J. Am. Chem. Soc. 1982, 104, 2247-2251

Barriers to Rotation of Methyl Groups in Methyltriptycenes

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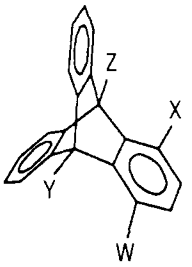
Received August 24, 1981

Abstract: Rotational barriers of methyl groups in methyltriptycenes are determined from the temperature dependence of the ^1H spin–lattice relaxation times. Barriers of bridgehead methyls increase appreciably by methyl substitution at peri positions, which suggests probable absence of the gear effect. Calculations by the molecular mechanics (MMI) method and the molecular orbital (CNDO/FK) method favor a clashed-gear conformation for adjacent bridgehead and peri methyls in the ground state. Thus, it seems that two adjacent methyl groups need not rotate synchronously in gear. Also, an unexpected remote buttressing effect by the bridgehead methyl in the backside of the triptycene molecule has been found to increase the barrier of the bridgehead methyl in the front side.

A resemblance of two adjacent alkyl groups to a meshed gear has been proposed[1] for their ground-state conformations and to interpret their relatively small barrier to rotation, because mutual steric interactions would be reduced by gearlike motion. For methyl groups, the gear effect has often been invoked by observations that the size[2] of the methyl group is smaller than that of a chlorine atom.[3] Charton and Charton[4] investigated correlations of $\Delta G^{\ddagger}$ values for barriers to internal rotation of various compounds with the modified Taft equation to conclude the gear effect to be negligible on the basis of the minimum spherically symmetric parameter for the methyl group. This argument is dubious[5] since the correlated parameter should be the maximum one to exclude the gear effect. In fact, Bott, Field, and Sternhell[6] determined the effective radius of the methyl group to be close to Charton's minimum size from their DNMR studies for biphenyl derivatives and concluded that it is "thus providing evidence for the cogwheeling effect". Ōki et al.[7] investigated the restricted rotation of the bridgehead methyl groups in 1,2,3,4-tetrachloro-9-methyltriptycene (**7**) and 1,4,9-trimethyltriptycene (**8**) by the DNMR method and estimated the activation energies for rotation to be 9.2 ± 0.4 and less than 7.8 kcal/mol for **7** and **8**, respectively. They attributed the small rotational barrier for **8** to the gear effect.

These experimental studies of substitutent effects on internal rotation have been carried out in solutions by the DNMR method.[8] However, errors in activation parameters obtained by DNMR experiments may become appreciably particular for spin systems such as methyl protons exhibiting simple line shapes.[9] The difficulty is due to a strong correlation between the effective spin–spin relaxation time T_2^* and the rate constant; a precise measurement of T_2^* is a prerequisite for correctly determining the rate constant.

With the controversial gear effect in mind, we are concerned in this paper primarily with studying effects of adjacent methyl groups on methyl rotation. The barriers to rotation of the bridgehead and the peri methyl groups (abbreviated hereafter as bh methyl and peri methyl, respectively) in methyltriptycenes (**1–6**) are determined from the temperature dependence of the ^1H spin–lattice relaxation times (T_1) in the solid state. The origin of the rotational barriers is examined by two different types of calculations, namely, an empirical molecular mechanical calculation (the MMI method[10]) and a semiempirical molecular orbital calculation (the CNDO/FK method, i.e., the CNDO method[11] modified by Fischer and Kollmar[12]); the latter calculation has been performed to estimate electronic effects on the rotation. The results are discussed in connection with the gear effect.



	W	X	Y	Z
1	Me	H	H	H
2	H	H	Me	H
3	Me	H	Me	H
4	Me	Me	H	H
5	H	H	Me	Me
6	Me	Me	Me	Me
8	Me	Me	Me	H

Experimental Section

Materials. Methyltriptycenes (**1–6**) were prepared by addition of benzyne or 3,6-dimethylbenzyne to methylanthracenes and purified by repeated recrystallizations. Melting points were uncorrected. NMR spectra were recorded on a Varian HA-100 spectrometer.

A. 1-Methyltriptycene (1): mp 193–194 °C (lit.[13] 190.5–192.5 °C); NMR δ ($CDCl_3$) 2.49 (3 H, s, methyl), 5.39 (1 H, s, bridgehead), 5.65 (1 H, s, bridgehead), 6.80–7.50 (11 H, m, aromatic).

B. 1,9-Dimethyltriptycene (3): mp 277–280 °C; NMR δ ($CDCl_3$) 2.60 (3 H, s, peri methyl), 2.62 (3 H, s, bh methyl), 5.34 (1 H, s, bridgehead), 6.60–7.50 (11 H, m, aromatic). Anal. ($C_{22}H_{18}$) C, H.

