A comparative study of partition coefficients determined by sorption and by liquid chromatography in alcohol–water–cellulose acetate systems

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Partition coefficients obtained from liquid chromatography are compared to those obtained from equilibrium sorption experiments for various alcohol–water–cellulose acetate systems. In the liquid chromatography experiments cellulose acetate powder was used as the stationary phase with water as the mobile phase and alcohols injected into the mobile phase. In the equilibrium sorption experiments, cellulose acetate power was equilibrated with an alcohol–water solution. The distribution coefficients determined using liquid chromatography and those determined using liquid phase sorption exhibit similar trends with changing solute structure. However, the chromatographic distribution coefficients are, in general, smaller than the equilibrium distribution coefficients. This discrepancy is attributed to the fact that equilibrium is not attained in the chromatographic column. The fact that the distribution coefficients are in reasonable agreement indicates that while the kinetics of diffusion prevent a true equilibrium distribution coefficient from being obtained from the chromatography column, the results of the chromatographic experiments give a qualitative representation of the affinity of the polymer phase for each solute.

(Keywords: cellulose acetate; partition coefficients; liquid chromatography)

Introduction

Water/cellulose acetate partition coefficients of organic compounds are of interest in membrane science as they figure prominently in the description of membrane separations through transport models. For example, the widely applied 'solution–diffusion' model of membrane transport contains the solute/solvent partition coefficient, k, defined as[1]:

$$k = \frac{\text{g solute/cm}^3 \text{ membrane phase}}{\text{g solute/cm}^3 \text{ solution}} \quad (1)$$

Other transport models, including the 'finely-porous' model[2], and the 'preferential sorption–capillary flow' model[3] contain similar parameters describing the distribution of a solute between solvent and membrane.

Liquid chromatography (l.c.) partition coefficients for organic–water–cellulose acetate systems[4–9] determined from chromatographic experiments have been applied to the analysis of membrane separations using cellulose acetate films[10–12]. For this type of analysis to be valid, the partition coefficients determined by l.c. and defined by the relation

$$K_{LC} = \frac{\text{g solute/cm}^3 \text{ stationary phase}}{\text{g solute/cm}^3 \text{ mobile phase}} \quad (2)$$

must satisfy two criteria. First, the chromatographic distribution coefficients must represent equilibrium values as do the partition coefficients used in membrane transport models. Second, the compositions of the membrane and the stationary phase must be equivalent. This requirement presents additional experimental difficulties since it is often difficult to determine accurately the makeup of the active layer of an integrally skinned membrane. Previous work (see, for example references 10 to 12) has not definitely established the link between the l.c. column and the membrane separation module on either point. In this work, only the question of equilibrium is examined.

Theory

The equation relating the retention volume of a solute in a chromatography column, V_R, to the column void volume, V_O (the volume of solvent in intra- and interparticle spaces), and the volume of the stationary phase, V_S, is generally given as[13]:

$$V_R = V_O + K_{LC} V_S \quad (3)$$

Equation (3) relates the chromatographic system parameters V_S and V_O to the experimental quantity V_R and the chromatographic distribution coefficient K_{LC}. The derivation of this equation is based on the following assumptions[14]:

1. K_{LC} is a constant everywhere in the column;
2. an equilibrium distribution of solute between the mobile and stationary phases is rapidly established;
3. plug flow exists in the column; and
4. the sample is introduced as a thin plug.

Since liquid chromatography involves the movement of solute molecules between a mobile phase and a stationary phase, the data obtained from solute interaction studies based on chromatography may not represent true equilibrium if the time required for this movement between phases is long compared to the sample elution time (i.e. assumption 2 above is false). One technique that can be used to test the equilibrium assumption is direct

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measurement of the equilibrium partition coefficient, K, defined as:

$$K = \frac{\text{g solute/cm}^3 \text{ polymer phase}}{\text{g solute/cm}^3 \text{ solution phase}} \quad (4)$$

Equations (2) and (4) each define a distribution coefficient as the ratio of the equilibrium concentration of a solute in a binary (solute–solvent) phase to the equilibrium concentration of a solute in a ternary (solute–solvent–polymer) phase. Thus, if equilibrium has been established in the chromatography column, and the 'stationary phase' and 'polymer phase' are identical in composition, these two equations are equivalent and $K = K_{LC}$.

