Utility of a Diene−Tricarbonyliron Complex as a Mobile Chiral Auxiliary: Regio- and Stereocontrolled Functionalization of Acyclic Diene Ligands

Yoshiji Takemoto,*,† Naoki Yoshikawa,‡ Yasutaka Baba,‡ Chuzo Iwata,‡ Tetsuaki Tanaka,‡ Toshiro Ibuka,† and Hirofumi Ohishi§

Contribution from the Graduate School of Pharmaceutical Sciences, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan, Graduate School of Pharmaceutical Sciences, Osaka University, 1-6 Yamada-oka, Suita, Osaka 565-0871, Japan, and Osaka University of Pharmaceutical Sciences, 4-20-1, Nasahara, Takatsuki, Osaka 569-1094, Japan

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Abstract: Stereoselective construction of contiguous stereogenic centers of acyclic compounds by using the $Fe(CO)_3$ moiety as a mobile chiral auxiliary is described. Although the reactions of acyclic (pentadienyl)-iron(1+) cations with nucleophiles generally occur in a stereoselective but nonregioselective manner, giving rise to several regioisomers, *O*-acyl and *O*-phosphoryl cyanohydrin $Fe(CO)_3$ complexes **2**−**5** undergo regio- and stereoselective 1,5-nucleophilic substitution with several heteroatomic nucleophiles, giving the 6-substituted hepta-2,4-dienonitrile $Fe(CO)_3$ complexes **6** and **7**, that is, 1,2-migration products of the $Fe(CO)_3$ group. These products were obtained as single products, even if the starting materials **3**−**5** were a mixture of diastereomers. The (2*E*,4*E*)/(2*E*,4*Z*) selectivity of the 1,5-substituted products (**6**/**7**) is strongly dependent on the Lewis acid catalyst, triphenylcarbenium perchlorate ($TrClO_4$) giving **6** (method A) and BF_3·etherate giving **7** (method B), respectively. Furthermore, by applying iterative 1,5-nucleophilic substitution to **6**, both 6,7-*anti*-disubstituted (2*E*,4*E*)-adduct *anti*-**10** and 6,7-*syn*-disubstituted (2*E*,4*Z*)-one *syn*-**11** were synthesized stereoselectively by switching the reaction conditions (method A and method B). The third introduction of the ethylsulfanyl group into *anti*-**10** proceeded efficiently by the same treatment of **10** with ethanethiol and $TrClO_4$ to afford the 6,7-*anti*-7,8-*anti*-trisubstituted (2*E*,4*E*)-adduct **19**. Further manipulation successfully converted **19** to the *N*-Boc-*O*-Me derivative **24** of *anti*-2,3-amino alcohol **25**, which had been isolated from a marine sponge.

Introduction

Owing to their biological action and structural interest, highly functionalized acyclic compounds, which are a constituent of macrolides and macrolactams, are attracting increasing attention.[1] With the aim of synthesizing these natural products, numerous new reactions and concepts for acyclic stereocontrol have been developed recently in organic chemistry.[2] Among these efforts, the use of a transition-metal complex offers a unique opportunity for attaining the synthesis of stereodefined organic molecules.[3] Due to their high ability of stereo- and regiochemical control, transition-metal-mediated construction of contiguous stereogenic centers onto the ligand seems to be very promising. Thus far, several elegant reactions such as nucleophilic or electrophilic addition[4a,b] to cyclodiene−Mo-$(CO)_2Cp$ or $-Fe(CO)_2P(OPh)_3$ complexes and $[6\pi + 4\pi]$ cycloaddition[4c,d] of cycloheptatriene−$Cr(CO)_3$ complexes have been developed and successfully applied to the asymmetric synthesis of the segments of macrocyclic antibiotics. However, these reactions have been restricted only to cyclic polyene metal complexes.[5]

To extend the applicability of the transition-metal complexes for multiple functionalization, we have recently begun to investigate the iterative use of acyclic (η^4-1,3-diene)$Fe(CO)_3$ complexes with concurrent 1,2-migration of the metal on the ligand (Scheme 1).[6] The use of acyclic diene−iron complexes

* Corresponding author. E-mail: takemoto@pharm.kyoto-u.ac.jp.
† Kyoto University.
‡ Osaka University.
§ Osaka University of Pharmaceutical Sciences.