C. 1,4-Dimethyltriptycene (4): mp 280–281 °C (lit.[14] 253.0–255.5 °C); NMR δ ($CDCl_3$) 2.46 (6 H, s, methyl), 5.65 (2 H, s, bridgehead), 6.72 (2 H, s, aromatic), 6.90–7.50 (8 H, AA′BB′, aromatic).

D. 9,10-Dimethyltriptycene (5): mp >300 °C (lit.[15] 329–330 °C); NMR δ ($CDCl_3$) 2.41 (6 H, s, methyl), 6.90–7.50 (12 H, AA′BB′, aromatic).

E. 1,4,9,10-Tetramethyltriptycene (6): mp 300–302 °C (lit.[16] 290–291 °C); NMR δ ($CDCl_3$) 2.59 (6 H, s, peri methyl), 2.64 (6 H, s, bh methyl), 6.58 (2 H, s, aromatic), 7.00–7.60 (8 H, AA′BB′, aromatic).

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(1) (a) Roussel, C.; Chanon, M.; Metzger, J. *Tetrahedron Lett.* **1971**, 1861–1864. (b) Berg, U.; Roussel, C. *J. Am. Chem. Soc.* **1980**, *102*, 7848–7853.

(2) Förster, H.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 429–441.

(3) See, for example: Leung, P.-T.; Curtin, D. Y. *J. Am. Chem. Soc.* **1975**, *97*, 6790–6799.

(4) (a) Charton, M.; Charton, B. *J. Am. Chem. Soc.* **1975**, *97*, 6472–6473. (b) Charton, M. *Ibid.* **1975**, *97*, 1552–1556.

(5) Hounshell, W. D.; Iroff, L. D.; Iverson, D. J.; Wroczynski, R. J.; Mislow, K. *Isr. J. Chem.* **1980**, *20*, 65–71.

(6) Bott, G.; Field, L. D.; Sternhell, S. *J. Am. Chem. Soc.* **1980**, *102*, 5618–5626.

(7) Nakamura, M.; Ōki, M.; Nakanishi, H.; Yamamoto, O. *Bull. Chem. Soc. Jpn.* **1974**, *47*, 2415–2419.

(8) Sternhell, S. "Dynamic Nuclear Magnetic Resonance Spectroscopy"; Jackman, L. M., Cotton, F. A., Eds.; Academic Press: New York, 1975; pp 163–201.

(9) Binsh, G., ref 8, pp 76–78.

(10) (a) Allinger, N. L.; Tribble, M. T.; Miller, M. A.; Wertz, D. H. *J. Am. Chem. Soc.* **1971**, *93*, 1637–1648. (b) Wertz, D. H.; Allinger, N. L. *Tetrahedron* **1974**, *30*, 1579–1586.

(11) Pople, J. A.; Beveridge, D. L. "Approximate Molecular Orbital Theory"; McGraw-Hill: New York, 1970.

(12) Fischer, H.; Kollmar, H. *Theor. Chem. Acta* **1969**, *13*, 213–219; *Ibid.* **1970**, *16*, 163–174.

(13) Friedman, L.; Logullo, F. N. *J. Org. Chem.* **1969**, *34*, 3089–3092.

(14) Regan, T. H.; Miller, J. B. *J. Org. Chem.* **1967**, *32*, 2789–2794.

(15) Theilacker, W.; Berger-Brose, U.; Beyer, K. H. *Chem. Ber.* **1960**, *93*, 1658–1681.

(16) Kricka, L. J.; Vernon, J. M. *J. Chem. Soc., Perkin Trans. 1* **1973**, 766–771.

