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Optimization of the separation of lysergic acid diethylamide in urine by a sweeping technique using micellar electrokinetic chromatography

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Abstract

The separation and on-line concentrations of lysergic acid diethylamide (LSD), *iso*-lysergic acid diethylamide (*iso*-LSD) and lysergic acid *N*,*N*-methylpropylamide (LAMPA) in human urine were investigated by capillary electrophoresis–fluorescence spectroscopy using sodium dodecyl sulfate (SDS) as an anionic surfactant. A number of parameters such as buffer pH, SDS concentration, Brij-30 concentration and the content of organic solvent used in separation, were optimized. The techniques of sweeping-micellar electrokinetic chromatography (sweeping-MEKC) and cation-selective exhaustive injection-sweep-micellar electrokinetic chromatography (CSEI-sweep-MEKC) were used for determining on-line concentrations. The advantages and disadvantages of this procedure with respect to sensitivity, precision and simplicity are discussed and compared.

Keywords: Lysergic acid diethylamide

1. Introduction

Lysergic acid diethylamide (LSD) is a powerful psychedelic drug that produces temporary hallucinations and a schizophrenic psychotic state. The detection of LSD and its metabolites in body fluids continues to represent a challenge because of the small doses which are typically taken [1,2]. A number of analytical methods have been developed for its identification, and each has unique advantages and disadvantages with respect to sensitivity, precision and simplicity of use. These methods include radioimmunoassay (RIA) [3], thin layer chromatographic analysis (TLC) [4], high-performance liquid chromatography (HPLC)/fluorescence detection alone [5–9], or combined with tandem mass spectrometry [10,11]. Needless to say, gas chromatography–mass spectrometry (GC–MS) constitutes the most popular and powerful technique for this analysis [12–17], not only in the area of forensic research, but also in clinical analysis. However, a derivatization step is required, as well as additional sample handling.

Capillary electrophoresis (CE) has become a popular technique and is a very useful method for the determination of drugs in body fluids because of its

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advantages in terms of speed, higher efficiency and resolution for separation, greater sensitivity and a smaller injection volume than is typically used for HPLC or GC. In particular, CE combined with laser-induced fluorescence (CE–LIF) detection provides high sensitivity and its use in the analysis of LSD has been reported [18,19]. In this study, we report on a simple and highly sensitive method for the detection of LSD in urine using the techniques of on-line sample concentration, including sweeping-micellar electrokinetic chromatography (sweeping-MEKC) and cation-selective exhaustive injection-sweep-micellar electrokinetic chromatography (CSEI-sweep-MEKC) [20–26]. These methods do not require any derivatization procedure and permit the detection of very small amounts of LSD in small volumes of urine. Several electrophoretic parameters, such as buffer pH, SDS concentration, Brij-30 concentration and the amount of organic solvent needed for the separation were optimized. The detection limits and the precision of these methods are discussed. Finally, the use of liquid–liquid and solid-phase extraction are discussed and compared.

2. Experimental

2.1. Chemicals

Lysergic acid diethylamide (LSD), *iso*-lysergic acid diethylamide (*iso*-LSD) and lysergic acid *N*,*N*-methylpropylamide (LAMPA) were acquired from Radian International (Austin, TX, USA). Acetonitrile and methanol (99.8%) were obtained from Fisher Scientific (Fair Lawn, NJ, USA). Sodium dodecyl sulfate (SDS) and ammonium carbonate were obtained from Acros (Belgium) and Sigma (St. Louis, MO, USA), respectively. Brij-30 was acquired from Aldrich (Milwaukee, WI, USA). All other chemicals were of analytical grade and are commercially available.

