

# An improved characteristic molecular volume parameter for linear solvation energy relationships of acyclic alkanes<sup>†</sup>

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**ABSTRACT:** Boiling point numbers ( $Y_{BP}$ ) of acyclic alkanes serve as the basis for an improved characteristic molecular volume parameter ( $V_Y$ ) for use in linear solvation energy relationships. These  $V_Y$  values correlate much better than do Abraham–McGowan  $V$  values with a wide range of physical properties of acyclic alkanes, including vapor pressure,  $\log L^{16}$  values, HPLC and GC retention indices, and aqueous solubilities. The  $V_Y$  parameter may be determined easily from literature boiling point data. Alternatively, it may be calculated from boiling points predicted by a wide variety of group contribution, connectivity, or computational methods when the experimental boiling point is unavailable. Thus, the results reported here enable fundamental physical properties of acyclic alkanes to be predicted directly from molecular structure. Copyright © 2006 John Wiley & Sons, Ltd.

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**KEYWORDS:** LSER; acyclic alkanes; boiling point numbers; characteristic molecular volume; vapor pressure; solubility; retention indices; partitioning

## INTRODUCTION

The linear solvation energy relationship (LSER) method, introduced by Kamlet and Taft<sup>1</sup> and subsequently developed by Abraham,<sup>2</sup> characterizes the interaction of a solute molecule with its environment through a correlation in the form of Eqn (1).<sup>3</sup>

$$P = c + vV + eE + sS + aA + bB \quad (1)$$

Here  $P$  represents a property, such as a partitioning equilibrium, of a solute in a particular environment. The constants  $c$ ,  $v$ ,  $e$ ,  $s$ ,  $a$ , and  $b$  are characteristic of the medium, while the parameters  $V$ ,  $E$ ,  $S$ ,  $A$ , and  $B$  are empirical descriptors of the solute. The first three parameters represent non-specific interactions of the solute with the system, that is, interactions that do not depend on a particular orientation of the solute with surrounding molecules.  $V$  is termed the characteristic volume of the solute<sup>4</sup> and is generally taken to be a

measure of cavitation and generalized dispersion interactions.  $E$  is the excess molar refraction of the solute in comparison with a hydrocarbon of the same molecular volume and is thought to model interaction of the solute with the system through  $\sigma$  and  $n$  electrons.  $S$  is a measure of the solute's dipolarity/polarizability and is said to characterize the interaction of the solute with the surrounding medium through non-specific dipole–dipole or dipole-induced dipole interactions.<sup>5</sup> The specific (orientation-dependent) interactions are characterized by parameters  $A$  and  $B$ , which respectively represent the sums of the hydrogen bond donor and hydrogen bond acceptor characteristics of the solute.

The LSER approach has been used to develop predictive equations for a wide variety of chromatographic and phase transfer processes.<sup>6</sup> In such cases, the LSER models the interactions of a set of solutes of diverse structure with a single solvent system or their transfer between two solvents or between a solvent and another phase. Recently, however, we began to explore the viability of the LSER approach for the estimation of physical properties of pure substances, such as the surface tension<sup>7</sup> and vapor pressure<sup>8</sup> of organic liquids and the work of interfacial adhesion of organic liquids with water.<sup>9</sup> In each case, we found a useful correlation of physical properties with the Abraham parameters. However, our results suggested that such correlations

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could be improved through a modification of the molecular volume parameter,  $V$ , for acyclic alkanes.

