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A comparison of two contact angle measurement methods and inverse gas chromatography to assess the surface energies of theophylline and caffeine

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Abstract

The wettability of two powders has been assessed by three methods and values for surface energies have been determined. Two contact angle methods have been used, both of which are variations of the Wilhelmy plate approach. One method was to use compressed plates of powder, the other to stick uncompacted powder to a glass plate (as a support). It was found that the method using adhesion to the glass plate gave more realistic values for the surface energy of the powders than did the compacted plate approach. It can be concluded that the use of plates with powder adhered to the surface offers a significant advantage for contact angle assessment. The third method used was inverse gas chromatography, which has seen little application to date in the pharmaceutical sciences. It was found that the dispersion component of surface energy obtained by inverse gas chromatography (IGC) was almost identical to the equivalent (Lifshitz-van der Waals) term obtained by use of the contact angle data from the glass side method. The acid-base (polar) contributions to surface energy were not directly comparable, due to the different data manipulation methods associated with contact angle and IGC data. It can be concluded that the little used methods of adhering powder to an inert support for contact angle measurement and IGC have great promise as means of assessing the surface properties of powders. Both these techniques have the advantage of not requiring powder compaction (or any other surface damaging treatment) prior to use.

Keywords: Contact angle; Inverse (phase) gas chromatography; Surface energy; Wettability

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1. Introduction

Measuring the contact angle (Θ) of powders is a useful indicator of wettability, giving information on surface energetics. All the techniques used to measure contact angles on powders have limitations (Buckton, 1995). Given the value of surface energy terms as a means of predicting the interaction between different materials it is desirable to gain clear insights into the relative merits

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of different contact angle techniques. In this study, a comparison is made between two contact angle methods and an alternative approach to the study of powder surface properties, inverse gas chromatography. The two contact angle methods are variations on a similar theme, one being the use of rectangular powder compacts as Wilhelmy plates, the other being the use of powder dusted onto a flat adhesive surface as a Wilhelmy plate. These provide an interesting comparison as the influence of compaction and possibly bed porosity can be probed. The use of powder adhered to a glass slide as a Wilhelmy plate has only been described once previously to our knowledge (Shanker et al., 1995) (although the use of powder precipitated from solution has been described for use as a thin layer wicking system (Van Oss et al., 1992); however, such precipitation will give a surface which will be influenced by the precipitation process rather than any previous processing history of the original powder). Wilhelmy plate contact angle techniques are of interest as they offer an operator independent contact angle. The other technique, inverse gas chromatography (IGC), has only recently been applied to pharmaceutical systems (Ticehurst et al., 1994). It is said that IGC offers the most sensitive approach to powder surface characterisation, and as such it is interesting to compare the data yielded from the different approaches.

2. Materials and methods

Theophylline and caffeine were both obtained from Sigma. The surface area of each was calculated by the BET method at 77 K with nitrogen as adsorbate.

2.1. IGC

Inverse gas chromatography was carried out using a Perkin Elmer F33 gas chromatograph. Nitrogen was used as the carrier gas, maintained at a constant pressure (inlet pressure) with the flow rate measured using a bubble flowmeter. The temperature of the fan oven housing the column was maintained at 35°C and monitored using a max/min thermometer. The injection port temperature was held at 100°C.

Each double-looped glass column (5 mm in diameter, 130 cm in length) was silanated in order that the glass surface would be hydrophobic and non-interactive with any gaseous probe (Mohammad and Fell, 1982).

The powder bed was packed sufficiently so that there were no air pockets seen, with about 3 cm of empty tube at either end. Silanated glass wool was packed into each end of the column. The powder bed was then completely dried by inserting the column onto the gas chromatography apparatus and passing dry nitrogen (35 kN/m^2) over the powder at an oven temperature of 100°C for 24 h.

The powder bed was allowed to settle for 24 h at an oven temperature of 35°C and a nitrogen flow of 28 kN/m^2. The oven temperature was monitored with a max/min thermometer, ensuring that the temperature of the column was constant throughout the experiment. A reference probe consisting mainly of methane (gas tap) was firstly injected into the column, since it would have no interaction with the column whatsoever, giving a minimum retention time (t_0). This reference was repeated at several times throughout the experiment to ensure that the retention times were constant and therefore none of the conditions had altered.