0002-7863/82/1504-2247$01.25/0

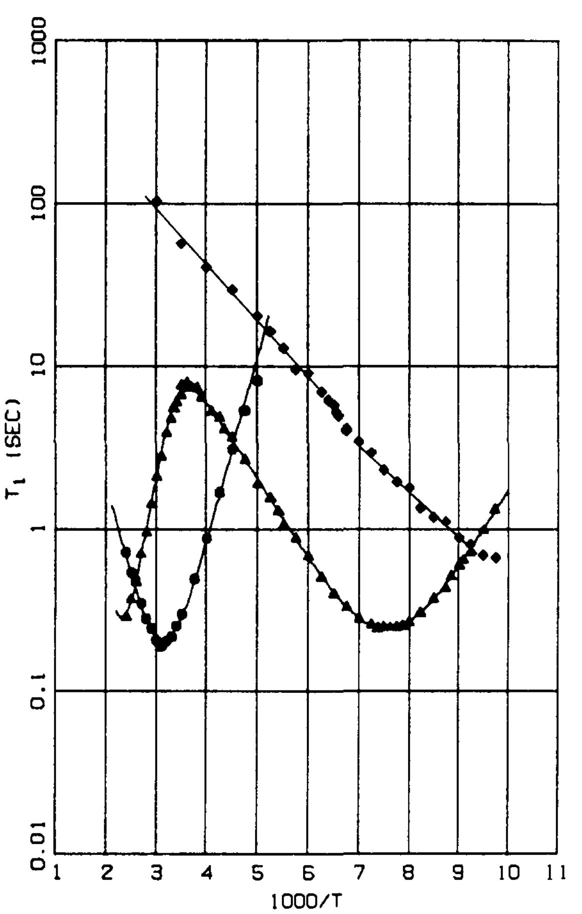

Figure 1. The temperature dependence of the ^{1}H spin-lattice relaxation time (T_1) for 1-methyltriptycene (**1**, ◆), 9-methyltriptycene (**2**, ●), and 1,9-dimethyltriptycene (**3**, ▲). The solid curves through the data points are "best fits" described by the parameters in Table I.

Measurements. Samples for NMR measurements were degassed by several freeze-pump-thaw cycles in glass tubes. Measurements of T_1 were performed by using a homemade pulsed spectrometer operating at 59.5 MHz as described previously.[17]

Results and Discussion

Determination of Rotational Barriers. Experimental values of T_1 are plotted against the reciprocal temperature in Figure 1 for **1**–**3** and in Figure 2 for **4**–**6**. Taking into account only the intramethyl contributions to the relaxation process, one can write the initial relaxation rate as[18]

$$\frac{1}{T_1} = \frac{N_{\mathrm{Me}}}{N_{\mathrm{all}}} K\left(\frac{\tau}{1 + \omega^2\tau^2} + \frac{4\tau}{1 + 4\omega^2\tau^2}\right) \qquad (1)$$

where N_{all} is the total number of protons in the molecule, N_{Me} is the number of protons in the methyl group, τ is the correlation time for the reorientation of the methyl group, and $K = 9\gamma^4\hbar^2/20r^6$, r being the intramethyl proton-proton distance. The correlation time, τ, is assumed to have an Arrhenius dependence on temperature

$$\tau = \tau_0 \exp(E_a/RT) \qquad (2)$$

where E_a is the activation energy and τ_0 is the correlation time at infinite temperature.

Since full T_1 curves are not observed for **1** and **4** in the present temperature range, activation energies are determined by a least-squares fit of the high-temperature branches to straight lines. A slight gradient change at 147 K in the T_1 curve for **1** is ascribed to a phase transition. The T_1 curves for **2** and **5** are satisfactorily fitted to eq 1, taking K in eq 1 and E_a and τ_0 in eq 2 as adjustable parameters,[19] while the T_1 curves for **3** and **6** are successfully fitted

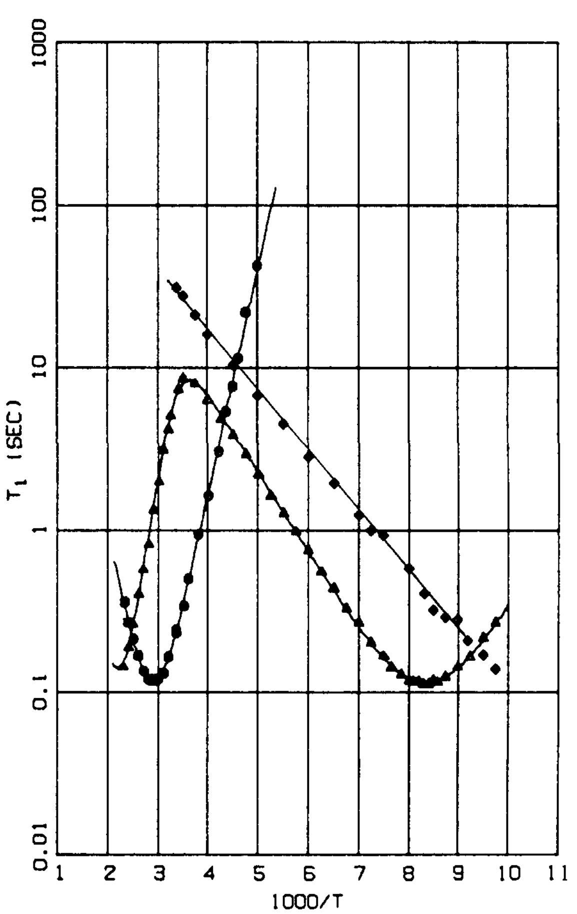

Figure 2. The temperature dependence of the ^{1}H spin-lattice relaxation time (T_1) for 1,4-dimethyltriptycene (**4**, ◆), 9,10-dimethyltriptycene (**5**, ●), and 1,4,9,10-tetramethyltriptycene (**6**, ▲). The solid curves through the data points are "best fits" described by the parameters in Table I.

