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Linear solvation energy relationships of mixed micelles of sodium dodecyl sulfate and decanol: towards a better model of octanol/water partitioning

David J. Bailey[1], John G. Dorsey*

Department of Chemistry, The Florida State University, Tallahassee, FL 32306-4390, USA

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Abstract

We show that we can alter the mechanism of micelle/water partitioning by the addition of decanol as a co-surfactant to an SDS micellar solution. Linear solvation energy relationship (LSER) studies indicate that as we increase the amount of decanol added to sodium dodecyl sulfate solution, the hydrogen bond donating ability of the aqueous phase increases and the cavity term of the micellar phase increases. We obtain a better correlation with octanol/water partitioning using the mixed micelle system compared to normal micelle solution. Choosing the appropriate micelle marker is very important. Significant changes in the LSER equations can occur if a different compound is used as the micelle marker.

Keywords: Linear solvation energy relationships; Partitioning; Mixed micelles; Micellar electrokinetic chromatography; Sodium dodecyl sulfate; Decanol

1. Introduction

One of the major difficulties facing pharmaceutical and environmental scientists is the accurate measurement of biopartitioning. These data are important to determine drug uptake, bioconcentration of compounds, and compounds' environmental fate and transport. Since the cost of determining biopartitioning values can range up to and exceed $10 000 per compound [1], an alternative approach is needed to predict biopartitioning. Hydrophobicity is the most used physical property to predict biopartitioning. To estimate hydrophobicity values, Hansch and coworkers suggested measuring the partitioning of a solute between octanol and water [2–4]. The octanol/water partition coefficient (K_{ow}) is defined as the concentration ratio of the solute in water-saturated octanol to octanol-saturated water. From these experiments, log K_{ow} values correlate with many biopartitioning values, but exceptions are common [5].

Since Hansch's work [3,4], several attempts to measure or estimate log K_{ow} values using different analytical techniques have been suggested. Reversed-

*Corresponding author. Tel.: +1-850-644-4496; fax: +1-850-645-5644.

E-mail address: dorsey@chem.fsu.edu (J.G. Dorsey).

[1]Present address: Department of Physical Sciences, The University of West Alabama, Livingston, AL 35470, USA.

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phase liquid chromatography (RPLC) has been the alternative method of choice [6–8]. Examples of other analytical methods include: the slow stirring method [9], counter current chromatography [10], computer modeling [11], solubility values [12], micellar electrokinetic chromatography (MEKC) [13], and activity coefficients [14]. Except for MEKC, all other methods are labor, time, or equipment intensive.

MEKC may quickly become the method of choice for estimating hydrophobicity due to the minimal amount of hazardous waste produced, calculated migration factors (k'_m) are in 100% water, and shorter analysis times. Herbert and Dorsey published the first comprehensive study of the use of k'_m values from MEKC to correlate with log K_{ow} values [15]. Hanna et al. have recently reinforced the ease and usability of MEKC to model octanol/water partitioning coefficients [16]. Herbert and Dorsey determined that the outliers in their correlations were charged compounds [15]. Khaledi et al. developed a method to correct for the electrophoretic mobility of the charged solute in MEKC [17], and using these corrected migration factors, they determined that the correlation of log k'_m to log K_{ow} resulted in three lines [18]. We have confirmed these results using both Khaledi's equation and our adaptation of the migration factor equation to correct for the electrophoretic mobility of charged solutes [19,20].

To better model octanol/water partitioning, we need to understand the driving forces of the partitioning process. Linear solvation energy relationships (LSER) have been used to describe many partitioning processes including biopartitioning [21,22], octanol/water partitioning [23], RPLC [24,25], MEKC [26,27], and supercritical fluid chromatography (SFC) [28] systems.

Since MEKC is our preferred measurement method, the surfactant must be charged and have similar characteristics to octanol. We investigated a mixed micelle system since there is no surfactant readily available that contains both alcohol functionality and an ionizable head group. Mixed micelles have been used in MEKC before. Often, the co-surfactant has been a bile salt [29,30], zwitterions [31], fluorocarbons [32], or non-ionic surfactant [33–35]. Straight chain alcohols have been used in conjunction with microemulsion electrokinetic chromatography [36,37].

In this work SDS is the primary surfactant and decanol is the co-surfactant. We wanted to use a straight chain alcohol, like decanol or dodecanol, as a co-surfactant to match the hydrocarbon chain length of the surfactant and to give an octanol-like interaction. The Krafft point of dodecanol and SDS is greater than 30°C, thus the mixture is opaque at room temperature. Decanol does form co-micelles with SDS and the mixture is transparent until we reached the Krafft point with a 70/30 SDS/decanol molar ratio. We investigated the solution mixtures of 90/10 and 80/20 molar ratios of SDS/decanol. Since decanol is highly insoluble in water, we assume that the decanol associates with the SDS micelle or any number of SDS molecules.

2. Theory

In capillary zone electrophoresis (CZE), charged species are separated due to differences in their electrophoretic mobilities (μ_s). Neutral compounds migrate with the electroosmotic flow (EOF) and are not separated. The electrophoretic mobility of a neutral solute is defined as zero. To determine the electrophoretic mobility of a charged solute, the electroosmotic mobility (μ_{EOF}) is subtracted from the observed electrophoretic mobility (μ_{obs}), as shown in Eq. (1):

$$\mu_s = \mu_{obs} - \mu_{EOF} \quad (1)$$

In MEKC, as described by Terabe [38,39], the buffer contains a surfactant above the critical micelle concentration, and neutral solutes are separated based on differences in their micelle/water partitioning coefficients. Migration (k'_m) values are calculated using electrophoretic mobilities as:

$$k'_m = \left(\frac{\mu_{sm}}{\mu_m - \mu_{sm}} \right) \quad (2)$$

where μ_m is the electrophoretic mobility of the micelle marker and μ_{sm} is the electrophoretic mobility of the solute determined in an MEKC system. For our study, all migration factor calculations will use

electrophoretic mobilities instead of time because of the possibility of EOF variation. EOF variability may be caused by changes in column conditions beyond the control of the experimenters, slight changes in the dielectric constant, or changes in the zeta potential.