The test probes used were hexane (Sigma), heptane (Sigma), octane (Sigma), acetone (Aldrich), ethyl acetate (Aldrich), chloroform (Aldrich), tetrahydrofuran (Aldrich), and all 99 + % pure.

For each probe, 1 μl was pulled up into a clean 10 μl Hamilton syringe several times before being emptied. The syringe was then used to inject 1 μl of air (containing minute concentrations of gaseous probe) into the column. The important assumption is that the gas probes were at infinite dilution over the powder column, since their retention times would be altered if too concentrated. That is to say, if all the interaction points on the powder surface are occupied, the remaining gas will pass unhindered out of the column thus artificially lowering their retention times. The retention times of each probe were measured using a flame ionisation detector and recorded on a chart recorder. Retention times were taken from the time of injection to the maximum peak height.

2.2. *Wilhelmy plate*

The test powder (300 mg) was spread evenly, to ensure an even porosity, into a polished rectangular die and compressed using the Specac press for 2 min at 3 × 10^{-3} kN of force.

Once made, the compact's perimeter was measured using a micrometer. The compact was subsequently attached to the balance loop of the microbalance in the Cahn Dynamic Contact Angle Analyser. The probe liquid was placed in a clean glass beaker inside the water bath underneath the compact. The water bath was maintained at 25°C.

The computer was programmed to raise and lower the platform a distance of approximately 10 mm at a constant speed of 151.7 μm/s. Force data were collected by the interfaced computer at regular intervals as a function of platform height. The resultant force-depth isotherms were used to calculate the contact angle of the powder with the liquid according to Eq. (1).

$$\cos \Theta = mg/p\gamma_{LV} \qquad (1)$$

where m is mass (mg), g is acceleration due to gravity (g/m^2), p is the perimeter of the solid compact (mm) and γ_{LV} is the surface tension of liquid (mJ/m^2)

2.3. *Glass slide method*

Glass slides were sprayed with an adhesive (3M Spray Mount Adhesive), and left for 1 min, after which they were shaken briefly in a container of the test powder. On removal, excess powder was blown off each slide using nitrogen (Shanker et al., 1995).

The contact angle for each coated glass slide was measured as described above using three polar liquids (distilled water, formamide (Sigma) and ethylene glycol (Aldrich)) and one apolar liquid (diiodomethane; Sigma).

3. Results and discussion

3.1. *IGC calculations*

The net retention volume V_N is determined as follows:

$$V_N = JF(t_r - t_0) \qquad (2)$$

(F is the carrier gas flow rate (ml/min), J is the correction factor due to pressure differences, t_r is the retention time of the probe, t_0 is the retention of the non-interacting standard) where

$$J = 3\{(P_i/P_o)^2 - 1\}/2\{(P_i/P_o)^3 - 1\} \qquad (3)$$

where P_i is the pressure at the inlet of the column and P_o is the atmospheric pressure since:

$$RT \ln V_N = 2N\,(\gamma_S^D)^{0.5}\cdot a(\gamma_L^D)^{0.5} + K \text{ (intercept)} \qquad (4)$$

where a is the molecular area of adsorbed molecule (Schultz et al., 1987), R is the gas constant, T is the absolute temperature, K is RT ln ($P_{s.g.}/\pi.w.S_a$), γ_S^D is the dispersion component of the surface energy of the solid (which is identical to the term described as a Lifshitz-van der Waals component by Van Oss and co-workers which is described in the next section) and γ_L^D is the dispersion contribution to the surface energy of the liquid.

A series of n-alkanes are used as apolar probes. Plotting a graph of RT ln V_N against $a.(\gamma_L^D)^{0.5}$ allows the dispersive interaction force of the test powder (γ_S^D) to be calculated from the gradient of the straight line as shown in Fig. 1.

