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Conformational analysis of methyl 2-methyl-2-(1-naphthyl)propionate

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Abstract—(*S*)-2-Methoxy-2-(1-naphthyl)propionic acid (MαNP acid **1**) is used for enantioseparation of many secondary alcohols and for determining the stereogenic centers. In the liquid state, based on the ^{1}H NMR anisotropy effect and reported results, it was shown that the MαNP ester preferred a coplanar relation between the methyl and naphthyl groups and a *synperiplanar* relation between the Cα–OMe and C=O groups. In the case of 1,2,3,4-tetrahydro-4-phenanthrenol, which is a secondary alcohol, the stereogenic center was determined by X-ray analysis. It was shown that MαNP ester adopted similar arrangements in the solid state. However, it was presumed that the strong repulsion between oxygen atoms may be disadvantageous in the solid state. Therefore, we carried out conformational analysis using the simplest MαNP methyl ester to clarify this unique relationship. From detailed results based on the energy surface determined using the RHF/STO-3G basis set, the *synperiplanar* positional relation was the most stable, and the calculated results agreed with many reported experimental results. At the same time, all conformational isomers of the MαNP methyl ester were used to clarify the internal conversion pathways.

In order to determine the configuration of stereogenic centers in organic molecules, a few physical methods have been utilized: X-ray crystallography, NMR spectroscopy, and exciton CD spectroscopy.[1] In particular, chemical shift reagents have been widely used to identify the chemical shifts of two diastereomers in NMR spectra. These chemical reagents are called Mosher's reagents: α-methoxy-α-trifluoromethylphenylacetic acid (MTPA),[2] α-methoxyphenylacetic acid (MPA),[3] α-(1- and 2-naphthyl)-α-methoxyacetic acids (1-NMA and 2-NMA),[4] α-(9-anthryl)-α-methoxyacetic acid (9AMA),[4] α-(2-anthryl)-α-methoxyacetic acid (2ATMA),[4] α-cyano-α-fluorophenylacetic acid (CFPA),[5] α-cyano-α-fluoro-*p*-tolylacetic acid (CFTA),[6] and 2-(2,3-anthracenedicarboximide)cyclohexanecarboxylic acid.[7] As shown in Figure 1a, **1** also belongs to the category of Mosher's reagents.

Acid **1** first reported by Goto et al.[8] is a chiral derivatization reagent for indirect enantiomer separation of amino acids. In 1999, from a study on diastereomeric mixtures of methyl 2-hydroxy-2-(1-naphthyl)propionate by Harada et al.,[9] it turned out that **1** has a potential anisotropy effect similar to that of Mosher's reagents.[10] A wide variety of racemic alcohols can be separated using acid **1** with HPLC, and then, the stereo configuration of chiral secondary alcohols can be determined by the ^{1}H NMR anisotropy method.[10]

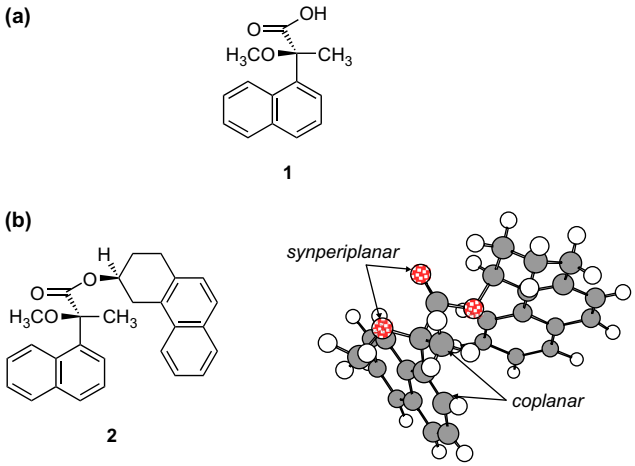

Figure 1. (a) MαNP acid **1** and (b) X-ray crystallographic results for MαNP ester **2**.

According to Kusumi et al.[11] and Riguera et al.,[12] the chemical shifts of substituents around an asymmetric center in the (*R*)- and (*S*)-derivatives of Mosher's esters reflect the correlation between the spatial position of the aryl ring in the

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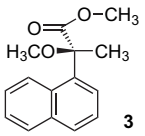

Figure 2. The structure of **3**.

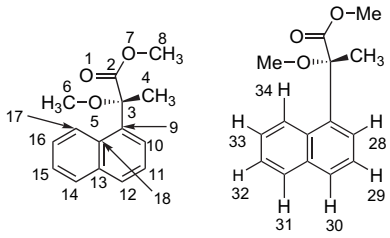

Figure 3. Atomic coordinate numbers in **3**.

chiral auxiliary reagent and the position of substituents in the substrate. In other words, the gap in the *syn* configuration is related to the steric repulsion between the substituents in chiral alcohols and the aromatic rings in the reagents and is common for Mosher's reagents. Riguera et al. have reported that the relation between the OMe and C=O groups is *syn* and that the relation between the aryl ring and Cα–H bond is almost planar based on MM, AM1, ab initio calculations, and NMR results. The above-mentioned results have been supported by many conformational analyses and experiments and are almost equal to the axiom for the advanced Mosher's method.[11] In particular, from results of highly accurate calculations by Houk et al.,[13] methoxyacetic acid prefers approximately coplanar arrangements between its C=O and Cα–O bonds, and the *syn* arrangement is favored over the *anti* by 0.9 kcal/mol. Though the nature of Mosher's reagents has been clarified from these reported results, some questions still remain unresolved. The internal conversion pathways of Mosher's esters are not always clear for all conformers in all conformational spaces. Moreover, in order to resolve the stereogenic centers using the ^{1}H NMR anisotropy effect, it must be possible to detect the coplanar relation between the methyl and naphthyl groups and the *synperiplanar* relation between the Cα–OMe and C=O groups in the liquid state. On the other hand, the stereogenic center in the MαNP ester (**2**) of 1,2,3,4-tetrahydro-4-phenanthrenol, shown in Figure 1b, has been determined by X-ray analysis,[14] and in the crystal state, **2** has a coplanar relation between the methyl and naphthyl groups and a *synperiplanar* relation between the Cα–OMe and C=O groups. It is presumed that the strong repulsion between oxygen atoms may be disadvantageous in the solid state. Therefore,

