Use of Binary Ethanol/Water Model Solutions to Mimic the Interaction Between a Plastic Material and Pharmaceutical Formulations

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ABSTRACT: The interaction of model compounds with a polyolefin plastic material was examined in binary mixtures of ethanol/water to assess the impact of the solvent polarity on the magnitude of the interaction. The interactions investigated included both compound sorption from the solution by the plastic material and leaching of plastic components into the solution. The magnitude of the interaction at equilibrium, expressed as an equilibrium interaction constant, could be linearly related to the compound's octanol–water partition coefficient ($P_{o/w}$) and the solvent's polarity (P_m). The utility of the resulting mathematical interaction model was assessed by examining the compatibility of the sample plastic system with a simulated pharmaceutical product vehicle containing a typically encountered surfactant. The nature of the plastic–solution interaction in the surfactant was unlike that observed in the binary model systems, consistent with the expectation that a surfactant's behavior is mediated by mechanisms other than simple polarity. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 1049–1057, 2003

INTRODUCTION

The use of polymeric materials to package, store, or deliver solution products in the food and pharmaceutical industries may be impacted by interactions which may occur between the stored product and the storage/delivery medium. Pertinent interactions include sorption, in which an ingredient from the stored product is taken up into the storage medium, and leaching, in which an ingredient of the storage medium is mobilized and accumulates in the stored product. Since both sorption and leaching can materially impact product safety and efficacy, it is a necessary part of storage/delivery system development to establish a particular system's propensity for interaction.

Investigation of the material/solution interaction under conditions of actual product use represents the most direct and least "controversial" approach for assessing compatibility. However, there are numerous practical considerations which can make such a direct approach difficult to implement in a scientifically and financially responsible manner. Prominent among such considerations are the following:

- Utilization of the material in a number of configurations and/or with a number of product types;
- Long contact durations;
- Cost, availability, and/or safety factors associated with the actual product; and
- Analytical constraints associated with the actual product matrix.

In situations when such practical considerations are of overriding importance, the utilization of simulated contact conditions can be considered. Temperature, contact stoichiometry, duration, and/or intensity of contact or processing events and solvent composition may be used to accomplish the simulation strategy. Regardless of the simulating strategy used, it is incumbent on the user of simulated methods to demonstrate a direct scientific link between the simulated and actual-use scenarios.

Comprehensive guidance with respect to the validation of specific solvent systems as simulants for pharmaceutical products in extraction studies is generally lacking. While the accumulation of polymer-related impurities in pharmaceutical products and their associated vehicles is well documented in the chemical literature (e.g., refs. 1–16), information related to the rigorous validation of simulating solvent systems for use in leachables' assessments is less readily obtained. For completely aqueous systems, the influence of the solution pH and common pharmaceutical excipients such as sugars, salts, buffers, and amino acids on leaching has been considered.[17,18] However, it can reasonably be anticipated that the interaction characteristics of new drug products, which are formulated with excipients such as cosolvents and solubilizing, wetting, suspending, or emul-

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TABLE I
Model Compounds Used in this Study

Group[a]	Abbreviation	Compound	Log $P_{o/w}$[b,c]	Log $P_{h/w}$[c,d]	Log E_b
I	BA	Benzoic acid	1.70	−1.00	0.500
	DMP	Dimethyl phthalate	1.56	0.76	0.076
	DEP	Diethyl phthalate	2.47	1.85	0.738
	DBP	Dibutyl phthalate	4.72	3.85	2.22
II	MBH	*p*-Toluic acid	2.34	−0.35	0.948
	EBH	4-Ethylbenzoic acid	2.97	0.40	1.35
	BBH	4-Butylbenzoic acid	3.66	1.78	2.15
III	MBOH	4-Methylbenzyl alcohol	1.58	−0.10	0.205
	ETPB	Ethyl 4-hydroxybenzoate	2.47	−0.87	0.162
	BUPB	Butyl 4-hydroxybenzoate	3.57	0.39	1.33
IV	ETBZ	Ethyl 4-aminobenzoate	1.86	−0.36	−0.278
	BUBZ	Butyl 4-aminobenzoate	3.02	0.65	0.624

[a] The compounds were grouped for analytical convenience.
[b] $P_{o/w}$ = octanol/water partition coefficient.
[c] Per ref. 22.
[d] $P_{h/w}$ = hexane/water partition coefficient.

sifying agents, will be strongly influenced by physiochemical mechanisms that are not present in purely aqueous simulating solutions. While some information exists with respect to the utilization of simulating solvent systems which may be applicable to such new drug products (e.g., refs. 19–21), these studies have not provided a substantive corroboration between theoretical and experimental aspects of specific solvent systems for specific types of drug products.