We use migration factors as the dependent variable in the LSER studies of solute partitioning from a mobile phase to a micellar phase. There are two similar forms of the equation used for LSER study, one equation developed by Kamlet and coworkers [40] and the other proposed by Abraham and coworkers [41].

We will use Kamlet's version of the LSER equation described as:

$$\text{Log } K = \text{Log } K_0 + mV_1/100 + s\pi^* + b\beta_m + a\alpha_m \quad (3)$$

where V_1 is the intrinsic molar volume of the solute, π is the polarizability/dipolarizability of the solute, and α and β are the hydrogen bond acidity and basicity, respectively. The terms *m*, *s*, *b*, and *a* are the coefficients we calculate. The δ term has been omitted from the LSER equation because it is a correction factor that accounts for differences in polarizability between polychlorinated compounds, aromatic compounds and alkanes. Since the solute list consists of only aromatic compounds, the δ term is ignored.

Carr and coworkers first presented chromatographic application of an LSER equation in 1986 [42]. Briefly, the interpretation of an LSER equation for chromatographic retention is based on the coefficients of the multivariable equation. Each coefficient describes the average degree of interaction each solute has with the mobile and stationary phase. Eq. (4) is the MEKC version of the LSER formalism:

$$\begin{aligned}\text{Log } k'_m = {} & \text{Log } k'_{mo} + M(v_s - v_m)V_1/100 \\ & + S(\pi_s - \pi_m)\pi^* + B(\alpha_s - \alpha_m)\beta \\ & + A(\beta_s - \beta_m)\alpha \end{aligned} \quad (4)$$

The subscript m is the mobile phase and the subscript s is the stationary phase. Each coefficient has been replaced by a proportionality constant and the difference between the mobile and micellar phase contribution to each parameter. A positive coefficient indicates that the influence of the micellar or stationary phase dominates, while a negative coefficient indicates the aqueous or mobile phase dominates.

The coefficients for the β term explain how the hydrogen bond acidity of the stationary phase compares to the mobile phase. When the coefficient is positive, the micellar phase is a stronger hydrogen bond donor than the mobile phase. Conversely, a negative coefficient indicates that the mobile phase is a better hydrogen donor. The coefficient for the α term compares the hydrogen bond basicity or accepting ability of the stationary phase to the mobile phase. The coefficient for the π term compares how the micellar or aqueous phase stabilizes the polarizability/dipolarizability of the solute, while the V_1 coefficient is a measure of the ability of the micellar or aqueous phase to form a cavity.

The solutes used in this study are all aromatic solutes. Many contain acidic or phenolic functional groups. To achieve a good LSER equation, the solutes must fit the following criteria: (i) the range of migration should cover the migration window in MEKC; (ii) the range in the LSER term must be comprehensive, for example, the β range is 0.0–0.82 and the solutes β-values must cover this range; (iii) the solutes are aromatic to be detected in this system. Abraham's solute parameters are more recent and accurate than Kamlet's. However, the most comprehensive list to date does not include the brominated, acidic, or selected polyaromatic compounds of our solute list. In fact, out of the 48 solutes in our list, only 32 have values published by Abraham. Even though we are using Kamlet's older values, we are aware that the coefficients might be different if we had used Abraham's values. The observed trends should be similar despite the differences of values.

3. Experimental

3.1. Standard and sample preparation

To prepare standard stock solutions of the solutes listed in Table 1, each solute was weighed and added to 10 ml of methanol to make an ~0.5–0.25-*M* standard. To prepare an analytical sample, 15 μl of

Table 1
Solutes used in LSER study with their LSER and log K_{ow} values [43]

