Interfacial Properties of Polar Liquids against Nonpolar Phases

GEORGE ZOGRAFI*ˣ and SAMUEL H. YALKOWSKY‡

Abstract □ The interfacial tension of 10 polar liquids against hexane and tetradecane and the contact angle against paraffin, polyethylene, and polytetrafluoroethylene were measured. Work-of-adhesion values against any one nonpolar phase, calculated from these data, are independent of the polar liquid used. Values for the same polar liquid, however, differ with the nonpolar phase used. These differences are attributed to differing surface group densities and, hence, a different number of dispersion force interactions per unit area. These results explain the variations occurring in the Fowkes dispersion component of surface tension, $\gamma_L{}^d$, for any liquid when it is determined using different nonpolar phases.

Keyphrases □ Polar liquids—interfacial properties against nonpolar phases, interfacial tension and contact angles measured, work-of-adhesion values calculated □ Nonpolar phases—interfacial properties of 10 polar liquids against hexane, tetradecane, paraffin, polyethylene, and polytetrafluoroethylene, interfacial tension or contact angle measured, work-of-adhesion values calculated □ Interfacial tension—10 polar liquids against hexane and tetradecane □ Contact angles—10 polar liquids against paraffin, polyethylene, and polytetrafluoroethylene, interfacial properties of polar liquids

In a study dealing with the free energy of solution per methylene group for a series of alkyl p-amino-benzoates in various polar solvents, it was found that a correlation exists between the free energy term and the interfacial tension of these solvents against the liquid alkane, tetradecane (1). Since the choice of tetradecane as a representative nonpolar surface was made arbitrarily for convenience, and since some solvents of interest were miscible with tetradecane, the use of other liquid and solid hydrocarbons for such correlations was considered. This led to the present study where the interfacial behavior of various polar liquids was measured against the liquids hexane and tetradecane and the solids paraffin, polyethylene, and polytetrafluoroethylene. By determining the interfacial behavior of any polar liquid against these systems, it was hoped that one could use such information more generally for the correlations mentioned.

THEORETICAL

Another reason for the interest in pursuing this study was the fact that polar liquids, such as glycerin or formamide, are often used to determine the surface free energy or some similar term for solids (2–5). The principle behind this approach centers on the work of Fowkes (2) who sought to define the interfacial free energy of systems in terms of measurable parameters such as surface tension, interfacial tension, and contact angle. The term of particular interest in this study is the work of adhesion, Wa^{12}, the free energy per unit area at the interface of phases 1 and 2. It is defined in terms of surface tension and interfacial tension as (6):

$$Wa^{12} = \gamma_1 + \gamma_2 - \gamma_{12} \qquad \text{(Eq. 1)}$$

When one phase is nonpolar and only contributes London dispersion forces, it can be shown (2) that:

$$Wa^{12} = 2(\gamma_1{}^d \gamma_2{}^d)^{1/2} \qquad \text{(Eq. 2)}$$

where $\gamma_1{}^d$ and $\gamma_2{}^d$ represent the part of the total surface tension of a substance that arises because of interactions due to dispersion forces. For the nonpolar phase, the surface tension is considered equal to γ^d, while for a semipolar substance:

$$\gamma = \gamma^d + \gamma^p \qquad \text{(Eq. 3)}$$

where γ^p is that part of the observed surface tension, γ, due to other forces of interaction.

For a solid–liquid system, one can utilize the Young equation to obtain the work of adhesion in terms of measurable parameters (6). Here:

$$\gamma_S - \gamma_{SL} = \gamma_L \cos\theta + \pi_{sv} \qquad \text{(Eq. 4)}$$

where S and L represent solid and liquid, respectively; θ is the contact angle; and π_{sv} is the surface energy change due to any adsorption of vapor from the liquid onto the solid. For systems where wetting is poor, this term is generally ignored (2). Thus, in general, the work of adhesion between a solid and liquid, Wa^{SL}, may be determined by combining Eqs. 1 and 4:

$$Wa^{SL} = \gamma_L + \gamma_L \cos\theta \qquad \text{(Eq. 5)}$$

and when one phase is nonpolar:

$$Wa^{SL} = 2(\gamma_S{}^d \gamma_L{}^d)^{1/2} \qquad \text{(Eq. 6)}$$

These expressions are useful because once the value of γ^d is known for a substance, it is then possible to determine γ^d for any substance that forms an interface with the first substance. This procedure has been utilized to determine $\gamma_S{}^d$ for various solids, including polymers (2, 3), metals (7), skin (8), and different pharmaceuticals (9–11). The term $\gamma_S{}^d$ provides a measure of the surface tension a completely nonpolar liquid would require to wet the solid completely (3, 4). In these cases the contact angle of various polar liquids of known $\gamma_L{}^d$ is measured against the solid; the $\gamma_L{}^d$ values are determined previously from contact angles measured on a nonpolar surface such as paraffin. The value of $\gamma_S{}^d$ for paraffin, in turn, is determined from water–paraffin wetting data, while the value of $\gamma_L{}^d$ for water originates from liquid hydrocarbon–water interfacial tension data and application of Eqs. 1 and 2.

In all of the calculations, it is necessary to assume that the value of $\gamma_L{}^d$ for any liquid is independent of the system used as the second phase. However, in the system providing the first $\gamma_L{}^d$ value, water–liquid alkane, the value of $\gamma_L{}^d$ for water is somewhat dependent on the hydrocarbon chosen (12, 13). This has been attributed to changes in water structure due to different alkane chain lengths (13) and to an alteration of alkane surface density due to the dispersion force field of water molecules (14). No further work in this regard has been reported, particularly with respect to the possible changes occurring when other polar solvents are used. Hoernschemeyer (15) attempted to explain differences in the wettability of nonpolar surfaces by alkanes in terms of differences in the packing density of solid surface groups. Thus, he attributed differences to the number of dispersion interactions that can take place per unit area; the more interactions per unit area, the greater is the wetting. This difference in surface group density could account for the differences in interfacial tension between water and different liquid alkanes as well.

Since the large number of polar liquids considered in this report

Table I—Interfacial Tension of Various Polar Liquids against Hexane and Tetradecane at 25°

Liquid	Surface Tension, dynes/cm	Interfacial Tension, dynes/cm	
		Hexane	Tetra-decane
Water	72.0	50.4	52.9
Glycerin	63.7	34.3	35.9
Formamide	58.3	29.1	31.8
1,3-Propanediol	49.2	17.9	20.6
Ethylene glycol	48.9	16.3	19.7
1,4-Butanediol	47.4	16.4	18.8
N-Methylformamide	40.2	9.3	12.3
1,3-Butanediol	39.1	11.0	13.0
1,2-Butanediol	38.0	9.6	12.7
N,N-Dimethylformamide	37.0	Miscible	4.6

Table II—Contact Angle for Various Polar Liquids on Paraffin, Polyethylene, and Polytetrafluoroethylene

Liquid	Contact Angle		
	Paraffin	Polytetra-fluoroethylene	Poly-ethylene
Water	106°	106°	85°
Glycerin	96°	97°	75°
Formamide	91°	91°	69°
1,3-Propanediol	78°	89°	54°
Ethylene glycol	79°	82°	56°
1,4-Propanediol	76°	81°	54°
N-Methylformamide	64°	68°	39°
1,3-Butanediol	62°	69°	41°
1,2-Propanediol	62°	67°	36°
N,N-Dimethylformamide	50°	59°	29°

are immiscible with liquid alkanes, results can be compared with liquid–liquid and liquid–solid systems over a wide range of conditions. Therefore, in the present study the interfacial tension of various polar liquids was measured against hexane and tetradecane, while the contact angle for these liquids was measured on paraffin, polyethylene, and polytetrafluoroethylene.

EXPERIMENTAL

Materials—The various polar solvents were of reagent grade quality and gave good agreement with available literature values of surface tension (2, 3). Hexane and tetradecane were of 99+% purity and gave surface tensions of 18.5 and 26.3 dynes/cm, respectively. These values agree well with reported values (12, 13). Water was doubly distilled from alkaline permanganate solution.

The polytetrafluoroethylene[1] had a bulk density of 2.13 g/cm³, in good agreement with previously reported values (15). Contact angles with water, glycerin, and formamide were in good agreement with the literature (2–5). Paraffin likewise gave contact angles in good agreement with the literature (2–5). Smooth surfaces were prepared by melting and wiping with a clean glass slide just before solidification. Parafilm "M" [2], which is a paraffin-coated sheet, gave identical results to the block paraffin. A sample of "high-density" polyethylene[3] had a bulk density of 0.932 g/cm³.