One common method used to measure equilibrium partition coefficients is liquid phase sorption. In liquid phase sorption experiments, known amounts of solvent, solute and polymer are placed in a sealed container and allowed to equilibrate for a period of time that is long compared to the time required for diffusion of the solute from the solution phase into the polymer phase. The concentration of solute in the solution phase is then determined. The equilibrium solute distribution coefficient can be calculated using the relationship[15]:

$$K = \frac{(n_2/C_2^{\alpha}) - V^{\alpha}}{V^{\beta}} \quad (5)$$

where n_2 is the total number of moles of solute in the system, C_2^{α} is the final solute concentration in the solution phase, V^{α} is the volume of the solution phase, and V^{β} is the volume of the polymer phase.

In this work, the polymer used as the stationary phase in the chromatography column and that used in the liquid phase sorption experiments were identical. In both cases, the polymer phase was defined as the polymer itself plus a small amount of closely associated water, in accordance with recent infra-red[16,17] and Raman[18] spectroscopy results.

The amount of water associated with the polymer (0.195 g water/g polymer) was estimated from water vapour sorption experiments[19]. Using this result, the swollen polymer density can be estimated from pure component densities. The value obtained using this definition is 1.233 g cm^{-3} for the polymer phase. This result is in good agreement with the density of 1.25 g cm^{-3} reported for water-swollen membranes[20].

Equilibration experiments

Polymer preparation. Cellulose acetate CA-398-3 of reported[21] average acetyl content 39.8 wt% and specific gravity 1.31 was obtained in powdered form from Eastman Chemical Products, Inc. To minimize the effect of particle size distribution, the polymer powder was sieved using Tyler sieves of 325 and 400 mesh to yield powder in the particle size range 38–45 μm. The dry, sieved powder was stored at room temperature in a flask sealed with Parafilm.

Experimental procedure. Equilibrium polymer–water partition coefficients were determined using the classical sorption method[15]. For each solute examined, a polymer sample weighing approximately 6 g was placed in a 150 ml crimp-top vial. This vial was then filled with approximately 140 g of water, and sealed with a Mininert valve (Alltech Associates). These sample vials were shaken vigorously, then left undisturbed in a controlled atmosphere chamber at 25°C overnight to allow the polymer and water to equilibrate.

After equilibration, a weighed amount of pure solute was syringed into each sample vial. Sufficient solute was added to yield a concentration of 0.05 mol% in the solution phase. The amount of solute used was determined from the equation:

$$M_S = \frac{M_W^1 - M_W^2}{0.9995} \quad (6)$$

where M_S is the number of moles of solute to be added, M_W^1 is the number of moles of water added initially, and M_W^2 is the number of moles of water sorbed by the polymer. This was taken to be 0.0108 mol water per gram of polymer present (0.195 g H_2O/g polymer) as determined previously[19].

Each solute was tested in duplicate. Additionally, control vials containing 0.05 mol% solution with no polymer, as well as polymer and water with no solute were prepared to check for loss of solute and emergence of confounding impurities, respectively. The sample vials were allowed to equilibrate for 72 h at 25°C in a controlled temperature room with occasional agitation.

After the vials had equilibrated, each bottle was reweighed to check for loss of sample through evaporation. No changes in weight were detected for any of the samples tested.

Sample analysis. For the normal and isomeric alcohols, 1,2-propanediol and 1,3-propanediol, solution concentrations were analysed by gas chromatography (g.c.). For the heavier glycols, concentration changes were determined using a refractive index detector (Waters R401). The gas chromatograph and refractive index detector were calibrated using standards prepared in the laboratory, and the equilibrium sample concentrations were determined from the resulting calibration curves.

Analyses were carried out by syringing samples directly from the sample vials. For the g.c. analyses, 10 samples of 1 μl each were required. For refractive index analyses, 10 samples of 5 μl each were needed. Analyses were made at the end of successive 72 h periods until the solution concentration achieved a steady value; typically, two or three analyses were required. Thus, the volume of solution removed for analysis was small in relation to the total solution volume.

