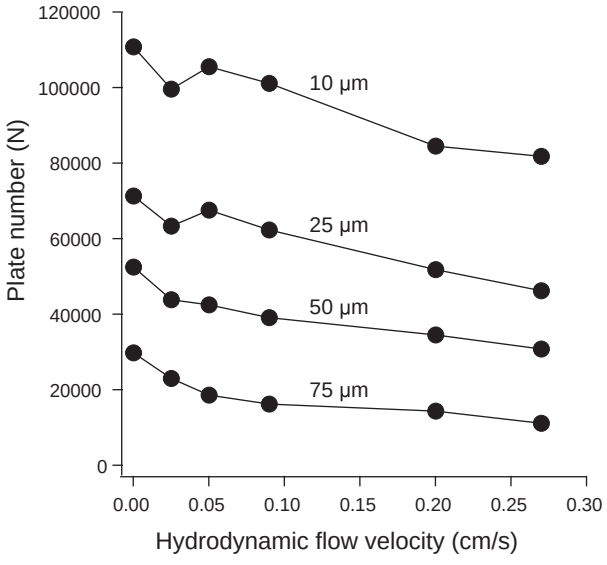

Fig. 2. Plate number versus superimposed hydrodynamic flow velocity for different capillary IDs. Analyte: Na^+ 100 μM in deionised water. Separation: l_{eff} = 37 cm; E = 300 V/cm.

diameters. For the largest capillary of 75 μm ID, the deterioration of about 50% from about 30,000 to 15,000 is significant, while the lowering of about 25% from the high initial level of 110,000 for the 10 μm capillary can easily be tolerated. Note the slight increase in plate numbers for capillaries of small IDs (10 μm and 25 μm) when going from flow rates of 0.025 cm/s to 0.05 cm/s. This phenomenon was also described by Grushka [31] and was ascribed to the fact that at small flow rates and with narrow capillaries, the increase in laminar flow induced dispersion is only small when increasing the flow rate, and is more than compensated for by a decrease in longitudinal diffusion.

Hydrodynamic pumping is thus well possible with capillaries of 10 μm ID as high separation efficiency ($N > 80{,}000$) can always be maintained at any of the flow rates tested which encompass a range relevant for modification of the mobilities of the ions due to electrophoretic and electroosmotic migration, and, as shown above, the loss in sensitivity is negligible.

4.2. Separations with hydrodynamic flow in the same direction as the electrophoretic mobility

4.2.1. Optimization of analysis time of inorganic cations

When the resolution between analytes in CE is found to be more than adequate ($R \geq 2$), an optimization of analysis time, and hence sample throughput, is possible. This can in principle be achieved by an increase of the separation voltage or by a shortening of the capillary. The first approach may however not be possible if the upper limit of the available voltage range is already used or Joule heating is problematic, and the second method requires mechanical manipulations which can only be reversed by installing and conditioning a new capillary. Using a hydrodynamic flow to push the ions through is an alternative, flexible and easily reversible approach. The electropherograms for the three inorganic cations K^+, Na^+ and Li^+ obtained subsequently without and with parallel pumping are shown in the two parts of Fig. 3 along with the recorded pressure profiles. As can be seen, the pressurization allows optimization of the analysis time on the fly, the separation time is reduced to less than half, while baseline resolution is still preserved.

For a further demonstration, the method was applied to the separation of inorganic cations in a sample of red wine. The electropherograms of a standard mixture containing 6 cationic species, as well as those of a diluted red wine sample, with and without pressure assistance, are shown in Fig. 4. To determine the cations present in the red wine sample, each peak was identified by comparing the migration time with that of the standard mixtures. It is seen that K^+, Ca^{2+}, $Mg^{2+}$and Na^+ are present in abundant amounts and the complete passage through the detector with more than adequate baseline resolution was observed after 5 min without the application of pressure (electropherograms a and b). By employing a pressure of 1.6 bar from the beginning of electrophoresis the running time could be reduced to around 2 min while still obtaining baseline resolution (electropherograms c and d). Thus the sample throughput could be significantly improved. Note that a number of additional peaks were detected, but no effort was made to identify these species.