Interfacial Tension Measurement—Interfacial tension was measured using the Wilhelmy technique (13, 16). The platinum plate was attached to a microtorsion balance[4]. Values of interfacial tension of water against hexane and tetradecane at 25° were in good agreement with earlier results (12, 13). Values for most polar liquids were reproducible to 0.3 dyne/cm; however, with the more viscous liquids like glycerin, reproducibility amounted to about 0.5 dyne/cm.

Contact Angle Measurement—Contact angles were measured using a contact angle analyzer[5], which allows one to project a mag-
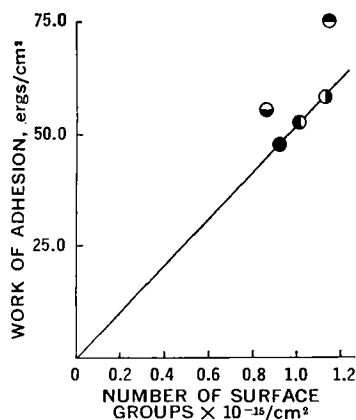

Figure 1—*Average work of adhesion for each polar liquid against a nonpolar phase versus surface group density of the nonpolar phase. Key: ●, hexane; ○, tetradecane; ◑, paraffin; ◐, polytetrafluoroethylene; and ◓, polyethylene.*

nified image of a liquid drop so that direct measurement of the contact angle may be made. The drop was introduced at constant volume from a microsyringe at a volume of 0.02 ml. The angle measured was an advancing angle, independent of time. The results recorded are the averages of at least 10 measurements, and the range of angles was no greater than 3°. As indicated previously, results that could be compared with the literature agreed quite well (2–5).

RESULTS

Table I lists the various liquids utilized in the order of their surface tensions at 25° as well as their interfacial tensions against hexane and tetradecane. Only in one case, N,N-dimethylformamide with hexane, was miscibility complete, so that an interfacial tension could not be measured. Table II lists the contact angles for the various liquids. Comparison of the two tables reveals the same general order of effect at liquid or solid interfaces.

Table III contains values for the work of adhesion calculated from Eq. 1 for the liquid–liquid systems and from Eq. 5 for the solid–liquid systems. Comparison of values for any one nonpolar phase indicates very small differences, if any, in the work of adhesion for the various polar solvents[6]. In view of this finding, and for convenience of later computation and discussion, an average value for work of adhesion is presented in Table III for all liquids against each nonpolar phase. Comparison of values for each polar liquid on different nonpolar phases indicated differences in the work of adhesion. This is reflected also in Table IV, where values of $\gamma_L{}^d$ are given. The $\gamma_L{}^d$ terms for the polar solvents were obtained using Eqs. 2 and 6. The $\gamma_L{}^d$ values for hexane and tetradecane were taken as their surface tensions, while the $\gamma_S{}^d$ values for paraffin and polytetrafluoroethylene were taken as 25.5 and 19.5 dynes/cm, respectively (2). No calculation of $\gamma_L{}^d$ was made from the polyethylene data because of the unknown character of polyethylene surfaces and the difficulty of choosing a correct $\gamma_S{}^d$ (17). It is clear from Tables III and IV that significant changes do occur in the work of adhesion and, hence, $\gamma_L{}^d$ as one changes the nature of the nonpolar phase used. Thus, this behavior is not limited to water–liquid alkane systems, as previously observed (13, 14). Moreover, except for water, the $\gamma_L{}^d$ terms are not too different for the various polar liquids on any one nonpolar phase.

DISCUSSION

The results of this experiment clearly indicate that the value of $\gamma_L{}^d$ obtained from interfacial tension or contact angle data for polar liquids against nonpolar phases depends on the nonpolar phase used. Thus, the observations made with water–liquid alkane systems (12–14) can be generalized to a wider range of other liquids. Previous discussion on this question has centered on specific effects of the nonpolar phase on water structure at the interface (13) or an effect of water on the surface density of the liquid hydrocarbons (14). The general effect on liquids ranging from water to N,N-dimethylformamide observed here and the fact that the effects are about the same for all liquids would suggest that a property of the polar liquid is not involved, but rather that an intrinsic

[1] Dupont Co.
[2] American Can Co.
[3] University of Wisconsin Plant Service.
[4] Federal Pacific Co.
[5] Imass, Inc.