2.2. Apparatus

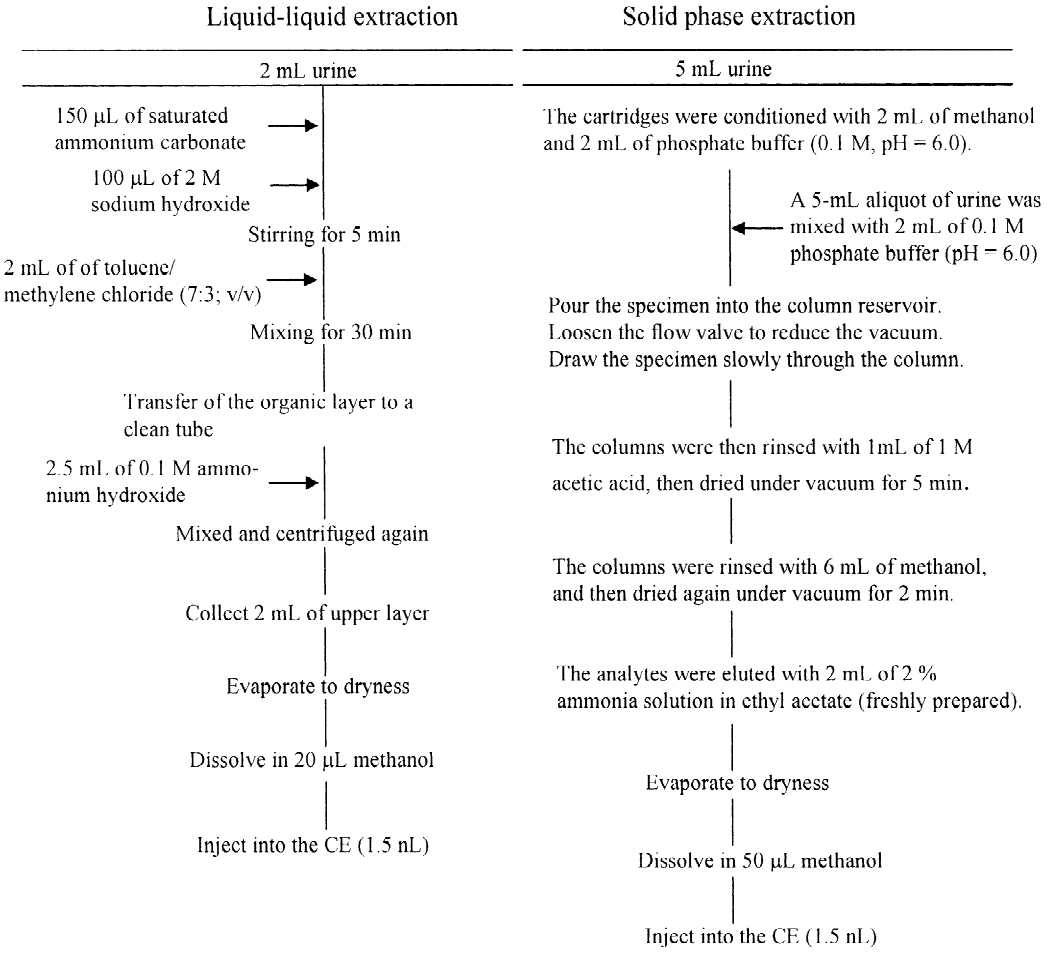
The CE set-up was fabricated in-house and is identical to that described previously [27–29]. Briefly, a high-voltage power supply (Model RR30-2R, 0–30 kV, 0–2 mA, reversible, Gamma, FL, USA) was used to drive the electrophoresis and a 50-μm I.D. fused-silica capillary column (J&W Scientific, CA, USA) was used for the separation (65 cm in length/60 cm to detector). The excitation source was selected by a monochromator (Acton Research Corporation; Model SP-150, 1200 grooves/mm grating) connected to a Xe lamp (Muller Elektronik Optik, SVX/LAX 1450, 500 W). The excitation wavelength was 320±8 nm (<1 mW). Fluorescence data were collected at a right angle to the light source and dispersed by a second monochromator (ARC Model SP-300i). Emission was measured at 390±2 nm (2400 grooves/mm) or 390±16 nm (300 grooves/mm), followed by detection by means of a photomultiplier tube (ARC Model P2-R928, for 190–900 nm). Electropherograms were collected at a speed of 200 ms/point with a data acquisition system (ARC's Spectra-Sense NCL package), connected to a personal computer. The solid-phase extraction equipment (Baker spe-12) was purchased from J.T. Baker (CA, USA). The cartridges (part number, 1211-3052; column type, LRC) were obtained from Varian (CA, USA).

2.3. Extraction procedures

2.3.1. Liquid–liquid extraction

A 2-ml aliquot of urine in a 15-ml glass tube was made alkaline by the addition of 150 μl of saturated ammonium carbonate and 100 μl of 2 *M* sodium hydroxide and briefly stirred for 5 min. Two millilitres of toluene–methylene chloride (7:3, v/v) were added, and the sample and solvent gently mixed for 30 min. After mixing, the tube was centrifuged. The organic layer was transferred to a clean tube, 2.5 ml of 0.1 *M* ammonium hydroxide were added and the solution was then mixed and centrifuged again. The upper layer was collected (2 ml) and this organic phase was evaporated to dryness. The residue was dissolved in 20 μl of methanol for the subsequent CE separation. To determine the extraction efficiency, eight control urine samples containing 1 ppm of LSD were divided into equal aliquots. At this point, the internal standard (LAMPA, 100 ppm) was added to one set of aliquots after extraction. The details of these procedures are summarized in Table 1 (left column).

Table 1
Sample preparation procedures



2.3.2. Solid-phase extraction

The cartridges were conditioned with 2 ml of methanol and 2 ml of 0.1 *M* phosphate buffer (pH 6.0). A 5-ml aliquot of urine was mixed with the phosphate buffer (2 ml, 0.1 *M*), and then added to the column reservoir. The flow valve was then loosened to reduce the vacuum. The columns were then rinsed with 1 ml of 1 *M* acetic acid followed by drying under vacuum for 5 min. The columns were again rinsed with 6 ml of methanol, and then dried again for 2 min. Finally, the analytes were eluted with 2 ml of 2% ammonia solution in ethyl acetate (freshly prepared). This organic phase was then evaporated to dryness. The residue was dissolved in 50 μl of methanol for the subsequent CE separation. The procedures are also summarized in Table 1 (right column).