Solute #	Compound	$V_1/100$	π	β_m	α_m	Log K_{ow}
1	Benzene	0.491	0.59	0.10	0.00	2.13
2	Toluene	0.592	0.55	0.11	0.00	2.73
3	Ethylbenzene	0.687	0.53	0.12	0.00	3.15
4	*n*-Propylbenzene	0.785	0.51	0.12	0.00	3.72
5	*n*-Butylbenzene	0.883	0.49	0.12	0.00	4.38
6	*m*-Dichlorobenzene	0.671	0.75	0.03	0.00	3.53
7	Nitrobenzene	0.631	1.01	0.30	0.00	1.85
8	Acetophenone	0.690	0.90	0.49	0.06	1.58
9	4-Chloronitrobenzene	0.721	1.01	0.26	0.00	2.39
10	Benzoic acid	0.650	0.74	0.40	0.75	1.87
11	*p*-Cresol	0.634	0.68	0.34	0.58	3.15
12	*m*-Cresol	0.634	0.68	0.34	0.58	3.20
13	Phenol	0.536	0.72	0.33	0.61	1.46
14	*p*-Chlorophenol	0.626	0.72	0.23	0.69	2.39
15	Naphthalene	0.753	0.70	0.15	0.00	3.30
16	Anthracene	1.015	0.80	0.20	0.00	4.45
17	Phenanthrene	1.015	0.80	0.20	0.00	4.46
18	Biphenyl	0.920	1.18	0.20	0.00	4.01
19	Pyridine	0.470	0.87	0.64	0.00	0.65
20	1,4-Dibromobenzene	0.758	0.79	0.02	0.00	3.79
21	1,3,5-Tribromobenzene	0.892	0.79	0.00	0.00	4.51
22	1,2,4,5-Tetrabromobenzene	1.026	0.79	0.00	0.00	5.13
23	1,4-Dichlorobenzene	0.671	0.70	0.03	0.00	3.44
24	4-Nitroaniline	0.702	1.25	0.48	0.47	1.39
25	3-Nitroaniline	0.702	1.15	0.46	0.39	1.85
26	4-Nitrophenol	0.676	1.15	0.32	0.93	1.91
27	*p*-Chlorobenzoic acid	0.740	0.74	0.36	0.79	2.65
28	Aniline	0.562	0.73	0.50	0.16	0.90
29	*p*-Toluidine	0.660	0.69	0.51	0.13	1.39
30	1-Methylnaphthalene	0.851	0.66	0.16	0.00	3.87
31	Quinoline	0.734	0.92	0.64	0.00	2.03
32	Isoquinoline	0.734	0.92	0.64	0.00	2.08
33	Acenaphthene	0.896	0.62	0.17	0.00	3.92
34	Fluoranthene	1.130	0.80	0.20	0.00	5.16
35	Fluorene	0.960	1.14	0.21	0.00	4.18
36	Pyrene	1.156	0.90	0.25	0.00	4.88
37	Chrysene	1.227	0.90	0.25	0.00	5.73
38	Perylene	1.415	1.00	0.30	0.00	5.82
39	Diphenylmethane	1.052	1.14	0.21	0.00	4.14
40	*t*-Butylbenzene	0.863	0.49	0.12	0.00	4.38
41	*o*-Dichlorobenzene	0.671	0.80	0.03	0.00	3.43
42	Dimethyl phthalate	0.953	0.86	0.78	0.00	1.56
43	Diethyl phthalate	1.153	0.84	0.82	0.00	2.47
44	Methyl benzoate	0.736	0.76	0.39	0.00	2.12
45	Ethyl benzoate	0.834	0.74	0.41	0.00	2.64
46	Fluorobenzene	0.520	0.62	0.05	0.00	2.27
47	*N*,*N*-Dimethylaniline	0.752	0.75	0.43	0.00	2.31
48	*p*-Toluic acid	0.748	0.70	0.41	0.73	2.27
Micelle markers						
MM-1	Decanophenone	NA	NA	NA	NA	NA
MM-2	Yellow AB	NA	NA	NA	NA	NA
MM-3	Orange OT	NA	NA	NA	NA	NA

NA, not available.

the standard was added to 100–250 μl of methanol, used as an EOF marker, and enough buffer to make 4 ml of sample. Decanophenone, Orange OT, or Yellow AB were used as a micelle marker and were analyzed separately.

3.2. Buffer preparation

To prepare 50 m*M* of 90/10 SDS/decanol molar ratio surfactant mixture in 20 m*M* phosphate buffer, decanol was added by weight to a flask so the final solution would be 5 m*M* decanol. Then 20-m*M* sodium phosphate solution was added until the flask was a third full. Enough SDS was added to make a 45-m*M* solution. More 20 m*M* sodium phosphate was added until the flask was two-thirds to three-quarters full, and the solution was then capped and heated in a water bath for 20 min at 60°C, or until the solution became clear. After the solution and flask cooled, the remaining 20 m*M* sodium phosphate was added. We adjusted the solution to pH 7 using either concentrated H_3PO_4 or NaOH solution.

To prepare 50 m*M* of 80/20 SDS/decanol molar ratio surfactant mixture in 20 m*M* phosphate buffer, decanol was added by weight to a flask so the final solution would be 10 m*M* decanol. Then 20-m*M* sodium phosphate solution was added until the flask was a third full. Enough SDS was added to make a 40-m*M* solution. More 20 m*M* sodium phosphate was added until the flask was two-thirds to three-quarters full and the solution was then capped and heated in a water bath for 20 min at 60°C, or until the solution became clear. After the solution and flask cooled, the remaining 20 m*M* sodium phosphate was added. We adjusted the solution to pH 7 using either concentrated H_3PO_4 or NaOH solution.

A brief note on the stability of these mixed micelle solutions is required. The heating step is used to increase the kinetics of dissolution of decanol. After the solution has cooled, the mixture is stable up to 1 week, and possibly longer. Instead of heating the solution, leaving the solution to set overnight will accomplish the same result.

To prepare the phosphate buffer, a 20-m*M* Na_2HPO_4 solution was prepared and adjusted to the appropriate pH with either concentrated H_3PO_4 or NaOH solution. To prepare the phosphate/sodium chloride buffer, a 20-m*M* Na_2HPO_4/50-m*M* NaCl solution was prepared and adjusted to the appropriate pH with either a concentrated H_3PO_4 or NaOH solution. To prepare the 50-m*M* SDS solution, a 20-m*M* Na_2HPO_4/50-m*M* SDS solution was prepared and adjusted to the appropriate pH using concentrated H_3PO_4 or NaOH solution.

3.3. Instrumentation

The data were collected using a Beckman Model 2100 Capillary Electrophoresis Instrument (Palo Alto, CA) attached to a 33-MHz 386 computer. The data were collected at a wavelength of 254 nm and processed and manipulated by Beckman's data acquisition software. The column was constructed from a 50-μm I.D. fused-silica capillary with a total length of 47 cm. The detection window was 7 cm from the outlet end, yielding a separation length of 40 cm. For the analysis of solutes the applied voltage was 17.5 kV and the electric field gradient was 372 V/cm. The analysis times varied, depending on the migration of the compounds of interest. Injections were performed hydrostatically for 2 s.

Calculations and LSER studies were performed on a Compaq Presario 50-MHz 486 computer using either Microsoft's Excel (Redmond, WA) or Addison-Wesley's Minitab (Reading, MA) software. The Minitab software identified solutes considered outliers in the multivariable relationships. Outliers were defined as solutes with a standardized residual (the residual divided by the standard deviation of the residual) being greater than two.