---

[6] The values for water tend to be slightly lower than the others in the case of the two liquid hydrocarbons, and this finding is commented on in the *Discussion* section.

Table III—Work of Adhesion[a] for Various Polar Liquids against Various Nonpolar Phases

Liquid	Work of Adhesion, ergs/cm²				
	Hexane	Tetradecane	Paraffin	Polytetrafluoroethylene	Polyethylene
Water	40.1	45.4	52.6	53.0	78.3
Glycerin	47.9	54.1	56.4	56.1	79.9
Formamide	47.7	52.8	57.6	59.7	79.4
1,3-Propanediol	49.8	54.9	59.5	58.4	78.0
Ethylene glycol	51.1	55.5	58.0	56.0	76.1
1,4-Butanediol	49.5	54.9	59.0	54.7	75.0
N-Methylformamide	49.4	54.0	58.0	55.8	71.4
1,3-Butanediol	46.6	52.4	57.5	53.1	68.5
1,2-Propanediol	46.9	51.3	55.9	53.2	68.8
N,N-Dimethylformamide	—	51.3	62.1	58.1	70.7
Average of all liquids	47.2	52.6	57.7	55.6	74.6

[a] Calculated from Eqs. 1 and 5. Based upon a maximum error of ±0.5 dyne/cm for interfacial tension and ±3° for contact angle, the maximum error associated with each work of adhesion is about ±0.5 erg/cm² and 3.0 ergs/cm² for liquid–liquid and liquid–solid systems, respectively.

property of the nonpolar phase such as the surface group density is responsible. Actually, these ideas were suggested earlier to explain differences in wettability of nonpolar solids by alkanes (15), but the concept has not been extended to polar liquid–nonpolar liquid or polar liquid–nonpolar solid systems to explain differences in γ_L^d values.

To see if this is a common factor for all systems studied, the number of methylene (CH_2) or difluoromethylene (CF_2) groups per square centimeter was calculated for each nonpolar phase using the two-thirds power of bulk group density (15). Figure 1 contains a plot of average work of adhesion (from Table III) versus surface group density. A line can be drawn through the three alkane data points such that it passes through the origin, while the two polymeric substances yield values of work of adhesion well above the straight line. A zero work of adhesion at zero surface group density (i.e., a vacuum) makes physical sense. This linearity suggests that differences in surface group density and, hence, the number of interactions per square centimeter indeed can account for differences in γ_L^d when using different alkanes, liquid or solid. Thus, it should be possible to relate data obtained with one alkane to those obtained with another.

The work of adhesion for polyethylene falls considerably above the value expected from an extrapolation of the straight line, too far above to be explained by experimental error. Since the methylene or methyl (CH_3) groups involved in the interactions of polyethylene with the various liquids are also responsible for alkane interactions, it is concluded that the deviation is associated with the use of a bulk density to calculate surface group density. Indeed, it is well established that polyethylene can exhibit a different surface structure depending on the method of crystallization (17). Fowkes (14), for example, estimated that, in the extremes, polyethylene chains at the surface can align normally so that only methyl groups are exposed or they can align parallel to the surface so that mainly methylene groups are exposed. The number of methyl groups exposed per square centimeter in the former case should be about $0.4–0.5 \times 10^{15}$, whereas in the latter case the number of methylene

groups per square centimeter should be about $1.75–2.0 \times 10^{15}$. In a real situation, any value in between could be the correct one. The sample of polyethylene used here is rated as a high density polyethylene and, indeed, from Fig. 1 an expected value for surface group density is about 1.5×10^{15} groups/cm². The liquid alkanes and paraffin have no crystallinity and, to a first approximation, can be regarded as being homogeneous up to and including their surface.