Acyclic alkanes have zero values for all of the solute parameters in Eqn (1) except  $V$ , and the  $V$  values for all isomers of a particular acyclic alkane are the same.<sup>2,10</sup> Therefore, all isomeric acyclic alkanes have identical predicted values for any correlation in the form of Eqn (1). Consider vapor pressure, for example, Fig. 1 (upper) shows the correlation of literature values<sup>8</sup> of  $\log P_{\text{vap}}$  for 53 acyclic alkanes (having from six to ten carbon atoms) with the  $\log P_{\text{vap}}$  values predicted with Eqn (2). Clearly there is a degree of correlation between predicted and literature values, but the 'stair-step' appearance of the plot results from the fact that all of the isomers of a given

alkane have the same predicted value for  $\log P_{\text{vap}}$ . In particular, the isomeric decanes have experimental  $P_{\text{vap}}$  values that differ by a factor of more than 6, but they are all predicted by Eqn (2) to have the same vapor pressure. Thus, it is readily apparent that the  $V$  parameter fails to account fully for the variation in  $\log P_{\text{vap}}$  for these compounds.

$$\log P_{\text{vap}}(\text{Pa}, 298 \text{ K}) = 7.597 - 3.290 V \quad (2)$$

$$(n = 53, R^2 = 0.922, \text{ standard error} = 0.163, F = 698)$$

In order to improve such LSER correlations, we sought to develop an improved characteristic volume parameter for acyclic alkanes that would significantly improve the correlations for these compounds without loss of the chemical significance of the resultant LSER. To that end, we report here an improved characteristic volume parameter,  $V_Y$ , which is numerically equal to  $V$  for  $n$ -alkanes yet is sensitive to the effects of branching in nonlinear alkanes.

## RESULTS AND DISCUSSION

A primary requirement for a characteristic volume parameter is that it be based either on readily available experimental data or on reliable empirical or theoretical estimation methods. Normal boiling points are the most widely reported and often the most accurately determined physical properties of alkanes, so we chose normal boiling point as the basis for the new characteristic molecular volume parameter. The key relationship between boiling point and molecular structure needed for this work was found in a 1938 paper by Kinney.<sup>11</sup> Kinney used the relationship in Eqn (3) to predict boiling points from a 'boiling point number' ( $Y$ ) that he calculated from structure by a group contribution method.

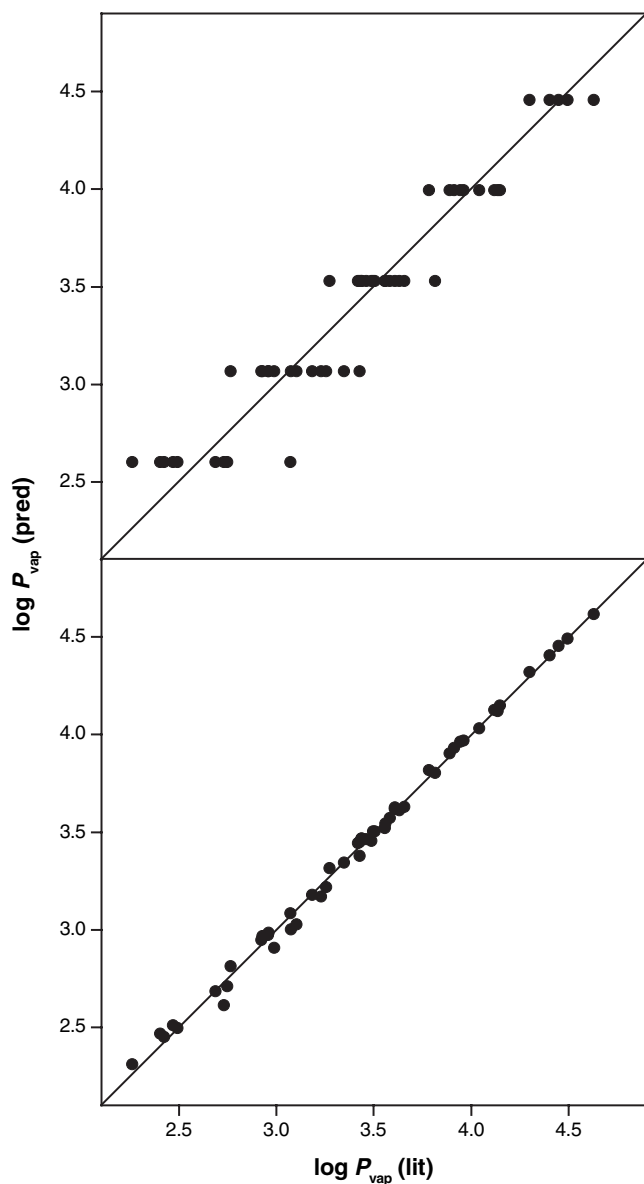
$$\text{BP}(K) = 230.14 Y^{1/3} - 270 \quad (3)$$

