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Evaluation of the ^{13}C NMR signals of saturated carbons in some long-chain compounds

Gerhard Knothe * and Terry C. Nelsen

National Center for Agricultural Utilization Research, US Department of Agriculture, Peoria, IL 61604, USA

The ^{13}C NMR shift values of saturated carbons in long-chain compounds can be mathematically approximated by equations of the kind:

$$s = -ax^{-b} + cx^{-d} + e$$

which are similar to those for the Lennard–Jones potential. Here s is the chemical shift of a carbon atom and x is the position in the chain of this atom or a functional group influencing its shift value. Equations have been determined for selected saturated carbons of methyl octadecanoate, *cis*- and *trans*-octadecenoic acids, methyl *cis*-octadecenoates, methyl oxo-, methyl hydroxy-, methyl acetoxy- and methyl epoxyoctadecanoates. Excellent correlation of experimental and theoretical data has been achieved (coefficients of determination in most cases >0.99; deviations of calculated shift data from theoretical data in most cases less than 0.1 ppm). These equations can be used for predicting ^{13}C NMR shift values of saturated carbons in compounds with long chains.

Introduction

We are interested in the synthesis of new long-chain compounds with properties that make them attractive for commercial applications. ^{13}C NMR is one of the most powerful methods for structure analysis of such fatty materials and consequently has received considerable attention.[1] Historically, most shift assignments were made empirically by comparison of newly-obtained spectra with existing literature data.

Two notable theoretical approaches exist for explaining the shifts of unsaturated carbons in fatty compounds. One approach is the electric field model[2,3] and approximations of literature data based thereon[4] and the second, more recent, approach is the σ-inductive model,[5–7] which challenges the electric field model.

The shifts of saturated (sp^3) carbons methylene (CH$_2$), methyl (CH$_3$) and those carrying functional groups (for example, C–OH) have been evaluated in terms of additivity rules.[8–10] The chemical shifts in the NMR spectra of various nuclei have been rationalized in terms of intramolecular van der Waals interactions.[11–14] Such interactions are significant in the rationalization of the Lennard–Jones potential, the term for the overall nonbonded potential in determining the total strain energy of a molecule.[15] In the present work, we now suggest that the ^{13}C NMR chemical shifts of long-chain compounds can be approximated and predicted with excellent results by utilizing a simple modified equation otherwise used for describing the Lennard–Jones potential.

Results and discussion

Intramolecular van der Waals interactions, as discussed in the rationalization of NMR chemical shifts of organic compounds, may be of a repulsive or attractive nature, depending on the internuclear distances within the molecule.[11–14] In turn, that causes shielding or deshielding effects in the NMR spectra.

The attractive and repulsive effects are terms in equations determining the overall nonbonded potential V_{nb} in nonpolar molecules.[15] V_{nb} is a contributing term to the determination of the total strain energy V_{tot} of a molecule according to equation (1) (taken from ref. 15) in which the other energy terms represent bond stretching or compression (V_r), bond angle deformations (V_θ), excess energy due to changes of torsion angles from their optima (V_ω), nonbonded energy of atoms 1,3 to each other (V_{UB}), the sum total of the intramolecular electrostatic energy (V_{E}), and solvation energy (V_{S}).

$$V_{\mathrm{tot}} = V_r + V_\theta + V_\omega + V_{\mathrm{UB}} + V_{\mathrm{nb}} + V_{\mathrm{E}} - V_{\mathrm{S}} \qquad (1)$$

For the purposes of this work, the symbol V_{nb} is replaced by s, which directly represents the ^{13}C chemical shift of a specific carbon atom. The equation for s comprising the attractive and repulsive terms is taken in the modified form from ref. 15.

$$s = -ax^{-b} + cx^{-d} + e \qquad (2)$$

In the corresponding equation in ref. 15, r (van der Waals radius) has been replaced by x, which represents the position of a carbon atom in an unbranched chain. The overall nonbonded potential V_{nb} is also termed the Lennard–Jones potential. In cases where $b = 6$ and $d = 12$, this potential has also been called the 6-12 potential. Note that in the Lennard–Jones potential, the exponents b and d have been modified for reasons of improving the empirical fit.[15] The values of $b = 6$ and $d = 12$ were used in the present work. Approximations using eqn. (2) but varying all four parameters a, b, c and d showed that fits leading to coefficients of determination of 0.9999 in most cases could be achieved but this is only a small improvement and is even less in terms of ppm values. The additive term e is the empirical shift value of a specific carbon which would ideally be reached in a chain of infinite length when no other neighbouring carbons except CH$_2$ are present. The parameters a and c were estimated by least-squares multiple regression procedures after b and d were set as 6 and 12, respectively.

When studying the ^{13}C NMR chemical shifts of CH$_2$ carbons in long-chain compounds, it is obvious that the shift values depend significantly on the proximity of a functional group such as CO$_2$Me, C–OH, C=O, C=C, C≡C and epoxy or the remoteness from one end of the molecule. Similar observations hold for the signals of terminal CH$_3$ and some functionalized carbons (for example, C–OH) within the chain. We have now approximated the shifts of these sp^3 carbons by means of eqn. (2) with excellent results. Again, note that other approaches hold for sp^2 and sp carbons.[2–7] Some selected chemical shifts of sp^3 carbons given in the literature are depicted in Figs. 1–6.