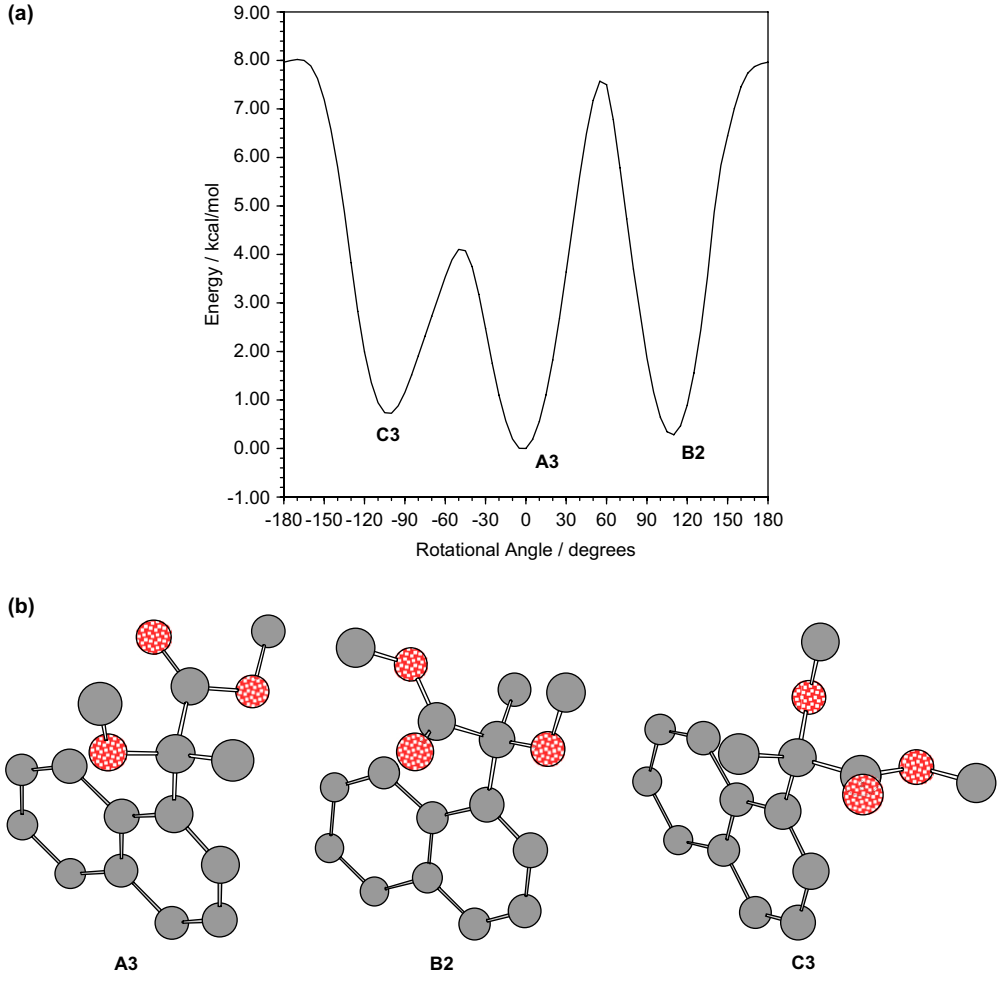

Figure 4. (a) The rotational energy to rotate around the torsion angle C_4–C_3–C_2–C_1 and (b) three minimum energy structures obtained from the rotational energy. Hydrogen atoms were omitted for clarity.

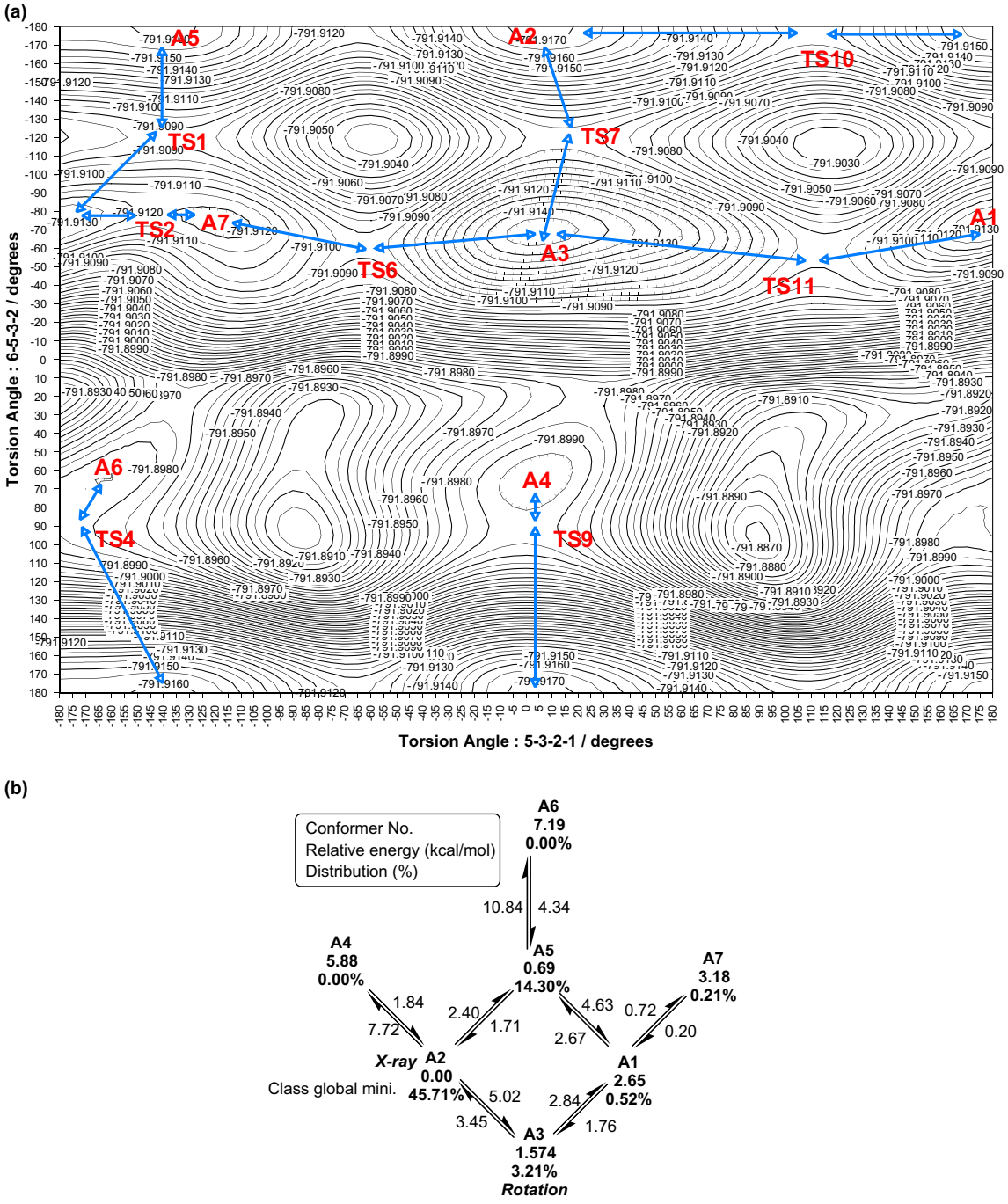

Figure 5. (a) The energy surface for group A, which was obtained using **A3** as the starting structure and (b) the relationship among seven conformers obtained from this energy surface.

we report the internal conversion pathways and the factors affecting the relation between the Cα–OMe and C═O groups using the simplest MαNP methyl ester (**3**) (Fig. 2).