3. Results and discussion

3.1. Separation condition

Fig. 1A shows the molecular structures of LSD, *iso*-LSD and LAMPA. It should be noted that LSD is converted to *iso*-LSD under a variety of different conditions, such as pH, temperature and UV-light. McNally et al. have previously reported on the stability of LSD under various storage conditions and

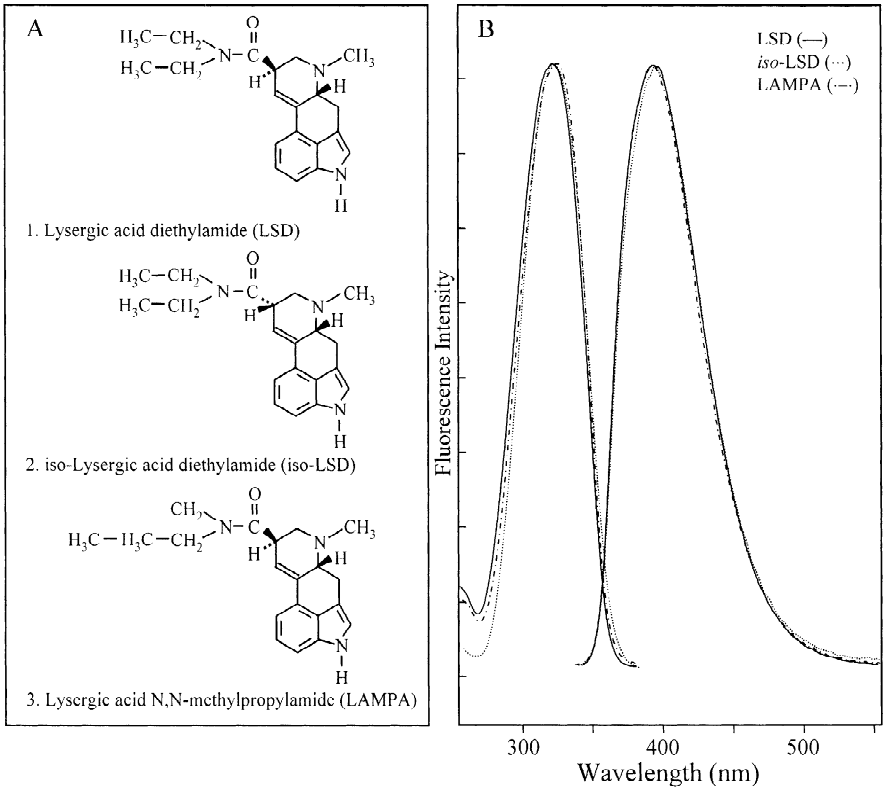


Fig. 1. (A) Molecular structures of (A) LSD, (B) *iso*-LSD and (C) LAMPA. (B) Typical excitation and fluorescence spectra of LSD (———), iso-LSD (- - -) and LAMPA (– · –) in methanol (λ_{ex} = 320 nm, λ_{em} = 390 nm; monochromator resolution = 0.3 nm) at room temperature.

pH [30,31]. This is the main reason why LAMPA is used as an internal standard. Fig. 1B shows the excitation and emission fluorescence spectra of LSD (———), *iso*-LSD (- - -) and LAMPA (– · –) in a methanol matrix (λ_{ex} = 320 nm; λ_{em} = 390 nm), respectively. The fluorescence spectra are analogous to each other and easily detected when excited by a UV lamp source or lasers.

Fig. 2A–D shows typical fluorescence electropherograms of the three analytes under different separation conditions. In frame A, the CE buffers were acetonitrile–methanol–water solutions (5:35:60, v/v), containing 3 m*M* Brij-30, 50 m*M* H_3PO_4 and different concentrations of SDS (electropherograms a–d: 25, 50, 100 and 150 m*M*). The sample concentration was 134, 66 and 100 ppm for LSD, *iso*-LSD and LAMPA, respectively. The optimum concentration of SDS was 100 m*M* (as shown in electropherogram c). In order to investigate the effects of organic solvents, under exactly the same experimental conditions, a methanol–water solution (15:85, v/v), a methanol–water solution (35:65, v/v) and an acetonitrile–water solution (25:75, v/v) were used and the findings showed that the separation had degraded, as shown in frame B (electropherograms e, f and g). In order to examine the effects of phosphate buffer under exactly the same experimental conditions as were used for electropherogram c, 25, 75 and 100 m*M* of phosphate buffer were then used and the findings showed that the separation became progressively worse, as shown in frame C (electropherograms h, i and j). Finally, Brij-30 was also tested, as shown in frame D (electropherograms k and l: 0 and 10 m*M*). A concentration of 3 m*M* Brij-30 was found to be the best concentration for stabilizing the sample solution. Thus, the complete,