3.4. Critical micelle concentration (CMC) determination — surface tension measurements

A set of solutions was prepared using 100 m*M* of the surfactant mixture in 20-m*M* sodium phosphate buffer as stock solution. A Model 21 Tensiomat from Fisher Scientific (Pittsburgh, PA) was used to measure the surface tension of the solutions; each solution was measured four times and the results were averaged. The resulting average was plotted against the concentration and the CMC was determined from the change in slope.

3.5. Ohm's law determination

To determine the applied voltage range for the surfactant systems, current was measured from 1 to 30 kV and plotted. When the curve of current versus voltage began to deviate, this point described the highest applied voltage for the system. We ramped the voltage for each solution three times, collecting current data for each ramp. The current was averaged for each applied voltage and plotted against the applied voltage.

4. Results and discussion

4.1. CMC determination

We determined the CMC for solutions of the mixed surfactants by surface tension measurements. Plotting both surface tension versus concentration and surface tension versus log of concentration, we determined the CMC for the 90/10 surfactant mixture and the 80/20 surfactant mixture, and these values are listed in Table 2. The values for both mixed micelle systems are identical, within experimental error, and are significantly lower than the CMC of pure SDS.

4.2. Ohm's law study of mixed micelle solutions

We performed an Ohm's law study to determine the maximum applied voltage the solution can withstand without adverse effects due to Joule heating. The results, shown in Fig. 1, indicate a slight decrease in the current was noticeable as the amount of decanol added to solution was increased. We assume that the decanol remains with the micelle or with smaller aggregates of SDS since the apparent conductivity of the solution does not change. However, the mixed micelle systems were found to be less conductive and able to withstand higher field strength than the pure SDS solution. The maximum applied electric field for the pure SDS solution was found to be 17.5 kV, or applied field strength of 372 V/cm. The maximum applied field for the 90/10 surfactant mixture was determined to be 17.9 kV (381 V/cm) and 18.9 kV (402 V/cm) for the 80/20 surfactant mixture. For all three of the solutions tested, the cooling system of our instrument cannot compensate for Joule heating effects after 20 kV (425 V/cm).

4.3. LSER study on mixed micelles

In the LSER equation, the migration factor (k'_m) is followed by a number in parentheses, which describes the percentage of SDS present out of the total amount of surfactant added. For example, k'_m (90) is the migration factor measured in 90 mol% SDS and 10 mol% decanol, also designated as a 90/10 surfactant mixture. We determined migration factors according to Eq. (2) for the solutes listed in Table 1 using decanophenone as the micelle marker. The results are listed in Table 3. The solutes that migrated after or co-migrated with decanophenone were excluded from the LSER study. For pure SDS solution the following were excluded: fluoranthene, pyrene, diphenylmethane, and *t*-butylbenzene. In the 90/10 mixture, we excluded 1,2,4,5-tetrabromobenzene and perylene and in the 80/20 mixture, we excluded fluoranthene, chrysene, 1,2,4,5-tetrabromobenzene, 1,3,5-tribromobenzene, and perylene. Table 4 contains the results of the LSER study for each of

Table 2
Results of CMC determinations and selected literature values

Solution	Method	Result (m*M*)
(90/10) SDS/decanol	Surface tension	0.460±0.05
(90/10) SDS/decanol	Surface tension (Log[γ])	0.810±0.5
(80/20) SDS/decanol	Surface tension	0.357±0.02
(80/20) SDS/decanol	Surface tension (Log[γ])	0.612±0.7
SDS in 20 m*M* phosphate	Conductance	2.9±0.02 [44]
SDS in 50 m*M* phosphate/100 m*M* borate	Conductance	2.9[a] [45]

[a] Error for this value was not reported.

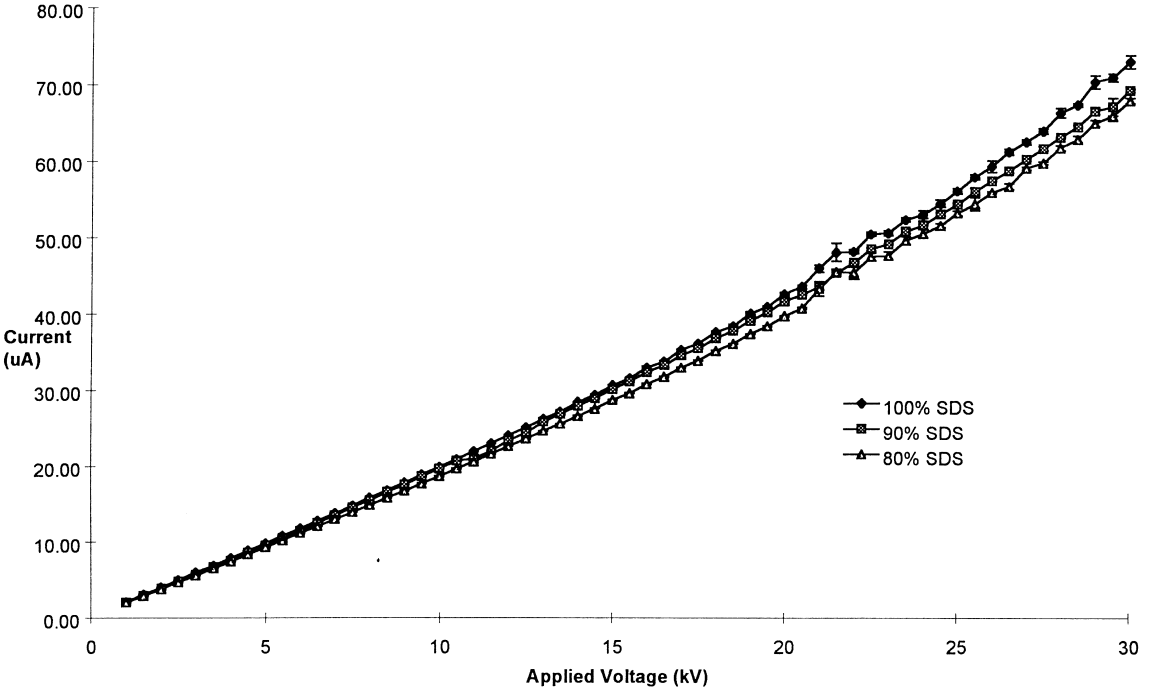

Fig. 1. Plot of current versus voltage.

the surfactant mixtures and for octanol/water partitioning.