In this study, the influence of binary ethanol/water mixtures on the interaction between a polyolefin plastic and a contacted solution was examined. Both the processeses of binding and leaching were studied. The behavior observed in these simulating solvent systems was then compared to the behavior observed in a simulated drug product vehicle containing a model surfactant. Such a comparison serves as the basis upon which the ability of the ethanol/water system to effectively mimic the interaction properties of the drug vehicle is judged.

EXPERIMENTAL

Materials

The plastic material used in this study is a multicomponent polyolefin film similar to the types of materials used in packaging systems for pharmaceutical and food industry applications. Model compounds used in the development of the test material's interaction model are summarized in Table I and were received from various vendors as reagent-grade reagents. Target leachable substances were internally synthesized and purified. The surfactant was obtained from Sigma–Aldrich (Milwaukee, WI). Ethanol (absolute) was obtained from Spectrum Quality Products, Inc. (New Brunswick, NJ).

Interaction assessment

The interaction assessment involved generating interaction models for all the test solutions examined. Essentially, the test material was contacted with aqueous solutions (donors) containing known amounts of the model organic compounds. These model organic compounds (see Table I) were ones whose theoretical partitioning behavior, as expressed by classical octanol–water and hexane–water partition coefficients, are well known and serve as analytically expedient surrogates for pharmaceutical formulation ingredients. The model compounds were grouped and prepared in mixtures to facilitate their individual quantitation. The equilibrium concentration of each model compound in the donor solution was analytically determined. The difference between the model's initial and equilibrium concentrations was used to generate interaction constants for all models in all the materials tested. An interaction model was then generated for the material by correlating the compound's partition coefficients with the material's binding constants. This correlation was then used to establish the relative interaction characteristics of the material for any organic compound whose partition coefficients are known or can be measured.

The donor experiment was performed at ≈40°C for a period of ≈10 days. Equilibrium is typically established under such conditions. The individual test articles contained 5.4 g of the plastic and 50 mL of the donor solution. Donor solutions included water, 10/90 (v/v) ethanol/water (10%), 25/75 ethanol/water (25%), and 40/60 ethanol/water (40%), all fortified with 0.1% phosphoric acid. The donor solutions were acidified so that the ionic model compounds would be in their nonionized (most strongly bound) form.

Accumulation of target leachables in model solvent solutions

The plastic material was fashioned into pouches, filled with 50 mL of the various extracting solutions, and stored at 40°C for 13 days and at ambient temperature for ≈6 weeks. The extracting solutions used included water, 10, 25, and 40% (v/v) ethanol in water, and approximately 4 g/L of the surfactant. Replicate samples were made for each container type/extracting solution pair. These test articles were analyzed for their levels of leachables by liquid chromatography (gradient elution) with mass spectrometric detection (LC/MS).

Total available pool

The intent of the total available pool assessment was to exhaustively extract, and thus quantitate, the entire amount of the targeted leachables that is present in the plastic material. As this intent is much different from directly assessing the level to which a leachable may accumulate under conditions of use, an extraction strategy much more aggressive than actual use is utilized. This objective was met by subjecting the test material to sequential extraction steps using 40% ethanol/water as the extracting solvent. Replicate 5.4-g portions of the test material were contacted with 50-mL portions of the extracting solvent. These samples were extracted at 40°C for 24 h. After this treatment, the resulting extract was decanted off and saved for analysis. A fresh 50-mL aliquot of the extracting solution was added and a second extraction was initiated. This sequential process was repeated to produce a total of four extracts per replicate.