Table I. "Best Fit" Parameters to the T_1 Data for **1**–**6**[a]

		10^9K, s^{-2}	E_a, kcal/mol	$10^{-13}\tau_0$, s
1	peri		1.62 ± 0.08[b] 1.17 ± 0.17[c]	
2	bh	6.77 ± 0.27	5.20 ± 0.13	4.4 ± 1.0
3	bh	5.46 ± 0.96	8.47 ± 0.41	0.9 ± 0.6
	peri	6.48 ± 0.12	2.26 ± 0.03	3.1 ± 0.3
4	peri		1.65 ± 0.06	
5	bh	6.78 ± 0.15	6.36 ± 0.07	1.5 ± 0.2
6	bh	6.89 ± 1.14	9.06 ± 0.30	0.7 ± 0.4
	peri	8.36 ± 0.18	2.24 ± 0.03	1.4 ± 0.2

[a] Error is 2.5σ. [b] Value above 147 K. [c] Value below 147 K.

Table II. Comparison of the Observed and the Calculated Values for the Minimum Spin-Lattice Relaxation Time[a]

		T_1^{exptl}(min), s	T_1^{calcd}(min), s	ratio
1	peri	<0.67	0.186	
2	bh	0.207	0.186	1.11
3	bh	0.288	0.209	1.38
	peri	0.242	0.209	1.16
4	peri	<0.14	0.104	
5	bh	0.116	0.104	1.12
6	bh	0.140	0.128	1.09
	peri	0.115	0.128	0.90

[a] Calculated from eq 1, r is taken to be 1.80 Å. The calculated assumes methyl reorientation around the C_3 axis.

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[17] Imashiro, F.; Terao, T.; Saika, A. *J. Am. Chem. Soc.* **1979**, *101*, 3762–3766. The K values in Table I of this paper are uncorrect. Correct values are 6.35 ± 0.21 and 6.48 ± 0.14 for **1** and **2**, respectively.

[18] (a) Stejskal, E. O.; Gutowsky, H. S. *J. Chem. Phys.* **1958**, *28*, 388–396. (b) Woessner, D. E. *Ibid.* **1962**, *36*, 1–4. (c) Anderson, J. E.; Slichter, W. P. *J. Phys. Chem.* **1965**, *69*, 3099–3104. (d) Stohrer, M.; Noack, F. *J. Chem. Phys.* **1977**, *67*, 3729–3738.

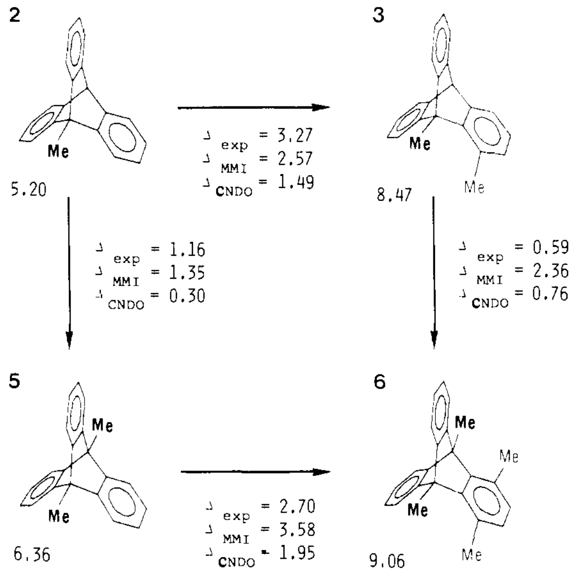

Figure 3. Experimental barriers of bh methyls and the differences among them: the experimental value (Δ_{exptl}) and the calculated values by the MMI method (Δ_{MMI}) and by the CNDO/FK method (Δ_{CNDO}). Engeries are given in units of kcal/mol.

to a combination of two BPP functions. The "best fit" values for the parameters thus obtained are given in Table I, and the "best fit" lines are shown as solid curves in Figures 1 and 2.

The "best fit" values for the T_1 minima, T_1^{exptl}(min), and those calculated with eq 1, T_1^{calcd}(min), are listed in Table II. The T_1^{exptl}(min) values are larger than the T_1^{calcd}(min) values by about 10% and the T_1^{exptl}(min) values for bh methyl are larger than those for peri methyl in the same molecule. Similar observations of longer T_1^{exptl}(min) compared with T_1^{cacld}(min)[20] have been accounted for by proposing that the partial averaging of the dipolar hamiltonian by torsional oscillations of methyl groups reduces the spin-lattice relaxation rate by a factor of 0.8–0.9.[21] This suggestion, however, leads to longer T_1(min) values for methyl groups with smaller barriers, in contradiction with the present results. Another suggestion[22] has been put forward that the longer T_1(min) may arise if slightly nonexponential recovery of the magnetization is erroneously analyzed by assuming single exponential behavior, but our observed T_1 curves obtained from initial relaxations, which are exponential up to 50% recovery, are distinctly symmetric above and below the temperature at T_1(min). Apart from this slight discrepancy T_1 may be considered to be controlled only by methyl reorientations over the present temperature range, thus giving activation energies which may be identified with the rotational barriers of methyl groups.

