Adrian S. Krawczeniuk,[1] *M.S. and Victor A. Bravenec*[2] *B.S.*

Quantitative Determination of Cocaine in Illicit Powders by Free Zone Capillary Electrophoresis

REFERENCE: Krawczeniuk AS, Bravenec VA. Quantitative determination of cocaine in illicit powders by free-zone capillary electrophoresis. J Forensic Sci 1998;43(4):738–743.

ABSTRACT: A free zone capillary electrophoresis method was developed for the quantitation of cocaine in illicit powders. The method uses a 75 mM sodium phosphate-sodium borate pH 8.5 buffered system and separates the most common cocaine adulterants and impurities in eight minutes. Linearity, accuracy and reproducibility studies are presented, as well as comparisons with quantitative results obtained by gas liquid chromatography and high pressure liquid chromatography methods.

KEYWORDS: forensic science, substance abuse detection, drugs, chemistry, capillary electrophoresis, quantitation, cocaine, illicit powders, detection

Capillary electrophoresis (CE) is emerging as a powerful technique for the separation of illicit drugs encountered in forensic laboratories. The technique of CE has expanded dramatically over the past several years from its original biological applications in the analysis of macromolecules (1) to its applications in the analysis of drugs of pharmaceutical (2) and clinical (3) importance to the analysis of illicit drugs of toxicological and forensic interest (4,5). CE is currently one of the most active areas in the separation sciences, especially in the analysis of drugs of abuse. This can be attributed to the inherent features of CE, which include high selectivity for compounds of similar structure, high separation efficiencies, minimal sample and solvent requirements, overall simplicity of the instrumentation and fast analysis times due to the high separation potentials employed (6).

CE has the ability to analyze drugs with efficiencies of capillary gas chromatography or greater with theoretical plates in the hundreds of thousand range (100,000 to 500,000). The technique also retains the positive attributes of high pressure liquid chromatography (HPLC), which is the ability to analyze drugs and related compounds that are nonvolatile, polar and thermally degradable without prior derivitization (4,5). This makes CE applicable to the widest array of analytes compared to any other separation technique.

HPLC analysis of cocaine and related compounds affords adequate resolving power but suffers from the effects of peak tailing and longer analysis times (7–9). This is attributed to the fact that the flow in HPLC is pressure induced, resulting in a laminar flow profile which will broaden the sample zone of many basic drugs of abuse. In comparison, CE exhibits a flat plug-like flow profile since the main driving force of flow is uniformly distributed along the capillary walls and does not directly contribute to the dispersion of solute zones as observed in HPLC (6). CE exhibits greater mass limits of detection (MLD) but its concentration limits of detection (CLD) are relatively poor using UV detection, in the range of 10^{-6} M, in comparison with HPLC. The limited sensitivity of UV absorbance detection in CE is caused by the geometric constraints imposed by the capillary inner diameter which functions as the optical pathlength (10). For example, if the CLD for a drug is 1 μg/mL and 10 nL is injected onto the capillary, the MLD will correspond to 10 pg. However, the use of low detection wavelengths (185 to 220 nm), modified capillaries to extend the optical pathlength, and sample preconcentration are a number of options that are available to improve the detection limits in CE (10).

The qualitative and quantitative separation of a wide variety of illicit drugs of forensic interest has been reported using three primary modes of separation: free zone capillary electrophoresis (FZCE) (11–13), micellar electrokinetic capillary chromatography (MEKC) (14–19), and cyclodextrin assisted chiral analysis (20). Previous researchers developed a free solution CE method consisting of a 0.05 M borate buffer pH 9.2 for the toxicological determination of cocaine in hair of illicit drug users (12,13). However, the method used tetracaine, a common adulterant found in illicit cocaine samples, as the internal standard in their quantitative assay.

Separations in free solution are based on the differing electrophoretic mobilities of analytes. The mobilities are a function of both the charge and size of the analytes. The charge is dependent on the number of ionizable groups and the degree of ionization, which is determined by the pH of the running buffer. Since the interior surface of a fused silica capillary possesses an excess of negative charges under normal electrophoretic conditions (pH 2 to 9), the positive ions from the running buffer will form an electrical double layer on the capillary wall to balance the charge. When voltage is applied across the capillary, the cationic species will migrate toward the cathode, creating a bulk electroosmotic flow (EOF) of the buffer solution toward the negatively charged electrode. The anionic species are electrophoretically attracted toward the anode, but if the velocity of EOF is greater than their electrophoretic mobility, their net mobility will be toward the cathode. Neutral species will be dragged along unresolved by the velocity of EOF while cationic species will migrate the fastest as a result of the additive effect (6).