(1) (a) *Macrolide Antibiotics: Chemistry, Biology, Practice*; Omura, S., Ed.; Academic Press: Orlando, FL, 1984. (b) Rychnovsky, S. D. *Chem. Rev.* **1995**, *95*, 2021−2040.

(2) (a) Paterson, I.; Mansuri, M. M. *Tetrahedron* **1985**, *41*, 3569−3624. (b) Oishi, T.; Nakata, T. *Synthesis* **1990**, 635−645. (c) Smith, A. B.; Boldi, A. M. *J. Am. Chem. Soc.* **1997**, *119*, 6925−6926. (d) Richardson, T. I.; Rychnovsky, S. D. *J. Am. Chem. Soc.* **1997**, *119*, 12360−12361. (e) Evans, D. A.; Kim. A. S.; Metternich, R.; Novack, V. J. *J. Am. Chem. Soc.* **1998**, *120*, 5921−5942.

(3) Reviews: (a) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987. (b) Grée, R. *Synthesis* **1989**, 341−355. (c) *Transition Metals in Total Synthesis*; Harrington, P. J., Ed.; John Wiley & Sons: New York, 1990. (d) Pearson, A. J. *Iron Compounds in Organic Synthesis*; Academic Press: London, 1994. (e) Iwata, C.; Takemoto, Y. *Chem. Commun.* **1996**, 2497−2504.

(4) (a) Pearson, A. J.; Blystone, S. L.; Nar, H.; Pinkerton, A. A.; Roden, B. A.; Yoon, J. *J. Am. Chem. Soc.* **1989**, *111*, 134−144. (b) Pearson, J. P.; Mallik, S.; Mortezaei, R.; Perry, M. W. D.; Shively, R. J., Jr.; Youngs, W. J. *J. Am. Chem. Soc.* **1990**, *112*, 8034−8042. (c) Rigby, J. H.; Ateeq, H. S.; Charles, N. R.; Cuisiat, S. V.; Ferguson, M. D.; Henshilwood, J. A.; Krueger, A. C.; Ogbu, C. O.; Short, K. M.; Heeg, M. J. *J. Am. Chem. Soc.* **1993**, *115*, 1382−1396. (d) Rigby, J. H.; Fales, K. R. *Tetrahedron Lett.* **1998**, *39*, 5717−5720.

(5) (a) Stephenson, G. R.; Alexander, R. P.; Morley, C.; Howard, P. W. *Philos. Trans. R. Soc. London A* **1988**, *326*, 545−556. (b) Pearson, A. J. *Synlett* **1990**, 10−19. (c) Stephenson, G. R.; Finch, H.; Owen, D. A.; Swanson, S. *Tetrahedron* **1993**, *49*, 5649−5662. (d) Heck, J.; Lange, G.; Reimelt, O. *Angew. Chem., Int. Ed.* **1998**, *37*, 520−522.

(6) (a) Takemoto, Y.; Yoshikawa, N.; Iwata, C. *J. Chem. Soc., Chem. Commun.* **1995**, 631−632. (b) Takemoto, Y.; Baba, Y.; Yoshikawa, N.; Iwata, C.; Tanaka, T.; Ibuka, T. *Chem. Commun.* **1998**, 1911−1912. The similar 1,2-migration reaction of $Fe(CO)_3$ group has been reported by the French group: Braun, A.; Toupet, L.; Lellouche, J.-P. *J. Org. Chem.* **1996**, *61*, 1914−1915.