bh Methyl Barriers. Experimental barriers of bh methyls and differences among them are arranged in Figure 3. Replacement of the peri hydrogen by a methyl group increases the barrier to rotation of bh methyl by about 3 kcal/mol. As for steric hindrance of the methyl group at a peri position, the rotational barriers of the methyl group have been reported[23] to be 2.4 and 3.2 kcal/mol for 1-methylnaphthalene (**9**) and 1,8-dimethylnaphthalene (**10**), respectively. Thus, the peri methyl group in naphthalene raises the rotational barrier of another peri methyl group by only 0.8 kcal/mol, which is about one-fourth of these observed for triptycene. This small effect of the peri methyl on the methyl rotation in naphthalene is mainly ascribable to avoidance of the steric compression by distortion or buckling of the substituent group. However, bh methyl in triptycene has no space to escape because of obstruction by the two extra peri hydrogens. Accordingly, one might consider that bh methyl and peri methyl are forced to reorient in gear, but the observed large increments of the rotational barriers do no seem compatible with the gear effect in the present triptycene system. The barrier of bh methyl in **8**[7] can be estimated to be nearly 8.6 kcal/mol from our results for **3** and **6**. This value may agree well with the barrier of bh methyl in **7** if the buttressing effect[24] in **7** is taken into account, thus negating the necessity of invoking the gear effect in **8**. It may be added here that one could hasten to rule out any possibility of gearlike rotation merely from the observed dissimilar barriers for bh and peri methyls in **3** and **6**. However, this dissimilarity is not inconsistent with the situation,[7] where the peri methyl is forced to rotate synchronously with bh methyl whereas bh methyl need not follow peri methyl rotation on the assumption of a meshed-gear ground-state conformation for **3** and **6**. In the above we have advanced an argument in favor of the absence of even such a partial gear effect.

Table III. Steric Energy Difference between the Transition and the Ground States for the bh Methyl Rotation Calculated by the MMI Method

steric energy[a] difference	2	5	3	6
bond stretching	1.58	1.48	2.11	1.90
angle bending	4.02	4.47	5.63	7.02
torsion	1.60	1.60	1.73	2.18
van der Waals	4.90	5.82	5.16	5.90
others[b]	−0.03	0.05	0.01	0.00
total	12.07	13.42	14.64	17.00
Grouped van der Waals[c]				
bh Me···peri C-Me			1.28	0.90
bh Me···peri C-H	3.91	4.23	2.63	3.17
sum	3.91	4.23	3.91	4.07
obsd	5.20	6.36	8.47	9.06

[a] Energies are given in units of kcal/mol. [b] Sum of stretch-bend, torsion-bend, and dipole energies. [c] Intergroup terms of van der Waals energies.

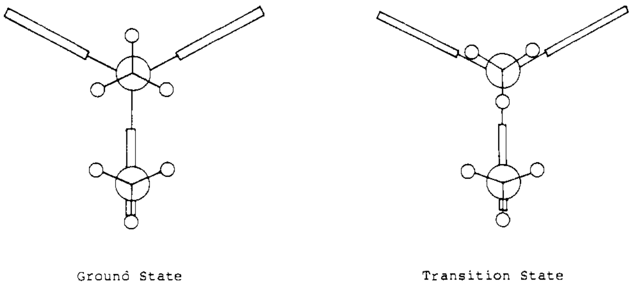

Figure 4. Schematical illustrations of the ground- and transition-state conformations for bh methyl rotation in **3**.

The barrier of bh methyl in **5** is larger than that in **2** by 1.16 kcal/mol. This increment can be attributed to an unexpected remote buttressing effect by the bh methyl in the backside of the triptycene molecule; the steric bulkiness of one bh methyl in **5** is propagated through the molecular framework to the other bh position and destabilizes the rotational transition state. The rigid, symmetric molecular structure containing three benzo substituents makes such a buttressing effect prominent. A similar effect is also found for **3** compared with **6**, but the increment in this case is only 0.6 kcal/mol. This is because increase of the barrier by methyl substitution at the peri position is large enough to shield the remote buttressing effect.

MMI Calculation for bh Methyl Barriers. MMI calculations have been performed for bh methyl rotations. The calculated

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(19) (a) Polak, M.; Steinblatt, M. *J. Magn. Reson.* **1973**, *12*, 261–269. (b) McDowell, C. A.; Raghunathan, P.; Williams, D. S. *Ibid.* **1976**, *24*, 113–123.

(20) See, for example: Kumar, A.; Johnson, C. S., Jr. *J. Chem. Phys.* **1974**, *60*, 137–146.

(21) Johnson, C. S., Jr. *J. Magn. Reson.* **1976**, *24*, 63–70.