Kinney's approach to estimating boiling points has been supplanted by other predictive methods, but Eqn (3) nonetheless provides a valuable link between structure and properties. Therefore, we inverted Eqn (3) to produce Eqn (4), which we used to calculate  $Y_{\text{BP}}$  values, that is,  $Y$  values based on experimental boiling points. The resulting  $Y_{\text{BP}}$  values for  $n$ -alkanes from propane to hexadecane are directly proportional to the corresponding  $V$  values, as is shown in Eqn (5).

$$Y_{\text{BP}} = \left( \frac{\text{BP} + 270}{230.14} \right)^3 \quad (4)$$

$$V(\text{for } n\text{-alkanes}) = 0.0498 Y_{\text{BP}} + 0.0015 \quad (5)$$

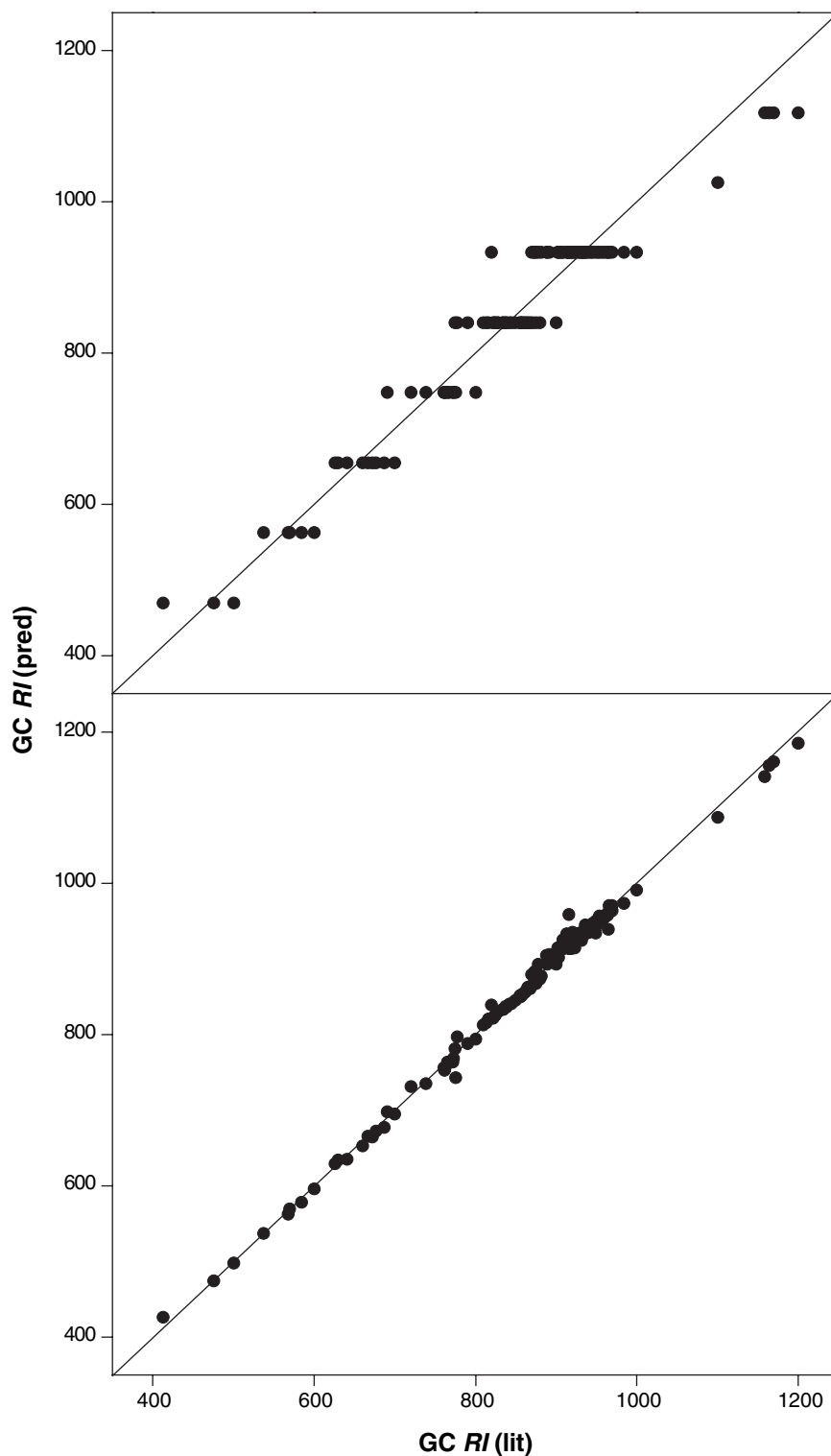
$$(n = 14, R^2 = 0.9999, \text{ standard error} = 0.0056, F = 213915)$$