The correlation of work of adhesion with surface group density did not work with polar liquids wetting polytetrafluoroethylene, whereas it did work for alkanes on polytetrafluoroethylene (15). This could be attributed to uncertainties in the surface group density, but the same variation in crystallinity is not expected with this polymer as is seen with polyethylene. For example, the sample of polytetrafluoroethylene used here was identical in bulk density to that used by Hoernschemeyer (15) in his correlations of wetting with surface group densities. Thus, although one cannot discount an error in the surface group density, it would seem less likely to produce the effect noted in Fig. 1. Another contributing factor might be the tendency of polar group interactions to occur when difluoromethylene groups are present, thus giving rise to larger work-of-adhesion values than predicted. Indeed, fluorocarbon groups, such as in methyl fluoride or methylene fluoride, have a much higher dipole moment than the corresponding hydrocarbon groups (18).

From this discussion, therefore, it can be concluded that values of γ_L^d, obtained from interfacial tension or contact angle data, depend on the intrinsic properties of the nonpolar phase. In the case of the liquid alkanes and paraffin, differences are simply related to

Table IV—Values[a] of γ_L^d for Various Polar Liquids Using Different Nonpolar Phases

Liquid	γ_L^d, dynes/cm			
	Hexane	Tetradecane	Paraffin	Polytetrafluoroethylene
Water	21.7	19.6	27.1	35.9
Glycerin	30.0	27.8	31.2	40.3
Formamide	31.3	27.0	32.5	45.6
1,3-Propanediol	33.5	28.7	34.6	43.7
Ethylene glycol	35.1	29.2	33.0	40.2
1,4-Butanediol	33.1	28.7	34.1	38.2
N-Methyl-formamide	32.8	27.6	32.9	39.8
1,3-Butanediol	29.3	26.1	32.4	36.0
1,2-Propanediol	28.6	24.4	30.6	36.1
N,N-Dimethyl-formamide	—	31.9	37.2	41.3

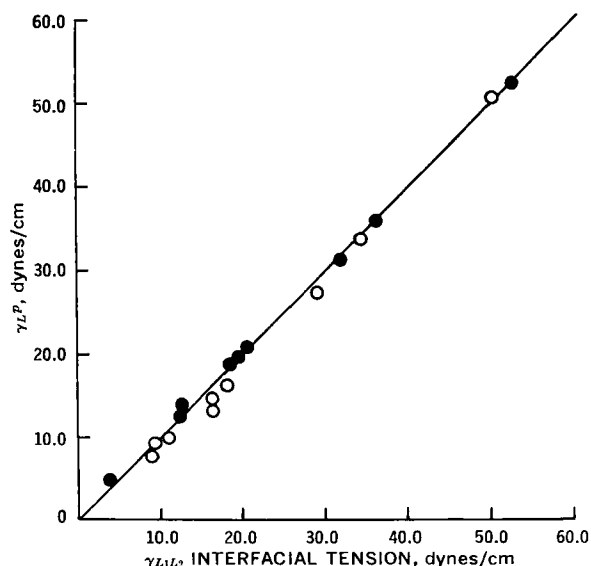[a] Calculated using Eqs. 2 and 6.

Figure 2—*Polar component, γ_L^p, for each polar liquid versus the interfacial tension of that liquid against:* (O) *hexane and* (●) *tetradecane. The solid line has a slope of one.*

the surface group density as calculated from bulk density, whereas the use of polymeric nonpolar phases introduces other uncertainties. From a practical point of view in evaluating the dispersion force component, γ_S^d, of polar solids using polar liquids, one can use a γ_L^d value obtained with one alkane and relate it to another; however, the use of polymers for this purpose is not appropriate. If one has to determine a γ_L^d for later use with solids, it is probably best, in a practical sense, to use data obtained with paraffin as the standard γ_L^d. The theoretical uncertainties of the entire concept behind γ^d, however, should still be kept in mind.

An earlier study (1) showed that the free energy of solution per methylene group for an homologous series of drugs correlates well with the interfacial tension of the various polar solvents used against tetradecane. Later unpublished results indicate that similar correlations exist for interfacial data obtained with hexane and paraffin. Explanations for these correlations are based upon the concept that this is a measure of the work required to create a cavity of given area in the polar solvent so as to allow a methylene group to enter and interact. From the results of this experiment, additional insight is gained into the major energetic factor contributing to this process. It is seen from the work-of-adhesion data that, regardless of the polar liquid used, the contribution of dispersion forces remains fairly constant. Water is a little lower in each case, possibly because of its smaller molecular size and polarizability relative to the organic solvents or because of some specific structure-forming ability. This suggests that the main difference between the various solvents is the work required to overcome polar–polar interactions.