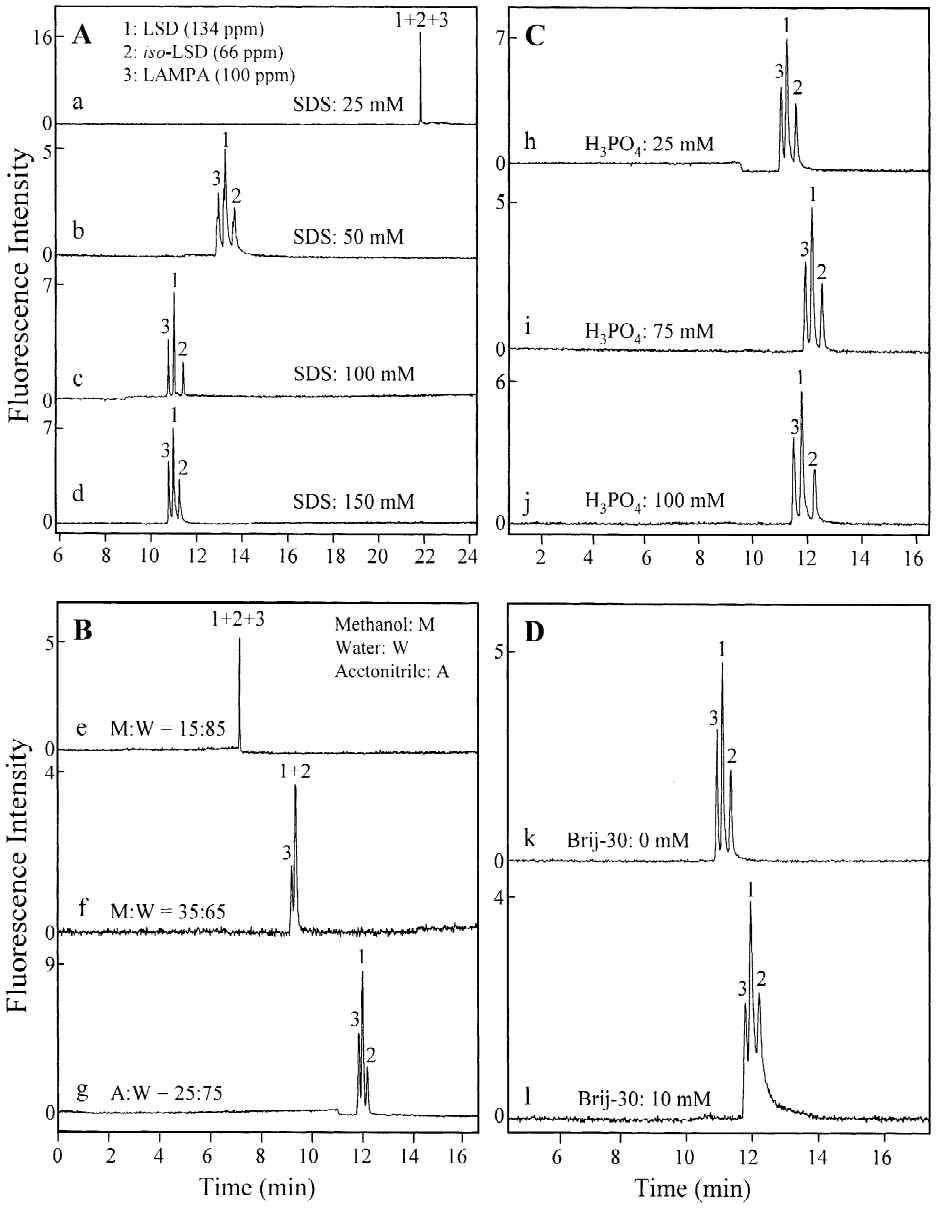


Fig. 2. Effects of different parameters on CE separation. Conditions: capillary, 65 cm (60 cm to detector), 50 μm I.D.; applied voltage, −20 kV; current ~−30 μA; λ_{ex} = 320 nm, λ_{em} = 390 nm. Sample concentrations: 134, 66 and 100 ppm for LSD, *iso*-LSD and LAMPA, respectively. Buffers: (A) 3 m*M* Brij-30 and 50 m*M* H_3PO_4 in an acetonitrile–methanol–water solution (5:35:60, v/v); pH 2.1; SDS concentrations: 25, 50, 100 and 150 m*M* (electropherograms a–d). (B) 100 m*M* SDS, 3 m*M* Brij-30 and 50 m*M* H_3PO_4 in different solutions (acetonitrile–methanol–water): 0:18:85, 0:35:65, 25:0:75, v/v (electropherograms e–f). (C) 100 m*M* SDS, 3 m*M* Brij-30 in an acetonitrile–methanol–water solution (5:35:60, v/v), H_3PO_4: 25, 75 and 100 m*M* (electropherograms h–j). (D) 100 m*M* SDS and 50 m*M* H_3PO_4 in an acetonitrile–methanol–water solution (5:35:60, v/v), Brij-30: 3 and 10 m*M* (electropherograms k and l).

optimal separation of the three analytes could be achieved with phosphate buffer (50 m*M*) containing SDS (100 m*M*), Brij-30 (3 m*M*) in an acetonitrile–methanol–water solution (5:35:60, v/v). Such a modification had no significant effect on sensitivity. Furthermore, a different surfactant (sodium cholate) was also tested, but resulted in a poor separation of the three analytes.

3.2. On-line sample concentration

As mentioned above, the detection of LSD in body fluids continues to be difficult because of the small dosage used. Therefore, a technique involving online concentration has become increasingly important. Recently, a series of reports appeared by Terabe et al., as well as other groups, concerning the so-called ''sweeping'' technique [15–21]. In the following sections, the applications of sweeping-MEKC and the CSEI-sweep-MEKC model are described and compared.