**Figure 1.** Correlation of literature values of  $\log P_{\text{vap}}$  with values predicted using Eqn (2) (upper) and Eqn (6) (lower) for a set of 53 linear and branched acyclic alkanes having from six to ten carbon atoms. In each case the solid line represents a perfect correlation of literature and predicted values

We then used Eqn (5) and  $Y_{BP}$  values calculated from literature boiling points to calculate  $V_Y$  values (for  $V$  values determined from  $Y$  values) for 168 branched alkanes having from four to twelve carbon atoms. The

resulting values of  $Y_{BP}$  and  $V_Y$ , along with the corresponding values of  $V$ , are available in the Supplementary Material. Figure 1 (lower) shows that the use of  $V_Y$  instead of  $V$  in a correlation of  $\log P_{vap}$  values for the



**Figure 2.** Correlation of literature GC RI values of linear and branched alkanes having from four to nine carbon atoms with values predicted using Eqn (7) (upper) and Eqn (8) (lower). In each case the diagonal line represents a perfect correlation of literature and predicted values

same compounds produces a much improved relationship [Eqn (6)].

$$\log P_{\text{vap}}(\text{Pa}, 298 \text{ K}) = 7.675 - 3.528 V_Y \quad (6)$$

$$(n = 53, R^2 = 0.996, \\ \text{standard error} = 0.036, F = 13241)$$

The boiling points of alkanes are closely related to their gas chromatographic retention index (GC *RI*) values, suggesting that GC *RI* data might also correlate with  $V_Y$  values. Literature GC *RI* values<sup>12</sup> determined with a squalane stationary phase at 100° do correlate somewhat with  $V$  values, as shown in Eqn (7), but the correlation with  $V_Y$  is indeed substantially better [Eqn (8)], as is evident in Fig. 2.

$$\text{GC } RI = -64.525 + 657.2 V \quad (7)$$

$$(n = 137, R^2 = 0.940, \\ \text{standard error} = 31.48, F = 2121)$$

$$\text{GC } RI = -63.868 + 694.0 V_Y \quad (8)$$

$$(n = 137, R^2 = 0.995, \\ \text{standard error} = 8.78, F = 28901)$$

Log  $L^{16}$  values of alkanes<sup>13</sup> are conceptually related to GC *RI* values determined with a hydrophobic stationary phase, since in both cases there is a partitioning of a substance between the vapor phase and a lipophilic liquid phase. Indeed, we find correlations of literature log  $L^{16}$  values with both  $V$  and  $V_Y$  as shown in Eqns (9) and (10). Again, however, the correlation is much better and much more precise when based on  $V_Y$  than when based on  $V$ , as is shown in Fig. 3.