1. Computational methods

To obtain the initial 3D molecular coordinates of **3**, CS Chem3D version 7.0 was used; the results are shown in Figure 3. Ab initio calculations using Gaussian 98[15] were performed on a Linux PC-Cluster and Compaq Alpha XP1000 computers. All geometrical optimizations were carried out by using the RHF/STO-3G basis set.[16] This basis set was set up to scan all conformational spaces from energy surfaces and to reduce calculating cost and time. To cover all conformational spaces, rotational steps of the single bonds in **3** were five degrees. Calculations of atomic charges based on Mulliken's population analysis[17] were carried out by using the RHF/STO-3G basis set, which can be applied to large molecules. This method required no significant calculation time. All analyses of conformational transitions and calculations of the energy barriers between conformers were also carried out by using RHF/STO-3G. During ab initio calculations, all internal coordinates were optimized by means of the Berny algorithm, and convergence was tested against criteria for the maximum force component, root-mean-square

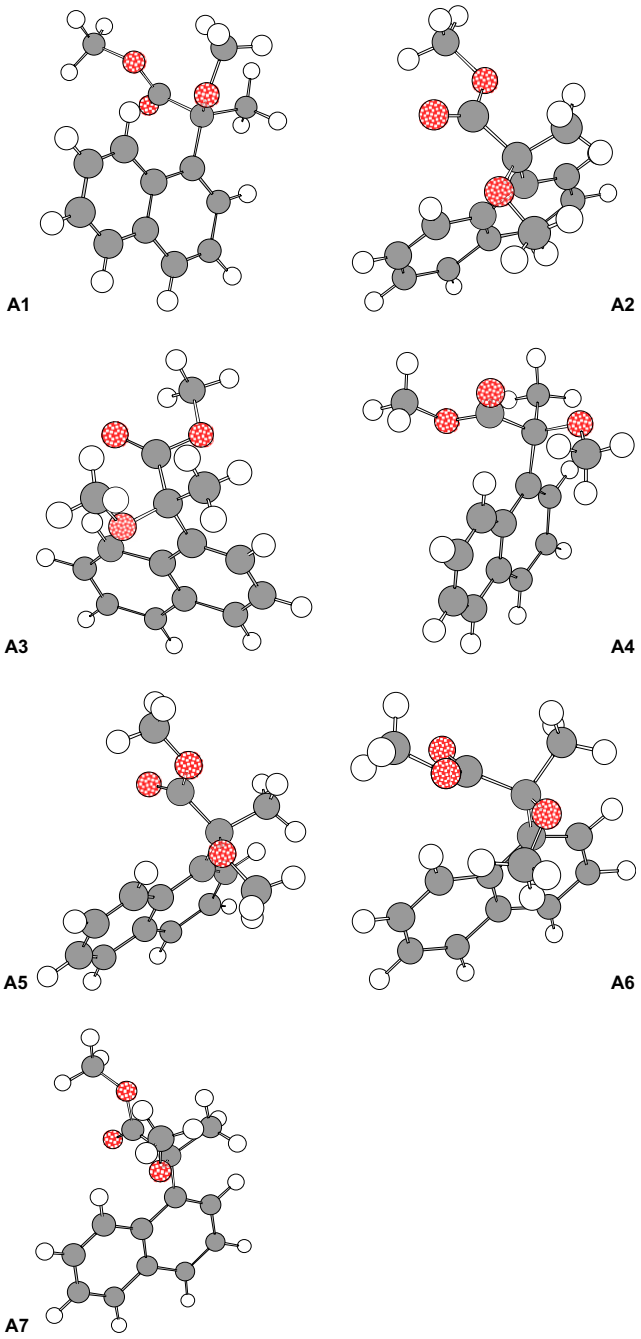

Figure 6. Seven stable conformers obtained from the energy surface for group A.

force, maximum displacement component, and root-mean-square displacement. Normal mode analyses and IRC calculations[18] confirmed all conformational transition states.

2. Results and discussion

2.1. The rotational energy of 3

As shown in Figure 3, **3** can rotate around three single bonds (C_2–C_3, C_3–C_5, and C_3–C_9), which can be used in systematical conformational analysis. Rotation around the C_3–C_9 bond defines the positional relation between the methyl and naphthyl groups, and rotation around C_2–C_3 and C_3–C_5 defines the relation between the Cα–OMe and C═O groups, which makes an energy surface. First, we investigated the relationship between the methyl and naphthyl groups.[20] The three stable structures **A3**, **B2**, and **C3**, which are rotational isomers, were obtained, as shown in Figure 4. Conformer **A3** was energetically the most stable among these rotational isomers, and the positional relation between the methyl group and the naphthyl plane was almost coplanar. This physical relation was consistent with results obtained from ^{1}H NMR spectroscopy and X-ray crystallography.[10,14] This rotational relation was important to the energy diagram derived from energy surfaces, as described later.

2.2. The energy surface of 3

Next, the relation between the Cα–OMe and C═O groups based on the three rotational conformers was used in order to search all conformational isomers systematically. In particular, two torsion angles O_5–C_3–C_2–C_1 and C_6–O_5–C_3–C_2 in **3**, as shown in Figure 3, were rotated. The energy surface obtained using **A3** as the starting structure is shown in Figure 5a. There were seven stable conformers (**A1**–**A7**), as shown in Figure 6. Concerning the relation between the Cα–OMe and C═O groups, **A2**, **A3**, and **A4** were *synperiplanar*, and **A1** and **A6** were *antiperiplanar*. **A5** and **A7** were almost *antiperiplanar*. The spatial relation between the OMe and C═O groups for **A1** and **A3** was perpendicular. **A2** was the most stable conformer; the positional relation between the OMe and C═O groups and the spatial correlation of the methyl group to the naphthyl plane were consistent with ^{1}H NMR spectroscopic and X-ray crystallographic results.[10,14] The correlation among conformers is shown in Figure 5b. Based on the energy barriers of the pathways on the energy surface, conformers **A1**, **A3**, **A4**, and **A6** easily moved to **A2** and **A5**. **A2** and **A5** had contributions of 45.7% and 14.3%, respectively, in the distribution. The two conformers were dominant isomers in group A. **A3** was important as the connection to other conformational groups.