3.2.1. Sweeping-MEKC

This is the most simple and convenient method for determining online concentration. The concentration effect relies on the pseudostationary phase that enters the sample solution zones. In this experiment, the background solution (BGS) consisted of 100 m*M* SDS, 3 m*M* Brij-30 and 50 m*M* H_3PO_4 in a mixed acetonitrile–methanol–water solution (5:35:60, v/v), the pH of which was 2.06. The samples (LSD, 0.4 ppm; *iso*-LSD, 0.20 ppm; LAMPA, 0.3 ppm) were dissolved in the same solution (without SDS) resulting in a non-micelle buffer, and adjusted to the conductivity of the BGS (5.37 mS/cm) by the addition of 100 m*M* H_3PO_4, the pH of which was 1.92. Hydrodynamic injection was achieved by raising the sample reservoir 20 cm relative to the exit reservoir for a period of 900 s. Using this procedure, a 30-cm length of solution can be injected into the capillary. When the injection was completed, −20 kV (current, ~−18 μA) was applied to power the CE separation. As a result, in comparison with a normal injection (20 cm relative to the exit reservoir for 3 s, ~0.5 mm) and separation (Fig. 2, electropherogram c), ~400-fold improvement ($S/N = 3$) in detection sensitivity could be obtained, as shown in Fig. 3A.

3.2.2. CSEI-sweep-MEKC

The cation-selective exhaustive injection-sweep MEKC model was first reported by Terabe et al. [21]. This method provides for a more sensitive detection than sweeping-MEKC and is sufficiently flexible to offer the potential to afford a detection limit for positively chargeable analytes even in parts per trillion (ppt) levels. At the beginning of the runs, the capillary was conditioned with a nonmicellar background buffer, followed by the injection of a high conductivity buffer void of organic solvent, and finally, by the injection of a short water plug. By electrokinetic injection (at positive polarity) the cationic analytes were then prepared in a low conductivity matrix or water. Herein, the cationic analytes focus or stack at the interface between the water zone and the high conductivity buffer. The injection was then stopped and the micellar background solutions are placed at both ends of the capillary. The voltage was then switched to negative polarity. This permits the entry of micelles from the cathodic vial into the capillary to sweep the stacked and introduced analytes to the narrow brands. Finally, the separation was performed using MEKC.

Herein, the background buffer consisted of only 75 m*M* H_3PO_4 in a mixed acetonitrile–methanol–water solution (5:35:60, v/v). The capillary was initially filled with the background buffer, followed by a 10-cm length of capillary with 100 m*M* H_3PO_4 solution and, lastly, a plug of water (~1.6 mm) was injected. By providing +25 kV for a period of 20 min (electrokinetic injection for cation), the currents changed from ~10 μA to ~20 μA. Meanwhile, the samples can be concentrated into the zone of the water. Following this, by quickly shifting the voltage to −20 kV (~−18 μA), the separation can be completed within the next 18 min, as shown in Fig. 3B. The sample concentrations of LSD, *iso*-LSD and LAMPA were 1.3, 0.7 and 1.0 ppb, respectively. Compared to a typical separation as shown in Fig. 2A (electropherogram c), an ~100,000-fold improvement ($S/N = 3$) in detection sensitivity can be obtained. Furthermore, as shown in the inset, when the grating was changed from 2400 to 300 grooves/mm, the detection limit of LSD, *iso*-LSD and LAMPA can be further improved by 12-, 13-, and 11-fold, respectively.