The control vials showed no significant loss of solute or evolution of impurities during the course of the experiments.

Chromatography experiments

Experimental details of this work have been reported previously[19]. Briefly, cellulose acetate polymer identical to that used in the equilibrium experiments described above was used as the stationary phase in an l.c. column. Purified water was used as the mobile phase. Solutions of the solutes listed in *Table 1* were injected into the column, and elution times were recorded. The chromatographic partition coefficients, K_{LC}, listed in *Table 1* were calculated from the solute retention times.

Results and discussion

Average values of the equilibrium distribution coefficients of 17 solutes are shown in *Table 1* together

Table 1 Distribution coefficients determined by equilibrium liquid phase sorption studies and liquid chromatography

Solute	K	K_{LC}
Methanol	0.283	0.315
Ethanol	0.640	0.407
1-Propanol	1.033	0.794
1-Butanol	1.799	1.658
1-Pentanol	4.159	3.655
2-Propanol	0.709	0.540
2-Methyl-2-propanol	0.771	0.606
3-Methyl-1-butanol	2.993	3.116
Cyclopentanol	1.944	1.689
1,2-Propanediol	1.000	0.175
1,3-Propanediol	0.990	0.175
1,4-Butanediol	0.975	0.216
1,6-Hexanediol	0.754	0.502
1,2,3-Propanetriol	0.094	0.079
1,2,4-Butanetriol	0.115	0.079
1,2,6-Trihydroxyhexane	0.354	0.134
Erythritol	0.134	0.043

with their corresponding chromatographic distribution coefficients[19]. For the solution equilibration experiments, duplicate determinations generally agreed within 10% or less. Londsale *et al.*[22] have reported a distribution coefficient of 0.097 for 1,2,3-propanetriol using a homogeneous cellulose acetate membrane, in good agreement with the value of 0.094 obtained here using liquid phase sorption.

The distribution coefficients determined using l.c. and those determined using liquid phase sorption exhibit similar trends with changing solute structure. With the exception of the diols, the distribution coefficients increase with increasing hydrocarbon chain length, decrease with increasing hydroxyl substitution, and decrease with increased main chain branching. However, the chromatographic distribution coefficients are, in general, smaller than the equilibrium distribution coefficients obtained from liquid phase sorption experiments. An understanding of this result may be obtained by examining the diffusion of solutes from the aqueous phase into the polymer phase.

If a solute does not penetrate the entire volume of the stationary phase in the chromatography column, the retention volume for that solute will be smaller than the true equilibrium value. Thus, the equation

$$K_{LC}=\frac{(V_R-V_O)}{V_S} \tag{7}$$

yields a chromatographic distribution coefficient that is smaller than the equilibrium value. To determine whether this may have occurred in the chromatography column used in these experiments, we must estimate the solute contact time required for the solute concentration at the centre of a polymer particle to approach the external solution concentration.

For diffusion into a sphere of radius a, initially containing no solute, from an external medium at constant concentration C_O, Crank[23] gives:

$$\frac{C}{C_O}=1+2\sum_{n=1}^{\infty}(-1)^n\exp\left(\frac{-Dn^2\pi^2t}{a^2}\right) \tag{8}$$

where C is the concentration at the centre of the sphere ($r=0$), D is the solute diffusion coefficient in the sphere and t is time. Crank also shows that for C to approach C_O (i.e. the ratio to approach 1), the value of the characteristic dimension (Dt/a^2) should be greater than approximately 0.5.

Using this value as a guide, the approximate equilibration time can be estimated by taking the radius of a polymer particle to be 2×10^{-3} cm, and the diffusion coefficient of 1,2,3-propanetriol in cellulose acetate to be 3.2×10^{-9} cm^2 s^{-1}, as determined by Lonsdale *et al.*[22]. This calculation gives an equilibration time of 625 s or approximately 10.4 min at the centre of the sphere. That is, a contact time of approximately 10.4 min is required for the 1,2,3-propanetriol concentration at the centre of a non-porous cellulose acetate particle of 20 μm radius to approach that of the surrounding solution.