In the same way, the energy surface starting from **B2** is shown in Figure 7a. The six stable conformers (**B1**–**B6**) that were obtained are shown in Figure 8. In **B1**–**B6**, the O atom of the OMe group was in the naphthyl plane, and the OMe group had two arrangements: almost vertical to the naphthyl plane and the other in the naphthyl plane. The vertical case includes **B2** and **B5**, and the other includes **B1**, **B3**, **B4**, and **B6**. The positional relation between the Cα–OMe and C═O groups was neither *synperiplanar* nor *antiperiplanar*. The correlation among conformers is shown in Figure 7b. From the pathways of group B, conformers **B1**, **B2**, **B3**, **B4**, and **B6** were easy to move to **B5**. **B4** and **B5** shared 3.6% and 8.9% distribution, respectively. The two conformers were the dominant isomers in group B. Conformer **B2** was important as the connection to other conformational groups.

The energy surface starting from **C3** is shown in Figure 9a. There were four stable conformers (**C1**–**C4**), as shown in Figure 10. The COOMe group of each conformer was

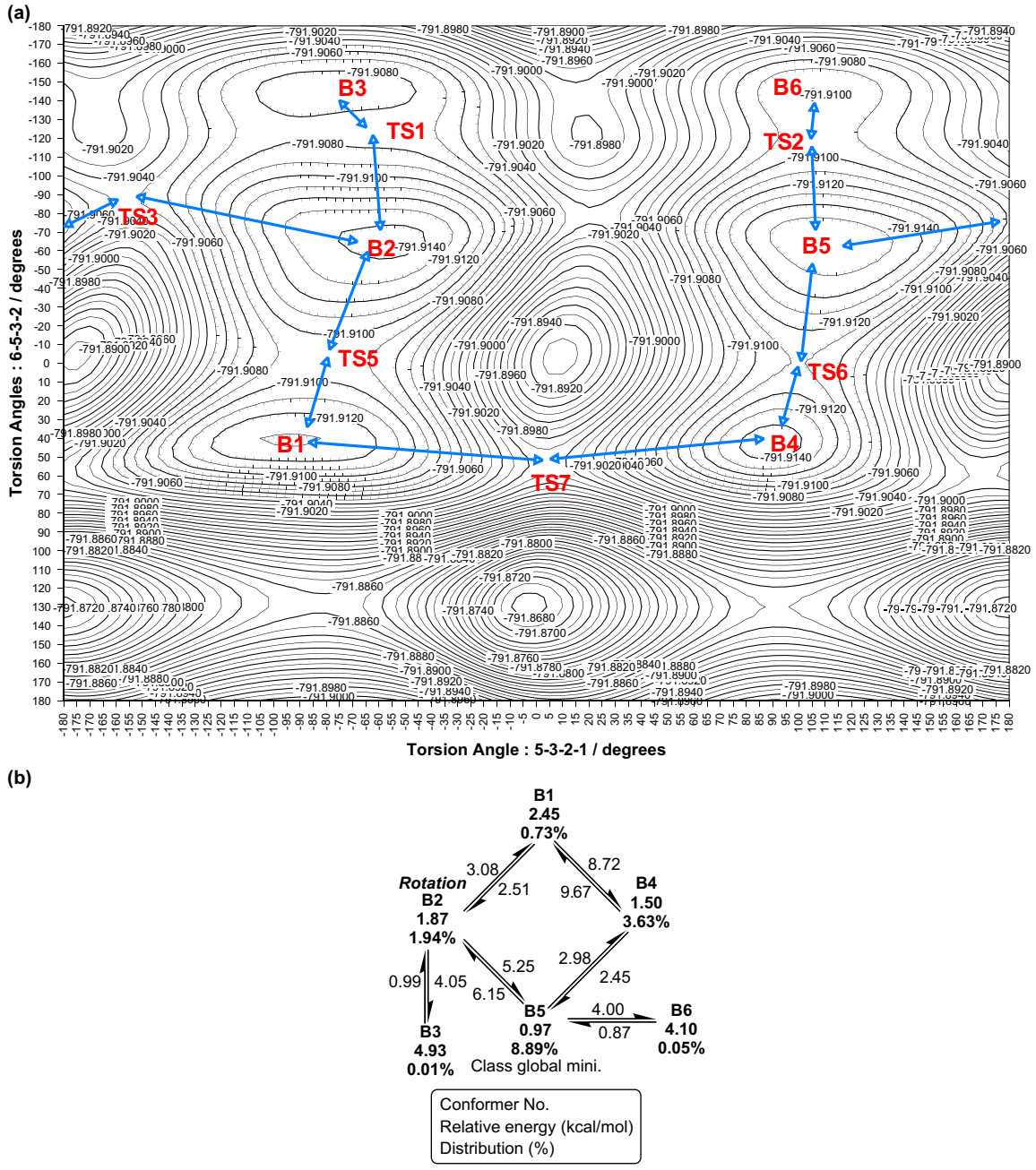

Figure 7. (a) The energy surface for group B, which was obtained using **B2** as the starting structure and (b) the relationship among six conformers obtained from this energy surface.

arranged vertically to the naphthyl plane. Conformers **C1** and **C2** had an almost *synperiplanar* relation between the OMe and C═O groups. The correlation among the conformers is shown in Figure 9b. From the energy barriers of the pathways on the energy surface of group C, **C1** and **C3** easily moved to **C2** and **C4**, and **C3** was the connection to other conformational groups.