The principal objective of this study was to develop a simple, fast, rugged and efficient quantitative FZCE method capable of

[1] Senior forensic chemist, United States Department of Justice, Drug Enforcement Administration, Northeast Laboratory, 99 10th Avenue, New York, NY.

[2] Forensic chemist, United States Department of Justice, Drug Enforcement Administration, South Central Laboratory, 1880 Regal Row, Dallas, TX.

Received 17 July 1997; and in revised form 28 Oct. 1997; accepted 31 Oct. 1997.

separating cocaine from its most common adulterants and impurities routinely encountered in our laboratory.

Methods and Materials

Reagents

All drug standards were obtained from the reference collection of the DEA Northeast Laboratory. The internal standard for the CE quantitation, histamine diphosphate, and the internal standard, heneicosane, for the gas liquid chromatography (GLC) quantitation were obtained from Sigma (St. Louis, MO). The *cis* isomer of cinnamoylcocaine was prepared by irradiating an acid solution of standard *trans*-cinnamoylcocaine at 254 nm, yielding a mixture of *cis*- and *trans*-cinnamoylcocaines and confirmed by gas chromatography-mass spectrometry (15). Sodium monobasic phosphate (Mallinckrodt, St. Louis, MO), sodium borate-hydrate form (Sigma, St. Louis, MO), hexylamine (Sigma, St. Louis, MO), o-phosphoric acid (J. T. Baker, Phillipsburg, NJ) were analytical reagent grade and acetonitrile and chloroform (J. T. Baker, Phillipsburg, NJ) were HPLC grade. Ultrapure water from a Milli-Q Plus system (Millipore, Bedford, MA) was used to prepare all buffers in the study.

Capillary Electrophoresis System Methodology

A Hewlett Packard 3D CE system equipped with a diode array detector (DAD) and controlled by a Vectra PC 486 processor and Chemstation software was used in this study. Capillaries were fused silica, 50 μm internal diameter, 48.5 cm total length, and 40 cm effective length to detector. The capillary cassette temperature was maintained at 40°C. Voltage was set at 10 kV (206 V/cm). Under the optimum conditions, the capillary current was typically 66 to 70 μA and the power was typically 0.7 W. The DAD was scanned in the wavelength range of 190 to 450 nm, and the electropherograms were monitored at 230 nm with a 30 nm bandwidth.

Samples were introduced using a hydrodynamic pressure injection of 150 mbar for three seconds. The running buffer consisted of 75 mM sodium monobasic phosphate—75 mM sodium borate adjusted to pH 8.5 with 2 N NaOH. The buffer was filtered through a 0.45 μm PVDF filter and degassed with sonication prior to use. The capillary was flushed with running buffer for two minutes between sample runs. The capillary column rinsing between injections is a critical factor in keeping the physical and chemical state of the walls of the capillary constant from run to run. The inlet, outlet, and flush vials were replenished with running buffer after ten injections using the automated buffer replenishment system. New capillaries were preconditioned by flushing with 1M NaOH for 10 min, 0.1 M NaOH for 10 min, water for 10 min, and running buffer for 10 min.

For quantitation, a standard solution of cocaine was prepared by dissolving a known amount of the hydrochloride salt in an appropriate volume of histamine diphosphate internal standard solution (2.0 mg/mL) dissolved in 0.01 M HCl to give a final concentration of 0.1 mg/mL. For the determination of cocaine in illicit seizures, approximately 100 mg of finely ground sample was dissolved in an appropriate volume of stock internal standard solution to give a concentration equal to the standard cocaine hydrochloride area concentration. Uncorrected area responses were used for the quantitative assay. Single level calibration using pre-sample and post-sample injections of standard cocaine hydrochloride were used for the quantitative assay calculations.