For the present discussion, it is convenient to introduce the

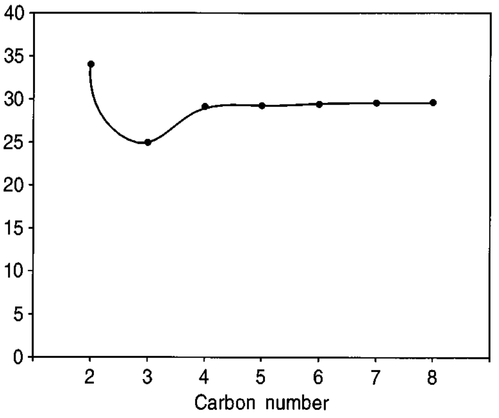

Fig. 1 Plot of the ^{13}C NMR signals of CH_2 (carbons 2–8) in methyl octadecanoate (see also Table 1, data from ref. 16)

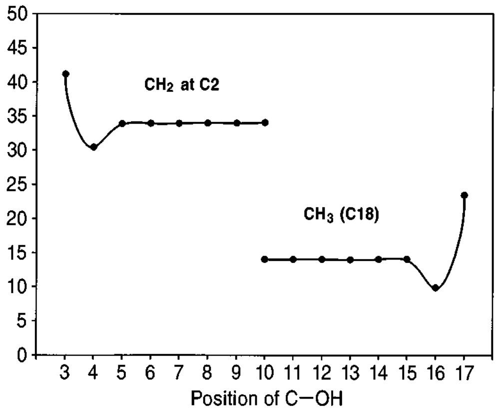

Fig. 4 Plot of the ^{13}C NMR signals of some sp^3 carbons in methyl hydroxyoctadecanoates (see also Table 3; data from ref. 17)

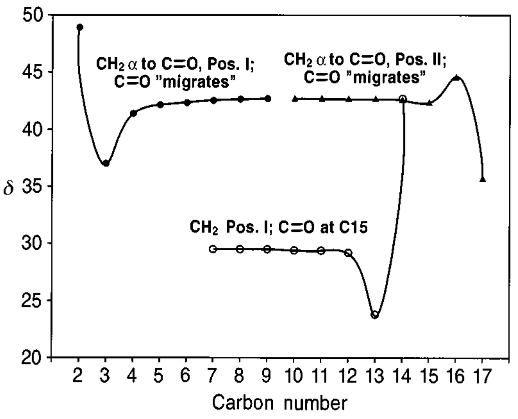

Fig. 2 Plot of the ^{13}C NMR signals of some CH_2 carbons in methyl oxooctadecanoates (see also Table 2; data from ref. 16)

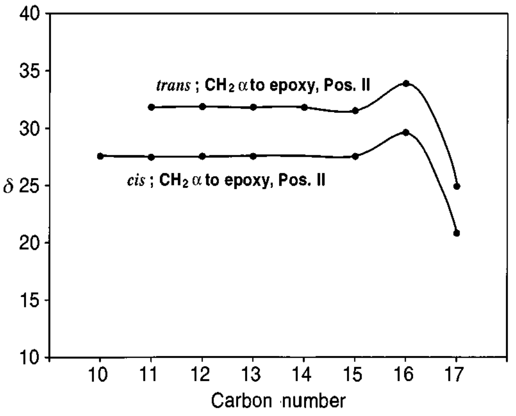

Fig. 5 Plot of the ^{13}C NMR signals of some CH_2 carbons in methyl epoxyoctadecanoates (see also Tables 5–6; data from ref. 18)

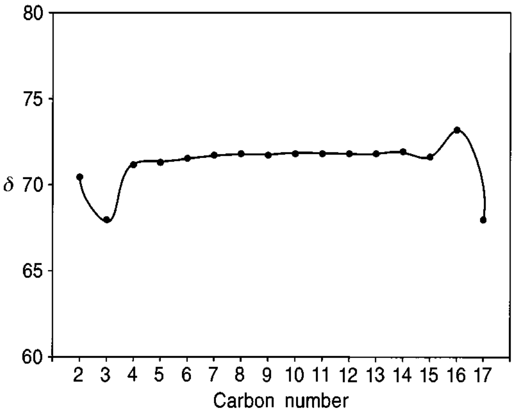

Fig. 3 Plot of the ^{13}C NMR signals of the *C*HOH carbons in methyl hydroxyoctadecanoates (see also Table 3; data from ref. 17)

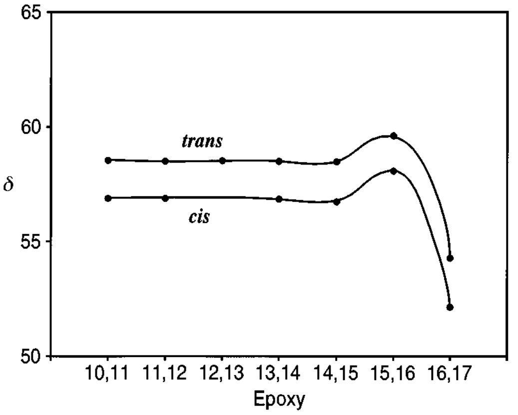

Fig. 6 Plot of the ^{13}C NMR signals of position II epoxy carbons in methyl epoxyoctadecanoates (see also Tables 5–6; data from ref. 18)

terms of a 'static' functional group and a 'dynamic' functional group. A static functional group is defined as one whose location will always remain constant in the chain. In the C18 compounds studied here, the functionality at C1 (usually CO_2Me) and CH_3 at C18 are static functional groups. Dynamic functional groups are those whose position in the chain can vary, *i.e.* C=C, C≡C, C–OH, C=O, *etc.*

Three approaches are possible for demonstrating the present effect. The assignment of $x = 1$ varies depending on the kind of carbon atom being studied in each approach. In the first case, shift values are discussed for consecutive carbons in the chain. For example, $x = 1$ is assigned to C2 in the case of methyl stearate. In the second case, the shift values of static functional groups are discussed for 'migration' of dynamic functional groups away from it. For example, when studying the shifts of CH_3 in compounds of chain length C18, $x = 1$ holds when the dynamic functional group is located at Δ16 for double bonds or C17 in the case of another dynamic functional group. $x = 2$ holds when the double bond has 'migrated' to Δ15 or the other functional group to C16. Some examples are the evaluations of terminal CH_3 in Tables 2–6. Thus x increases with increasing distance of the dynamic functional group. In the third case, the shifts of a 'migrating' dynamic functional group or its α-CH_2 are discussed. $x = 1$ holds for the position of the dynamic functional group closest to the static functional group (CH_3 or CO_2Me). Again, x increases with increasing distance between the two functional groups. Note that the shifts of some carbons can be approximated by more than one set of parameters. For