4.2.2. Concurrent separation of fast and slow migrating amines

A related, but slightly more complex situation are separations of mixtures of fast and slowly migrating analytes. Optimization of separation then has to be done for the fast ions, but this can lead to exceedingly long migration times for the slow ions. The separation of a range of 9 amines, separated in their protonated cationic form, shown in the electropherogram of Fig. 5a illustrates the situation. The first 6 ions are separated within about 7 min while the passage of the slow ions (with negative going peaks) requires more than 20 min. The situation is also familiar from HPLC and is the reason why for this method usually gradient elution is employed. However, this approach is not possible in capillary electrophoresis. As more than adequate baseline resolution was obtained with the conditions employed, a significant overall shortening of the analysis time to 4 min is possible by superimposing a hydrodynamic flow using an applied pressure of 0.9 bar as illustrated in electropherogram of Fig. 5b. A further improvement is possible by increasing the applied pressure to 3 bar after passage of the faster ions, as shown in Fig. 5c. Note that a constant pressure of 3 bar from the beginning of the separation would not allow resolution of any of the analytes. The calibration data obtained under parallel-flow driven CE with moderate pressure of 0.9 bar is given in Table 2. The detection limits achieved for the conditions are in the range from 1.5 μM to 15 μM and calibration curves were acquired up to 300 μM. As the reproducibility data for retention time (approximately 1%) and for peak area (between 2 and 5%) also given in Table 2 shows, the precision obtained in the approach is not deteriorated compared to conventional CE without pumping.

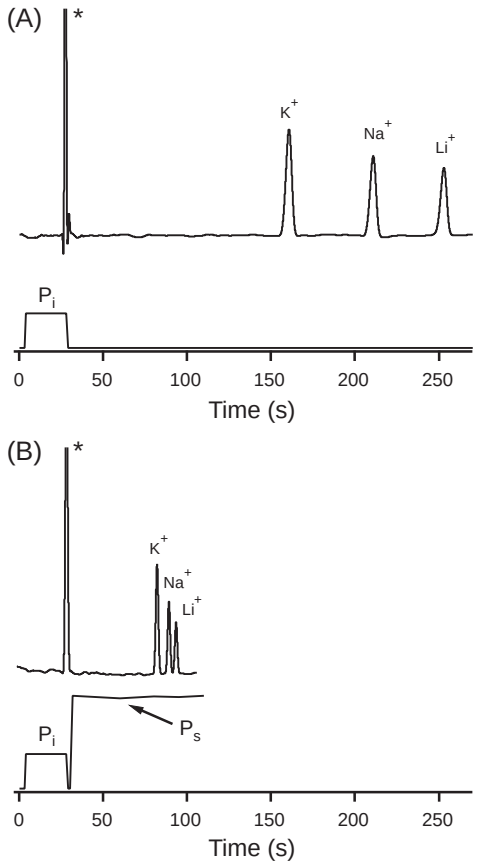

Fig. 3. Optimization of electrophoresis time with hydrodynamic flow. Analytes: 100 μM. Separation: 10 μm ID capillary with $l_{eff} = 37$ cm; $E = 400$ V/cm. The pressure was recorded on-line during hydrodynamic injection and (pressure-assisted) electrophoretic separation. (A) Separation without pressure; (B) separation with pressure. P_i: pressure applied for injection; P_s: pressure applied for separation; *Voltage pulse occurring when HV is turned on, indicating the start of the electrophoresis process.

4.3. Separations with hydrodynamic flow against the electrophoretic mobility

4.3.1. Separation of high mobility inorganic cations

In CE-C^4D fast migrating cations may not be resolved under given conditions, and this is more pronounced when the concentrations are high. Overlaps can generally be minimized by reducing the injected volume, or by dilution of the sample, but this approach is

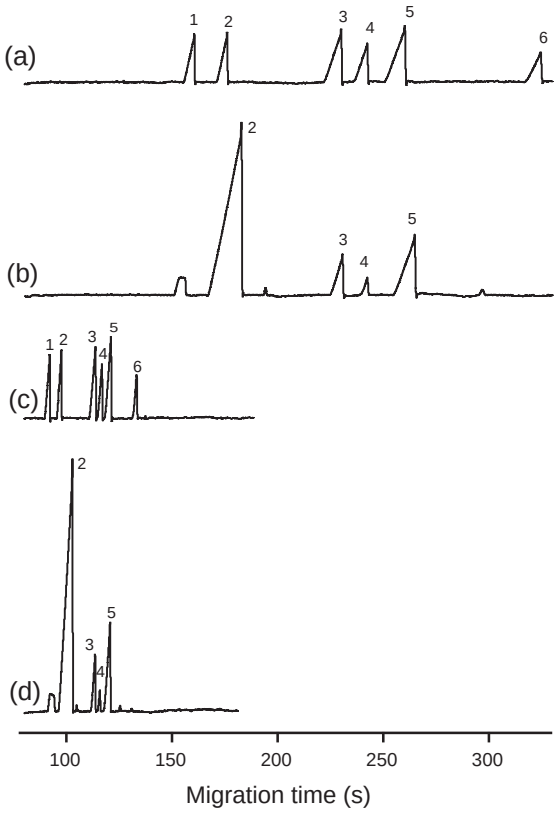

Fig. 4. Separation of inorganic cations in a red wine sample. (a) Solutions of standards, 200 μM, $P = 0$ bar; (b) diluted red wine sample, $P = 0$ bar; (c) solution of standards, 200 μM, $P = 1.6$ bar; (d) diluted red wine sample, $P = 1.6$ bar. CE conditions: 10 μm ID capillary with $l_{eff} = 43$ cm; $E = 400$ V/cm; BGE: His 12 mM and 18-Crown-6 2 mM adjusted to pH 4 with acetic acid. Analytes: (1) NH_4^+; (2) K^+; (3) Ca^{2+}; (4) Na^+; (5) Mg^{2+}; (6) Li^+.