High Pressure Liquid Chromatography Methodology

HPLC analyses were done with a Hewlett Packard Series II 1090 system equipped with a diode array detector. The chromatographic conditions were as follows: Partisil 5 ODS-3 column, 150 × 3.2 mm, 5-μm particle size (Phenomenex, Torrance, CA) coupled with a Partisil 5 ODS-3, 30 × 4.60 mm guard column; mobile phase consisted of 0.18 M H_3PO_4/0.03 M hexylamine (pH 2.5): acetonitrile (78:22, v/v) at a flow rate of 0.5 mL/min at 40°C. Sample injection volume was 5 μL and the UV detector was set at 230 nm. For quantitation, a standard solution of cocaine HCl was prepared by accurately weighing the standard material, adding an appropriate amount of injection solvent (buffer: acetonitrile [78:22, v/v]) to produce a final concentration of 0.5 mg/mL. Illicit cocaine samples were prepared by accurately weighing approximately 100 mg into an appropriate volumetric flask to produce a final cocaine concentration of 0.5 mg/mL through dilution with injection solvent. Single level calibration using pre-sample and post-sample injections of standard cocaine hydrochloride were used for the quantitative assay calculations.

Gas-Liquid Chromatography Methodology

Quantitative analyses were performed on a Hewlett Packard 5890 gas chromatograph equipped with a Hewlett Packard Ultra 2 capillary column, crosslinked 5% phenylmethylsilicone (50 m × 0.2 mm × 0.33 μm film thickness), a flame ionization detector, and operated with a 75:1 split ratio. The method was run isothermally at 230°C, injection port set at 265°C, detector set at 285°C. Helium was used as the carrier gas, nitrogen was used as the makeup gas. Heneicosane was used as the internal standard. The standard solution of cocaine was prepared by dissolving a known amount of the hydrochloride salt in an appropriate volume of chloroform to give a final concentration of 1.5 mg/mL (0.8 mg/mL heneicosane). For the determination of cocaine in illicit seizures, 100 mg of sample was dissolved in an appropriate volume of chloroform and internal standard solution to give a concentration that will give an area response approximately equal to that of the standard cocaine response. Single level calibration using pre-sample and post-sample injections of standard cocaine hydrochloride were used for the quantitative assay calculations.

Results and Discussion

The FZCE method developed was found to be highly efficient for the quantitative determination of cocaine in illicit seizures. The CE separation exhibited in excess of 570,000 theoretical plates for cocaine as opposed to 215,000 for the capillary gas-liquid chromatography method and 10,000 for the high performance liquid chromatography method using the following equation:

$$N = 16(t_m/W_b)^2$$

where t_m is the migration time of analyte and W_b is the width of analyte peak at baseline.

Experimental conditions such as sample size, voltage, pH, and buffer concentration were varied in order to obtain the optimum separation as illustrated by the electropherogram in Fig. 1. Initial experiments examined two buffer systems: sodium phosphate at pH's ranging from 2.0 to 4.0 and 7.0 to 9.0 and sodium borate at pH's ranging from 7.0 to 9.0. However, these buffer systems did not provide adequate resolution for the analytes examined in this