Table 1 Chemical shifts of consecutive CH_2 in methyl octadecanoate.[a] Experimental data from ref. 16. C2 corresponds to $x = 1$ in eqn. (1), C3 to $x = 2$, *etc.*

a R^2	b	c Std. dev.	d	e	Experimental shift data *Theoretical shift data* Standard error of prediction						
					C2	C3	C4	C5	C6	C7	C8
					34.08	24.97	29.16	29.26	29.45	29.59	29.64
308.723	*6*	*313.103*	*12*	*29.7*	*34.08*	*24.95*	*29.28*	*29.62*	*29.68*	*29.69*	*29.70*
0.9949		13.39			0.29	0.29	0.21				
					C17	C16	C15	C14	C13	C12	C11
					22.69	31.92	29.36	29.66	29.71	29.71	29.71
−141.282	*6*	*−148.29*	*12*	*29.7*	*22.69*	*31.87*	*29.89*	*29.73*	*29.71*	*29.70*	*29.70*
0.9946		15.67			0.34	0.34	0.24				
					C17	C16	C15	C14	C13	C12	C11
					22.69	31.92	29.36	29.66	29.71	29.71	29.71
279.870	*6*	*27 004.58*	*12*	*29.7*	—[a]	*31.92*	*29.37*	*29.63*	*29.68*	*29.69*	*29.70*
0.9996		17.28/1109.90				0.03	0.03	0.02			

[a] In the last data set, value for C17 is disregarded to eliminate the second 'well' and compare approximations with and without the C17 value. See text.

Table 2 Methyl oxooctadecanoates; experimental data from ref. 16

C functionality a R^2	b	c Std. dev.	d	e	Experimental shift data *Theoretical shift data* Standard error of prediction							
$\mathit{C}H_2CO_2Me$, C=O 'migrates' C3–C10					48.93	27.78	33.06	33.81	33.78	33.92	34.01	34.05
410.584	*6*	*425.464*	*12*	*34.05*	*48.93*	*27.74*	*33.49*	*33.95*	*34.02*	*34.04*	*34.05*	*34.05*
0.9989		13.98			0.31	0.30	0.22					
terminal $\underline{C}H_3$, C=O 'migrates' C17–C10					29.74	7.82	13.72	13.79	13.85	13.98	14.02	14.05
404.223	*6*	*419.913*	*12*	*14.05*	*29.74*	*7.84*	*13.50*	*13.95*	*14.02*	*14.04*	*14.05*	*14.05*
0.9996		8.81			0.19	0.19	0.14					
					C2	C3	C4	C5	C6	C7	C8	C9
$MeO_2C{-}\cdots{-}\underline{C}H_2C{=}O$, C=O migrates					48.93	37.02	41.39	42.18	42.34	42.54	42.66	42.71
374.552	*6*	*380.782*	*12*	*42.7*	*48.90*	*36.94*	*42.19*	*42.61*	*42.68*	*42.69*	*42.70*	*42.70*
0.9868		25.94			0.57	0.57	0.40					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H_2C{=}O$, C=O 'migrates'					35.75	44.60	42.41	42.66	42.74	42.75	42.78	42.78
−120.947	*6*	*−127.897*	*12*	*42.7*	*35.75*	*44.56*	*42.87*	*42.73*	*42.71*	*42.70*	*42.70*	*42.70*
0.9956		12.68			0.28	0.28	0.20					
$-\underline{C}H_2{-}\cdots{-}C{=}O$, C=O at C15					42.74	23.82	29.22	29.37	29.40	29.52	29.52	29.52
368.259	*6*	*381.499*	*12*	*29.5*	*42.74*	*23.84*	*29.00*	*29.41*	*29.48*	*29.49*	*29.50*	*29.50*
0.9997		6.47			0.14	0.14	0.10					

example, in Table 2, C2 in methyl 3-oxooctadecanoate can be approximated as static CH_2 with C=O migrating away from it or as position I α-carbon of the dynamic functional group C=O. Also note that the bonds of the carbons investigated remain the same in each example, for example, the CH_2 carbons always are bonded to two other carbons besides the two hydrogens. If a heteroatom such as oxygen is introduced (an example would be the carbons in the alcohol moiety of an ester, thus regarding the ester as a keto ether), more significant deviations occur as discussed below.

Tables 1–10 contain selected examples for the approximation of shifts of CH_2, CH_3 and functionalized carbons from the literature[16–20] by eqn. (2). For the present calculations, values were calculated for $x = 1$–8. The calculated shift values are represented by s. The values of $b = 6$ and $d = 12$ remain constant in all approximations except for some approximations discussed below. The values $b = 6$ and $d = 12$ were selected because of common analogy to the Lennard–Jones potential. The values for e were selected for each type of carbon atom depending on its base ('equilibrium') value obtained from the same literature. For example, for CH_2 moieties remote from any functional groups, e is in the range of 29.5–29.7 ppm. Mathematical approximation was carried out with the aid of a computer. Statistical analysis resulted in coefficients of determination of usually $R^2 > 0.99$ (exact values given in the Tables), indicating that the calculated values fit the experimental values remarkably well. In terms of shift values, the present evaluation permits calculation with deviations in usually well under 0.5 ppm, in most cases even less than 0.1 ppm (only a few exceptions found for some values with C=C as functional group, see Tables 7–9). The statistical standard errors of prediction also given in the tables are in most cases smaller than 0.4 ppm. Additional statistical evaluation given in the Tables pertains to the standard deviation (std. dev.) of the approximations. Furthermore, with the present evaluation, accurate prediction of ^{13}C NMR chemical shifts is possible by applying the equations to molecules containing moieties such as the substituted long chains discussed here.