$$\log L^{16} = -0.894 + 3.535 V \quad (9)$$

$$(n = 22, R^2 = 0.937, \text{standard error} = 0.178, F = 296)$$

$$\log L^{16} = -0.748 + 3.567 V_Y \quad (10)$$

$$(n = 22, R^2 = 0.998, \\ \text{standard error} = 0.035, F = 8210)$$

The partitioning in reversed-phase HPLC is quite different from that in GC because the mobile phase is a polar liquid. Nevertheless, Fig. (4) shows that we also find a much better correlation [Eqn (12)] of HPLC retention indices of acyclic alkanes<sup>14</sup> with  $V_Y$  than with  $V$  [Eqn (11)].

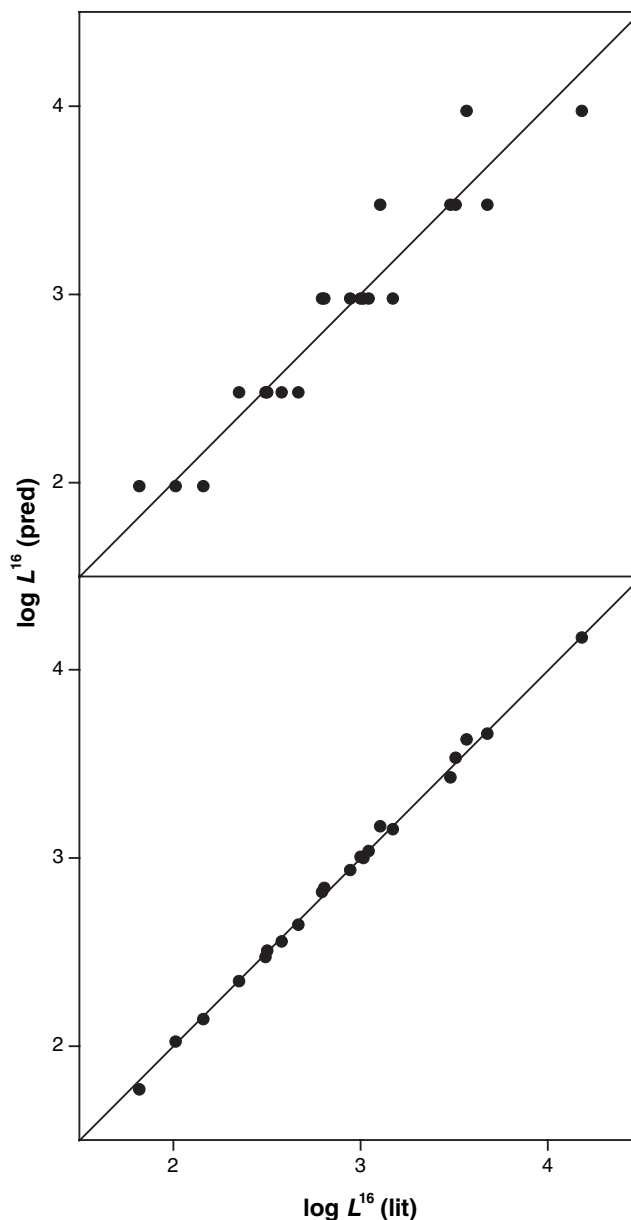
$$\text{HPLC } RI = -69.53 + 659.6 V \quad (11)$$