By using the γ_L^d values obtained from hexane and tetradecane data and Eq. 2, it is possible to calculate γ_L^p for each liquid. This term is directly related to polar group interactions in the solvent. If γ_L^p is plotted *versus* the interfacial tension of that liquid against the corresponding liquid alkane, one can see that the points all fall on a line with a slope of unity or that in all cases γ_L^p is equal to interfacial tension. Thus, it is concluded that, when one sees a correlation with interfacial tension, as observed in the solubility work (1), one is dealing with energetic differences solely associated with the polar portion of the molecule.

REFERENCES

(1) S. H. Yalkowsky, G. L. Amidon, G. Zografi, and G. L. Flynn, *J. Pharm. Sci.*, in press.

(2) F. M. Fowkes, *Ind. Eng. Chem.*, **56**, 40(1964).

(3) J. R. Dann, *J. Colloid Interface Sci.*, **32**, 302(1970).

(4) J. R. Dann, *ibid.*, **32**, 321(1970).

(5) D. H. Kaeble, *J. Adhesion*, **2**, 66(1970).

(6) A. W. Adamson, "Physical Chemistry of Surfaces," 2nd ed., Interscience, New York, N.Y., 1967, p. 71.

(7) M. E. Schrader, *J. Phys. Chem.*, **78**, 87(1974).

(8) A. L. Rosenberg, R. Williams, and G. Cohen, *J. Pharm. Sci.*, **62**, 920(1973).

(9) P. D. Krause and D. O. Kildsig, *ibid.*, **61**, 281(1972).

(10) S. W. Harder, D. A. Zuck, and J. A. Wood, *ibid.*, **59**, 1787(1970).

(11) S. W. Harder, *Can. J. Pharm. Sci.*, **6**, 63(1971).

(12) R. Aveyard and D. A. Haydon, *Trans. Faraday Soc.*, **61**, 2255(1965).

(13) W. R. Gillap, N. D. Weiner, and M. Gibaldi, *J. Amer. Oil Chem. Soc.*, **44**, 71(1967).

(14) F. M. Fowkes, "Chemistry and Physics of Interfaces–II," American Chemical Society Publications, Washington, D.C., 1971, p. 154.

(15) D. Hoernschemeyer, *J. Phys. Chem.*, **70**, 2628(1966).

(16) L. Wilhelmy, *Ann. Phys.*, **119**, 177(1863).

(17) H. Schonhorn and F. W. Ryan, *J. Phys. Chem.*, **70**, 3811(1966).

(18) J. A. Pople and D. L. Beveridge, "Approximate Molecular Orbital Theory," McGraw-Hill, New York, N.Y., 1970, p. 114.

ACKNOWLEDGMENTS AND ADDRESSES

Identification of Desmethylcyproheptadine-10,11-epoxide and Other Cyproheptadine Metabolites Isolated from Rat Urine

A. FRIGERIO ˣ, N. SOSSI, G. BELVEDERE, C. PANTAROTTO, and S. GARATTINI

Abstract ☐ Desmethylcyproheptadine-10,11-epoxide, cyproheptadine-10,11-epoxide, and desmethylcyproheptadine were identified in rat urine collected after administration of 40 mg/kg ip of cyproheptadine. Mass spectrometric characterization confirmed the structure of these metabolites.

Keyphrases ☐ Cyproheptadine—isolation of metabolites from rat urine, identification of desmethylcyproheptadine-10,11-epoxide, metabolism pathways suggested ☐ Desmethylcyproheptadine-10,11-epoxide—identification as a metabolite of cyproheptadine in rat urine, isolation of other metabolites ☐ Metabolism—cyproheptadine, identification of desmethylcyproheptadine-10,11-epoxide and other metabolites, rat urine

In previous studies it was established that carbamazepine (I) can be transformed in humans and rats into an epoxide in the 10,11-double bond (II) (Scheme I) (1). This finding suggested that other

chemicals with similar structures could be metabolized to form an epoxide.

As a part of a systematic investigation, this paper describes the identification of some metabolites of