In each table and for each set of data, the carbons being studied are given on the first line. The second line of each data set contains the experimental data. The third line contains values of a, b, c, d and e which give good fits with the experimental data. The equations have been calculated for values of $x = 1$–8. The assignment of $x = 1$ can vary depending on the type of carbon being studied: (a) for CH_3, the values are derived for 'migration' of the functional group away from CH_3, with the

Table 3 Methyl hydroxyoctadecanoates; experimental data from ref. 17

$\underline{C}$ functionality					Experimental shift data							
a	*b*	*c*	*d*	*e*	*Theoretical shift data*							
R^2		Std. dev.			Standard error of prediction							
$\underline{C}H_2CO_2Me$, C–OH ‘migrates’ C3–C10					41.19	30.51	33.91	33.97	33.96	34.01	34.03	34.04
232.893	*6*	*239.983*	*12*	*34.10*	*41.19*	*30.52*	*33.78*	*34.04*	*34.09*	*34.10*	*34.10*	*34.09*
0.9992		6.09			0.13	0.13	0.09					
terminal $\underline{C}H_3$; C–OH ‘migrates’ C17–C10					23.43	9.86	14.13	14.07	14.02	14.05	14.07	14.08
269.875	*6*	*279.255*	*12*	*14.05*	*23.43*	*9.90*	*13.68*	*13.98*	*14.03*	*14.04*	*14.05*	*14.05*
0.9980		12.20			0.27	0.27	0.19					
					C2	C3	C4	C5	C6	C7	C8	C9
$MeO_2C{-}\cdots{-}\underline{C}H_2C{-}OH$, C–OH migrates					41.19	32.17	36.72	36.97	37.17	37.30	37.40	37.45
348.906	*6*	*352.596*	*12*	*37.5*	*41.19*	*32.13*	*37.02*	*37.42*	*37.48*	*37.49*	*37.50*	*37.50*
0.9899		17.41			0.38	0.38	0.27					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H_2C{-}OH$, C–OH ‘migrates’					30.14	39.68	37.19	37.44	37.47	37.47	37.49	37.48
−138.844	*6*	*−146.204*	*12*	*37.5*	*30.14*	*39.63*	*37.69*	*37.53*	*37.51*	*37.50*	*37.50*	*37.50*
0.9955		13.59			0.30	0.30	0.21					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}COH{-}\underline{C}H_2$					32.81	39.36	36.97	37.52	37.51	37.47	37.47	37.45
−116.994	*6*	*−121.684*	*12*	*37.5*	*32.81*	*39.30*	*37.66*	*37.53*	*37.51*	*37.50*	*37.50*	*37.50*
0.9812		18.41			0.40	0.40	0.28					
					C14	C13	C12	C11	C10	C9	C8	C7
$\underline{C}H_2{-}\cdots C{-}OH$, C–OH at C15					37.52	25.65	29.71	29.60	29.60	29.60	29.60	29.57
254.216	*6*	*262.136*	*12*	*29.6*	*37.52*	*25.69*	*29.25*	*29.54*	*29.58*	*29.59*	*29.60*	*29.60*
0.9972		13.45			0.29	0.29	0.21					
					C2	C3	C4	C5	C6	C7	C8	C9
$\underline{C}$–OH					70.44	67.98	71.18	71.33	71.55	71.75	71.83	71.75
250.432	*6*	*249.072*	*12*	*71.8*	*70.44*	*67.95*	*71.46*	*71.74*	*71.78*	*71.79*	*71.80*	*71.80*
0.9822		14.60			0.32	0.32	0.23					
					C17	C16	C15	C14	C13	C12	C11	C10
$\underline{C}$–OH					67.98	73.21	71.63	71.94	71.83	71.83	71.83	71.83
−90.166	*6*	*−93.986*	*12*	*71.8*	*67.98*	*73.19*	*71.92*	*71.82*	*71.81*	*71.80*	*71.80*	*71.80*
0.9938		8.51			0.19	0.19	0.13					

Table 4 Methyl acetoxyoctadecanoates; experimental data from ref. 17

$\underline{C}$ functionality					Experimental shift data							
a	*b*	*c*	*d*	*e*	*Theoretical shift data*							
R^2		Std. dev.			Standard error of prediction							
$\underline{C}H_2CO_2Me$, CH_3CO ‘migrates’ C3–C10					39.01	30.08	33.73	33.88	33.89	33.95	34.03	34.00
258.157	*6*	*263.117*	*12*	*34.05*	*39.01*	*30.08*	*33.69*	*33.99*	*34.03*	*34.04*	*34.05*	*34.05*
0.9989		5.62			0.12	0.12	0.09					
terminal $\underline{C}H_3$, $C{-}COCH_3$ ‘migrates’ C17–C10					19.92	9.57	13.94	13.96	13.94	14.02	14.03	14.02
289.751	*6*	*295.621*	*12*	*14.05*	*19.92*	*9.59*	*13.65*	*13.98*	*14.03*	*14.04*	*14.05*	*14.05*
0.9983		8.08			0.18	0.18	0.13	0.12				
					C2	C3	C4	C5	C6	C7	C8	C9
$MeO_2C{-}\cdots{-}\underline{C}H_2CH(COCH_3)$					39.01	29.28	33.41	33.73	33.89	33.99	34.07	*34.08*
321.762	*6*	*326.672*	*12*	*34.10*	*39.01*	*29.15*	*33.66*	*34.02*	*34.08*	*34.09*	*34.10*	*34.10*
0.9960		12.79			0.28	0.28	0.20					
$CH_3{-}\cdots{-}\underline{C}H_2{-}CH(COCH_3){-}$					26.92	36.29	33.81	34.05	34.11	34.10	34.09	34.11
−139.625	*6*	*−146.805*	*12*	*34.10*	*26.92*	*36.25*	*34.29*	*34.13*	*34.11*	*34.10*	*34.10*	*34.10*
0.9957		12.97			0.28	0.28	0.20					
					C2	C3	C4	C5	C6	C7	C8	C9
$\underline{C}H(COCH_3)$					72.27	70.44	73.26	73.66	73.94	74.10	74.15	74.29
255.635	*6*	*253.605*	*12*	*74.3*	*72.27*	*70.37*	*73.95*	*74.24*	*74.28*	*74.29*	*74.30*	*74.20*
0.9521		26.34			0.57	0.57	0.41					
					C17	C16	C15	C14	C13	C12	C11	C10
$\underline{C}H(COCH_3)$					70.93	75.39	74.00	74.30	74.30	74.30	74.31	74.25
−68.621	*6*	*−71.991*	*12*	*74.30*	*70.93*	*75.35*	*74.39*	*74.32*	*74.30*	*74.30*	*74.30*	*74.30*
0.9876		11.47			0.25	0.25	0.18					