The LSER relationships described in Eqs. (5) and (6) (Table 4) are consistent with other published results [23,25,28,29]. The most important driving force in octanol/water partitioning is the cavity term for the octanol phase and hydrogen bond basicity for the aqueous phase. In micelle/water partitioning with pure SDS, the driving forces are similar, but the coefficients are distinctly smaller for the cavity and β terms. The observed trend for the surfactant mixtures is an overall increase in the cavity term when decanol is added to the SDS. There is also a general decrease with respect to the aqueous phase for hydrogen bond acidity and an increase in hydrogen bond basicity with respect to the micellar phase. These trends were expected, although the apparent variability of the cavity term was unexpected. Also, the regression coefficient increases as the decanol concentration increases.

Does the correlation between micelle/water partitioning and octanol/water partitioning increase when the LSER shows a closer relationship between the two systems? To answer this question, we looked at the relationship between log k'_m of the different surfactant systems and log K_{ow}. The equations below describe the relationship between log k'_m in each surfactant system to log K_{ow}. The outliers for Eq. (9) are *p*-cresol, *m*-cresol, chrysene, perylene, and diethyl phthalate. For Eq. (10), the outliers include *p*-cresol, *m*-cresol, fluoranthene, and chrysene. The outliers for Eq. (11) are *m*-cresol, *p*-cresol and pyrene.

$$\text{Log } k'_m\,(100) = 0.592(0.051)\log K_{ow} - 0.766(0.160): \quad r^2 = 0.765,\ n = 44 \tag{9}$$

$$\text{Log } k'_m\,(90) = 0.708(0.047)\log K_{ow} - 1.105(0.150): \quad r^2 = 0.836,\ n = 46 \tag{10}$$

$$\text{Log } k'_m\,(80) = 0.678(0.049)\log K_{ow} - 1.076(0.146): \quad r^2 = 0.825,\ n = 43 \tag{11}$$

When we compare the correlation of micelle/water partitioning to octanol/water partitioning, we find a

Table 3
Log of migration factor in each surfactant solution

Solute #	Compound	Log k'_m (100)	Log k'_m (90)	Log k'_m (80)
1	Benzene	0.075	0.047	0.012
2	Toluene	0.509	0.479	0.470
3	Ethylbenzene	0.925	0.838	0.870
4	*n*-Propylbenzene	1.344	1.480	1.490
5	*n*-Butylbenzene	1.754	1.847	1.884
6	*m*-Dichlorobenzene	1.186	1.239	1.079
7	Nitrobenzene	0.179	0.132	0.068
8	Acetophenone	0.316	0.229	0.138
9	4-Chloronitrobenzene	0.585	0.502	0.485
10	Benzoic acid	0.381	0.356	0.381
11	*p*-Cresol	0.154	0.145	0.154
12	*m*-Cresol	0.179	0.096	0.048
13	Phenol	−0.196	−0.288	−0.282
14	*p*-Chlorophenol	0.455	0.410	0.442
15	Naphthalene	1.285	1.170	1.206
16	Anthracene	2.935	2.534	2.216
17	Phenanthrene	1.622	2.266	1.934
18	Biphenyl	1.721	1.655	1.608
19	Pyridine	−0.409	−0.460	−0.588
20	1,4-Dibromobenzene	1.362	1.381	1.331
21	1,3,5-Tribromobenzene	2.128	2.296	N/A
22	1,2,4,5-Tetrabromobenzene	1.856	N/A	N/A
23	1,4-Dichlorobenzene	1.060	1.063	1.051
24	4-Nitroaniline	0.147	0.071	−0.038
25	3-Nitroaniline	0.369	0.316	0.264
26	4-Nitrophenol	0.215	0.187	0.148
27	*p*-Chlorobenzoic acid	0.280	0.283	0.337
28	Aniline	−0.238	−0.287	−0.339
29	*p*-Toluidine	0.328	0.243	0.262
30	1-Methylnaphthalene	1.670	1.532	1.566
31	Quinoline	0.716	0.641	0.510
32	Isoquinoline	0.929	0.873	0.749
33	Acenaphthene	1.849	1.771	1.697
34	Fluoranthene	N/A	3.627	N/A
35	Fluorene	2.006	1.931	2.007
36	Pyrene	N/A	2.638	2.955
37	Chrysene	2.302	3.011	N/A
38	Perylene	3.238	N/A	N/A
39	Diphenylmethane	N/A	1.931	2.329
40	*t*-Butylbenzene	N/A	1.538	1.846
41	*o*-Dichlorobenzene	1.092	1.153	1.084
42	Dimethyl phthalate	0.699	0.625	0.506
43	Diethyl phthalate	1.698	1.269	1.211
44	Methyl benzoate	0.641	0.551	0.502
45	Ethyl benzoate	1.043	0.929	0.860
46	Fluorobenzene	0.142	0.140	0.115
47	*N*,*N*-Dimethylaniline	1.240	0.483	0.421
48	*p*-Toluic acid	0.296	0.267	0.293

N/A indicates that the log of migration factor was undefined ($k'_m < 0$).