Based on the correlations among all of the conformers in each group, the internal conversion pathways for **3** are shown in Figure 11. The global minimum conformer was **A2**, which had a coplanar relation between the methyl and naphthyl groups and a *synperiplanar* relation between the Cα–OMe and C═O groups. The internal conversion between **A3** and **C3** was smaller than other internal conversions. As shown in Figure 12, **3** preferred the conformational isomers of group A on the whole. In other words, group A was the dominant set of conformers, and groups B and C were minor ones. This result is consistent with the experimental results obtained from ^{1}H NMR spectroscopy[10] and is important because the determination of chiral centers in Mosher's derivatives from the chemical shifts in ^{1}H NMR spectra needs conformational isomers with a coplanar relation between the methyl and naphthyl groups and a *synperiplanar* relation between the Cα–OMe and C═O groups.[10–12,14]

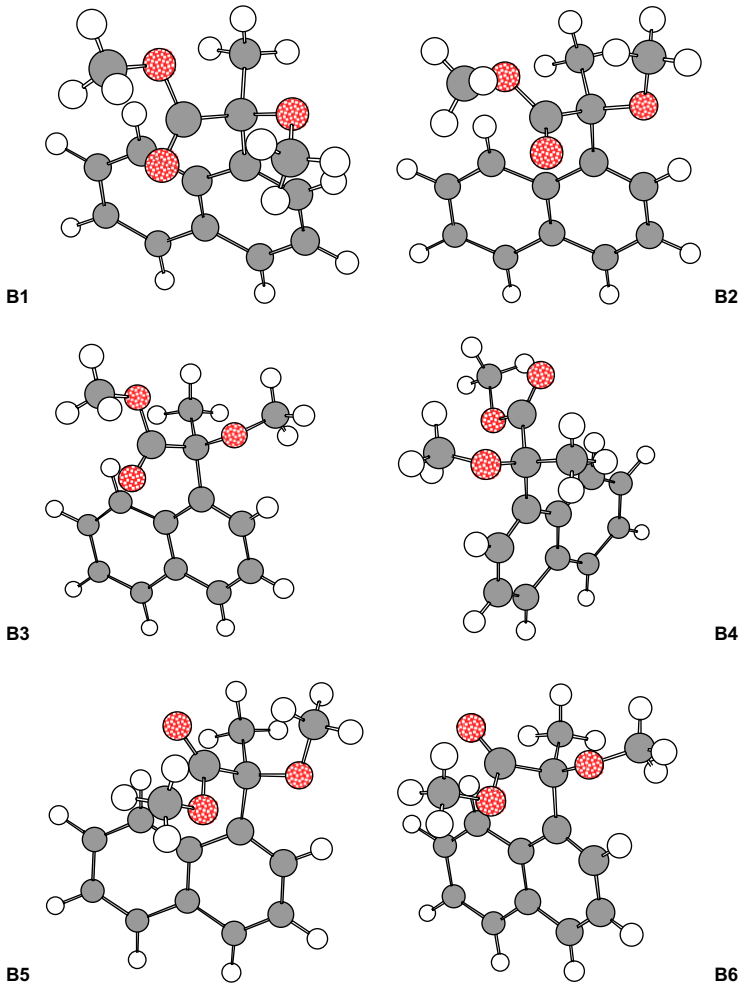

Figure 8. Six stable conformers obtained from the energy surface for group B.

2.3. Stabilization of the *synperiplanar* conformation in 3

Finally, regardless of the strong repulsion between oxygen atoms, the main reason why MαNP esters preferred the *synperiplanar* relation between the Cα–OMe and C=O groups remains unclear. In order to achieve this relation, the strong repulsion between the oxygen atoms must be suppressed by attractive interactions. To clarify the reason, internal distances and charges on all of the conformers in group A were calculated. In the case of the most stable conformer **A2**, the O_1–H_{34} and O_5–H_{34} interatomic distances were 2.57 Å and 2.21 Å, respectively, as shown in Table 1. The distances in **2**, which were determined experimentally, were similar to the calculated bond distances in **3**. As shown in Table 2, the charges on the oxygen atoms had large negative values, meaning that there was a large amount of repulsion between the oxygen atoms of the Cα–OMe and C=O groups. The charge on H_{34} atom in the naphthyl group had the largest positive value (+0.090), while charges on other hydrogen atoms were +0.060 to +0.065. Based on the distances, charges, and reported experimental results,[19] we believe that interactions between the oxygen and hydrogen atoms exist in **3**. The sum of the interactions between O_1–H_{34} and O_5–H_{34} could overcome the large repulsion between the oxygen atoms of the Cα–OMe and C=O groups. In other words, it is reasonable to assume that attractive interactions between hydrogen and oxygen atoms must have eased the large repulsion between the two oxygen atoms.

Table 1. Calculated internal distances between oxygen and hydrogen atoms for conformers in group A (unit: Å)

Conformer	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	X-ray of **2**
Geometrical relation[a]	*ap*[b]	*sp*[b]	*sp*	*sp*	*ap*	*ap*	*ap*	*sp*
O_1–O_5	3.66	2.66	2.86	2.84	3.45	3.67	3.46	2.59
O_5–O_7	2.67	3.62	3.70	3.70	2.64	2.66	3.03	3.53
O_1–H_{34}	3.64	2.57	2.48	2.51	3.08	2.78	2.86	2.30
O_5–H_{34}	2.27	2.21	2.27	3.35	2.21	3.28	2.24	2.39
O_7–H_{34}	2.24	3.74	3.70	2.77	3.25	2.50	3.49	3.53

[a] This relation is the spatial relation between Cα–OMe and C=O groups.
[b] Abbreviated *ap* and *sp* means *antiperiplanar* and *synperiplanar*, respectively.

Table 2. Charges on some of the atoms in **3**

Conformer	A1	A2	A3	A4	A5	A6	A7
O_1	−0.266	−0.254	−0.266	−0.267	−0.262	−0.268	−0.255
O_5	−0.242	−0.242	−0.243	−0.242	−0.242	−0.241	−0.245
O_7	−0.250	−0.254	−0.253	−0.252	−0.245	−0.250	−0.257
H_{28}	0.065	0.066	0.065	0.069	0.064	0.069	0.063
H_{29}	0.063	0.064	0.063	0.066	0.064	0.066	0.062
H_{30}	0.063	0.064	0.063	0.064	0.064	0.065	0.062
H_{31}	0.060	0.061	0.061	0.063	0.061	0.063	0.060
H_{32}	0.063	0.064	0.063	0.065	0.064	0.066	0.062
H_{33}	0.061	0.065	0.063	0.065	0.063	0.064	0.061
H_{34}	0.090	0.090	0.083	0.063	0.080	0.062	0.072