Table 5 Methyl *cis*-epoxyoctadecanoates; experimental data from ref. 18

$\underline{C}$ functionality					Experimental shift data							
a	*b*	*c*	*d*	*e*	*Theoretical shift data*							
$\underline{R^2}$		Std. dev.			Standard error of prediction							
$\underline{C}H_2CO_2Me$, epoxy 'migrates' C3/4–C10/11					33.49	30.80	—	33.74	33.60	33.76	33.63	33.82
195.115	*6*	*194.805*	*12*	*33.80*	*33.49*	*30.80*	*33.53*	*33.75*	*33.79*	*33.80*	*33.80*	*33.80*
0.9929		7.43			0.16	0.16	0.11					
$MeO_2C{-}\cdots{-}\underline{C}H_2CH(O)CH{-}\cdots$					33.49	23.25	—	27.36	27.38	27.61	27.48	27.61
283.146	*6*	*289.036*	*12*	*27.60*	*33.49*	*23.25*	*27.21*	*27.53*	*27.58*	*27.59*	*27.60*	*27.60*
0.9984		8.43			0.18	0.18	0.13					
term. $\underline{C}H_3$, epoxy 'migrates' C16/17–C9/10					12.85	10.34	13.79	13.70	—	13.78	13.79	13.66
223.280	*6*	*222.330*	*12*	*13.80*	*12.85*	*10.37*	*13.49*	*13.75*	*13.79*	*13.80*	*13.80*	*13.80*
0.9915		8.76			0.19	0.19	0.14					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H_2{-}CH(O)CH{-}$					20.89	29.66	27.60	—	27.61	27.61	27.48	27.61
−132.981	*6*	*−139.691*	*12*	*27.6*	*20.89*	*29.64*	*27.78*	*27.63*	*27.61*	*27.60*	*27.60*	*27.60*
0.9990		6.36			0.14	0.14	0.10					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H(O)CH{-}$					52.13	58.08	56.72	56.85	—	56.88	56.89	
−78.651	*6*	*−83.371*	*12*	*56.85*	*52.13*	*58.06*	*56.96*	*56.87*	*56.86*	*56.85*	*56.85*	*56.85*
0.9976		9.01			0.20	0.20	0.14					
					C2	C3	C4	C5	C6	C7	C8	C9
$\underline{C}H_2$ epoxy at C15–C16					33.87	24.74	28.96	29.34	29.34	29.34	29.24	29.34
299.613	*6*	*304.133*	*12*	*29.35*	*33.87*	*24.74*	*28.94*	*29.28*	*29.33*	*29.34*	*29.35*	*29.35*
0.9996		3.67			0.08	0.08	0.06					

Table 6 Methyl *trans*-epoxyoctadecanoates; experimental data from ref. 18

$\underline{C}$ functionality					Experimental shift data							
a	*b*	*c*	*d*	*e*	*Theoretical shift data*							
$\underline{R^2}$		Std. dev.			Standard error of prediction							
$\underline{C}H_2CO_2Me$, epoxy 'migrates' C3/4–C10/11					37.30	30.14	33.30	33.67	33.76	—	33.82	33.82
239.092	*6*	*242.592*	*12*	*33.8*	*37.30*	*30.12*	*33.47*	*33.74*	*33.78*	*33.79*	*33.80*	*33.80*
0.9986		5.55			0.12	0.12	0.09					
					C2	C3	C4	C5	C6	C7	C8	C9
$MeO_2C{-}\cdots{-}\underline{C}H_2CH(O)CH{-}\cdots$					37.30	27.22	31.19	31.45	31.66	—	31.89	31.90
306.395	*6*	*311.795*	*12*	*31.90*	*37.30*	*27.19*	*31.48*	*31.83*	*31.88*	*31.89*	*31.90*	*31.90*
0.9958		13.43			0.29	0.29	0.21					
term. $\underline{C}H_3$, epoxy 'migrates' C16/17–C9/10					17.44	9.62	13.66	13.68	13.64	13.73	13.77	13.81
270.589	*6*	*274.229*	*12*	*13.80*	*17.44*	*9.64*	*13.43*	*13.74*	*13.78*	*13.79*	*13.80*	*13.80*
0.9973		7.56			0.17	0.17	0.12					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H_2{-}CH(O)CH{-}$					24.95	33.94	31.57	31.84	31.87	31.90	31.89	—
−129.698	*6*	*136.648*	*12*	*31.90*	*24.95*	*33.89*	*32.08*	*31.93*	*31.91*	*31.90*	*31.90*	*31.90*
0.9949		16.82			0.37	0.37	0.26					
					C17	C16	C15	C14	C13	C12	C11	C10
$CH_3{-}\cdots{-}\underline{C}H(O)CH{-}$					54.27	59.61	58.49	58.51	58.53	58.52	58.55	58.54
−71.610	*6*	*−75.840*	*12*	*58.50*	*54.27*	*59.60*	*58.60*	*58.52*	*58.50*	*58.50*	*58.50*	*58.50*
0.9993		3.67			0.08	0.08	0.06					
					C2	C3	C4	C5	C6	C7	C8	C9
$\underline{C}H_2$, epoxy C15–C16					33.87	24.74	28.99	29.34	29.34	29.34	29.34	29.34
299.437	*6*	*303.957*	*12*	*29.35*	*33.87*	*24.75*	*28.94*	*29.28*	*29.33*	*29.34*	*29.35*	*29.35*
0.9998		2.37			0.05	0.05	0.04					

functional group located at C17 corresponding to $x = 1$; (b) for the functional group or adjacent carbons, the functional group 'migrates' along the chain, with $x = 1$ being assigned to the position closest to a chain end; (c) there is no 'migration' of a functional group, *i.e.* the shift values are consecutive for the carbons along the chain. A functional group position at C15 was selected to study this effect in chains containing functional groups. This guarantees a CH_2 chain of sufficient length to attain the *e* value. The terms 'Pos. I' and 'Pos. II' refer to positions closer to C1 or to C18, respectively, for CH_2 on the corresponding sides of a functional group in the chain. The acronyms PIe and PIIe refer to the functional group being closer to C1 or C18, respectively.