Table 4
LSER equations using decanophenone as a micelle marker (SD)

Equation #		Intercept	*m*	*s*	*B*	*a*	*n*	r^2	Outliers
5	Log K_{ow}	0.655 (0.269)	4.931 (0.272)	−0.646 (0.293)	−3.548 (0.262)	0.129 (0.199)	48	0.936	11,12,32
6	Log k'_m (100)	−1.269 (0.231)	3.568 (0.235)	−0.101 (0.252)	−1.249 (0.213)	−0.506 (0.160)	44	0.905	16
7	Log k'_m (90)	−1.664 (0.227)	4.255 (0.240)	−0.119 (0.231)	−1.734 (0.210)	−0.369 (0.157)	46	0.926	32,34,43
8	Log k'_m (80)	−1.599 (0.191)	4.119 (0.217)	−0.131 (0.184)	−1.779 (0.172)	−0.300 (0.125)	43	0.938	32,43

better correlation with the mixed micelle systems than with pure SDS, and fewer outliers.

5. Comparison of mixed surfactant systems using identical solute lists

In Table 4, each LSER study was performed using as many compounds as possible, with 48 as the maximum number of solutes. However, since a few solutes migrated with or after decanophenone, another LSER study was performed using an abbreviated solute list. All the solutes from Table 3 were used in this phase of our study except for 1,3,5-tribromobenzene, 1,2,4,5-tetrabromobenzene, fluoranthene, pyrene, chrysene, perylene, diphenylmethane, and *t*-butylbenzene. Table 5 shows the results of the LSER calculations.

As a function of increasing decanol concentration, the α term decreases with respect to the aqueous phase while β and π terms increase. The cavity term remains statistically constant as a function of decanol concentration. The regression coefficient still increases as a function of decanol concentration. Comparing the LSER studies described in Table 5 to the LSER results in Table 4, the coefficients for V_1 and π decrease but the others can be considered unchanged. The decrease in V_1 and π can be explained as we eliminated eight solutes that were large and contained aromatic rings.

As shown below, the correlation of the migration factors from the different surfactant mixtures with octanol/water partition coefficients shows an interesting trend. As we increase the amount of decanol in the mixture, the regression coefficient of the correlation increases. For all three relationships, the common outliers are *p*-cresol and *m*-cresol. For Eq. (16), anthracene and diethyl phthalate are also included as outliers. Anthracene is an additional outlier for Eq. (17) and diethyl phthalate is an additional outlier for Eq. (18).

$$\text{Log } k'_m\,(100) = 0.588(0.065)\log K_{ow} - 0.756(0.186): \quad r^2 = 0.682,\ n = 40 \tag{16}$$

$$\text{Log } k'_m\,(90) = 0.627(0.055)\log K_{ow} - 0.922(0.156): \quad r^2 = 0.775,\ n = 40 \tag{17}$$

$$\text{Log } k'_m\,(80) = 0.620(0.050)\log K_{ow} - 0.951(0.142): \quad r^2 = 0.803,\ n = 40 \tag{18}$$

Table 5
LSER equations using the abbreviated solute list (SD)

Equation #		Intercept	*m*	*s*	*b*	*a*	*n*	r^2	Outliers
12	Log K_{ow}	0.721 (0.361)	4.711 (0.414)	−0.537 (0.333)	−3.538 (0.299)	0.108 (0.212)	40	0.888	11,12
13	Log k'_m (100)	−1.543 (0.257)	3.978 (0.295)	−0.084 (0.237)	−1.349 (0.213)	−0.469 (0.151)	40	0.888	16,17,32
14	Log k'_m (90)	−1.530 (0.223)	3.953 (0.256)	−0.047 (0.206)	−1.661 (0.185)	−0.401 (0.131)	40	0.916	16,32
15	Log k'_m (80)	−1.441 (0.207)	3.868 (0.237)	−0.142 (0.191)	−1.709 (0.171)	−0.311 (0.121)	40	0.923	32
19	Log k'_m (100)	−0.422 (0.180)	2.089 (0.182)	−0.184 (0.196)	−0.862 (0.175)	−0.465 (0.133)	48	0.855	38
20	Log k'_m (90)	−1.040 (0.168)	3.148 (0.175)	−0.098 (0.171)	−1.452 (0.153)	−0.400 (0.116)	47	0.934	32
21	Log k'_m (80)	−1.157 (0.159)	3.451 (0.161)	−0.203 (0.174)	−1.644 (0.155)	−0.297 (0.118)	48	0.948	32
26	Log k'_m (100)	−0.375 (0.280)	1.838 (0.285)	−0.065 (0.309)	−0.933 (0.272)	−1.212 (0.237)	46	0.766	48
27	Log k'_m (90)	−0.952 (0.404)	2.606 (0.422)	−0.431 (0.415)	−1.575 (0.369)	−1.707 (0.295)	46	0.783	14,27,48
28	Log k'_m (80)	−1.117 (0.291)	3.099 (0.295)	−0.176 (0.319)	−1.737 (0.284)	−1.289 (0.227)	47	0.872	14,27,48

Table 6
List of electrophoretic mobilities of micelle markers (cm^2/Vmin)

Micelle marker	100% SDS	90% SDS	80% SDS
Decanophenone	−0.02194±0.00003	−0.02237±0.00006	−0.02194±0.00010
Yellow AB	−0.02261±0.00005	−0.02230±0.00009	−0.02214±0.00008
Orange OT	−0.02190±0.00003	−0.02245±0.00006	−0.02188±0.00003

5.1. LSER studies using different micelle markers

Along with the 48 solutes, we investigated three compounds for their suitability as micelle markers; decanophenone, Yellow AB, and Orange OT. Orange OT migrated faster than decanophenone and Yellow AB, as shown in Table 6. Yellow AB migrated with decanophenone within experimental error. However, if you compare only the absolute values of the electrophoretic mobilities, Yellow AB was consistently higher than decanophenone. Using Yellow AB as the micelle marker, we revisited the LSER relationship of our solutions, except for the 90/10 surfactant mixture. The compound with the highest electrophoretic mobility was perylene ($\mu = -0.02256$ cm^2/Vmin). Therefore for the solutes analyzed in 90/10 surfactant mixture, we recalculated all of our migration factors using perylene as the micelle marker. These results of the calculations of k'_m are described in Table 7 and results of LSER studies are described in Table 8.