Analytical methods

The levels of the model compounds in the donor solutions were determined by isocratic, reversed-phase HPLC procedures. Separations were accomplished with C_{18} stationary phases and buffered binary methanol/water or acetonitrile/water mixtures. Since the model compounds contained a strong UV chromophore, analyte detection was by UV spectroscopy. The levels of the targeted leachables were measured via a gradient HPLC method with MS detection. Operating conditions for the LC/MS analyses were as follows: The chromatographic column was a Phenomenex Hypersil C8, 150 × 4.6 mm, 5 μm particles. The injection volume was 100 μL and the mobile phase flow rate was 0.7 mL/min. The mobile phase component A was 0.025% formic acid, the mobile phase component B was methanol, and the gradient program was as follows. MS detection was accomplished via atmospheric pressure ionization, chemical ionization, in the positive ion mode:

Time (min)	Proportion A (%)	Proportion B (%)
0	95	5
2	95	5
20	3	97
32	3	97
32.5	95	5
35	95	5

The accuracy of the analytical methods employed was established by spiking test solutions with a known amount of the analytes of interest and assessing the method's ability to quantitatively recover the spike. In all cases, the spike recovery ranged between 90 and 110%, which was deemed adequate for this application.

RESULTS AND DISCUSSION

Interaction model

The equilibrium distribution of a compound between a donor solution and an associated contact material can be expressed in terms of a partition coefficient or equilibrium constant. The equilibrium interaction constant, E_b, is defined as the ratio of the compound's equilibrium concentration in the container (C_c) and solution (C_s):

$$E_b = C_c / C_s$$

It is useful that E_b be a dimensionless number and thus that C_c and C_s be expressed in equivalent units. This is difficult for container/solution interactions because C_c is expressed in terms of the container weight (e.g., grams) and C_s is expressed in terms of the solution volume (e.g., milliliters). However, if the density of the solution is known, its volume can be converted to mass and E_b becomes dimensionless. In this study, the density of the donor solution was taken as 1 g/mL since the donors studied were essentially binary aqueous mixtures.

In the experiment performed in this study, C_s is measured. Additionally, the initial concentration of the compound in the donor solution (C_i) is known (and was also measured as the control). Thus, C_c can be calculated from the measured values of C_i and C_s as

$$C_c = [(C_i - C_s) \times V_s]/W_c$$

where W_c is the container weight (in kilograms), V_s is the solution volume (in liters), and the units of C_c and C_i are in milligrams per liter. With the values of C_c and C_s, E_b can be calculated. Since the units of C_c as calculated above are in milligrams per kilogram, these units must also be used for C_s to obtain a dimensionless E_b.

It is highly desirable that the interaction data generated in this study provide a general mechanism by

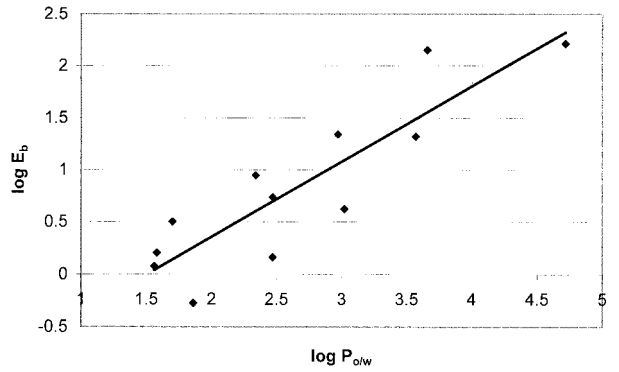

Figure 1 Interaction model: linear relationship between the model compound's equilibrium interaction constants (E_b) and octanol/water partition coefficients ($P_{o/w}$). While, in general, a linear relationship can be established for all the model compounds, there is a clear distinction in the clustering of data for the general compound classes of acids (see Fig. 2) and neutrals (see Fig. 3).