To determine the polar character of the powders, a selection of polar probes all with known acid-base characters are used. In this case, a plot of RT ln V_N against ΔH^d_{vap}, the dispersive component of the heat of vaporisation of probes, was used (Chehimi and Pigoislandureau, 1994). The distance separating each polar probe from the point on the apolar straight line vertically below (Fig. 2) corresponds to the specific acid/base free energy of adsorption, $\Delta G_{a\text{-}sp}$, data for which are shown in Table 1.

Gutmann (1978) originally theorised that the polar interaction could be expressed in terms of acid-base properties. Each probe could be given

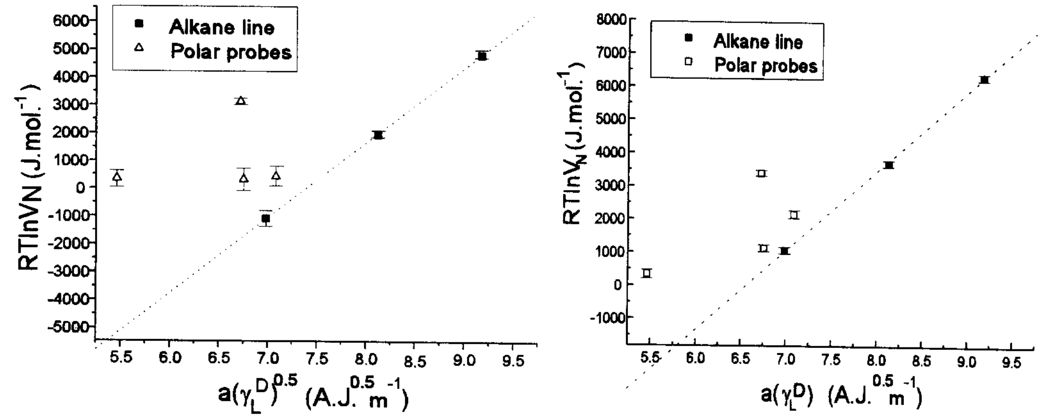

Fig. 1. (a) Passage of gaseous polar probes over a theophylline powder column at 35°C. (b) Passage of gaseous polar probes over a caffeine powder column at 35°C.

two values (Gutmann numbers) which were equivalent to the probe's electron donating (base), *DN*, and the electron accepting (acid), *AN*, properties. Riddle and Fowkes (1990) determined that part of the electron acceptor value, *AN*, was due to dispersive forces; therefore, *AN** was developed, being solely due to polar interaction forces. Assuming negligible entropic effects (Ticehurst et al., 1994), the specific free energy of adsorption, $\Delta G^{\circ}_{\text{a-sp}}$, can be used to calculate acid-base parameters according to:

$$-\Delta G^{\circ}_{\text{a}-\text{sp}} = K_A \cdot DN + K_D \cdot AN^* \qquad (5)$$

Rearranging allows a suitable plot of $-\Delta G^{\circ}_{\text{a-sp}}/AN^*$ against DN/AN^* to determine the acid (K_A) and base (K_D) parameters of the test powder (Fig. 3; Table 2).

$$\therefore -\Delta G^{\circ}_{\text{a}-\text{sp}}/AN^* = K_A \cdot (DN/AN^*) + K_D \qquad (6)$$

Since the surface areas (S_a) of the two powders were known, it was possible to calculate values for the total free energy of adsorption of each vapour onto each solid (Table 3) using the following equation:

$$\Delta G^{\circ}_{a} = -RT \ln(V_N \cdot P_{s.g}/\pi.w.S_a) \qquad (7)$$

where $P_{s.g} = 1.013 \times 10^5$ Pa, $\pi = 3.38 \times 10^{-4}$ Nm^{-1} (DeBoer, 1953) and w is the weight of adsorbent in the column.

The total free energy of adsorption data (Table 3) represents the sum of the polar and non-polar free energy of adsorption of the two powders with each probe. Since the polar energy value is known, the non-polar free energy can be determined with a simple subtraction.