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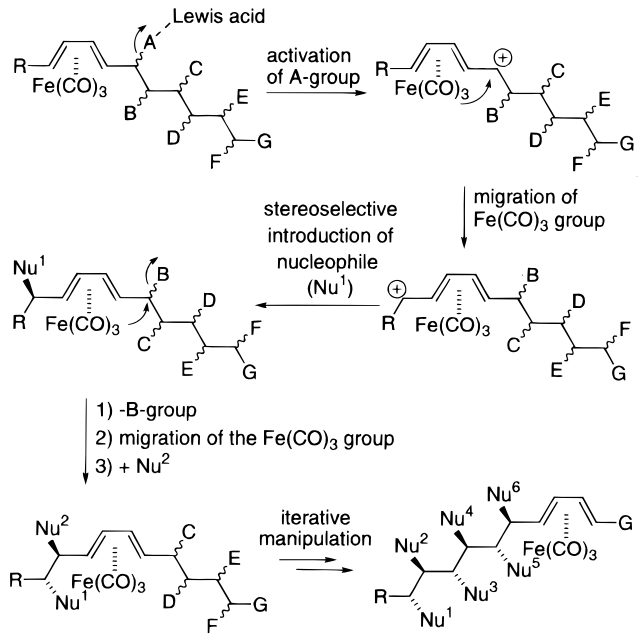
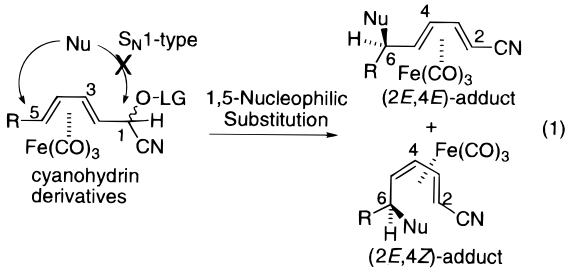
Scheme 1. Utility of an Iron−Tricarbonyl Group as a Mobile Chiral Auxiliary



has the following advantages: (i) the starting complexes are readily available in an enantiomerically pure form;[3] (ii) since the $Fe(CO)_3$ moiety possesses excellent stereodirecting ability, the intermolecular addition of nucleophiles to carbocations adjacent to the $Fe(CO)_3$ group and/or (pentadienyl)iron(1+) cations generally occurs with high stereoselectivity; (iii) distinct from cyclic metal complexes, the introduction of desired nucleophiles into acyclic complexes can be conducted iteratively with no limitation of ring size (multifunctionalization); and (iv) the $Fe(CO)_3$ moiety is easily removed under mild oxidative conditions in the final stage of the synthesis. In this paper, we report that both enantiomers can be obtained by switching the reaction conditions of 1,5-nucleophilic substitution of acyclic *O*-phosphoryl cyanohydrin complexes with perfect stereoselectivity; furthermore, several diastereomers bearing contiguous stereogenic centers can be synthesized via the iterative 1,5-substitution with concurrent 1,2-migration of the $Fe(CO)_3$ group.

Results

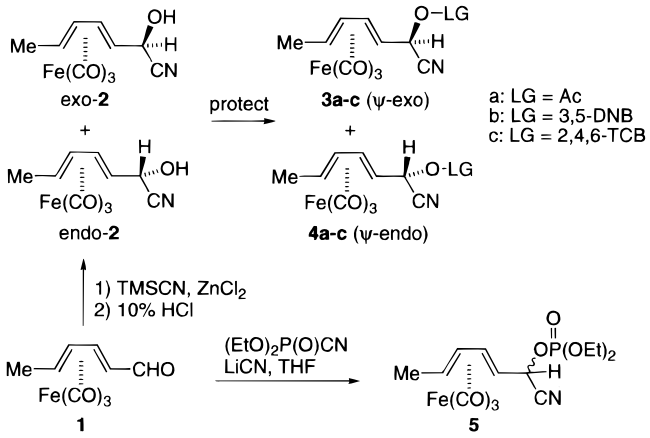
Preparation of Starting Complexes 2−5 and Their Reactivity to the 1,5-Nucleophilic Substitution with Concurrent 1,2-Migration of the Fe(CO)$_3$ Group. To examine the 1,5-nucleophilic substitutions accompanied with 1,2-migration of the $Fe(CO)_3$ group (eq 1), the (*O*-protected 2-hydroxy-η^4-3,5-heptadienenitrile)$Fe(CO)_3$ complexes **3a**−**c**, **4a**−**c**, and **5** with various protecting groups were prepared from hexadienal $Fe(CO)_3$ complex **1**[7] (Scheme 2). Treatment of **1** with trimethylsilyl