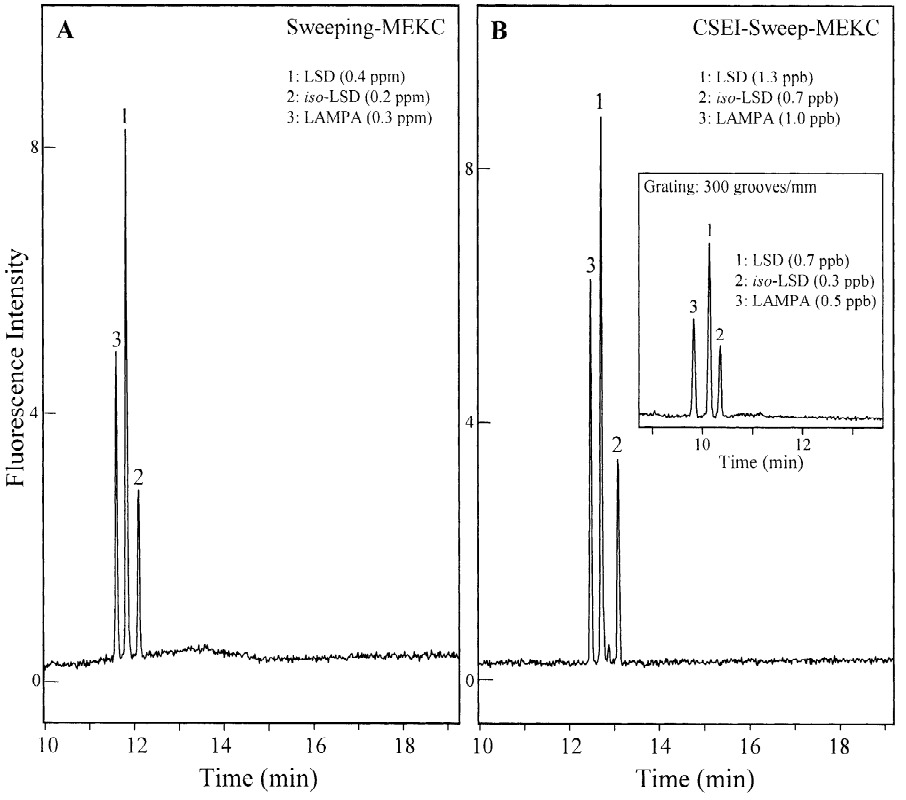


Fig. 3. (A) Sweeping-MEKC analysis of LSD, *iso*-LSD and LAMPA in the presence of a small amount of organic solvent in the sample matrix: BGS, 100 m*M* SDS, 3 m*M* Brij-30, 50 m*M* H_3PO_4 in a mixed acetonitrile–methanol–water solution (5:35:60, v/v); S, three analytes in the same solvent (containing 3 m*M* Brij-30 and 50 m*M* H_3PO_4) adjusted to the conductivity of BGS (5.37 mS/cm) by the addition of 100 m*M* H_3PO_4; injected length of S, 30 cm; applied voltage, −20 kV; concentrations of LSD, *iso*-LSD and LAMPA were 0.4, 0.2 and 0.3 ppm; capillary, 60 cm to the detector (65 cm total). (B) CSEI-sweep-MEKC analysis of LSD, *iso*-LSD and LAMPA. Steps: (1) capillary is filled with the background buffer (75 m*M* H_3PO_4 in a mixed acetonitrile–methanol–water solution; 5:35:60, v/v), (2) a 10-cm length of capillary containing a 100 m*M* H_3PO_4 solution was injected, (3) a plug of water (~1.6 mm) is injected, (4) +25 kV is applied for 20 min, (5) the voltage is shifted to −20 kV (~−18 μA) for normal CE separation. The sample concentrations of LSD, *iso*-LSD and LAMPA were 1.3, 0.7 and 1.0 ppb, respectively. Inset, higher sensitivity when a 300 grooves/mm grating was applied.

3.3. Accuracy and precision

Using the conditions described in Fig. 3A and B, linearity, limit of detection (LOD) values, relative standard deviations (RSD %) of peak area and migration times, and plate numbers were calculated and these data are summarized in Table 2. Both the sweeping-MEKC and the CSEI-sweep-MEKC showed good linearity. Sweeping-MEKC provides better RSD values, but poor LOD values, compared to CSEI-sweep-MEKC. Although the lamp source is still not superior to laser-induced fluorescence (LIF) detection, a combination of the sweeping techniques and LIF clearly lead to further improvement in the LOD values.

In terms of extraction and recovery, Fig. 4A (electropherogram a) shows a typical fluorescence electropherogram of an extract of normal human urine by liquid–liquid extraction. Only one major peak (indicated as ''*'') at ~10 min was detected. Thus, it is clear that in typical human urine samples, only a few natural fluorescent compounds are present which fluoresce in the wavelength range of 390±2 nm. With this fluorescence detection, the elec-

Table 2
Limit of detection (LOD) values, RSD values, and plate numbers for LSD, *iso*-LSD and LAMPA with sweeping-MEKC/CSEI-sweep-MEKC

	LSD	*iso*-LSD	LAMPA
A. Sweeping-MEKC			
Equation of the line	$y = 4.58 \times 10^5 x - 1.65 \times 10^4$	$y = 3.23 \times 10^5 x - 3.75 \times 10^3$	$y = 3.74 \times 10^5 x - 1.07 \times 10^4$
Coefficient of variation	$r^2 = 0.9934$	$r^2 = 0.9934$	$r^2 = 0.9914$
LOD ($S/N = 3$)	16 ppb	22 ppb	18 ppb
	(4.8×10^{-8} *M*)	(6.9×10^{-8} *M*)	(5.6×10^{-8} *M*)
RSD			
(a) Migration time ($n = 6$) %			
Intra-day	1.0	1.01	1.04
Inter-day	2.36	2.30	2.69
(b) Peak area ($n = 6$) %			
Intra-day	3.36	4.37	4.54
Inter-day	5.03	7.80	7.36
Plate number	1.8×10^5	2.0×10^5	1.8×10^5
B. CSEI-sweep-MEKC			
Equation of the line	$y = 2.59 \times 10^5 x - 5.69 \times 10^4$	$y = 1.98 \times 10^5 x - 3.24 \times 10^4$	$y = 2.01 \times 10^5 x - 3.53 \times 10^4$
Coefficient of variation	$r^2 = 0.9904$	$r^2 = 0.9963$	$r^2 = 0.9948$
LOD ($S/N = 3$)	58 ppt	68 ppt	80 ppt
	(1.8×10^{-10} *M*)	(2.1×10^{-10} *M*)	(2.5×10^{-10} *M*)
RSD			
(a) Migration time ($n = 6$) %			
Intra-day	2.29	2.78	2.40
Inter-day	4.32	4.40	4.26
(b) Peak area ($n = 6$) %			
Intra-day	5.66	6.43	5.01
Inter-day	9.35	8.87	8.38
Plate number	3.5×10^5	3.6×10^5	3.3×10^5