(22) (a) Emid, S.; Baarda, R. J.; Smidt, J.; Wind, R. A. *Physica B+C (Amsterdam)* **1978**, *93B+C* 327–343. (b) Hilt, R. L.; Hubbard, P. S. *Phys. Rev.* **1964**, *134*, A392–A398. (c) Runnels, L. K. *Ibid.* **1964**, *134*, A28–A36.

(23) (a) von Schütz, J. U.; Wolf, H. C. *Z. Naturforsch., A* **1972**, *27A*, 42–50. (b) Saika, A.; Kawamori, A.; Takagi, R. *J. Magn. Reson.* **1972**, *7*, 324–326.

(24) (a) Westheimer, F. H. "Steric Effects in Organic Chemistry"; Newman, M. S., Ed.; Willey: New York, 1956, Chapter 12. (b) Eliel, E. L. "Stereochemistry of Carbon Compounds"; McGraw-Hill: New York, 1962; pp 162–164.

Table IV. Intra- and Intergroup Energy Differences between the Transition and the Ground States for the bh Methyl Rotation Calculated by the CNDO/FK Method[a]

	2	5	3	6
bh Me	2.63	2.90	3.24	3.90
peri C–Me			1.94	2.01
peri C–H	3.18	3.50	2.47	2.77
bh Me···peri C–Me			−0.46	−0.69
bh Me···peri C–H	−1.41	−1.47	−1.13	−1.13
bh Me···others	2.07	1.91	2.06	1.81
others	−0.92	−0.99	−1.08	−0.87
total	5.55	5.85	7.04	7.80
obsd	5.20	6.36	8.47	9.06

[a] Energies are given in units of kcal/mol.

rotational barriers, which are equal to the sum of various steric energy differences between the transition and the ground states, are collected in Table III. Variations in the van der Waals interactions divided into bh methyl and peri groups to estimate the steric compression are also listed in Table III. To obtain the rotational transition states, Wiberg–Boyd's one-bond driving technique[25] is applied to the rotation of bh methyls, with three dihedral angles $C_{ar}–C_{bh}–C_{Me}–H_{Me}$ simultaneously varied.[26] The dihedral angles in the transition states thus calculated are 0° as previously reported for **2**.[17] The calculated ground- and transition-state conformations[27] for **3** are schematically depicted in Figure 4, where the methyl groups are found to take a clashed-gear conformation in the ground state.[5] An X-ray study[28] reports a similar conformation for the two methyl groups in **10**. The hollow between the "three-pronged"[29] arms of the methyl group is not so deep as often imagined.

Although the calculated barriers in Table III are greater than the experimental values, the differences among the MMI barriers of bh methyls (Δ_{MMI} shown in Figure 3) are in good agreement with those among the experimental barriers (Δ_{exptl}). The systematic overestimation for the bh methyl barriers by the MMI calculation is mainly ascribable to the neglect of the nonbonded attractive interactions[17] between the peri substituents and the bh methyl. The major contributions to the barriers are the van der Waals and the angle bending energies due to the rotation of the $C_{sp^3}–C_{sp^3}$ bonds. The increase in the angle bending terms of **3** and **6** compared with those of **2** and **5**, respectively, accounts for the increase in the steric energy by peri methyl substitution. The increment of the van der Waals terms of **5** and **6** compared with those of **2** and **3**, respectively, on the other hand, suggests the remote buttressing effect. Interestingly, since bh methyls of **3** and **6** are forced to lean toward the opposite peri hydrogens owing to peri methyls, contributions of the van der Waals term between the bh methyl and a peri hydrogen to the rotational barriers are rather larger than those between the bh methyl and the peri methyl as shown in the grouped van der Waals terms in Table III.

CNDO/FK Calculation for bh Methyl Barriers. To estimate the electronic effects, which are not fully taken into account by the molecular mechanical method, the CNDO/FK method[12] has been applied. The CNDO/FK method is the CNDO/2 method modified so as to remedy the original defect of predicting too compact equilibrium geometries or conformations. The most stable conformations calculated by the MMI method are adopted as the ground-state geometries for CNDO/FK calculations. The methyl group is treated as a rigid rotor, and the geometries of the transition state thus obtained are similar to those by the MMI method (Figure 4). One-center and two-center energy terms are recombined to group energy terms in order to clarify intra- and intergroup interactions as listed in Table IV. The CNDO/FK calculations yield barriers appreciably smaller than the MMI ones, and in fair agreement with experiment. Relative differences (Δ_{CNDO} in Figure 3) among the barriers of bh methyls, however, are not well reproduced. The major origin of the rotational barrier by the CNDO/FK method is the destabilization of bh methyl and the peri substituents. The nonbonded interaction between bh methyl and the peri substituents, which is ca. +4 kcal/mol by the MMI calculation (Table III), is found to be ca. −1.5 kcal/mol by the CNDO/FK calculation. Therefore, the systematic overestimation for the bh methyl barriers by the MMI method is mainly due to its failure to incorporate the nonbonded attractive interaction in the rotational transition states.