(1)

cyanide in the presence of zinc chloride was followed by acidic

Scheme 2



hydrolysis with aqueous 10% HCl in methanol to give the desired cyanohydrin complexes **2** as a 1:1 mixture of diastereomers in a quantitative yield. The obtained cyanohydrins **2** were converted to the esters **3a**−**c** and **4a**−**c** in 78−97% yields by reaction with acetic anhydride, 3,5-dinitrobenzoyl (3,5-DNB) chloride, and 2,4,6-trichlorobenzoyl (2,4,6-TCB) chloride, respectively. Although the 3,5-DNB esters **3b** and **4b** were an inseparable mixture, the acetates **3a**, **4a** and 2,4,6-TCB esters **3c**, **4c** were separated by silica gel column chromatography. Then, the diastereomerically pure 3,5-DNB esters **3b** and **4b** were synthesized from the cyanohydrin complexes *ψ-exo*-**2** and *ψ-endo*-**2**, which were obtained in a diastereomerically pure form by recrystallization from hexane/benzene and subsequent silica gel column chromatography, respectively. The relative stereochemistries (*ψ-exo* and *ψ-endo*) of **3a**−**c** and **4a**−**c** were estimated by comparison with their R_f values on thin-layer chromatography of each diastereomer according to Clinton and Lillya's report.[8] The *O*-diethylphosphoryl cyanohydrin complexes **5** were synthesized as a 2/3 diastereomixture by reaction of **1** with diethyl phosphorocyanidate in the presence of LiCN.[9] The obtained products **5** were unstable toward silica gel column chromatography and, therefore, were used for the next reaction without purification.

With the requisite cyanohydrin derivatives **2**−**5** in hand, we turned our attention to their reactivity with heteroatomic nucleophiles in the presence of several acidic catalysts.[10] At first, the cyanohydrin complexes **2** were treated with HBF_4 in acetic anhydride at room temperature, but the migrated product **6** (Nu = OAc) was obtained in very poor yield along with **1** and the corresponding acetates **3a** and **4a** (eq 2).

We next investigated the substitution reactions of **3a**−**c** and **4a**−**c** with methanol under various acidic conditions to clarify

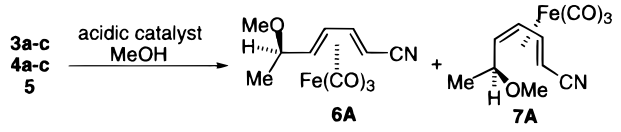
(7) Franck-Neumann, M.; Martina, D.; Heitz, M. P. *Tetrahedron Lett.* **1982**, *23*, 3493−3496.

(8) Clinton, N. A.; Lillya, C. P. *J. Am. Chem. Soc*. **1970**, *92*, 3058−3064.

(9) (a) Harusawa, S.; Yoneda, R.; Kurihara, T.; Hamada, Y.; Shioiri, T. *Tetrahedron Lett.* **1984**, *25*, 427−430. (b) Harusawa, S.; Nakamura, S.; Yagi, S.; Kurihara, T.; Hamada, Y.; Shioiri, T. *Synth. Commun*. **1984**, *14*, 1365−1371.

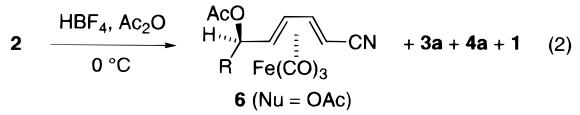
(10) (a) Grée, R.; Laabassi, M.; Mosset, P.; Carrié, R. *Tetrahedron Lett.* **1985**, *26*, 2317−2318. (b) Hachem, A.; Teniou, A.; Grée, R. *Bull. Soc. Chim. Belg*. **1991**, *100*, 625−626. (c) Grée, D.; Grée, R.; Lowinger, T. B.; Martelli, J.; Negri, J. T.; Paquette, L. A. *J. Am. Chem. Soc*. **1992**, *114*, 8841−8846. (d) Donaldson, W. A.; Tao, C. *J. Org. Chem*. **1993**, *58*, 2134−2143. (e) Hachem, A.; Toupet, L.; Grée, R. *Tetrahedron Lett*. **1995**, *36*, 1849−1852. (f) Grée, D. M.; Martelli, J. T.; Grée, R. L.; Toupet, L. J. *J. Org. Chem*. **1995**, *60*, 2316−2317. (g) Grée, D. M.; Kermarrec, C. J. M.; Martelli, J. T.; Grée, R. L.; Lellouche, J.-P.; Toupet, L. J. *J. Org. Chem*. **1996**, *61*, 1918−1919. (h) Pearson, A. J.; Alimardanov, A.; Pinkerton, A. A.; Fouchard, D. M.; Kirschbaum, K. *Tetrahedron Lett*. **1998**, *39*, 5919−5922.