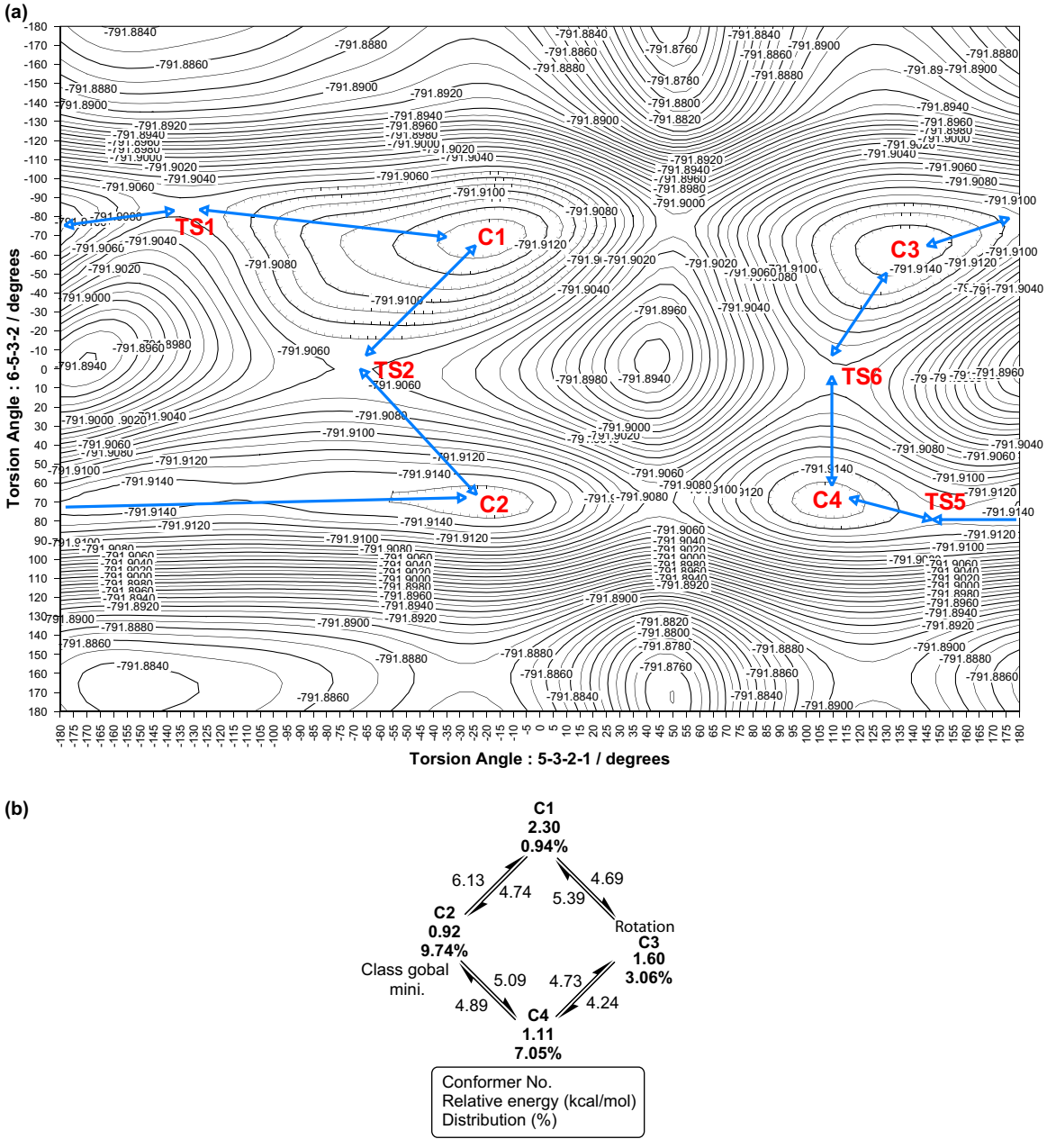

Figure 9. (a) The energy surface for group C, which was obtained using **C3** as the starting structure and (b) the relationship among four conformers obtained from this energy surface.

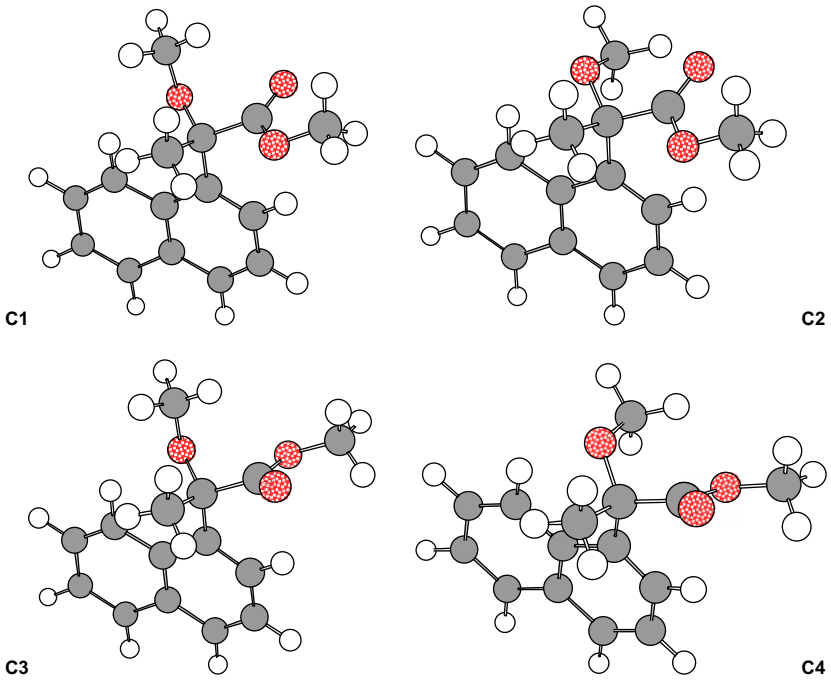

Figure 10. Four stable conformers obtained from the energy surface for group C.