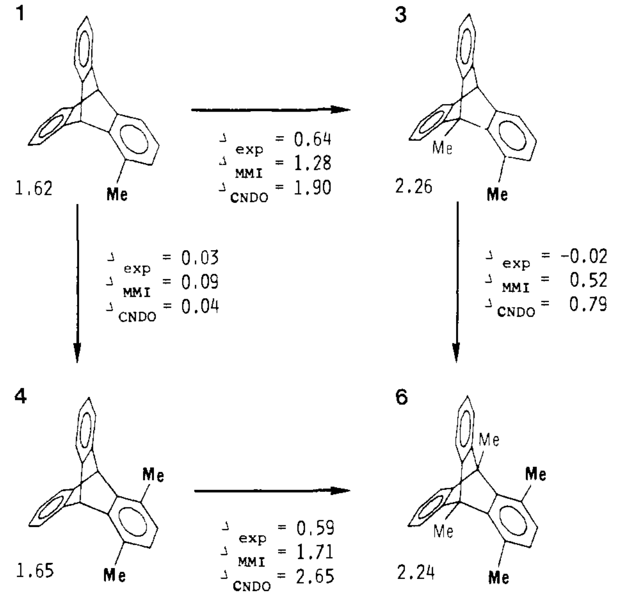

Figure 5. Experimental barriers of peri methyls and the differences among them: the experimental value (Δ_{exptl}) and the calculated values by the MMI method (Δ_{MMI}) and by the CNDO/FK method (Δ_{CNDO}). Energies are given in units of kcal/mol.

Table V. Steric Energy Differences between the Transition and the Ground States for the Peri Methyl Rotation Calculated by the MMI Method

steric energy[a] difference	1	4	3	6
bond stretching	0.08	0.10	0.22	0.22
angle bending	0.67	0.72	1.55	1.88
torsion	0.00	0.00	0.00	0.00
van der Waals	0.60	0.62	0.87	1.04
others[b]	−0.01	−0.01	−0.02	0.00
total	1.34	1.43	2.62	3.14
Grouped van der Waals[c]				
peri Me···bh C-Me, C-H	0.55	0.56	0.63	0.54
obsd	1.62[d] 1.17[e]	1.65	2.26	2.24

[a] Energies are given in units of kcal/mol. [b] Sum of stretch-bend, torsion-bend, and dipole energies. [c] Intergroup terms of van der Waals energies. [d] Value above 147 K. [e] Value below 147 K.

Peri Methyl Barriers. Experimental barriers of peri methyls and differences among them are arranged in Figure 5. Replacement of the bridgehead hydrogen by a methyl group increases the barrier to rotation of peri methyl by about 0.6 kcal/mol. This increment nearly equals the difference (0.8 kcal/mol) between **9** and **10**, indicating that peri methyls in triptycene have space to escape from the steric compression like the peri methyl groups in naphthalene. This flexibility is also reflected in the absence of the buttressing effect, which is suggested because the barriers for **4** and **6** are not increased compared with that for **1** and **3**, respectively.

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(25) Wiberg, K. B.; Boyd, R. H. *J. Am. Chem. Soc.* **1972**, *94*, 8426–8430.

(26) While one dihedral angle is varied, the bh methyl becomes deformed and the steric energy for the transition state increases.

(27) Due to the rigidity of benzene rings calculated by the MMI method apparent rocking motion of the peri methyl as reported in ref 5 is not present.

(28) Bright, D.; Maxwell, I. E.; de Boer, J. *J. Chem. Soc., Perkin Trans. 2* **1973**, 2101–2105.

(29) Nilsson, B.; Martinson, P.; Olsson, K.; Carter, R. E. *J. Am. Chem. Soc.* **1974**, *96*, 3190–3197.

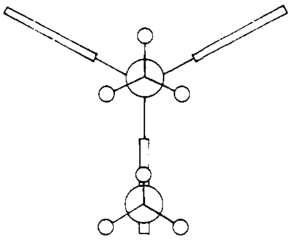

Figure 6. A schematical illustration of the transition state conformation for peri methyl rotation in **3**.

Table VI. Intra- and Intergroup Energy Differences between the Transition and the Ground States for the Peri Methyl Rotation Calculated by the CNDO/FK Method[a]

	1	4	3	6
peri Me	0.60	0.72	1.18	1.67
bh C–H, C–Me	0.96	0.99	2.09	2.47
peri Me···bh C–H, C–Me	−0.45	−0.43	−0.45	−0.33
peri Me···others	0.53	0.36	0.64	0.29
others	−0.26	−0.22	−0.18	−0.03
total	1.38	1.42	3.28	4.07
obsd	1.62[b]	1.65	2.26	2.24
	1.17[c]			

[a] Energies are given in units of kcal/mol. [b] Value above 147 K. [c] Value below 147 K.