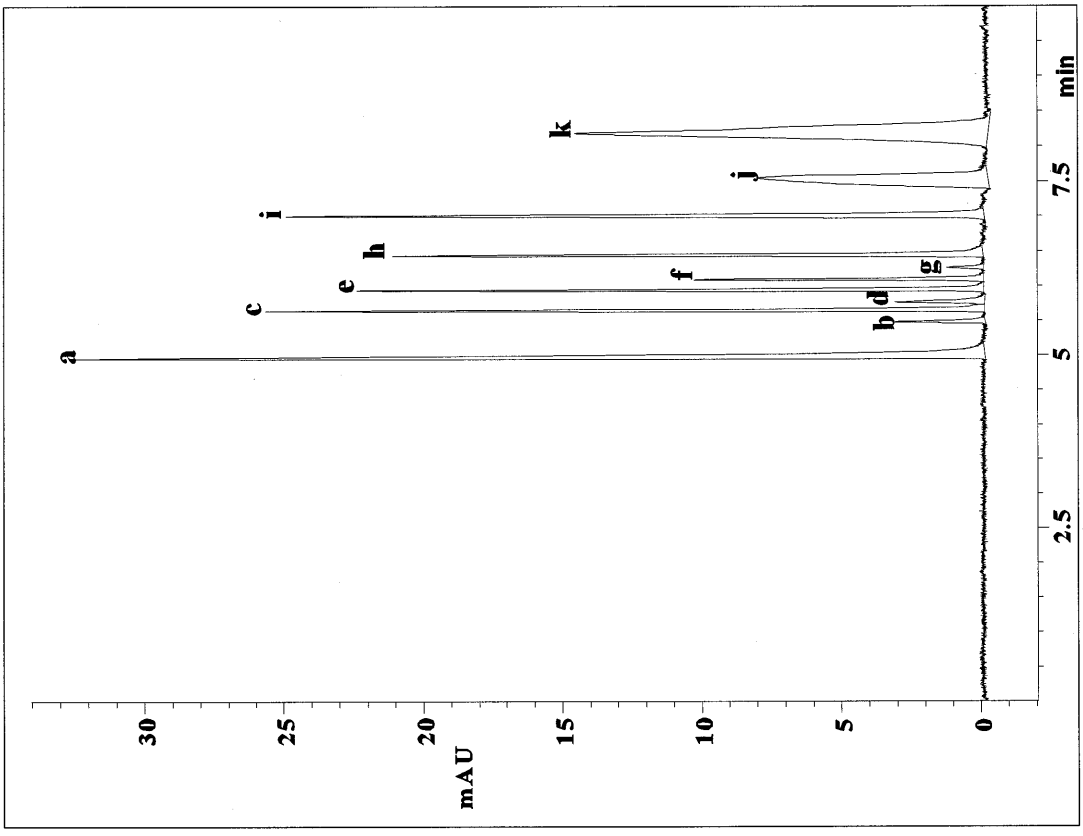

FIG. 1—*Free solution electropherogram of cocaine, adulterants and impurities. Key: (a) histamine (internal standard at 2.00 mg/mL), (b) ephedrine, (c) procaine, (d) phenylpropanolamine, (e) cocaine, (f)* trans-cinnamoylcocaine *(at 0.084 mg/mL), (g)* cis-cinnamoylcocaine *(prepared via UV irradiation at 254 nm), (h) tetracaine, (i) lidocaine (at 0.23 mg/mL), (j) benzocaine, (k) acetaminophen. All other compounds at approximately 0.10 mg/mL.*

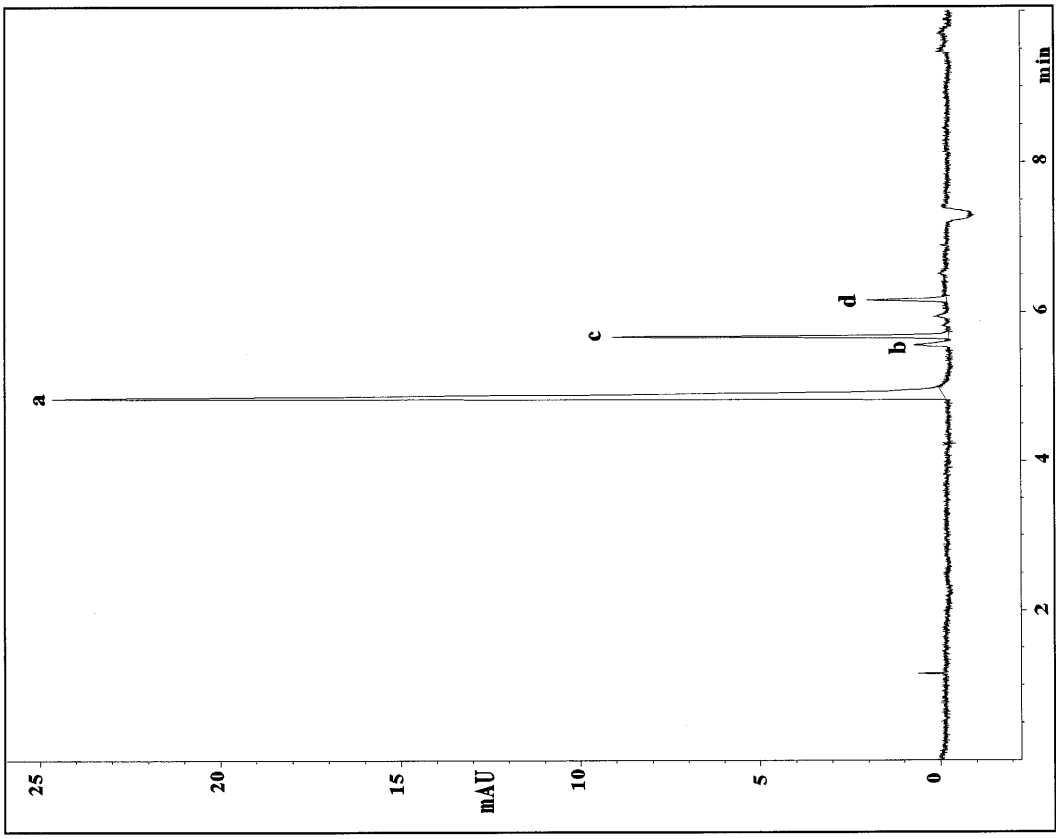

FIG. 2—*Free solution electropherogram of illicit cocaine seizure. Key: (a) histamine (internal standard at 2.00 mg/mL), (b) phenylpropanolamine, (c) cocaine, (d) tetracaine.*