Table 1. Nucleophilic Substitution of the Cyanohydrin Derivatives **3**−**5** with MeOH in the Presence of Acidic Catalysts



entry	substrate	reaction conditions	product (yield, %)	ratio **6A**/**7A**[a]	de of **6A**[a]
1	**3a**	Dowex 50W, reflux, 48 h	**6A** (23)	>98:<2	<50
2	**4a**	Dowex 50W, reflux, 48 h	0	−	>98
3	**3b**	Dowex 50W, 60 °C, 6 h	**6A** (65)	>98:<2	>98
4	**4b**	Dowex 50W, 60 °C, 23 h	**6A** (45)	>98:<2	>98
5	**3c**	Dowex 50W, 60 °C, 5 h	**6A** (71)	>98:<2	>98
6	**4c**	Dowex 50W, 60 °C, 10 h	**6A** (53)	>98:<2	>98
7	**5**	HBF_4, room temp, 6 h	**6A**/**7A** (53)	40:60	>98
8	**5**	Nafion NR-50, 60 °C, 24 h	**6A** (61)	>98:<2	>98

[a] Determined by 500-MHz ^{1}H NMR analysis.



the difference in reactivity between the diastereomers **3** and **4** in the nucleophilic substitution and to find a suitable leaving group and acidic catalyst which would give the maximum chemical yield (Table 1). While a variety of acidic catalysts could be used to generate the (η^5-pentadienyl)$Fe(CO)_3$ cation in these reactions, we preferred to use acidic ion-exchange resins such as Dowex 50W and Nafion NR-50 due to the ease of workup procedure. Treatment of the *ψ-exo* acetate **3a** with Dowex 50W in refluxing methanol afforded the desired (2*E*,4*E*)-adduct **6A** in 23% yield. The diastereoselectivity at C6 of **6A** decreased slowly with increasing reaction time (after 48 h, de < 50%) (entry 1). On the other hand, the *ψ-endo* acetate **4a** did not undergo the 1,5-nucleophilic substitution under the same conditions, and only the starting material **4a** was recovered, along with the aldehyde **1** (entry 2). From these results, the acetate is revealed to be unsuitable as a leaving group for the 1,5-nucleophilic substitution. In contrast to these results, both diastereomers of the 3,5-DNB and 2,4,6-TCB esters **3b,c** and **4b,c**, possessing a more reactive leaving group, gave rise to **6A** in moderate yield under milder reaction conditions (entries 3−6). The C6-diastereomer of **6A** could not be detected by 500-MHz ^{1}H NMR analysis. It should be also noted that both isomers **3b,c** and **4b,c** gave the same product **6A** irrespective of the C1-chirality of the starting materials, even though the reaction of **4b,c** required prolonged reaction time to consume the starting material completely and gave **6A** in a lower chemical yield than **3b,c**. Furthermore, a similar reaction of the phosphates **5** in the presence of HBF_4 proceeded smoothly even at room temperature, but a mixture of the (2*E*,4*E*)-adduct **6A** and (2*E*,4*Z*)-adduct **7A** was obtained in 53% combined yield with a **6A**/**7A** ratio of 40:60 (entry 7). In this case, both diastereoselectivities at C6 of **6A** and **7A** were still high (>98% de). On the other hand, the above reaction was performed at 60 °C in the presence of Nafion NR-50, resulting in the single production of **6A** in good yield (entry 8). Based on these results, we speculate that **7A** would be isomerized to the energetically more stable isomer **6A** by heating (>60 °C) the reaction mixture, while both **6A** and **7A** are initially produced. This speculation was proven by the acid-catalyzed isomerization experiment of **7A** to **6A** in refluxing methanol (eq 3). The olefin geometry of **6A** and **7A** was determined by the chemical shift values (δ) and NOE experiment of the C2 and C5 olefinic protons. In general, the signals of the *anti*-protons Ha and Hb of (1*E*,3*E*)-1,4-disubstituted diene $Fe(CO)_3$ complexes (**I**) are observed around 0.5 and 1.0 ppm, respectively (Figure 1).[10d,11] In contract, those of the *anti*- and *syn*-protons Hc and Hd of (1*E*,3*Z*)-1,4-disubstituted diene $Fe(CO)_3$ complexes (**II**) are observed around 1.5 and 2.5 ppm, respectively. Indeed, the signals of the C2 protons of **6A** and **7A** appear at 0.42 ppm for **6A** and 1.56 ppm for **7A**, and those of the C5 protons appear at 1.17 ppm for **6A** and 2.60 ppm for **7A**. In addition, the nuclear Overhauser effect (NOE) enhancement between C2−H and C6−H and also between C4−H and C5−H confirmed that **6A** adopts (2*E*,4*E*)-geometry and **7A** adopts (2*E*,4*Z*)-geometry (Figure 1). The relative stereochemistry of C6 in **6A** and **7A** was elucidated from the reported examples[10] and the reaction mechanism described below (Scheme 5). Furthermore, the elucidation was unambiguously confirmed by chemical transformation of the related compound **6E** into the compound **24**.