MMI Calculation for Peri Methyl Barriers. For the MMI calculations of the rotational transition states, Wiberg–Boyd's one-bond driving technique is also applied to rotation of peri methyls. The results of MMI calculations are listed in Table V. They are in satisfactory agreement with experiment suggesting the absence of electronic effects such as the nonbonded attractive interaction for bh methyls. The calculated transition-state conformation for **3** is sketched in Figure 6, with the methyl groups taking a meshed-gear conformation. The angle bending and the van der Waals terms make a dominant contribution to the rotational barrier. The increase in the steric energy by the bh methyl substitution comes mainly from the increase in the angle bending term.

CNDO/FK Calculation for Peri Methyl Barriers. The CNDO/FK rotational barriers presented in Table VI are in substantial agreement with the experimental as well as the MMI barriers. A nonbonded attractive interaction between the peri methyl and the bh substituent negligibly negligible small, about 0.4 kcal/mol for all the compounds in Table VI. Therefore, the MMI calculations gave results in good agreement with experimental results. The major origin of the peri methyl barrier is the destabilization of peri methyl and bh substituents.

To conclude, the observed appreciable increment of barriers to rotation of bh methyls by methyl substitution at peri positions is not compatible with the gear effect. Furthermore, both MMI and CNDO/FK calculations indicate the two adjacent methyl groups prefer a clashed-gear conformation in the ground state and bh and peri methyls need not rotate synchronously. Thus, the idea of gearlike rotation may be needless for two adjacent methyl groups.

Acknowledgment. We wish to express our thanks to Professor Eiji Ōsawa of Hokkaido University for his kind offer of the modified MMI program source. The efficient service of the Data Processing Center at Kyoto University and the Computer Center at the Institute for Molecular Science is gratefully acknowledged. This work was supported by a grant for Fundamental Research in Chemistry from the Japan Society for the Promotion of Science.

Registry No. 1, 20711-97-1; **2**, 793-39-5; **3**, 75979-95-2; **4**, 17417-17-3; **5**, 15254-35-0; **6**, 33671-75-9.

Effects of Divalent Metal Ions on Hydrolysis of Esters of 2-(Hydroxymethyl)picolinic Acid. Metal Ion Catalysis of the Carboxyl, Hydroxide Ion, and Water Reactions

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Abstract: The effects of divalent metal ions (Cu^{2+}, Ni^{2+}, Co^{2+}, and Zn^{2+}) on the hydrolysis reactions of phthalate, succinate, and acetate esters of 2-(hydroxymethyl)picolinic acid have been determined at 50 °C. With these esters the metal ion saturates at low metal ion concentration (<0.01 M). Large rate enhancements are observed in the hydroxide ion catalyzed reactions at saturating concentrations of metal ion, ranging from 10^4 with Ni^{2+} to 10^6 with Cu^{2+}. A pH-independent reaction also occurs in the case of the phthalate monoester which is associated with the neighboring carboxyl nucleophilic reaction. Rate enhancements of 10^2–10^4 are obtained in this reaction at saturating concentrations of Ni^{2+}, Co^{2+}, and Cu^{2+}. Rate constants in the Ni^{2+} and Co^{2+} catalyzed reaction are closely similar to those for 2-pyridylmethyl hydrogen phthalate with which metal ion binding is weak. Thus, metal ion catalysis of the nucleophilic reaction, which occurs through leaving group stabilization in the transition state, is not appreciably enhanced by increased strength of binding to the reactant. Such a reaction does not occur with Cu^{2+} in hydrolysis of the succinate monoester, showing that when the leaving group is poor, steric fit of the nucleophile and the carbonyl must be excellent for a nucleophilic mechanism to occur even though the leaving group can be greatly stabilized by a metal ion, i.e., there cannot be degrees of freedom for rotation of the nucleophile away from the carbonyl. At pH <3 k_{obsd} is pH independent in the Cu^{2+}-catalyzed hydrolysis of the succinate and acetate esters due to a metal ion promoted water catalyzed reaction. Thus, three different mechanisms for metal ion catalysis can be observed in hydrolysis of esters of 2-(hydroxymethyl)picolinic acid: (1) catalysis of a neighboring carboxyl nucleophilic reaction, (2) metal ion promoted OH^- catalysis, and (3) metal ion promoted water catalysis. The first of these mechanisms is dependent upon the strength of binding of the metal ion to the leaving group oxygen in the transition state, whereas the latter two mechanisms are facilitated by strength of binding to the reactant.

Carboxypeptidase A is a Zn(II)-requiring enzyme, catalyzing the hydrolysis of ester and peptide substrates.[2] X-ray crystallographic analysis at 2-Å resolution has shown the zinc ion to be chelated to the carbonyl oxygen of poor peptide substrates.[2–4] The

0002-7863/82/1504-2251$01.25/0