3.2. Surface energy calculations from contact angle data

The following adaption of Young's equation is used for surface energy calculations involving contact angles:

$$\gamma_L^{TOT}(1+\cos\Theta) = 2((\gamma_S^{LW} \cdot \gamma_L^{LW})^{0.5} + (\gamma_S^{+} \cdot \gamma_L^{-})^{0.5} + (\gamma_S^{-} \cdot \gamma_L^{+})^{0.5}) \qquad (8)$$

where γ_L^{TOT} is the total surface energy of the liquid, being the sum of the Lifshitz-van der Waals contribution (γ_L^{LW}) and the acid-base contribution (γ_L^{AB}), the acid-base contribution being derived from the electron donor and electron acceptor terms (γ_L^{-}. and γ_L^{+}) according to Eq. (9) (Van Oss et al., 1987, 1988).

$$\gamma_L^{AB} = 2\,(\gamma_L^{-} \cdot \gamma_L^{+})^{0.5} \qquad (9)$$

The terms with subscript S in Eq. (8) have the same meaning as described above for those with subscript L, except describing the respective contributions to the solid rather than the liquid. (As noted above the Lifshitz-van der Waals term which is used in the work of Van Oss et al. and

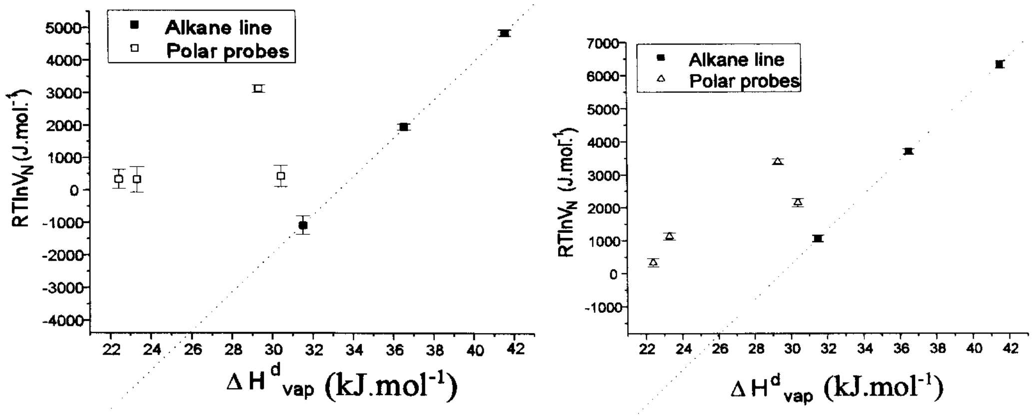

Fig. 2. (a) Passage of gaseous polar probes over a theophylline powder column at 35°C. (b) Passage of gaseous polar probes over a caffeine powder column at 35°C.

described in this section with the conventional notation is equivalent to the dispersive contribution to surface energy which is used in IGC (and elsewhere) conventionally denoted by the symbol γ^{D}. Within the context of this work these two symbols can be considered interchangeable.)

3.3. Wilhelmy plate method

The values for the contact angles obtained using water, ethylene glycol and formamide on a compressed wafer of powder as a Wilhelmy plate are given in Table 4. Diiodomethane (apolar) spread over the two powder compacts immediately on contact (contact angle of zero).

Eq. (8) was used incorporating the values from three polar liquids, thus allowing the surface energies of the two powders to be calculated without contact angle data from a non-polar liquid (Table 5).

Table 5 shows all the powder compacts to have an unusually large dispersive component, which is greater than that of diiodomethane (50.8 mJ/m^2). In theory, this would explain why diiodomethane spreads over each compact immediately on contact. It follows that the apparent high value for the dispersive nature of the surface which has been obtained using the contact angle data for the polar liquids on the solids (Table 5) is in keeping with the zero contact angle for the apolar liquid on the surface. The internal consistency of these independent data sets is encouraging, but cannot be taken to imply that the data are a true reflection of the nature of the material (i.e. the material in a non-compacted form). It has been shown previously (Buckton et al., 1995) that the Wilhelmy plate compact approach gives different contact angle data for a gold coated compact of powder than it does for a gold coated glass plate. As the surface energy of the two gold coated

Table 1
Specific free energy of adsorption of polar probes and the dispersive component of caffeine and theophylline at 35°C