Notice the dramatic decrease in the cavity and hydrogen bond donating term for the pure SDS solution. There was also a slight increase with the polarizability term and a small decrease with the hydrogen bond accepting term. It is clear that proper choice of a micelle marker is essential for accurate determination of LSER coefficients. The differences between the data shown in Table 8 and the equations in Tables 4 and 6 are the decrease of the cavity, α and β terms and an increase in the polarizability term. This change in cavity term is not as large as with the SDS solution. The important trend we noticed was as we increased the amount of decanol in the surfactant solution, the cavity term increases and the hydrogen bond basicity term becomes more negative. This is significant since these terms are large in the LSER for octanol/water partitioning. The LSER equation determined for the 80/20 surfactant mixture is closest to the LSER equation determined for octanol/water partitioning.

The results of the relationships of log K_{ow} with log k'_m from each surfactant solution are described below. The outliers for each equation were *p*-cresol, *m*-cresol, and diethyl phthalate.

$$\text{Log } k'_m\,(100) = 0.382(0.033)\log K_{ow} - 0.391(0.109): \quad r^2 = 0.745,\ n = 48 \tag{22}$$

$$\text{Log } k'_m\,(90) = 0.550(0.035)\log K_{ow} - 0.781(0.113): \quad r^2 = 0.846,\ n = 47 \tag{23}$$

$$\text{Log } k'_m\,(80) = 0.617(0.033)\log K_{ow} - 0.975(0.109): \quad r^2 = 0.825,\ n = 48 \tag{24}$$

Comparing the three correlations, the best correlation is with the 90/10 surfactant mixture. The slight, unexpected decrease of the regression coefficient in the 80/20 surfactant mixture may be explained by the outliers that are present in the relationship.

5.2. Removal of p- and m-cresol from the relationship between log k'_m and log K_{ow}

In every comparison of log k'_m to log K_{ow}, the only consistent outliers were *p*-cresol and *m*-cresol. These two compounds are also outliers in the LSER study for octanol/water partitioning. One possible explanation is poor accuracy of the literature log K_{ow} values for *p*-cresol and *m*-cresol. The log K_{ow} for the cresols are ~3.1 while similar compounds have lower log K_{ow} values, i.e. phenol has a log K_{ow} of 1.46 and *p*-chlorophenol has a log K_{ow} of 2.39. We eliminated the two cresols from our solute list and reviewed the correlation of log k'_m in the 80/20 surfactant mixture with log K_{ow}. The resulting correlation is shown in Fig. 2. The regression

Table 7
Migration factors determined by either Yellow AB or perylene

Solute #	Compound	Log k'_m (100)	Log k'_m (90)	Log k'_m (80)
1	Benzene	0.075	0.039	0.004
2	Toluene	0.456	0.464	0.454
3	Ethylbenzene	0.815	0.809	0.837
4	*n*-Propylbenzene	1.111	1.376	1.376
5	*m*-Butylbenzene	1.311	1.638	1.647
6	*m*-Dichlorobenzene	1.009	1.175	1.029
7	Nitrobenzene	0.147	0.123	0.059
8	Acetophenone	0.277	0.219	0.128
9	4-Chloronitrobenzene	0.525	0.487	0.469
10	Benzoic acid	0.338	0.344	0.367
11	*p*-Cresol	0.123	0.136	0.145
12	*m*-Cresol	0.147	0.087	0.039
13	Phenol	−0.218	−0.294	−0.288
14	*p*-Chlorophenol	0.406	0.397	0.427
15	Naphthalene	1.075	1.114	1.141
16	Anthracene	1.496	1.935	1.810
17	Phenanthrene	1.257	1.850	1.675
18	Biphenyl	1.299	1.509	1.466
19	Pyridine	−0.427	−0.465	−0.593
20	1,4-Dibromobenzene	1.122	1.295	1.248
21	1,3,5-Tribromobenzene	1.416	1.861	2.115
22	1,2,4,5-Tetrabromobenzene	1.346	2.428	2.535
23	1,4-Dichlorobenzene	0.920	1.018	1.004
24	4-Nitroaniline	0.116	0.063	−0.046
25	3-Nitroaniline	0.326	0.305	0.253
26	4-Nitrophenol	0.182	0.177	0.138
27	*p*-Chlorobenzoic acid	0.242	0.272	0.324
28	Aniline	−0.258	−0.292	−0.345
29	*p*-Toluidine	0.288	0.233	0.251
30	1-Methylnaphthalene	1.278	1.416	1.434
31	Quinoline	0.640	0.621	0.493
32	Isoquinoline	0.818	0.843	0.723
33	Acenaphthene	1.344	1.589	1.528
34	Fluoranthene	1.542	2.050	2.633
35	Fluorene	1.389	1.689	1.715
36	Pyrene	1.530	1.959	1.980
37	Chrysene	1.446	2.016	2.361
38	Perylene	1.505	–[a]	2.838
39	Diphenylmethane	1.585	1.688	1.851
40	*t*-Butylbenzene	1.519	1.422	1.624
41	*o*-Dichlorobenzene	0.943	1.099	1.034
42	Dimethyl phthalate	0.625	0.606	0.489
43	Diethyl phthalate	1.290	1.201	1.146
44	Methyl benzoate	0.575	0.534	0.485
45	Ethyl benzoate	0.906	0.895	0.828
46	Fluorobenzene	0.112	0.131	0.106
47	*N,N*-Dimethylaniline	1.046	0.468	0.407
48	*p*-Toluic acid	0.258	0.256	0.281

[a] For the 90% SDS solution, the micelle marker was perylene.