Fluorescence emission was measured at 390±2 nm (2400 grooves/mm).

tropherogram was considerably simpler than UV detection due to the UV-absorption of numerous organic compounds in a urine sample. Because *iso*-LSD can be converted to LSD under a variety of conditions, as described above, for the calculation of recovery, only LAMPA was selected for comparison. In Fig. 4A, electropherogram b shows that LAMPA (100 ppm) was added to one set of aliquots after extraction. Due to the fact that the fluorescence intensity of LAMPA (in methanol) and LSD is 8 to 10, as evidenced by comparing the ratio to the LAMPA standard in each pair of aliquots, the extraction efficiency of liquid–liquid extraction for LSD was determined to be ~51%. The average recovery was 56±6%. In contrast, the average recovery by solid-phase extraction was higher, as shown in Fig. 4B. No natural fluorescent compound is present in the wavelength range of 390±2 nm, as shown in electropherogram c. Again, electropherogram d shows the results of an experiment where LAMPA (100 ppm) was added to one set of aliquots after solid-phase extraction. The average recovery was 70±8%. Thus, solid-phase extraction is more efficient and provides cleaner extracts than can be obtained by liquid–liquid extraction.

3.4. Analysis of LSD in urine samples

In the analysis of an actual sample (either urine or blood), the application of sweeping techniques continues to be a challenge because of complicated matrix effects. In Fig. 5, frames A, B and C, D show results obtained for liquid–liquid extraction and solid-phase extraction, respectively. The electropherograms a, b (liquid–liquid extraction) and

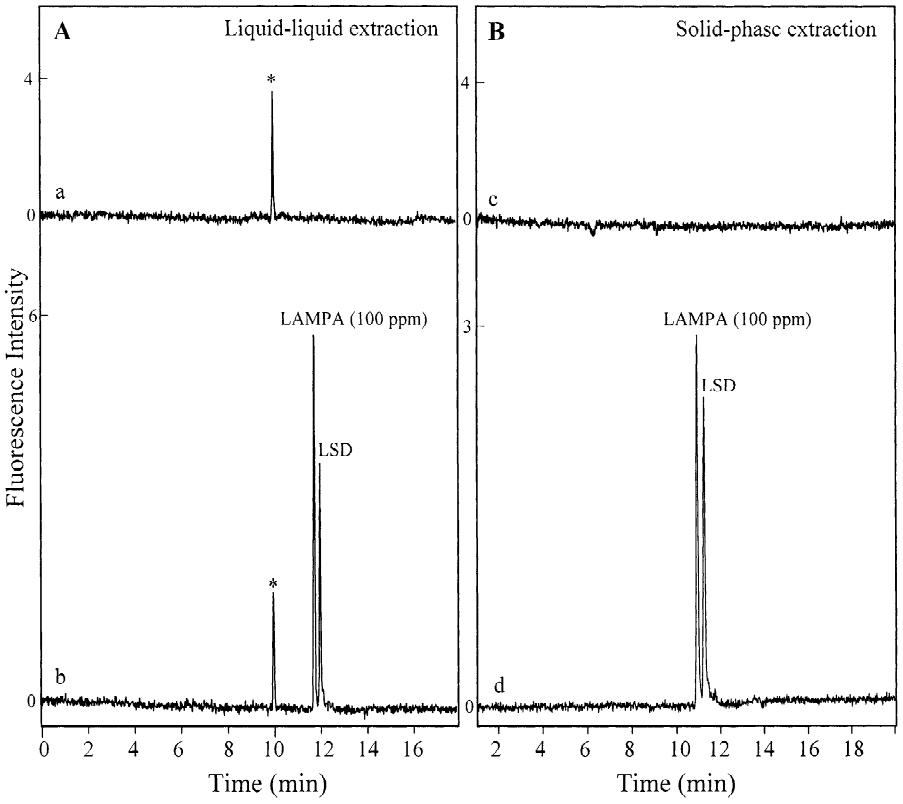


Fig. 4. Comparison of recoveries by liquid–liquid extraction (A) and solid-phase extraction (B) by spiking 1 ppm LSD. Electropherogram a and c, normal human urine extracts. Electropherogram b and d, LAMPA (100 ppm) was added to one set of aliquots, after extraction.

electropherograms e, f (solid-phase extraction) show typical electropherograms of normal human urine extracts, and the LSD and LAMPA standards (spiked with 50 ppb of each for the same urine sample) after applying the sweeping-MEKC technique. Using this approach, LSD can be efficiently extracted, concentrated and detected. In contrast, using CSEI-sweep-MEKC, electropherograms c, d (liquid–liquid extraction) and g, h (solid-phase extraction) show electropherograms of normal human urine extracts, and the LSD and LAMPA standards again (spiked both at 5 ppb for the same urine sample). Because of the numerous unknown matrix effects, many unknown peaks appear when the CSEI-sweep-MEKC technique was applied. The detection limit of LSD in urine was 0.6 ppb ($S/N = 3$), much higher than that of a regular separation.