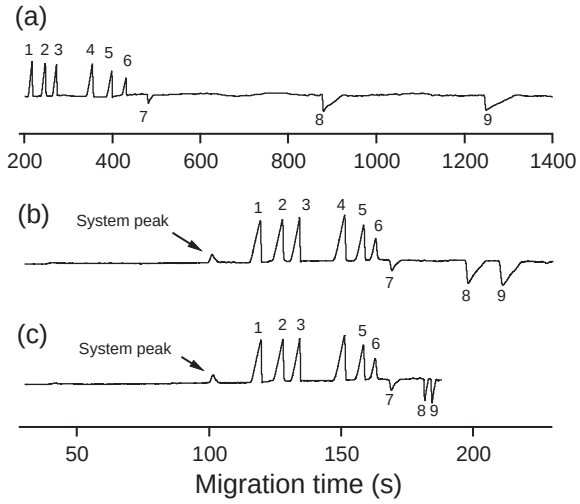

Fig. 5. Concurrent separation of fast and slowly migrating amines. Analytes: (1) methylamine (100 μM); (2) dimethylamine (100 μM); (3) trimethylamine (100 μM); (4) 1-amino-2-propanol (200 μM); (5) 2-amino-1-butanol (200 μM); (6) 1-phenyl-ethylamine (200 μM); (7) 3,5-dimethylaniline (200 μM); (8) 2,6-dimethylaniline (100 μM); (9) 2,6-diisopropylaniline (100 μM). Separation: 10 μm ID capillary with $l_{eff} = 40$ cm; $E = 400$ V/cm. (a) No pressure applied; (b) $P = 0.9$ bar from $t = 0$ s; (c) $P_1 = 0.9$ bar from $t = 0$ s and $P_2 = 3$ bar from $t = 175$ s.

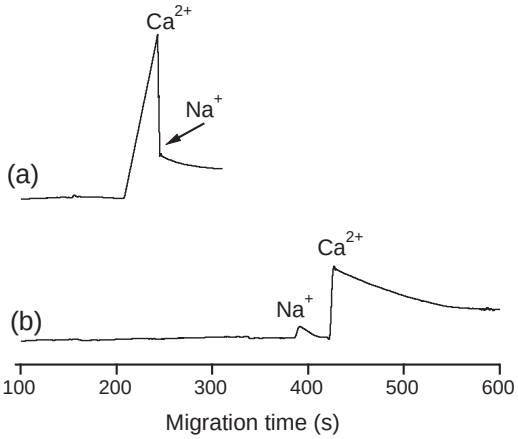

Fig. 6. Separation of Ca^{2+} (2000 μM) and Na^+ (100 μM). (a) Normal CE, 10 μm ID capillary with $l_{eff} = 40$ cm; $E = 400$ V/cm; (b) counter-pressure assisted CE, 10 μm ID capillary with $l_{eff} = 7$ cm; $E = 400$ V/cm, $P = 0.9$ bar.

not possible when one of the adjacent peaks is at low concentration. This situation is illustrated by electropherogram (a) of Fig. 6. The relatively small signal for the sodium ion is completely obscured by the large and tailing peak for calcium ions. As demonstrated by electropherogram (b) of Fig. 6, it is possible to resolve the peaks by increasing the residence time of the ions via the introduction of a hydrodynamic flow against the electrophoretic and electroosmotic migration. This requires a reversal of the applied voltage. The analytes then migrate electrophoretically towards the injection end, but are slowly pushed hydrodynamically to the detector end. This leads to a swapping of the peak order and the more slowly migrating Na^+ is now arriving at the detector first. The separation was achieved in a short capillary of only 7 cm length. The triangular peak shapes are a common feature of capillary electrophoresis due to electrodispersion which occurs because of differences in the electrophoretic mobilities (μ) of analyte and buffer ions, and this effect is more pronounced for higher concentrations. For conductivity detection a certain mismatch is necessary for good detection

Table 2
Calibration ranges, detection limits (LODs) and reproducibility for the determination of amines with pressure-assisted CE.