study. Experiments involving a mixture of sodium phosphate-sodium borate provided promising results for the solutes of interest. The determination of the optimum sodium phosphate-sodium borate concentration was performed by varying the buffer concentration from 100 mM to 10 mM. The pH was optimized by varying the pH units by 0.5 from 7.0 to 9.0. The operating voltage of 10 kV was chosen from the linear portion of an Ohm's Law plot of current for the particular capillary length and buffer concentration used in this particular assay experimentally observed to give optimum separation. Overall, the best resolution and efficiency for the analytes of interest was achieved with an experimental pH of 8.5 at a buffer concentration of 75 mM sodium phosphate-sodium borate.

The mixed buffering system of sodium phosphate-sodium borate provided the best separation when attempting to separate small molecules with similar pKa's and similar molecular masses such as cocaine (pKa = 8.6) and tetracaine (pKa = 8.5); histamine (pKa = 9.7), ephedrine (pKa = 9.6), procaine (pKa = 9.0) and phenylpropanolamine (pKa = 9.4). The best separation is often achieved when the buffer pH is equal to the average pKa of the analytes of interest. If the buffer pH is far from the pKa of the analytes, the charges will be constant, and analytes with similar molecular masses will exhibit identical electrophoretic mobilities. However, if the buffer pH is equal to the average analyte pKa, the charges will not be constant and analytes with similar molecular masses will exhibit different electrophoretic mobilities.

The most commonly occurring adulterants and impurities (peaks a-k in Fig. 1) are considered cationic species, migrating before the EOF and appearing as sharp symmetrical peaks. Baseline resolution was observed between all critical pairs (e.g., cocaine and phenylpropanolamine or cocaine and *trans*-cinnamoylcocaine) as illustrated in Table 1. The resolution was determined by the equation:

$$R = 1/4N^{1/2}(\Delta\mu_{app}/\mu_{avg})$$

where N is the number of theoretical plates, μ_1 is the migration time of analyte 1, μ_2 is the migration time of analyte 2, $\Delta\mu_{app}$ is the difference in apparent electrophoretic mobility of two analytes, and μ_{avg} is the average mobility of two analytes. The net mobilities of the analytes of interest were determined using dimethylsulfoxide as the EOF marker. Compounds such as benzocaine and the cocaine impurity benzoylecgonine exhibit the same electrophoretic mobility and are unresolved, migrating as a broad peak with the EOF. These compounds are neutral species at the experimental pH. Acetaminophen, the only acidic species studied, is anionic at the experimental pH 8.5, as shown in Table 1, and migrates after the EOF. Figure 2 shows an electropherogram of a mixture of a typical illicit cocaine seizure containing 7.0% cocaine HCl, and the adulterants tetracaine and phenylpropanolamine. No interferences were observed between the compounds listed in Table 1 except for the two neutral species previously mentioned. MEKC provides the alternative of separating both the neutral and charged species by using surfactants such as sodium dodecylsulfate (SDS) and cetyltrimethylammonium bromide (CTAB) (13–18). The prime advantage of the FZCE method is that it uses a simple buffer system, a short analysis time, and provides adequate resolution for the analytes of interest.

The precision of the method was evaluated by making 40 replicate injections of a solution containing cocaine hydrochloride at 0.1 mg/mL and the internal standard, histamine diphosphate at 2.0 mg/mL on three separate days, with buffer replenishment after every ten injections. These are the relative concentrations that are used in the day-to-day quantitative assay. Table 2 shows the migration times, absolute peak areas, and the peak area response ratios of cocaine/histamine resulting from 40 replicate injections of a standard solution of cocaine and histamine diphosphate.

The relative standard deviation (RSD) for the migration times ranged from 0.21 to 0.62% for the replenishment injections on three separate days. The reproducibility of peak areas is extremely critical for quantitative analysis. Many factors affect peak area reproducibility, some of which are technique dependent while others are instrument dependent. Since the reproducibility of migration times and absolute peak areas were excellent, it was not necessary to use migration time corrected areas, which normalize any peak area changes caused by migration time shifts. The relative standard deviation of the absolute peak areas of cocaine are of the same magnitude (1.05 to 1.37%) for the replenishment injections on three separate days while the area response ratios of cocaine to histamine internal standard ranged from 0.88 to 1.23% RSD.