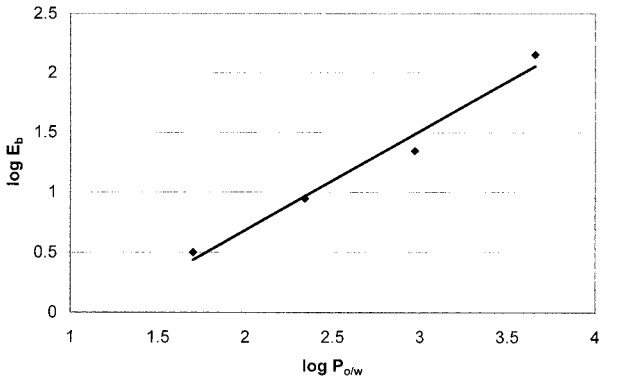

Figure 2 Interaction model: linear relationship between the model compound's equilibrium interaction constants (E_b) and octanol/water partition coefficients ($P_{o/w}$); acidic model compounds.

which the relative compatibility of specific compounds with the device material can be assessed. One way to accomplish this objective is to develop an interaction model for the material, where the interaction model seeks to relate a compound's E_b with a more readily available binding indicator, such as the octanol/water partition coefficient ($P_{o/w}$). Such a model, if the relationship were linear, would take the form

$$\log E_b = \text{slope}(\log P_{o/w}) + \text{intercept}$$

The slope and intercept for this relationship can be obtained from the data set representing the model compounds. Specifically, the compound's log E_b can be regressed versus their log $P_{o/w}$ and the model parameters obtained.

The utility of the model is as follows: As an example, consider the case where one desires to assess the compatibility of drug X in the packaging/delivery system studied. If the log $P_{o/w}$ for the drug can be obtained, then its log E_b can be calculated via the interaction model. Once the drug's E_b is known, its fractional binding by the container (F_b) can be calculated.[22] Once the fractional binding is known, then the compatibility assessment, from a binding perspective, can be made. Alternatively, the model can be used to estimate the level that a device that is leachable will accumulate in solution if the leachable's E_b and total pool in the container are known and the container weight and fill volume are specified.

The measured interaction constants for all model compounds and the test material are summarized in Table I. The relationship between the interaction constants and the model compound's octanol/water partition coefficients are shown in Figure 1. As shown in this figure, the binding constants (log E_b) are generally linearly related to the model compound's log $P_{o/w}$. Curve-fit parameters are given in Table II. Closer examination of the data reveals that the correlation between log E_b and log $P_{o/w}$ is improved if the model compounds are classified as acids or neutrals (see, e.g., Table II and Figs. 2 and 3). The implication is that the material interacts with acidic compounds via a secondary mechanism that is not captured by the octanol-water simulating solvent, although the nature of the secondary interaction is not known. While in previous

TABLE II
Curve-fit Parameters and Binding Models

Compound class	Curve-fit parameters		
	Slope	Intercept	r^2
All	0.800	−1.22	0.835
Acids[a]	0.890	−1.05	0.968
Neutrals[b]	0.775	−1.35	0.951

Model is log E_b = slope (log $P_{o/w}$) + intercept.
[a] Acids include BA, MBH, EBH, and BBH.
[b] Neutrals include DMP, DEP, DPP, MBOH, ETPB, BUPB, ETBZ, and BUBZ.

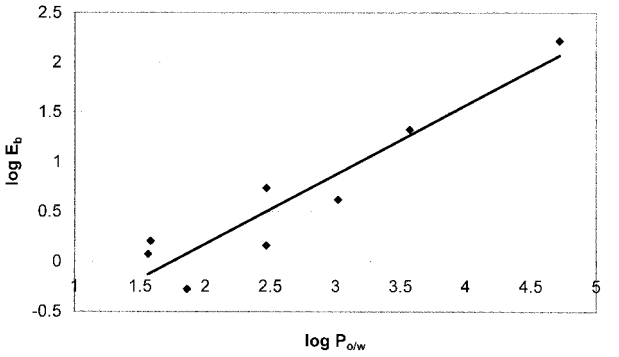

Figure 3 Interaction model: linear relationship between the model compound's equilibrium interaction constants (E_b) and octanol/water partition coefficients ($P_{o/w}$); neutral target compounds.

TABLE III
Polarity (P_m) Values for Solvents

Proportion of solvent		
Water	Ethanol	P_m
100	0	25.52[a]
90	10	24.33[b]
75	25	22.55[b]
60	40	20.77[b]
0	100	13.65[a]

[a] From ref. 25.
[b] Calculated from the solution composition and P_m values of the end members.

investigations similar behavior was addressed by the development of multivariant models which consider paired solvent systems (e.g., octanol/water and hexane/water[22,23]), the octanol/water models developed in this study are sufficiently accurate that this additional mathematical treatment of the data is unnecessary. Thus, to a first approximation, one can account for the impact of compound identity on the material/solution interaction via the compound's log $P_{o/w}$.