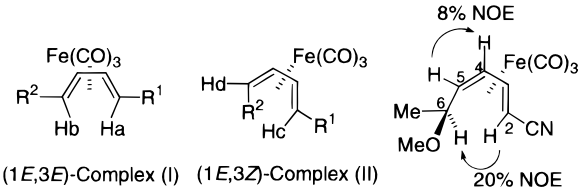
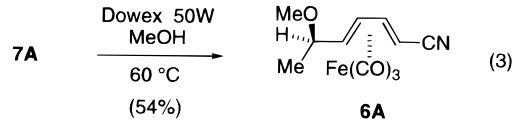


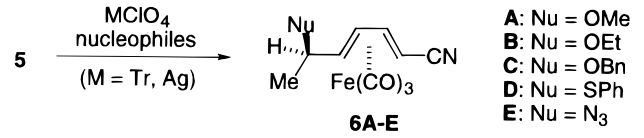
Figure 1. Chemical shift values and NOE experiment of **7A**.



Stereoselective Synthesis of 6-Substituted (2*E*,4*E*)- and (2*E*,4*Z*)-(η^4-2−5-hepta-2,4-dienenitrile)$Fe(CO)_3$ Complexes 6A−E and 7A−E. Expecting a stereoselective 1,5-nucleophilic substitution with various nucleophiles other than methanol, we investigated the reactivity of the phosphates **5**, substitution of which occurs at room temperature. Attempts to introduce other nucleophiles were unsuccessful under similar conditions. For example, treatment of **5** with thiophenol in the presence of Nafion NR-50 or HBF_4 in ether at room temperature resulted in formation of the demetalated 1,5-substituted (2*E*,4*Z*)-adduct. We were unable to improve this reaction with Brønsted acids, but these results did indicate that it would be possible to achieve regioselective 1,5-nucleophilic substitution of **5** with other soft nucleophiles, if demetalation of the product is suppressed. We next directed our attention to Lewis acids as an acidic catalyst for the 1,5-nucleophilic substitution of **5**. After many experiments with various solvents and Lewis acids, we found that the reaction of **5** with 2.5−10 equiv of nucleophile in the presence of 1.1 equiv of triphenylcarbenium perchlorate ($TrClO_4$) furnished the corresponding (2*E*,4*E*)-adducts **6A**−**E** in moderate yields (Table 2). A variety of heteroatomic nucleophiles such as ethanol, thiophenol, and $TMSN_3$ could be used in this reaction, and only 6-substituted (2*E*,4*E*)-adducts **6A**−**E** were produced in all cases, irrespective of the nucleophiles employed (entries 1−5). Although neither $TrBF_4$ nor $LiClO_4$ gave the desired product **6E**, resulting in the formation of **7E** and its demetalated product (see Table 3), silver perchlorate ($AgClO_4$) could be employed in CH_2Cl_2 instead of $TrClO_4$ (entry 6). The reaction should be performed with a stoichiometric amount of $TrClO_4$ or $AgClO_4$ at room temperature to furnish

(11) (a) Maglio, G.; Musco, A.; Palumbo, R. *J. Organomet. Chem.* **1971**, *32*, 127−136. (b) Adams, C. M.; Cerioni, G.; Hafner, A.; Kalchhauser, H.; von Philipsborn, W.; Prewo, R.; Schwenk, A. *Helv. Chim. Acta* **1988**, *71*, 1116−1142. (c) Enders, D.; Jandeleit, B.; von Berg, S. *J. Organomet. Chem.* **1997**, *533*, 219−236.