Table 8
LSER equations using alternate micelle markers (SD)

Equation #		Intercept	*m*	*s*	*b*	*a*	*n*	r^2	Outliers
19	Log k'_m (100)	−0.422 (0.180)	2.089 (0.182)	−0.184 (0.196)	−0.862 (0.175)	−0.465 (0.133)	48	0.855	38
20	Log k'_m (90)	−1.040 (0.168)	3.148 (0.175)	−0.098 (0.171)	−1.452 (0.153)	−0.400 (0.116)	47	0.934	32
21	Log k'_m (80)	−1.157 (0.159)	3.451 (0.161)	−0.203 (0.174)	−1.644 (0.155)	−0.297 (0.118)	48	0.948	32

coefficient has improved to 0.932, while covering almost seven orders of magnitude in K_{ow}. This 80/20 molar ratio of SDS/decanol is an easily prepared mobile phase, which appears to provide an excellent model for octanol/water partitioning.

6. Conclusions

The SDS/decanol mixed micelle system shows great promise in estimating octanol/water partition coefficients. The LSER studies indicate as we increase the alcohol content of the system, the closer we get to accurately modeling octanol/water partitioning. However, a disadvantage to using decanol in the mixed micelle system is the limited amount of decanol we can add. The 70/30 mixture is very opaque at room temperature and slowly precipitates. The mixed micelle system was shown to endure a larger electric field gradient than pure SDS solution. Also, with a lower CMC for the mixed surfactant solutions, we can use lower concentrations of total surfactant.

Choosing the appropriate micelle marker is crucial for LSER studies of MEKC systems. The difference in the electrophoretic mobility between decanophenone and Yellow AB was 3% in pure SDS, 0.9% in 90/10 surfactant mixture and 0.8% for the 80/20 surfactant mixture. The higher the difference, the more dramatic the coefficients change. However, the percent difference is within the peak width of the solutes in question, so if these solutes were analyzed together, they would be judged to co-migrate. The appropriate micelle marker for this study was

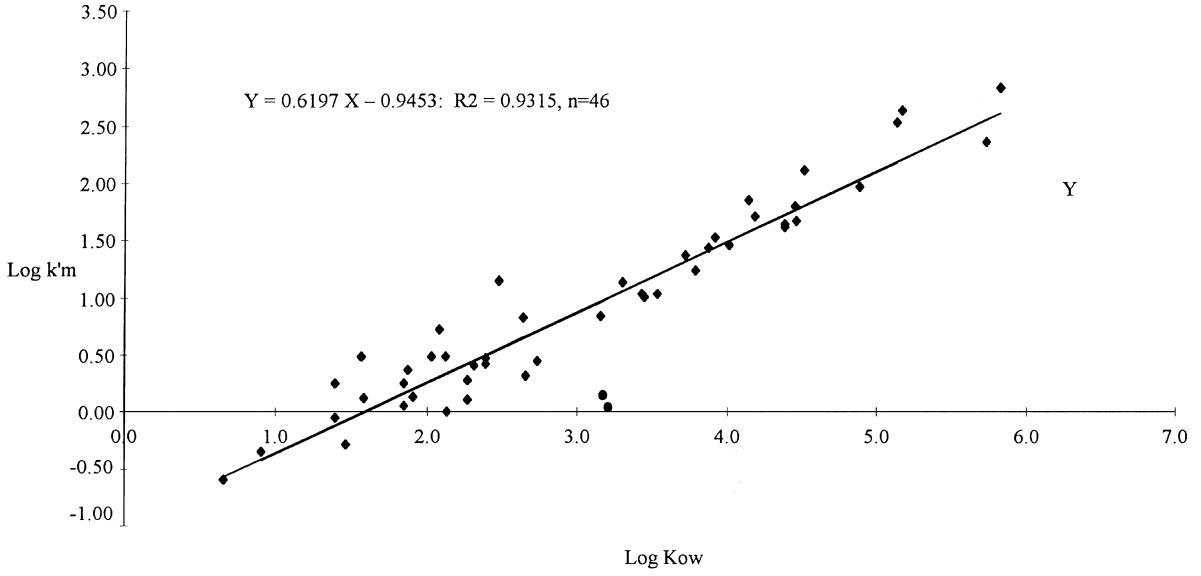

Fig. 2. Plot of log k'_m versus log K_{ow} in 80/20 surfactant mixture with *p*- and *m*-cresol excluded. *p*- and *m*-Cresol are shown on plot as solid circles.

perylene for 100% SDS and the 80/20 SDS/decanol molar ratio and Yellow AB for the 90% SDS/decanol solution.

There is a concern that the regression coefficients are lower than some of the published results. One source of variability is due to the nature of MEKC. The magnitude of percent error is related to the migration time of the solute relative to the migration time of the micelle marker. If the solute migrates through the column at or near the migration time of the micelle marker, the error is relatively higher. This relationship is inherent to the calculation of migration factors not due to the measurement of migration times [19]. Also, another source of error is contributed by the lower number of solutes used in this study and the type of compounds used for this study. Since the LSER equations are highly dependent on solute number and the solutes themselves, a comparison between different studies should be done with caution.

As we increased the amount of decanol in the surfactant solution, the LSER equation better mimics the LSER for octanol/water partitioning. Also, the correlation between octanol/water partitioning and partitioning in the mixed micelle system improves as the amount of decanol is increased.

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