The previous consideration of the interaction phenomenon is based on water as the solvent. It is anticipated that drug formulations may behave differently from water in interaction situations due to the presence of a surfactant or other excipients in the formulation. Since performing analyses directly in the drug formulation may be an analytical or practical challenge, the use of binary ethanol/water mixtures to simulate a drug formulation was investigated. For such an investigation to be relevant, the effect of the drug formulation would be manifested as a change in polarity, as this is the solvent characteristic which is changed as the proportion of water and ethanol is varied.

The impact of the ethanol/water ratio on the binding of the model compounds was assessed in this study. The various mixtures used and their calculated polarity values (P_m) are summarized in Table III. The various interaction models generated in the solvent systems examined (including the surfactant) are shown in Figure 4. As expected, the absolute magnitude of the interaction is decreased as the polarity of the solvent system is decreased. However, the interaction models in all the solvent systems remain roughly linear with respect to log $P_{o/w}$. Consistent with the change in the interaction, each model's slope and intercept decrease as the solvent polarity decreases. Thus, not only is the absolute magnitude of the interaction decreased with a decreasing solvent polarity (i.e., intercept), but the influence of compound's log $P_{o/w}$ on the interaction is also lessened as solvent polarity decreases (i.e., slope).

If the material interaction in the surfactant is effectively mimicked by the ethanol/water mixtures (i.e., that the effect in the surfactant is polarity-mediated), one expects to see the binding model in the surfactant to be colinear with the interaction models in ethanol/water. The slope and the intercept of the surfactant's model would be compared to the slope and intercept of the ethanol/water systems to define what ethanol/water proportion most effectively mimics the surfactant. However, as shown in Figure 4, the surfactant's model is not colinear to the ethanol/water models but, rather, crosses several of the ethanol/water isobars. Thus, the action of the surfactant is not solely polarity-driven and, in fact, is a function of the interacting

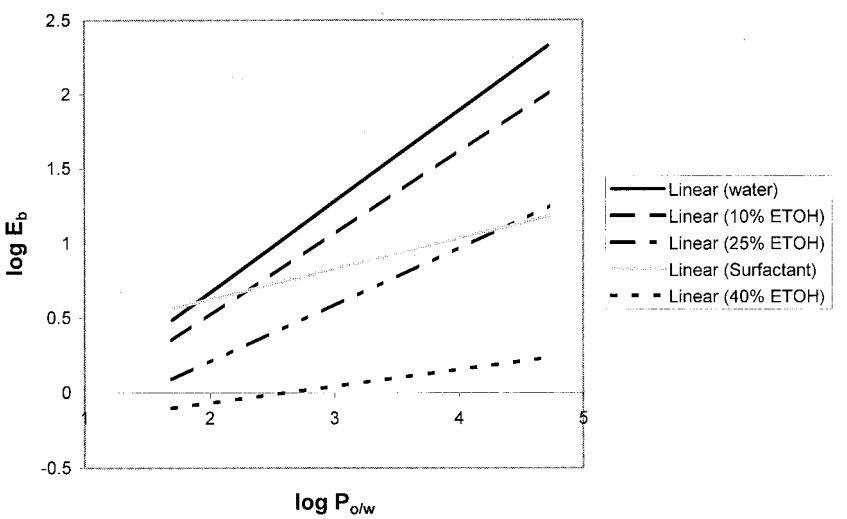

Figure 4 Interaction models obtained in the various solvent systems examined. As the water content (polarity) of the solvent system decreases, the magnitude of the binding interaction decreases, resulting in a lower slope on intercept in the interaction model. While the models for the alcohol-containing solvents are roughly colinear, the binding model for the surfactant system crosses the ethanol-content contours. Thus, no single ethanol content mimics the interaction properties of the surfactant system.