Turning to the chromatography column, the contact time of this solute with a single particle of the stationary phase can now be estimated. The measured elution volume for 1,2,3-propanetriol (a weakly retained solute) was approximately 3.55 ml. At a nominal mobile phase flowrate of 0.8 ml min^{-1}, this translates to a linear sample velocity of 6.76 cm min^{-1} through the 30 cm chromatography column. If the fractional volume occupied by the column packing is considered, a 100 μl sample injection would fill a 0.88 cm long cylinder in the column (the column diameter was 0.46 cm, and the packing fraction approximately 0.68). Thus, the sample plug would contact a single point in the column for 0.13 min (7.8 s).

Calculations for 1-pentanol (a strongly retained solute) under similar flow conditions, result in an estimated contact time of 0.39 min (23.2 s). Here, the solute elution volume was 10.54 ml, and the linear sample velocity was 2.28 cm min^{-1}.

The contact time allowed in the chromatography column for 1,2,3-propanetriol represents approximately 1% of the time required for equilibration according to the previous calculation. Assuming the diffusion coefficient of 1-pentanol in a water-swollen cellulose acetate matrix is of the same order of magnitude as 1,2,3-propanetriol, the calculated contact time for that solute could represent between 4 and 10% of the total time required for equilibration.

Clearly, the measured distribution coefficients listed in *Table 1* and plotted in *Figure 1* do not show

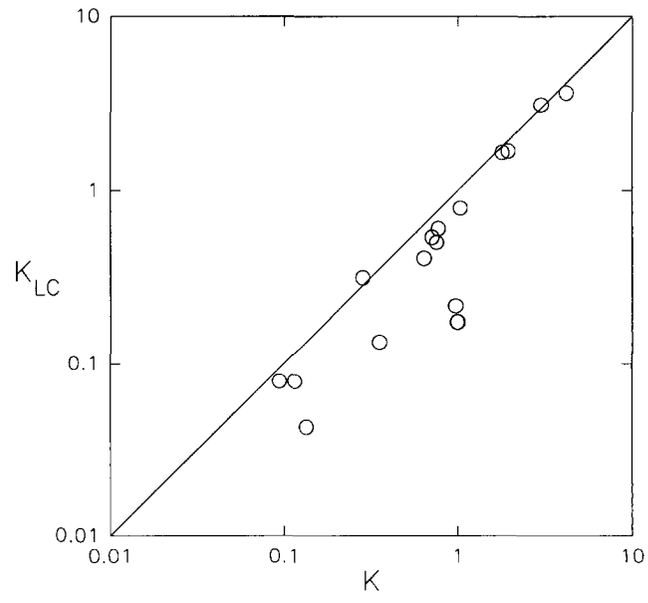

Figure 1 *K versus* K_{LC} for the solutes listed in *Table 1*

order of magnitude differences from the corresponding chromatographic distribution coefficients. This result is most likely due to the fact that the polymer particles used in these experiments were porous. Thus, the solutes did not diffuse through a solid polymer matrix, as the diffusion calculations above assume, but rather infiltrated the polymer phase at various points through a series of solution-filled channels. While it is impossible to determine the exact thickness of polymer penetrated by each solute (i.e. the diffusion path length), the fact that K_{LC} is smaller than K is consistent with the contention that the solute–polymer contact time in the chromatography column was insufficient to establish an equilibrium distribution of solute between the aqueous phase and the entire volume of polymer phase.

The fact that K and K_{LC} show reasonable agreement in *Figure 1* indicates that while the kinetics of solute diffusion prevent a true equilibrium distribution coefficient from being obtained from the chromatography column, the results of the chromatographic experiments give a qualitative representation of the affinity of the polymer phase for each solute.

Conclusions

The solutes examined in these experiments do not penetrate the entire volume of the stationary phase in the chromatography column because of the short solute–polymer contact times. Thus, the distribution coefficients determined using liquid chromatography should not be used in quantitative membrane transport studies. Rather, the distribution coefficients obtained from liquid phase sorption experiments, where sufficient solute–polymer contact time to achieve equilibrium is allowed, should be relied upon for membrane transport modelling.

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