	γ_S^D (mJ/m^2)	Acetone	Ethyl acetate	THF	Chloroform
Caffeine	39.9				
$-\Delta G_{a\text{-}sp}$ (kJ/mol)		4.07	3.51	4.40	1.67
$SD_{(n-1)}$ ($n = 5$)	1.49	0.13	0.84	0.11	0.12
Theophylline	50.76				
$-\Delta G_{a\text{-}sp}$ (kJ/mol)		6.80	5.50	6.25	2.14
$SD_{(n-1)}$ ($n = 5$)	4.17	0.30	0.12	0.40	0.33

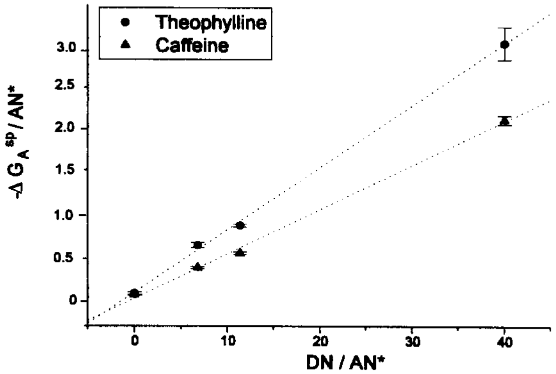

Fig. 3. Plot of $-\Delta G_A^{SP}/AN^*$ against DN/AN^* of polar probes for theophylline and caffeine.

surfaces was assumed to be the same, it was argued that the error was due to the geometry of the powder compact, and perhaps associated with a serious error in the true perimeter of the plate due to substantial penetration into the compact by the liquid. Such an error in effective perimeter may explain the consistent observation in these data that the solid has a very high apolar surface energy (which, given the nature of the solids, seems unrealistic).

3.4. Glass slide approach

The contact angle data for the four liquids on the two test powders are presented in Table 6.

In contrast to the compressed plate of powder (Table 5) diiodomethane did give a contact angle (of greater than zero) with each powder, suggesting that the dispersive component of the powders were all below 50.8 mJ/m^2 (the surface energy of diiodomethane). This was found to be the case when the surface energies for theophylline and caffeine were calculated using the contact angle data for the three polar liquids (water, ethylene glycol and formamide) (Table 7).

Table 2
Acid-base parameters of the test powders from Fig. 3

Powder	$RT\ln V_N$ against ΔH_{vap}^{d}		
	K_A (acid parameter)	K_D (Basic parameter)	r
Theophylline	0.0719	0.1052	0.999
Caffeine	0.0512	0.0344	0.999

3.4.1. The influence of coverage of the slide by the powder on the measured contact angle

A concern over the use of the approach of coating the glass slide with powder is the influence of any uncoated adhesive. In an attempt to assess the influence of this, plates were prepared such that varying amounts of their surface was covered with powder (caffeine). This was achieved by covering one region totally, whilst leaving another region with just adhesive. The contact angle data are shown in Table 8 for different extents of powder contact.

It can be seen that as the percentage of caffeine coverage decreases to zero (all adhesive), the contact angle increases in a linear fashion, this is in keeping with the well known Cassie equation, in that the observed contact angle is a weighted mean of the contact angles for both adhesive and powder. This does not prove that the area where powder is coated on the glass is a total coverage, but shows it to be a consistent value which is distinctly different from the contact angle obtained for the adhesive. It is reasonable to assume that this is a fair reflection of the surface properties of uncompacted powder.

Table 3
The total free energy of adsorption values of the test powders with a selection of probes (kJ/mol)

	Hexane	Heptane	Octane	Acetone	Ethyl acetate	THF	Chloroform
Caffeine	48.0	50.6	53.2	47.3	50.3	48.1	49.1
Theophylline	47.2	50.3	53.2	48.7	51.5	48.6	48.8

Table 4
Contact angles of the test powders using the Wilhelmy plate method ($n = 5$)

	Caffeine (SD_{n-1})	Theophylline (SD_{n-1})
Water (72.8) (mJ/m^2)	29.09 (2.43)	47.62 (2.97)
Ethylene glycol (48.0) (mJ/m^2)	17.98 (1.52)	15.99 (3.00)
Formamide (58.0) (mJ/m^2)	22.77 (2.50)	27.89 (2.57)