The greatest deviations of calculated and experimental values usually occur for $x = 3$. Note that Grant and Paul[9] discussed anomalous shifts for these carbons and rationalized this effect by assuming that all allowed conformations (*trans*, *gauche*) are equally probable. Furthermore, in some cases there is a second

Table 7 *cis*-Octadecenoic acids; experimental data from ref. 19

$\underline{C}$ functionality *a* R^2	*b*	*c* Std. dev.	*d*	*e*	Experimental shift data *Theoretical shift data* Standard error of prediction							
					C2	C3	C4	C5	C6	C7	C8	C9
HO$_2$C–····–$\underline{C}$H$_2$–CH=CH–					33.12	22.66	26.58	26.88	27.13	27.28	27.31	27.30
303.923	*6*	*309.743*	*12*	*27.3*	*33.12*	*22.63*	*26.88*	*27.23*	*27.28*	*27.29*	*27.30*	*27.30*
0.9958		12.84			0.28	0.28	0.20					
					C17	C16	C15	C14	C13	C12	C11	C10
CH$_3$–····–$\underline{C}$H$_2$–CH=CH–					20.60	29.69	26.99	27.29	27.29	27.30	27.31	27.28
−152.436	*6*	*−159.136*	*12*	*27.3*	*20.60*	*29.64*	*27.51*	*27.34*	*27.31*	*27.30*	*27.30*	*27.30*
0.9946		13.85			0.33	0.33	0.24	0.23				
CH$_3$–$\underline{C}$H$_2$–····–CH=CH–; C=C migrates C15–C8					20.60	22.96	22.40	22.68	22.72	22.76	22.80	22.80
−7.907	*6*	*−10.107*	*12*	*22.80*	*20.60*	*22.92*	*22.81*	*22.80*	*22.80*	*22.80*	*22.80*	*22.80*
0.9617		11.62			0.25	0.25	0.18					
HO$_2$C–$\underline{C}$H$_2$–··· CH=CH–···					33.12	34.27	33.58	34.13	34.22	34.22	34.24	34.22
−0.907	*6*	*−1.987*	*12*	*34.20*	*33.12*	*32.21*	*34.20*	*34.20*	*34.20*	*34.20*	*34.20*	*34.20*
0.7462		16.65			0.36	0.36	0.26					
					C2	C3	C4	C5	C6	C7	C8	C9
$\underline{C}$H$_2$, C=C at Δ15					34.23	24.79	29.21	29.39	29.57	29.75	29.75	29.75
323.443	*6*	*327.923*	*12*	*29.75*	*34.23*	*24.78*	*29.31*	*29.67*	*29.73*	*29.74*	*29.75*	*29.75*
0.9975		9.78			0.21	0.21	0.15					

Table 8 Methyl *cis*-octadecenoates; experimental data from ref. 19

$\underline{C}$ functionality *a* R^2	*b*	*c* Std. dev.	*d*	*e*	Experimental shift data *Theoretical shift data* Standard error of prediction							
MeO$_2$C–····–$\underline{C}$H$_2$–CH=CH–					32.80	22.98	26.69	27.02	27.14	—	27.32	—
282.502	*6*	*288.002*	*12*	*27.30*	*32.80*	*22.96*	*26.91*	*27.23*	*27.28*	*27.29*	*27.30*	*27.30*
0.9976		9.91			0.22	0.22	0.15					
MeO$_2$C–$\underline{C}$H$_2$–····–CH=CH–···					32.80	34.21	33.48	33.98	34.08	—	34.12	—
−3.426	*6*	*−4.726*	*12*	*34.10*	*32.80*	*34.15*	*34.10*	*34.10*	*34.10*	*34.10*	*34.10*	*34.10*
0.8054		20.70			0.45	0.45	0.32					

Table 9 *trans*-Octadecenoic acids; experimental data from ref. 19

$\underline{C}$ functionality *a* R^2	*b*	*c* Std. dev.	*d*	*e*	Experimental shift data *Theoretical shift data* Standard error of prediction							
					C17	C16	C15	C14	C13	C12	C11	C10
CH$_3$–····–$\underline{C}$H$_2$–CH=CH–					25.65	34.79	32.36	32.65	32.69	32.68	32.66	32.68
−132.879	*6*	*−139.929*	*12*	*32.7*	*25.65*	*34.74*	*32.88*	*32.73*	*32.71*	*32.70*	*32.70*	*32.70*
0.9948		15.44			0.34	0.34	0.24					
CH$_3$–$\underline{C}$H$_2$–····–CH=CH					25.65	22.82	22.27	22.62	22.73	22.77	22.76	22.76
−1.5755	*6*	*1.325*	*12*	*22.75*	*25.65*	*22.77*	*22.75*	*22.75*	*22.75*	*22.75*	*22.75*	*22.75*
0.9709		13.28			0.29	0.29	0.21					

'well' which is not accounted for by eqn. (1) and it usually is observed in position II, *i.e.* near the terminal methyl group. This second well also occurs at $x = 3$. Likely, another term in eqn. (1) would need to account for it. Nevertheless, the agreement of calculated and experimental values is still remarkable. If the value for $x = 1$ is removed from consideration, there is only one well but the values for a and especially c deviate from the other examples, although R^2 is improved. An example for this is shown in Table 1 for the CH$_2$ carbons in the sequence C17–C11.