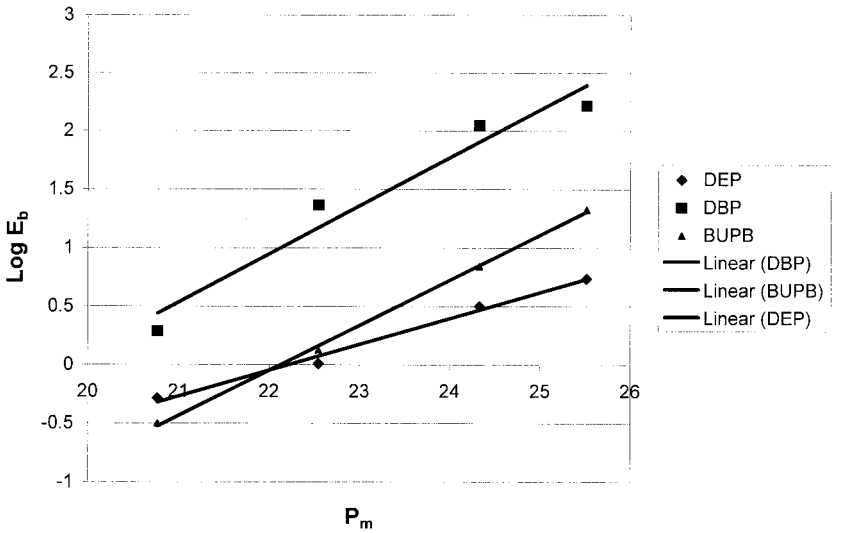

Figure 5 Effect of solvent system polarity on the interaction constants for the neutral model compounds. The magnitude of the interaction constant can be directly related to the solvent's polarity in binary ethanol/water systems.

compound's characteristics. Specifically, it seems that the compound's behavior in the surfactant is influenced by the compound's $P_{o/w}$, an observation that has been made by other investigators.[24] While the nature of this juxtaposition, which is related to the micellular nature of the surfactant, could be the topic of extensive investigation, it is sufficient for this study to observe that binary ethanol/water models do not effectively model the material/surfactant interaction.

Considering the interaction behavior observed in the ethanol/water solvent systems, it is expected that within such a system the solvent polarity P_m would have a clear and consistent impact on a compound's binding characteristics. As shown in Figures 5 and 6, a linear relationship between log E_b and P_m can be established for all model compounds whose binding characteristics could be accurately measured in all the solvent systems studied. The plots for all the analytes are roughly colinear, which suggests that the impact of P_m is consistent among all the model compounds. The differing intercepts of the log E_b versus P_m plots for the different compounds reflect the compounds' differing log $P_{o/w}$ values.

Accumulation of target leachables in test solutions

Four related compounds, typical of those associated with polyolefin materials (e.g., ref. 26), were identified as leachables during the initial qualitative characterization of extracts of the plastic. The identifications, made based on molecular weights and fragmentation patterns obtained by chromatographic analyses with

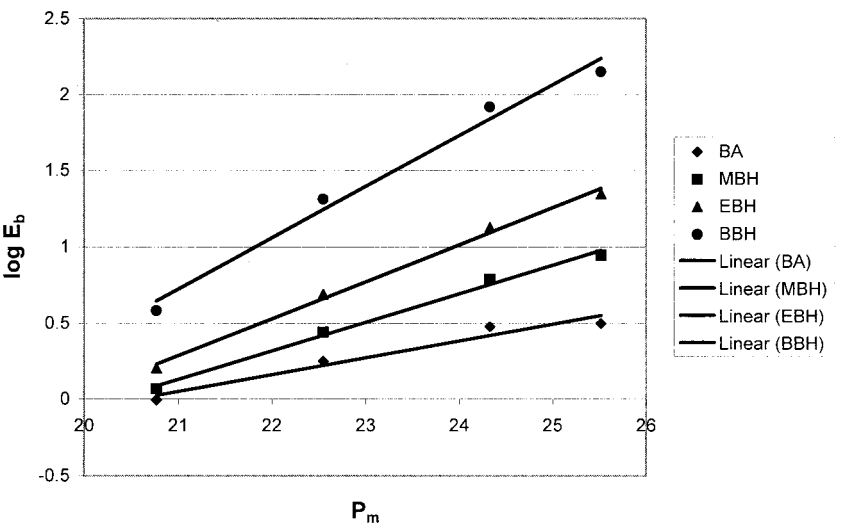

Figure 6 Effect of solvent system polarity on the interaction constants for the acid model compounds. The magnitude of the interaction constant can be directly related to the solvent's polarity in binary ethanol/water systems.