The performance of the system was examined to determine

TABLE 1—*Relative migration times, electrophoretic mobilities μ_e, and resolution for compounds studied.*

Compound	RMT*	RSD(%)†	R‡	μ_e(cm^2/Vs)
Histamine	0.83	0.32	9.93	2.28×10^{-4}
Ephedrine	0.92	0.28	5.05	1.65×10^{-4}
Procaine	0.95	0.25	4.05	1.48×10^{-4}
Phenylpropanolamine	0.97	0.25	5.3	1.36×10^{-4}
Cocaine	1.00	0.23	4.71	1.20×10^{-4}
Trans-Cinnamoylcocaine	1.02	0.002	5.11	1.06×10^{-4}
Cis-Cinnamoylcocaine	1.05	0.002	5.59	0.92×10^{-4}
Tetracaine	1.08	0.002	15.32	0.77×10^{-4}
Lidocaine	1.17	0.002	12.9	0.36×10^{-4}
Benzoylecgonine	1.26	0.001	§	0.03×10^{-4}
Benzocaine	1.26	0.003	§	0.03×10^{-4}
DMSO‡	1.27	0.001	§	4.30×10^{-4}
Acetaminophen	1.37	0.002	§	-0.30×10^{-4}

* Relative migration time to cocaine.
† Within day percent relative standard deviation of migration time (n = 10).
‡ Neutral marker for measuring electroosmotic flow.
§ No resolution data.

TABLE 2—*Reproducibility of migration time, peak areas of cocaine and peak area ratios of cocaine/internal standard with buffer replenishment.*

	RSD(%) MT	RSD(%) Absolute Peak Area	RSD(%) Peak Area Ratio*
Day 1	0.21	1.05	1.23
Day 2	0.62	1.27	0.89
Day 3	0.32	1.37	0.90

* Peak area response ratio determined relative to internal standard.

TABLE 3—*Reproducibility of migration time, peak areas of cocaine and peak and area ratios of cocaine/internal standard without buffer replenishment.*

Injections	RSD(%) MT	RSD(%) Absolute Peak Area	RSD(%) Peak Area Ratio*
10	0.16	0.95	0.64
20	0.23	1.08	0.64
30	0.26	1.92	1.93
40	0.32	2.18	1.81

* Peak area response ratio determined relative to internal standard.

the optimum number of injections that could be run under the experimental conditions without any buffer replenishment. The number of replicate injections was varied from 10 to 40. Experiments indicated that it is possible to run 20 consecutive injections without any buffer replenishment and still obtain reproducible peak area responses within 1% RSD and migration times less than 0.25% RSD. The reproducibility of the absolute peak area responses begin to increase to 2% relative standard deviations after 30 to 40 injections but the migration time reproducibility was still less than 0.32% RSD as indicated in Table 3. However, the quantitative assay includes a buffer replenishment step after ten injections so as to prevent ion depletion of the buffer solution.

The linear range for the determination of cocaine was conducted at eight different concentrations ranging from 0.014 to 1.017 mg/mL by measuring the ratio of the absolute peak area response of cocaine relative to the absolute peak area of the internal standard histamine diphosphate. The response of cocaine was found to be linear in the concentration ranges studied with a correlation coefficient (r^2) of 0.9996.

The accuracy of the method was examined by preparing seven blind illicit samples encompassing the purity levels from 1 to 90%. The samples were prepared by one analyst and quantitatively assayed by a different analyst for cocaine purity. The method exhibited good accuracy for the seven samples examined with the difference ranging from 0.36 to 2.07%. The results of the quantitative assay for the seven samples analyzed are illustrated in Table 4.

The limits of detection (LOD) for cocaine and its most common adulterants and impurities are listed in Table 5 along with the signal to noise (S/N) ratios at the 1% level. The LOD is defined as the concentration yielding a S/N of approximately 2. The LOD for cocaine was found to be 0.0028 mg/mL, which represents approximately 0.89% of a 0.312 mg/mL cocaine solution used in this study. All compounds except benzoylecgonine were detectable at the 1% level.

TABLE 4—*Summary of FZCE quantitative results from accuracy study.**

Sample #	Actual Purity	Assay Purity	%Difference†
1	1.27	1.32	3.78
2	5.03	5.16	2.57
3	10.23	10.33	0.96
4	24.90	25.05	0.59
5	49.43	50.94	2.96
6	73.86	76.71	3.71
7	87.99	89.50	1.68

* All data are presented as % relative to cocaine.
† Difference is determined from actual purity to assay purity.