$$(n = 48, R^2 = 0.952, \text{standard error} = 29.72, F = 907)$$

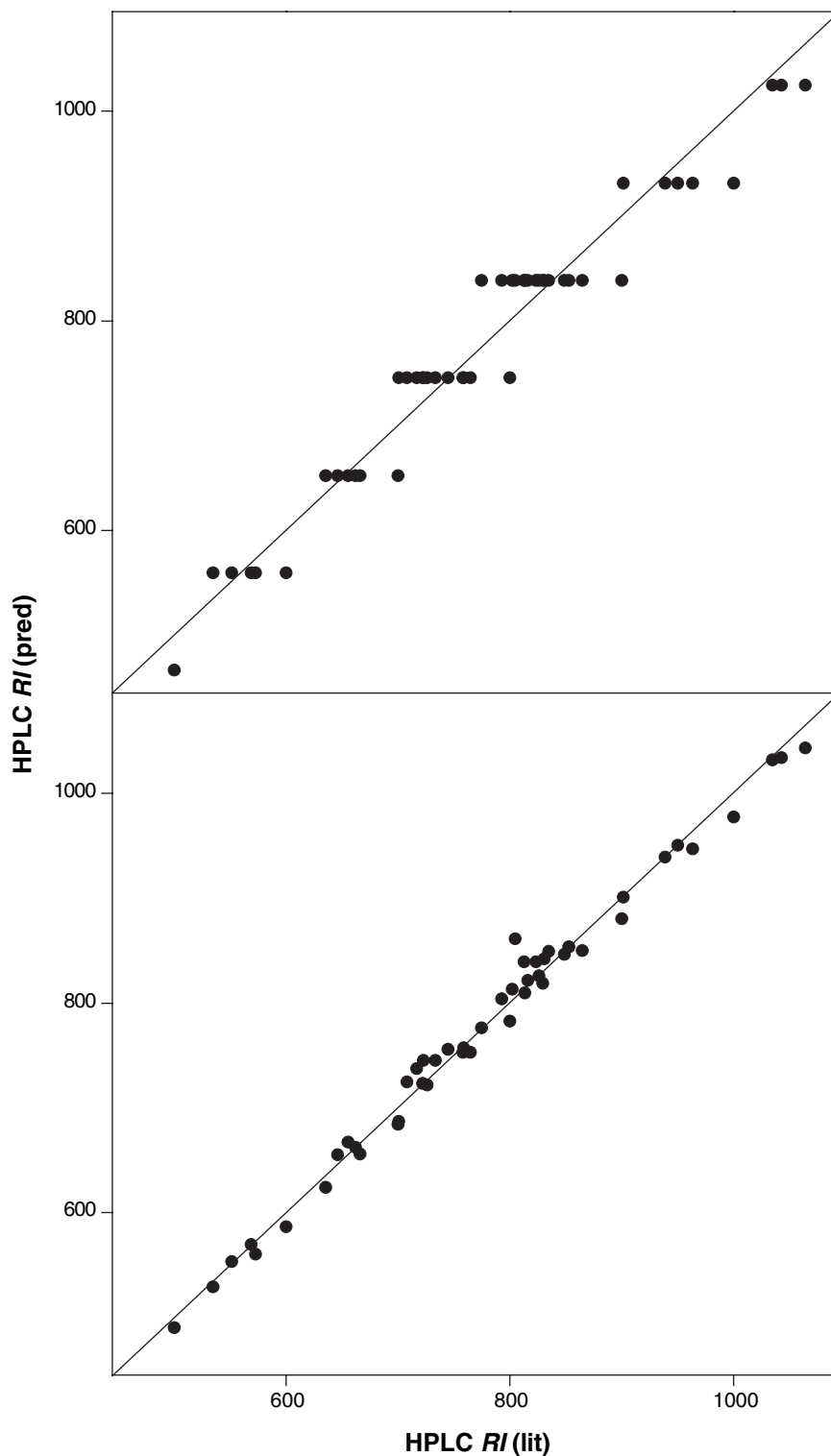
$$\text{HPLC } RI = -65.98 + 686.5 V_Y \quad (12)$$