TABLE IV
Accumulation of Target Leachables Extracted from the Test Material

Solution	Accumulation level, fraction of total pool			
	Leachable A	Leachable C	Leachable B	Leachable D
Water	0.40	0.36	0.11	0.03
10% Ethanol	0.53	0.56	0.20	0.09
25% Ethanol	0.67	0.59	0.32	0.19
40% Ethanol	0.77	0.66	0.37	0.28
Surfactant (≈4 g/L)	0.37	0	0.14	0.05
Log $P_{o/w}$	1.67	2.12	2.82	4.01

MS detection, were confirmed by comparison of the analytical results obtained from extracts and authentic reference standards of the specific compounds.

The levels of the four target leachables were measured in several solutions contacted with the test material. Utilization of these targets is significant since they are present in the material at measurable levels and they encompass a wide range of compound polarity (log $P_{o/w}$ from 1.7 to 4.0). The results of these analyses are tabulated in Table IV and graphically illustrated in Figure 7. In general, the levels of these targets in the extracts increase linearly with a decrease in the solvent polarity. This trend is significant not only because it establishes a relationship between accumulation levels and P_m but also because it indicates that the levels observed in the strongest solvent system (40% ethanol) do not represent the total available pool. The slopes of the accumulation profiles in Figure 7 are roughly the same, as is to be expected since the slope is a property of the material studied. The intercepts of the lines are related to the nature of the leachables and mirror the order of the log $P_{o/w}$ values for the four targets.

The levels of leachables in the surfactant solution are not directly comparable to a single simulating binary solvent. As with binding, the level to which the leachable accumulates in the surfactant (versus the level it accumulates to in a binary simulating solvent) depends on the leachable's log $P_{o/w}$. For the lowest log $P_{o/w}$ leachables, the levels in the surfactant are similar to those observed in water. However, for the higher log $P_{o/w}$ leachables, the levels measured in the surfactant approach the levels measured in the 10% ethanol simulating solvent.

Total available pool

The maximum level to which an leachable can accumulate in solution is achieved if its total available pool in the plastic material is completely mobilized into a solution. In this study, the total available pool was assessed by performing sequential extractions (fresh solvent each successive extraction) using a strong solvent (40% ethanol in water). Specifically, four sequential extracts were obtained and the analyte concentration in each extract was measured. In such a experiment, the resulting concentration versus the extract number can exhibit several trends as follows:

1. The analyte may not be present at measurable levels in any extract (even the first). In this case, the total available pool of the analyte is essentially 0.

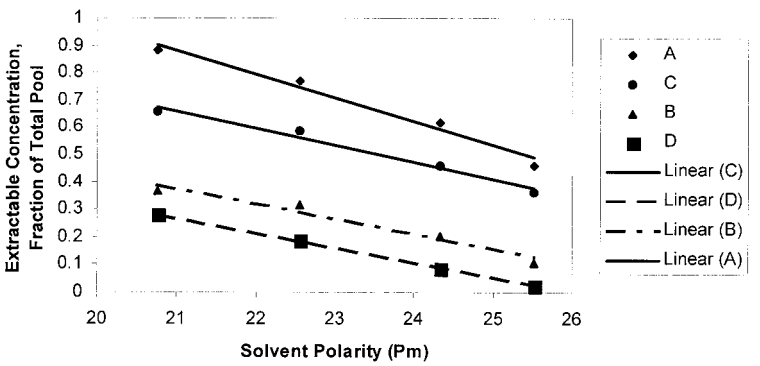

Figure 7 Accumulation of the target leachables in the ethanol/water mixtures as a function of their polarity. As the proportion of ethanol in the solution increases (polarity decreases), the levels of the target leachables increase proportionally. The log $P_{o/w}$ values for the target leachables are 1.67, 2.12, 2.82, and 4.01, respectively, for A, B, C, and D. The slope of the lines, a function of the material examined, are roughly colinear while the intercepts are directly related to the leachable's log $P_{o/w}$.