TABLE 5—*Limits of detection for compounds of interest at S/N 2:1.*

Compound	LOD*	S/N†
Cocaine	0.0028	8:1
Procaine	0.0040	5:1
Tetracaine	0.0050	4:1
Lidocaine	0.0050	4:1
Benzocaine	0.0100	2:1
Trans-Cinnamoylcocaine	0.0530	4:1
Ephedrine	0.0340	2:1
PPA	0.0160	2:1
Benzoylecgonine	0.0118	‡
Acetaminophen	0.0041	5:1

* Limits of detection in mg/mL.
† S/N at 1% level.
‡ Not detectable at 1% level.

The specificity of the FZCE separation was evaluated using three fused silica capillaries from different batches from the same manufacturer. The resolution between critical pairs of the compounds of interest showed a high degree of reproducibility using different capillaries from the same manufacturer.

Originally, water and the running buffer were considered as two potential choices for an injection solvent. However, appreciable conversion of cocaine to benzoylecgonine was observed after 24 h in both water and in alkaline buffer solution. It is hypothesized that the heating in the capillary may have accelerated the hydrolysis conversion of cocaine to benzoylecgonine. In an attempt to eliminate acid hydrolysis of cocaine, 0.01 M HCl was investigated as a potential injection solvent for our quantitative assay. The stability of a standard solution of cocaine hydrochloride and internal standard in 0.01 M HCl at the normal assay concentration was monitored over a 30-day period. The absolute peak area response ratio of cocaine/histamine was approximately 2% RSD over this time period, and no breakdown of cocaine was detected. Therefore, 0.01 M HCl was chosen as the injection solvent.

The method was validated by the analysis of 21 illicit cocaine seizures. The concentration of cocaine in these seizures ranged from 6 to 89% and contained both the free base and HCl salt forms of cocaine as well as different adulterants. A comparison study of the chromatographic precision of CE versus HPLC and GLC was undertaken using these 21 illicit samples. A summary of these results is shown in Table 6.

Overall, there is good agreement between the FZCE quantitative method and the HPLC and GLC methods for the determination of cocaine purity in the illicit samples studied. The RSD of the three quantitative methods varied between 0.53 and 6.10%. Illicit sample #5 exhibited the greatest percent relative standard deviation between the three quantitative methods at 6.10%. Overall, the reproducibility of the FZCE method proved to be highly accurate and exhibited good correlation with HPLC and GLC quantitation

TABLE 6—*Comparison of CE, HPLC and GLC quantitation methods.**

Sample	Salt Form	HPLC	GLC	CE	RSD(%)
1	HCl	83.31	82.30	82.50	0.53
2	HCl	78.75	77.29	76.01	1.45
3	HCl	15.74	15.90	16.30	1.48
4	HCl	32.76	31.58	33.05	1.94
5	HCl	6.57	6.04	7.02	6.10
6	base	83.90	83.81	82.87	0.56
7	base	80.81	80.70	81.85	0.64
8	base	88.80	86.85	89.73	1.35
9	base	80.42	78.80	83.02	2.16
10	base	30.04	30.70	31.77	2.32
11	base	53.57	53.38	54.59	0.99
12	base	45.97	44.27	46.19	1.87
13	base	67.85	65.33	64.81	2.03
14	base	46.24	45.00	47.50	2.21
15	base	49.35	50.27	50.79	1.18
16	base	49.06	48.43	49.05	0.60
17	base	46.91	46.60	48.97	2.24
18	base	46.74	46.14	47.35	1.06
19	base	46.67	47.02	48.13	1.32
20	base	56.28	55.56	57.41	1.35
21	base	48.33	49.46	50.96	2.10

* All data are presented as % relative to cocaine.

methods, regardless of salt form, concentration or adulterants present.

Conclusions

The FZCE method developed for the quantitative and qualitative analysis of cocaine and common adulterants offers a highly efficient and selective alternative to the traditional chromatographic techniques of GLC and HPLC. It has been demonstrated that CE is capable of providing quantitative data on illicit cocaine seizures which are comparable to those obtained by previously validated GLC and HPLC methods. CE coupled with DAD allows for the storage of retention parameters and UV spectra. Peak purity can be evaluated through the review of the UV spectral data.