$$(n = 48, R^2 = 0.988, \\ \text{standard error} = 14.86, F = 3765)$$

The correlation of HPLC *RI* values with the  $V_Y$  parameter suggests that  $V_Y$  might also be used to model the properties of alkanes in other polar environments. Indeed, literature values for the solubilities of alkanes in water<sup>15</sup> can be modeled much better by  $V_Y$  than by  $V$ , even when the data are reported in units that are not strictly thermodynamic. We have also found that  $V_Y$  values correlate better than do  $V$  values with log  $L^{\text{MeOH}}$  data reported by Katritzky *et al.*<sup>16</sup> with octanol-water partition data reported by Oliferenko *et al.*<sup>17</sup> and with log  $L^{87}$  values reported by Weckwerth *et al.*<sup>18</sup> Details of these correlations are available in the Supplementary Material.



**Figure 3.** Correlation of literature log  $L^{16}$  values of linear and branched alkanes having from five to ten carbon atoms with values predicted using Eqn (9) (upper) and Eqn (10) (lower). In each case the diagonal line represents a perfect correlation of literature and predicted values



**Figure 4.** Correlation of HPLC *R<sub>i</sub>* values of linear and branched alkanes having from five to eleven carbon atoms with values predicted using Eqn (11) (upper) and Eqn (12) (lower). In each case the diagonal line represents a perfect correlation of literature and predicted values

All of these correlations could have been developed using the  $Y_{BP}$  parameter itself since  $V_Y$  is linearly related to  $Y_{BP}$ . Because the Abraham–McGowan  $V$  parameter has long been used in quantitative structure–property relationships, however, we chose to renormalize our

new parameter to make  $V_Y$  numerically equal to  $V$  for the  $n$ -alkanes. This renormalization makes the interpretation of  $V_Y$  transparent as a molecular volume parameter that is adjusted for the subtle differences in intermolecular interactions between linear ( $V_Y = V$ ) and branched

( $V_Y < V$ ) isomeric alkanes. Thus, we believe that it is appropriate to call  $V_Y$  a characteristic molecular volume parameter. Indeed, as a model for net cavitation and dispersion interactions,  $V_Y$  appears to be more characteristic of the intermolecular interactions of acyclic alkanes than is  $V$  itself.

The correlations reported here are based on  $V_Y$  values calculated from experimental boiling points. However, since there are a large number of reliable group contribution, connectivity, and computational<sup>19</sup> methods for the estimation of alkane boiling points, estimation of the value of the  $V_Y$  parameter does not require experimental boiling point data. In principle, therefore, correlations analogous to 8, 10, 12, and 14 can be established and employed to predict fundamental properties of acyclic alkanes directly from molecular structure, without recourse to experimental data.

## CONCLUSIONS

The  $V_Y$  parameter reported here produces significantly better LSERs than does the Abraham–McGowan  $V$  parameter for a wide variety of physical properties of acyclic alkanes, including vapor pressure, water solubility, gas, and liquid chromatographic retention indices, and  $\log L^{16}$  values. Furthermore, the  $V_Y$  parameter may be easily determined either from literature boiling point data or, alternatively, through any of a large number of estimation methods when the boiling point is unavailable. Because of its demonstrated success in the diverse correlations reported here, we recommend consideration of the use of  $V_Y$  instead of  $V$  for all LSER correlations for acyclic alkanes.

## Supplementary material

Plot of literature  $V$  values of  $n$ -alkanes and  $Y_{BP}$  values calculated from boiling points. Table of  $Y_{BP}$ ,  $V$ , and  $V_Y$  values of 180 linear and branched acyclic alkanes. Equations and plots showing correlations of  $-\log S_w$ ,  $L^{MeOH}$ ,  $\log K_{ow}$ , and  $\log L^{87}$  values of acyclic alkanes with both  $V$  and  $V_Y$  values.

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