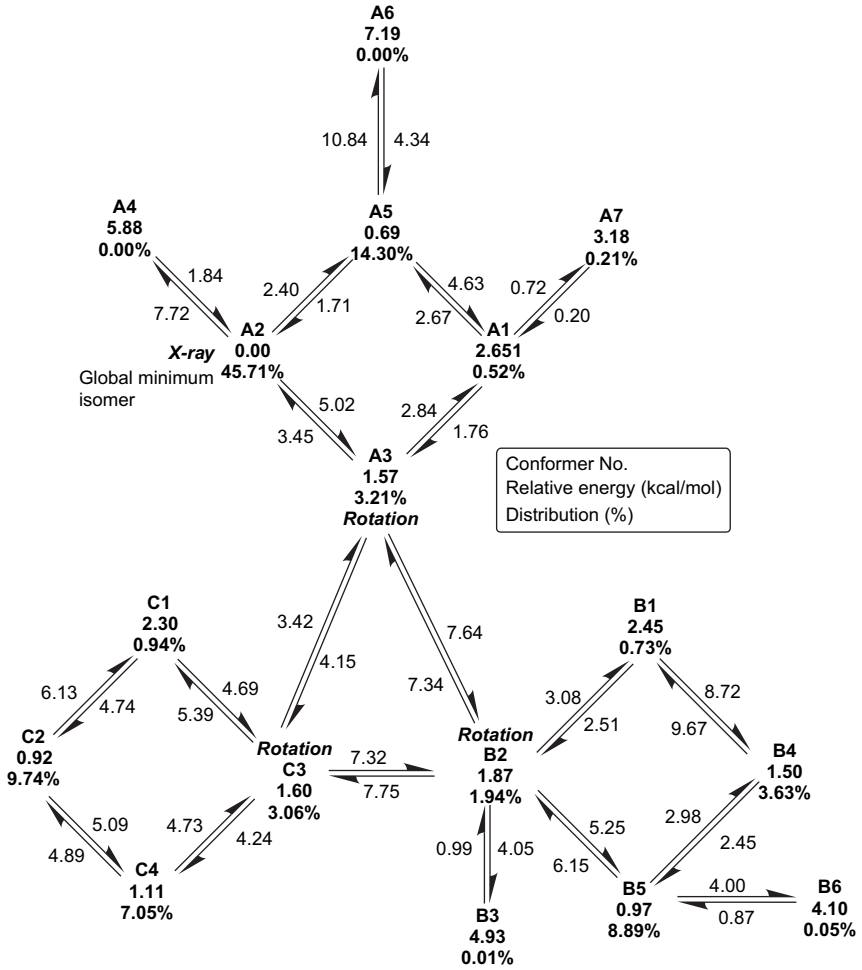

Figure 11. The internal conversion pathways for **3**.

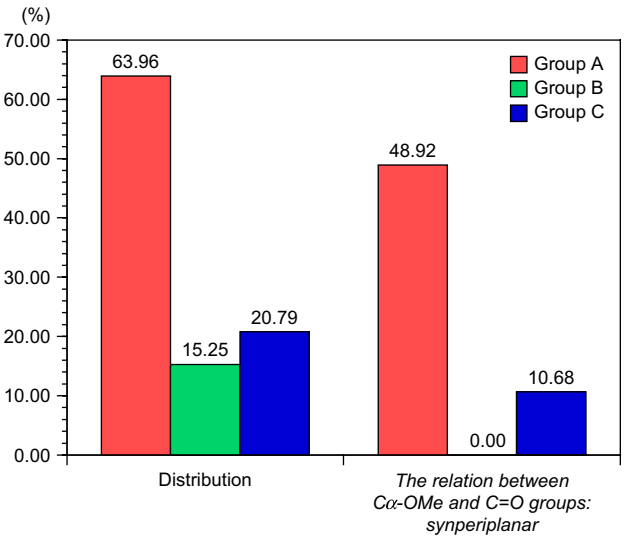

Figure 12. The distribution for each group in **3** and the distribution showing that the relation between Cα–OMe and C═O groups is *synperiplanar*.

Consequently, MαNP esters adopted a *synperiplanar* relation between the Cα–OMe and C═O groups.

3. Conclusion

In conclusion, from conformational analysis on the simplest MαNP methyl ester **3**, all of the conformers and internal conversion pathways were clarified. The results are summarized as follows. (1) The most stable conformer **A2** had a coplanar relation between the methyl and naphthyl groups and a *synperiplanar* relation between the Cα–OMe and C═O groups, which is consistent with reported experimental and calculated results (Figs. 5 and 6). (2) Based on the internal conversion pathways shown in Figure 11, it was easy to move among each conformational group. MαNP methyl ester **3** preferred conformers in group A that have a coplanar relation between the methyl and naphthyl groups, see Figure 12. (3) Finally, MαNP esters maintained a *synperiplanar* relation between the Cα–OMe and C═O groups, because of the attractive interactions between the hydrogen atoms in the naphthyl group and oxygen atoms in the OMe and C═O groups, as shown in Tables 1 and 2. These results are consistent with the experimental results obtained from ^{1}H NMR spectroscopy and X-ray crystallography, and they should lead to development of new advanced Mosher's reagents. Work is underway to elucidate the characteristics of larger MαNP esters.

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2006.11.017.