TABLE V
Total Available Pool of Identified Leachables

Extract no.	Amount of compound extracted, μg compound/g of material extracted[a,b]			
	Leachable A	Leachable C	Leachable B	Leachable D
1	0.24	0.97	19.2	16.7
2	0.00	0.25	5.05	6.10
3	0.00	0.13	1.66	2.82
4	0.00	0.06	1.26	2.20
Total pool	0.24	1.41	27.2	27.8

[a] Extracting solution was 40% ethanol.
[b] Results are the mean values obtained for three replicate test articles.

2. The levels of the analyte may decrease consistently as a function of the extraction number. This means that a significant fraction of the total pool is liberated in each extraction step. The total pool then can be determined as the sum of the analyte concentrations in all extraction steps. If the analyte level in the last extraction is much less than that in the first extraction, then the total pool is essentially completely liberated during the extraction sequence and the summation accurately reflects the total pool. If the analyte concentration in the last extract is still a considerable fraction of the concentration in the first extract, then the pool is not completely liberated. In such a case, the summation underestimates the total pool. A closer estimate of the total pool may be obtained by performing more extractions or by projecting the extraction sequence based on partitioning considerations.[27]
3. The levels of the analyte do not decrease significantly as a function of the extraction number. This occurs when either the total pool is large, when the analyte has a strong affinity for the plastic, or when the extraction conditions are insufficiently rigorous to allow for the attainment of equilibrium. In such cases, the total pool cannot be accurately determined by the analyte concentrations measured in the successive extracts. The sum of the analyte levels in all extracts provides only a poor estimate of the analyte's total available pool in the plastic.

Sequential extraction data for the identified leachables are summarized in Table V. In all cases, these leachables show the type of behavior specified in scenario 2 and, thus, the total available pools can be approximated as the sum of the levels observed in each extraction. For example, the total available pool for leachable B is 2720 ppb. Thus, the levels of leachable B could not exceed 3000 ppb or 3 ppm in the 50-mL product configuration. It is noted in passing that the levels of the targeted leachables observed in the test samples were all less than their total available pools.

Correlation between interaction model and leachables' accumulation

The interaction models developed herein and the accumulation data (total pool and equilibrium levels) for the target leachables allows for an assessment of the consistency of the generated dataset. Consistency can be evaluated as the ability to obtain constant values for the interaction constants (E_b) generated by one or more ways. Knowing the total pool (T_p) and equilibrium level of an leachable (C_e), the defining equation for E_b can be rewritten as

$$E_b = (T_p - C_e)/C_e$$

if the units of T_p and E_b are consistent. Alternatively, the interaction model equation can be solved for E_b if the target leachable's $P_{o/w}$ is known. Since all the required information is available in this study, consistency in an approach can be assessed by comparing E_b for the targeted cyclic leachables using both approaches.

The results of such an assessment are summarized in Table VI. The agreement between log E_b calculated by both methods is excellent, considering the accumulated analytical uncertainty. Thus, the model, based on the solute uptake, and the leaching data provide an internally consistent view of the interaction of the studied plastic material and aqueous solutions.

CONCLUSIONS

The interaction of model compounds with, and the accumulation of targeted leachables from, a polyolefin

TABLE VI
Comparison of the Equilibrium Interaction Constants Obtained for the Targeted Leachables

Leachable	Log E_b (water as solution phase)	
	From interaction model	From total pool and equilibrium level
A	−0.056	0.067
C	0.293	0.237
B	0.836	0.929
D	1.76	1.55

plastic material was examined in binary mixtures of ethanol/water to assess the impact of the solvent polarity on the magnitude of the interaction. The magnitude of the interaction at equilibrium, expressed as an equilibrium interaction constant, could be linearly related to the compound's octanol–water partition coefficient ($P_{o/w}$) and the solvent's polarity (P_m). Consistent interaction results were obtained with both binding and leaching information. The resulting mathematical interaction model did not reflect the interaction of the plastic with a simulated pharmaceutical product vehicle containing a model surfactant. The nature of the plastic–solution interaction in the surfactant was unlike that observed in the binary model systems, consistent with the expectation that the surfactant's interactions are mediated by mechanisms other than simply polarity.

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