4. Conclusions

We demonstrate here that the method of capillary electrophoresis–fluorescence spectroscopy can be successfully used for the separation and on-line concentration of three similar analytes of LSD, *iso*-LSD and LAMPA using the sweeping-MEKC and CSEI-sweep-MEKC techniques. The former provides higher plate numbers (N), better RSD values for migration times and peak area, but poor LOD; whereas the latter provides much better LOD. When the CSEI-sweep-MEKC technique was applied to a urine containing LSD, the analysis of LSD can be achieved in a short time, without the need for a derivatization step and additional sample handling, which are necessary when MS is used. Although all of the separation conditions are discussed as well as

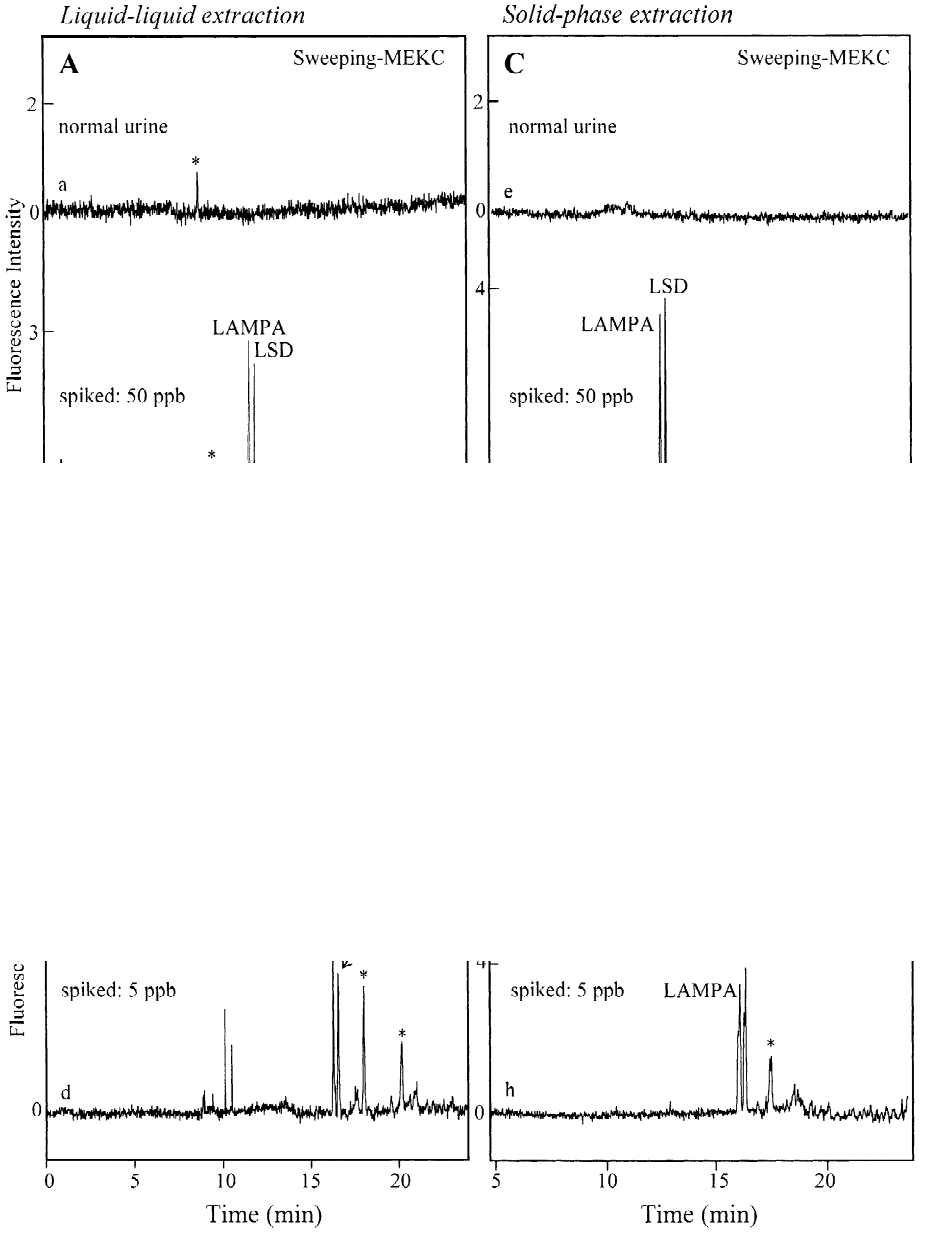


Fig. 5. Comparison of the detection limit of LSD and LAMPA by liquid–liquid extraction (frames A and B) and solid-phase extraction (frames C and D) with different on-line concentration techniques (sweeping-MEKC, frames A and C; CSEI-sweep-MEKC, frames B and D). Electropherograms a, e, c and g, normal human urine extracts; electropherograms b and f, the same samples spiked with LSD and LAMPA at a level of 50 ppb after applying the sweeping-MEKC; electropherograms d and h, the same samples spiked with LSD and LAMPA at a level of 5 ppb after applying the CSEI-sweep-MEKC technique.

the results of excitation by a lamp, it is definitely clear that the use of a combination of a sweeping technique and a laser, especially a He–Cd laser (325 nm), can further improve the analysis of LSD in urine.

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