Table 6
Contact angles of the test powders using the alternative slide method ($n = 5$)

	Caffeine (SD_{n-1})	Theophylline (SD_{n-1})
Water (72.8) (mJ/m^2)	73.2 (2.97)	77.0 (3.07)
Ethylene glycol (48.0) (mJ/m^2)	33.3 (1.75)	47.9 (2.46)
Formamide (58.0) (mJ/m^2)	44.4 (2.75)	54.0 (3.51)
Diiodomethane (50.8) (mJ/m^2)	49.0 (4.92)	57.4 (2.90)

3.5. Comparison of the three methods

It can be seen that the contact angle method which utilised the glass plate gave data which were more in keeping with the expected order of magnitude of apolar surface energy than did the data from the compacted plates. The approach based on sticking powder to a glass plate seems to be of value despite initial reservations about extent of coverage and risks of the adhesive spreading over the powder. There are many advantages to adhering the powder to a glass slide, i.e. the experiment can be done with small quantities of powder, the material is not altered in form (as would happen with compaction or precipitation of the material) and the approach is rapid and simple to perform.

The IGC approach was found to give an almost identical value for the apolar aspect of surface energy for the sample of caffeine as was obtained using contact angles on the coated glass plate. The values for the apolar surface energy of theophylline differed by only 7 mJ/m^2 (Tables 1 and 7), which is still in close agreement given experimental error and the fact that the two techniques are so different in nature. If in future experiments such differences are found to be outside the realms of error that can be expected between two different techniques, a reason may be the fact that IGC can suffer from the preferential interaction of the infinitely dilute vapour with high energy sites on the surface of the solid.

Table 5
Surface energy components of the test powders (mJ/m^2)

	γ_{LV}^{TOT}	γ_S^{LW}	γ_S^{AB}	γ_S^+	γ_S^-
Theophylline	73.1	73.1	0	0	47.3
Caffeine	60.2	60.2	0	0	26.5

Regarding the acid/base nature of the surface, there are fundamental differences between the data sets which are obtained from the two approaches which will ultimately need to be resolved if comparisons are to be made. The acid-base nature from contact angle data is based on the assumption made by Van Oss and co-workers (e.g. Van Oss et al., 1987, 1988) that all acid-base data for unknowns should be quoted by reference to an arbitrary standard. Water was selected as a standard and was allocated a surface energy of electron donor = electron acceptor term = 25.5 mJ/m^2. It is perfectly reasonable to describe all data to a standard, even if that standard cannot be proved as being correct; however, it is not possible to relate the IGC data to this as they are not determined on the same set of assumptions.

Table 7
Surface energy components of the test powders using the contact angle data for the three polar liquids from the glass slide method (mJ/m^2)

	γ_{LV}^{TOT}	γ_S^{LW}	γ_S^{AB}	γ_S^+	γ_S^-
Theophylline	44.4	43.8	0.7	0.0	6.7
Caffeine	47.9	44.5	3.4	0.5	5.9

Table 8
Contact angles (degrees) of water with slides variably covered by caffeine

% caffeine coverage	0	25	50	75	100
Contact angle	89.7	84.5	81.4	78.7	73.2
SD_{n-1} ($n = 5$)	1.1	1.6	3.2	1.2	3.0

4. Conclusion

The value of the simple approach of adhering powder to a glass plate to assess contact angles has been demonstrated. The use of compacts of powder as Wilhelmy plates results in data which are internally consistent, and as such can be used to make comparisons between materials, but which are probably displaced from the true values of surface energy of the solid.

There is very good agreement between the values for the apolar terms of surface energy that have been obtained by the coated glass slide contact angle approach and by IGC. This gives encouragement that both techniques are measuring the same aspects of the solids nature. Furthermore both techniques do not require excessive powder treatment (e.g. compaction) prior to use and as such assess surface energies which reflect the powders in their true state. These two techniques offer considerable advantages in pharmaceutical materials characterisation.

Efforts in the future should be directed towards correlating the acid-base data obtained by the techniques of contact angle and IGC for a range of solid samples.

Acknowledgements

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