In cases of positive a and c, their values are greatest when the functional group in the chain is carbonyl (C=O) and lowest when it is *cis*-epoxy. For terminal CH$_3$ with the functional group 'migrating' in the position I direction, the order is, analogous to CH$_2$ at C2: C=O > CH–COCH$_3$ > *trans*-epoxy > CHOH > *cis*-epoxy. For the CH$_2$ at C2 and 'migrating' functional group, the order of declining a and c values is: C=O > CH–CO–CH$_3$ > *trans*-epoxy > CHOH > *cis*-epoxy. For CH$_2$ α to the functional group (position I side), the corresponding order is: C=O, C–OH > CH–CO–CH$_3$ > *trans*-epoxy > *cis*-epoxy. In eqn. (2), when given for V_{nb}, a is proportional to the polarizability of the atoms approaching each other.[15] In the present work, both a and b depend on the nature of the functional group and its shielding or deshielding effect.

Although no calculations were carried out, the present evaluation of the signals of sp^3 carbons likely holds for other functional groups in the chain, including 'double' or 'multiple' such as allylic hydroxy (enol) or allylic dihydroxy [2(*E*)-ene-1,4-diol],[21–24] enone[21,25,26] and allylic hydroperoxide[25] groups for which NMR data has been reported. On the other hand, to our knowledge no other data which would not fit the present approximation of the ^{13}C NMR shifts of long-chain compounds has been reported.

Table 10 Octadecynoic acids; experimental data from ref. 20

C functionality *a* R^2	*b*	*c* Std. dev.	*d*	*e*	Experimental shift data *Theoretical shift data* Standard error of prediction							
					C17	C16	C15	C14	C13	C12	C11	C10
CH_3–···–CH_2–C≡C–					12.48	20.87	18.53	18.84	18.85	18.82	18.87	*18.86*
−128.514	*6*	*−134.884*	*12*	*18.85*	*12.48*	*20.83*	*19.03*	*18.88*	*18.86*	*18.85*	*18.85*	*18.85*
0.9944		14.52			0.32	0.32	0.23	0.22				
					C2	C3	C4	C5	C6	C7		
HO_2C–···–CH_2–C≡C–···[a]					25.98	14.60	18.29	18.56	18.71	18.86	—	—
277.731	*6*	*284.861*	*12*	*18.85*	*25.98*	*14.58*	*18.47*	*18.78*	*18.83*	*18.84*		
0.9986		10.09			0.22	0.22	0.16					
–CH_2–CH_3, C≡C ‘migrates’ C15–C10					12.48	22.66	22.01	22.33	22.67	22.70	22.77	22.81
13.929	*6*	*3.609*	*12*	*22.80*	*12.48*	*22.58*	*22.78*	*22.80*	*22.80*	*22.80*	*22.80*	*22.80*
0.9921		24.31			0.53	0.53	0.38					
HO_2C–CH_2–···; C≡C ‘migrates’ C3–C8[a]					25.98	34.13	33.00	33.76	34.13	34.17	—	—
11.748	*6*	*3.528*	*12*	*34.20*	*25.98*	*34.02*	*34.18*	*34.20*	*34.20*	*34.20*	*34.20*	*34.20*
		41.10			0.90	0.90	0.64	0.63				

[a] Chain length C_{14}.

Table 11 ^{13}C NMR shift values (in $CDCl_3$) of the alcohol moieties in ethyl, propyl and butyl esters of palmitic (hexadecanoic), stearic (octadecanoic), oleic [9(*Z*)-octadecenoic] and linoleic [9(*Z*),12(*Z*)-octadecadienoic] acids

	Ethyl		Propyl			Butyl			
Acid	CH_3···	CH_2···	CH_3···	CH_2···	CH_2···	CH_3···	CH_2···	CH_2···	CH_2···
Palmitic	14.18	60.05	10.32	21.95	65.72	13.63	19.09	30.65	63.99
Stearic	14.19	60.06	10.34	21.96	65.75	13.66	19.10	30.66	64.03
Oleic	14.18	60.06	10.31	21.94	65.69	13.64	19.09	30.65	64.00
Linoleic	14.17	60.03	10.32	21.95	65.73	13.63	19.09	30.65	63.98

Table 12 Evaluation of CH_3 in the alcohol moiety of fatty esters.[a] Experimental data from Table 11 (oleic acid) and ref. 19

C functionality *a* R^2	*b*	*c*	*d*	*e*	Experimental shift data *Theoretical shift data* Methyl	Ethyl	Propyl	Butyl	Pentyl	Hexyl	Heptyl
CH_3–$(CH_2)_n$–O–···					51.30	14.18	10.31	13.64	13.85[b]	13.96[b]	14.05[b]
14.17	*6*	*51.42*	*12*	*14.05*	*51.30*	*13.84*	*14.03*	*14.05*	*14.05*	*14.05*	*14.05*
0.9899											
2945	*6*	*188 992*	*12*	*14.05*	—	*14.18*	*10.37*	*13.34*	*13.86*	*13.99*	*14.02*
0.9934											

[a] The second data set disregards the methyl ester shift value and improves the approximation, showing the effect of bonding to the same kinds of atoms as discussed in the text. [b] Assumed values based on terminal CH_3 attaining a value of 14.05 ppm when sufficiently remote from moieties other than CH_2.

The present approximation was also applied to the alcohol moiety of fatty esters. For this purpose, the ^{13}C NMR spectra of ethyl, *n*-propyl and *n*-butyl esters of some fatty acids were recorded (value for methyl ester taken from ref. 1; esters of oleic acid taken as standard). ^{13}C shift values of the alcohol moiety of the ethyl, *n*-propyl and *n*-butyl esters are given in Table 11. Assignments agree with literature data on other, shorter-chain esters.[21] An approximation for the CH_3 shifts of these esters was accordingly developed and is given in Table 12 (shift values for esters with alcohol moieties > 4 were assumed). Note that a difference to the other approximations given in Tables 1–10 is the presence of the functional group in the chain in the form of a heteroatom, the ester oxygen. Therefore, approximations of the present kind hold even for heteroatoms in the chain, although the values for *a* and *c* deviate from those determined for other functional groups. Similar to the discussion above on the existence of a second well, this example also illustrates the necessity to consider only the kind of atoms a carbon is bonded to when determining the parameters *a* and *c*. In the methyl esters, the methyl carbon is bonded to oxygen besides three hydrogens, while in higher esters, of course, it is bonded to carbon (CH_2). When the methyl ester is removed from evaluation, the quality of the approximation increases significantly as the data in Table 12 show. Thus, for the approximations to be valid, the bonds on the carbons being evaluated must consistently be to the same kinds and numbers of atoms.