In addition, the high separation efficiencies exhibited between cocaine and the most common adulterants examined in this study allow for the quantitation of these compounds if necessary. The separation was found to be reproducible from capillary to capillary over a period of one year. Overall, CE offers the added benefit of low solvent consumption, minimal sample size requirements, and short analysis times, which can be potentially valuable in a high-production forensic laboratory.

References

1. Guzman NA, Hernandez L, Terabe S. High resolution nanotechnique for separation, characterization and quantitation of micro- and macromolecules. In: Horvath C, Nikelly JG, editors. Analytical Biotechnology Capillary Electrophoresis and Chromatography. ACS Symposium Series 434, Washington, DC, 1990;1–35.
2. Wainright A. Capillary electrophoresis applied to the analysis of pharmaceutical compounds. J Micro Separations 1990;2:166–217.
3. Marsh DB, Nutall KL. Methylmalonic acid in clinical urine specimens by capillary zone electrophoresis using indirect detection. J Capillary Electrophoresis 1995;2:63–7.
4. Lurie IS. Application of capillary electrophoresis to the analysis of seized drugs. American Laboratory Jan. 1996;26–34.
5. Lurie IS. Analysis of seized drugs by CE. In: Adamovics JA, editor. Analysis of addictive and misused drugs. New York: Marcel Dekker, 1995;151–219.
6. Heiger DN. High performance capillary electrophoresis—An introduction. Hewlett Packard GmbH, Germany, 1992.
7. Lurie IS. Improved isocratic mobile phases for the reverse phase ion-pair chromatographic analysis of drugs of forensic interest. J Liq Chromatogr 1981;4:399–408.
8. Lurie IS. The use of multiple detectors for HPLC forensic drug analysis. LC-GC 1990;8:454–66.
9. Lurie IS, Moore JM, Cooper DA, Kram TC. Analysis of manufacturing by-products and impurities in illicit cocaine via high pressure liquid chromatography and photodiode array detection. J Chromatogr 1987;405:273–81.
10. Pentoney SL, Sweedler JV. Optical detection techniques for capillary electrophoresis. In: Landers JP, editor. Handbook of Capillary Electrophoresis. CRC Press, 1997;379–423.
11. Walker JA, Marche HL, Newby N, Bechtold EJ. A free zone capillary electrophoresis method for the quantitation of common illicit drug samples. J Forensic Sci 1996;4:824–929.
12. Tagliaro F, Antennal C, Maraud S, Arcade S, Ghielmi S, Marigo M. High sensitivity low-cost methods for determination of cocaine in hair: high performance liquid chromatography. Forensic Sci Int 1993;63:227–38.
13. Tagliaro F, Poiesi C, Aiello R, Dorizzi R, Ghielmi S, Marigo M. Capillary electrophoresis for the investigation of illicit drugs in hair: determination of cocaine and morphine. J Chromatog 1993; 638:303–9.
14. Weinberger R, Lurie IS. Micellar electrokinetic capillary chromatography of illicit drug substances. Anal Chem 1991;63:823–7.
15. Walker JA, Krueger ST, Lurie IS, Marche HL, Newby N. Analysis of heroin drug seizures by micellar electrokinetic capillary chromatography (MECC). J Forensic Sci 1995;40:6–9.
16. Trenerry VC, Robertson J, Wells RJ. The determination of cocaine and related substances by micellar electrokinetic capillary chromatography. Electrophoresis 1994;14:103–8.
17. Krogh M, Brekke S, Tonnesen F, Rasmussen KT. Analysis of drug seizures of heroin and amphetamine by capillary electrophoresis. J Chromatog Adv 1994;674:235–40.
18. Trenerry VC, Wells RJ, Robertson J. The analysis of illicit heroin seizures by capillary zone electrophoresis. J Chromatog Sci 1994; 32:1–60.
19. Lurie IS, Sperling AR, Meyers RP. The determination of anabolic steroids by MECC, gradient HPLC, and capillary GC. J Forensic Sci 1994;39:74–85.
20. Lurie IS, Klein RFX, Dal Cason TA, LeBelle MJ, Brennelsen R, Weinberger RE. Chiral resolution of cationic drugs of forensic interest by capillary electrophoresis with mixtures of neutral and anionic cyclodextrins. Anal Chem 1994;66:4019–26.

Additional information and reprint requests:
Adrian S. Krawczeniuk
United States Department of Justice
Drug Enforcement Administration
Northeast Laboratory
99 10th Avenue, Suite 721
New York, NY 10011