Amine	Range (μM)[a]	Correlation coefficient, r	LOD[b] (μM)	RSD% MT[c] ($n = 4$)	RSD% PA[d] ($n = 4$)
Methylamine	5–200	0.9992	1.5	0.7	2.2
Dimethylamine	5–200	0.9995	1.5	0.7	2.6
Trimethylamine	5–200	0.9993	1.5	0.8	2.4
1-Amino-2-propanol	10–300	0.9991	3.0	0.8	2.9
2-Amino-1-butanol	10–300	0.9992	3.0	0.9	3.1
1-Phenyl-ethylamine	15–300	0.9993	5.0	0.8	3.0
3,5-Dimethylaniline	40–400	0.9980	15.0	0.9	3.9
2,6-Dimethylaniline	5–200	0.9993	2.0	1.0	4.2
2,6-Diisopropylaniline	5–200	0.9989	2.0	1.2	4.6

[a] 5 concentrations.
[b] Based on peak heights corresponding to 3 times the baseline noise.
[c] Effective migration time.
[d] Peak area.

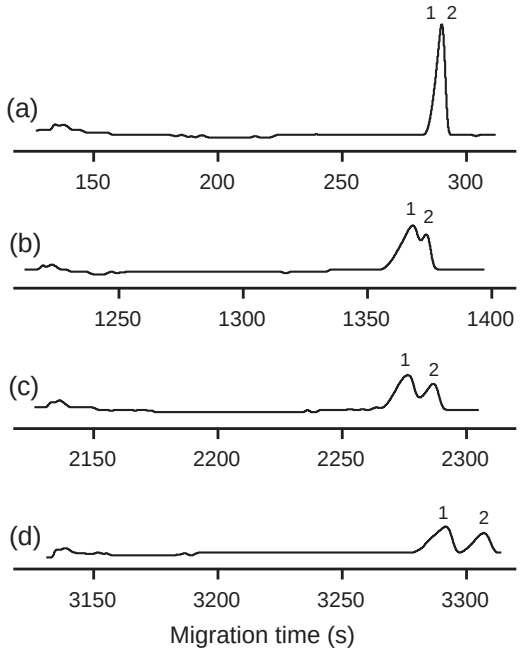

Fig. 7. Separation of diethylamine (1) and 1-amino-2-propanol (2) (300 μM) by normal CE, but repeated several times by using hydrodynamic flow to return the sample to the starting point before each run. (a) 1st electrophoresis run; (b) 4th run; (c) 7th run; (d) 10th run. 10 μm ID capillary with l_{eff} = 7 cm; E = 400 V/cm. Fluidic pressure for sample delivery: 5.5 bar.

sensitivity as mobility is directly related to ionic conductivity (λ) according to $\lambda = \mu F$, where F is the Faraday constant.

4.3.2. Separation of organic cations of moderate electrophoretic mobility

Previous work in our group showed that the two amines, 1-amino-2-propanol and diethylamine can be separated in capillary electrochromatography (CEC) carried out in monolithic columns with contactless conductivity measurements [36], but no success was obtained when trying to achieve baseline separation under normal CE conditions in open capillaries with conductivity detection. Therefore the use of a hydrodynamic flow to counter-balance the mobility and electroosmotic flow, as described above for the fast inorganic cations, was also investigated for this pair of hard to separate species. It was found that this was more challenging than for the inorganic cations in that a much longer residence time was required. This poses a difficulty in that it was also found hard to accurately balance the electroosmotic flow for extended periods, as this depends on the surface condition of the capillary and is not perfectly stable over time. A different approach was therefore chosen. First, the sample plug is delivered close to the high voltage end of the capillary by using hydrodynamic pumping while the separation voltage is off. During this process no separation is expected. Pressurization is then ended by opening the stop valves and the anodic separation voltage turned on. The two amines then move towards the grounded end of the capillary electrophoretically. As soon as the amines reach the proximity of the grounded end, the separation voltage is turned off, and pressurization triggered again to force the two amines to move back to the HV-end by hydrodynamic flow. These steps are repeated several times until baseline separation of the two amines is obtained. Note that the detector is positioned near the grounded end of the capillary in this case. The process is illustrated by the electropherograms of Fig. 7, which show the detector response following increasing numbers of passages. Complete separation is achieved at the 10th round.

5. Conclusions

Pressure assisted capillary electrophoresis can be carried out without significant penalty in terms of resolution and sensitivity in capillaries of 10 μm internal diameter when contactless conductivity detection is employed. The use of hydrodynamic flow as an additional parameter leads to increased flexibility in the optimization of separations and can be implemented on the fly for different tasks at hand without requiring mechanical changes to the system geometry. This then allows separations which otherwise are difficult to achieve. The use of an SIA manifold for pressurization was found to be straightforward, allows precise control, and is highly flexible.

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