In conclusion, the ^{13}C NMR chemical shifts of sp^3 carbons in long-chain compounds can be evaluated in terms of a modified equation derived from that describing the Lennard–Jones potential. Besides any theoretical implications, the parameters derived here for various compounds for application in eqn. (2) can be used for predicting with excellent results the ^{13}C NMR chemical shifts of various sp^3 carbons in long-chain compounds and pose an alternative to procedures based on additive increments.

Experimental

Most ^{13}C NMR data were obtained from refs. 16–20. Spectral acquisition parameters for this literature data are given in these references. All approximations and statistical evaluations were performed using SAS/STAT software[27] on a personal computer. Statistical parameters that were determined (least-squares multiple regression) for evaluating the quality of the approximations were the coefficient of determination (R^2), standard deviation (std. dev.) and standard error of prediction.

Ethyl, propyl and butyl esters of palmitic, stearic, oleic and linoleic acids were purchased from NuChekPrep, Inc. (Elysian, MN). The ^{13}C NMR spectra of these compounds were determined at ambient temperature (22–23 °C) in $CDCl_3$ solutions on a Bruker ARX-400 spectrometer operating at 100 MHz (2500 acquisitions, digital resolution 0.803 Hz, reference TMS). The spectra were not concentration-dependent. All ^{13}C NMR shift data in the literature used in this work were obtained with $CDCl_3$ as solvent, so that any solvent-based deviations on the results can be excluded.

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References

1 For recent reviews see: (*a*) F. D. Gunstone, High Resolution ^{13}C-NMR Spectroscopy of Lipids, in *Advances in Lipid Methodology—Two*, ed. W. W. Christie, The Oily Press, Dundee, 1993, pp. 1–68; (*b*) M. S. F. Lie Ken Jie and J. Mustafa, *Lipids*, 1997, **32**, 1019. See also references in these reviews.

2 J. G. Batchelor, J. H. Prestegard, R. J. Cushley and S. R. Lipsky, *J. Am. Chem. Soc.*, 1973, **73**, 6358.

3 J. G. Batchelor, R. J. Cushley and J. H. Prestegard, *J. Org. Chem.*, 1974, **39**, 1698.

4 G. Knothe and M. O. Bagby, *J. Chem. Soc.*, *Perkin Trans. 2*, 1995, 615.

5 G. Bianchi, O. W. Howarth, C. J. Samuel and G. Vlahov, *J. Chem. Soc.*, *Chem. Commun.*, 1994, 627.

6 G. Bianchi, O. W. Howarth, C. J. Samuel and G. Vlahov, *J. Chem. Soc.*, *Perkin Trans. 2*, 1995, 1427.

7 O. W. Howarth, C. J. Samuel, and G. Vlahov, *J. Chem. Soc.*, *Perkin Trans. 2*, 1995, 2307.

8 E. G. Paul and D. M. Grant, *J. Am. Chem. Soc.*, 1963, **85**, 1701.

9 D. M. Grant and E. G. Paul, *J. Am. Chem. Soc.*, 1964, **86**, 2984.

10 E. Breitmaier and W. Voelter, *Carbon 13 NMR Spectroscopy*, VCH Verlagsgesellschaft, Weinheim, 1989, and references therein.

11 D. B. Chesnut, D. W. Wright and B. A. Krizek, *J. Mol. Struct.*, 1988, **190**, 99.

12 S. Li and D. B. Chesnut, *Magn. Reson. Chem.*, 1986, **24**, 93.

13 D. B. Chesnut and W. P. Johnson, *J. Magn. Reson.*, 1985, **65**, 110.

14 S. Li and D. B. Chesnut, *Magn. Reson. Chem.*, 1985, **23**, 625.

15 For a discussion of the Lennard–Jones potential in organic stereochemistry, see: E. L. Eliel and S. H. Wilen: *Stereochemistry of Organic Compounds*, John Wiley & Sons, New York, 1994, pp. 36–37. See also references therein.

16 A. P. Tulloch, *Can. J. Chem.*, 1977, **55**, 1135.

17 A. P. Tulloch, *Org. Magn. Reson.*, 1978, **11**, 109.

18 E. Bascetta and F. D. Gunstone, *Chem. Phys. Lipids*, 1985, **36**, 253.

19 F. D. Gunstone, M. R. Pollard, C. M. Scrimgeour and H. S. Vedanayagam, *Chem. Phys. Lipids*, 1977, **18**, 115.

20 F. D. Gunstone, M. R. Pollard, C. M. Scrimgeour, N. W. Gilman and B. C. Holland, *Chem. Phys. Lipids*, 1976, **17**, 1.

21 G. Knothe, M. O. Bagby, D. Weisleder and R. E. Peterson, *J. Chem. Soc.*, *Perkin Trans. 2*, 1994, 1661.

22 G. Knothe, M. O. Bagby, D. Weisleder and R. E. Peterson, *J. Am. Oil Chem. Soc.*, 1995, **72**, 703.

23 G. Knothe, M. O. Bagby and D. Weisleder, *J. Am. Oil Chem. Soc.*, 1995, **72**, 1021.

24 E. N. Frankel, R. F. Garwood, B. P. S. Khambay, G. P. Moss and B. C. L. Weedon, *J. Chem. Soc.*, *Perkin Trans. 1*, 1984, 2233.

25 N. A. Porter and J. S. Wujek, *J. Org. Chem.*, 1987, **52**, 5085.

26 B. B. Snider and Z. Shi, *J. Am. Chem. Soc.*, 1992, **114**, 1790.

27 SAS Institute Inc., *SAS/STAT® User's Guide*, *Version 6*, 4th edn., vol. 1, Cary, NC: SAS Institute Inc., 1989, 943 pp.

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