References and notes

1. (a) Muranaka, A.; Asano, Y.; Tsuda, A.; Osuka, A.; Kobayashi, N. *ChemPhysChem* **2006**, *7*, 1235; (b) Grajewski, J.; Gawronska, K.; Gawronski, J. *Monatsh. Chem.* **2005**, *136*, 447; (c) Giorgio, E.; Parrinello, N.; Caccamese, S.; Rosini, C. *Org. Biomol. Chem.* **2004**, *2*, 3602; (d) Dong, J.; Bornmann, W.; Nakanishi, K.; Berova, N. *Phytochemistry* **1995**, *40*, 1821; (e) Boiadjiev, S.; Person, R.; Puzicha, G.; Knobler, C.; Maverick, E.; Trueblood, K.; Lightner, D. *J. Am. Chem. Soc.* **1992**, *114*, 10123.
2. (a) Dale, J. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 512; (b) Sullivan, G. R.; Dale, J. A.; Mosher, H. S. *J. Org. Chem.* **1973**, *38*, 2143.
3. Trost, B. M.; Belletire, J. L.; Godleski, S.; McDougal, P. G.; Balkovec, J. M. *J. Org. Chem.* **1986**, *51*, 2370.
4. (a) Seco, J. M.; Latpov, Sh.; Quiñoá, E.; Riguera, R. *Tetrahedron Lett.* **1994**, *35*, 2921; (b) Kusumi, T.; Takahashi, H.; Xu, P.; Fukushima, T.; Asakawa, Y.; Hashimoto, T.; Kan, Y.; Inouye, Y. *Tetrahedron Lett.* **1994**, *35*, 4397; (c) Kouda, K.; Kusumi, T.; Xu, P.; Kan, Y.; Hashimoto, T.; Asakawa, Y. *Tetrahedron Lett.* **1996**, *37*, 4541.
5. Takeuchi, Y.; Itoh, N.; Note, H.; Koizumi, T.; Yamaguchi, K. *J. Am. Chem. Soc.* **1991**, *113*, 6318.
6. Takahashi, T.; Fukushima, A.; Tanaka, Y.; Takeuchi, Y.; Kabuto, K.; Kabuto, C. *Chem. Commun.* **2000**, 787.
7. (a) Ohtaki, N.; Akasaka, K.; Kabuto, C.; Ohrui, H. *Chirality* **2005**, *17*, S171; (b) Akasaka, K.; Ohtaki, T.; Kabuto, C.; Kitahara, T.; Ohrui, H. *Biosci. Biotechnol. Biochem.* **2005**, *69*, 2002; (c) Ohrui, H.; Kato, R.; Kodaira, T.; Shimizu, H.; Akasaka, K.; Kitahara, T. *Biosci. Biotechnol. Biochem.* **2005**, *69*, 1054.
8. Goto, J.; Hasegawa, M.; Nakamura, S.; Shimada, K.; Nambara, T. *J. Chromatogr.* **1978**, *152*, 413.
9. (a) Kuwahara, S.; Fujita, K.; Watanabe, M.; Harada, N.; Ishida, T. *Enantiomer* **1999**, *4*, 141; (b) Matsumoto, T.; Ishida, T.; Takeda, Y.; Soh, K.; Kubo, I.; Sakamoto, M. *Chem. Pharm. Bull.* **1995**, *43*, 216; (c) Matsumoto, T.; Ishida, T.; Takeda, Y.; Yagi, J. *Biol. Pharm. Bull.* **1994**, *17*, 1441; (d) Ishida, T.; Matsumoto, T. *Xenobiotica* **1992**, *22*, 1291.
10. (a) Ichikawa, A.; Hiradate, S.; Sugio, A.; Kuwahara, S.; Watanabe, M.; Harada, N. *Tetrahedron: Asymmetry* **1999**, *10*, 4075; (b) See Ref. 9a; (c) Harada, N.; Watanabe, M.; Kuwahara, S.; Sugio, A.; Kasai, Y.; Ichikawa, A. *Tetrahedron: Asymmetry* **2000**, *11*, 1249; (d) Taji, H.; Kasai, Y.; Sugio, A.; Kuwahara, S.; Watanabe, M.; Harada, N.; Ichikawa, A. *Chirality* **2002**, *14*, 81; (e) Imamura, Y.; Takikawa, H.; Sasaki, M.; Mori, K. *Org. Biomol. Chem.* **2004**, *2*, 2236; (f) Junpei, N.; Kosaka, M.; Sugio, T.; Watanabe, M.; Harada, N.; Pirkle, W. H. *Chirality* **2003**, *16*, 22; (g) Nishimura, T.; Taji, H.; Harada, N. *Chirality* **2004**, *16*, 13; (h) Kosaka, M.; Sugio, T.; Kasai, Y.; Kuwahara, S.; Watanabe, M.; Harada, N.; Job, G. E.; Shvet, A.; Pirkle, W. H. *Chirality* **2003**, *15*, 324; (i) Kasai, Y.; Watanabe, M.; Harada, N. *Chirality* **2003**, *15*, 295; (j) Narumi, F.; Yamabuki, W.; Hattori, T.; Kameyama, H.; Miyano, S. *Chem. Lett.* **2003**, *32*, 320; (k) Okumura, Y.; Ando, A.; Stevens, R. W.; Shimizu, M. *Tetrahedron* **2002**, *58*, 8729; (l) Ichikawa, A.; Ono, H.; Hiradate, S.; Watanabe, M.; Harada, N. *Tetrahedron: Asymmetry* **2002**, *13*, 1167; (m) Kosaka, M.; Sekiguchi, S.; Naito, J.; Uemura, M.; Kuwahara, S.; Watanabe, M.; Harada, N.; Hiroi, K. *Chirality* **2005**, *17*, 218.

11. Ohtani, I.; Kusumi, T.; Kashman, Y.; Kakisawa, H. *J. Am. Chem. Soc.* **1991**, *113*, 4092.
12. (a) Latypov, S. K.; Ferreiro, M. J.; Quiñoá, E.; Riguera, R. *J. Am. Chem. Soc.* **1998**, *120*, 4741; (b) Seco, J. M.; Latypov, S. K.; Quiñoá, E.; Riguera, R. *J. Org. Chem.* **1997**, *62*, 7569; (c) Latypov, S. K.; Seco, J. M.; Quiñoá, E.; Riguera, R. *J. Org. Chem.* **1996**, *61*, 8569; (d) Latypov, S. K.; Seco, J. M.; Quiñoá, E.; Riguera, R. *J. Org. Chem.* **1995**, *60*, 504; (e) Seco, J. M.; Quiñoá, E.; Riguera, R. *Chem. Rev.* **2004**, *104*, 17.
13. Tucker, J. A.; Houk, K. N.; Trost, B. M. *J. Am. Chem. Soc.* **1990**, *112*, 5465.
14. (a) Fujita, T.; Kuwahara, S.; Watanabe, M.; Harada, N. *Enantiomer* **2002**, *7*, 219; (b) Akasaka, K.; Krisztina, G.-F.; Michael, L.; Fujita, T.; Watanabe, M.; Harada, N.; Wolfgang, L. *Chirality* **2005**, *17*, 544.
15. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Baboul, A. G.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98, Revision A.9*; Gaussian: Pittsburgh, PA, 1998.
16. (a) Hehre, W. J.; Stewart, R. F.; Pople, J. A. *J. Chem. Phys.* **1969**, *51*, 2657; (b) Collins, J. B.; Schleyer, P. v. R.; Binkley, J. S.; Pople, J. A. *J. Chem. Soc.* **1976**, *64*, 5142.
17. Mulliken, R. S. *J. Chem. Phys.* **1955**, *23*, 1833.
18. (a) Gonzalez, C.; Schlegel, H. B. *J. Chem. Phys.* **1989**, *90*, 2154; (b) Gonzalez, C.; Schlegel, H. B. *J. Phys. Chem.* **1990**, *94*, 5523.
19. (a) Lakshmi, B.; Samuelson, A. G.; Jovan, K. V.; Gadre, S. R.; Arunan, E. *New J. Chem.* **2005**, *29*, 371; (b) Hansen, P. E.; Bolvig, S.; Wozniak, K. *J. Mol. Struct.* **2005**, *749*, 155; (c) Ribeiro-Claro, P. J. A.; Drew, M. G. B.; Félix, V. *Chem. Phys. Lett.* **2002**, *356*, 318; (d) Okazaki, M.; Uchino, N.; Ishihara, M.; Fukunaga, H. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 1713.
20. Casarini, D.; Lunazzi, L.; Mazzanti, A. *J. Org. Chem.* **1998**, *63*, 4746.