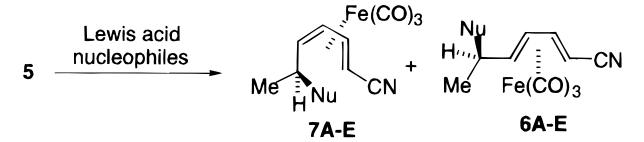
Table 2. Nucleophilic Substitution of the *O*-Diethylphosphoryl Cyanohydrins **5** with Various Nucleophiles in the Presence of $TrClO_4$ and $AgClO_4$



entry	$MClO_4$[a]	NuH	solvent	time	product (yield, %)	de of major product (**6**/**7**)[e]
1	$TrClO_4$	MeOH	THF	4 h	**6A** (49)	>95 (>98:<2)
2	$TrClO_4$	EtOH	THF	4 h	**6B** (56)	>95 (>98:<2)
3	$TrClO_4$	BnOH	THF	4 h	**6C** (39)	>95 (>98:<2)
4	$TrClO_4$	PhSH[b]	CH_2Cl_2	4 h	**6D** (25)	>95 (>98:<2)
5	$TrClO_4$	$TMSN_3$	THF	4 h	**6E** (56)	>95 (>98:<2)
6	$AgClO_4$	$TMSN_3$[b]	CH_2Cl_2	3 h	**6E** (43)	>95 (>98:<2)
7	$TrClO_4$[c]	$TMSN_3$[b]	THF	4 h	**7E** (47)	>95 (<2:>98)
8	$AgClO_4$[d]	$TMSN_3$[b]	CH_2Cl_2	10 min	**7E** (60)	>95 (<2:>98)

[a] The reactions were carried out with $MClO_4$ (1.1 equiv) and nucleophile (10 equiv) at room temperature. [b] 2.5 equiv of nucleophile was added. [c] 0.1 equiv of $TrClO_4$ was used. [d] At 0 °C. [e] Determined by 500-MHz ^{1}H NMR analysis.

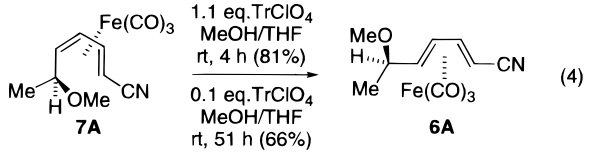
Table 3. Nucleophilic Substitution of the *O*-Diethylphosphoryl Cyanohydrins **5** with Various Nucleophiles in the Presence of Lewis Acid Catalyst



entry	Lewis acid	nucleophile (NuH)	product (yield, %)	ratio **6**/**7**[c]	de of **7**[c]
1	$LiClO_4$[a]	$TMSN_3$	**7E** (60)	<2:>98	>95
2	$TrBF_4$[b]	$TMSN_3$	**7E** (22)	10:90	>95
3	$HClO_4$[b]	$TMSN_3$	**7E** (32)	10:90	>95
4	BF_3·Et_2O[c]	$TMSN_3$	**7E** (58)	<2:>98	>95
5	$LiClO_4$[a]	MeOH	**7A** (51)	16:84	>95
6	$LiClO_4$[a]	EtOH	**7B** (53)	17:83	>95
7	BF_3·Et_2O[c]	MeOH	**7A** (52)	<2:>98	>95
8	BF_3·Et_2O[c]	EtOH	**7B** (54)	<2:>98	>95
9	BF_3·Et_2O[c]	BnOH	**7C** (42)	<2:>98	>95
10	BF_3·Et_2O[c]	PhSH	**7D** (54)	<2:>98	>95

[a] $LiClO_4$ (1.1 equiv) and nucleophile (10 equiv) were kept in diethyl ether at room temperature. [b] Lewis acid (1.1 equiv) and nucleophile (2.5 equiv) were kept in THF at room temperature. [c] BF_3·etherate (0.1 equiv) and nucleophile (10 equiv) were kept in THF at 0 °C. [c] Determined by 500-MHz ^{1}H NMR analysis.

the (2*E*,4*E*)-adducts exclusively. If not, **7E** was obtained as a major product (entries 7 and 8). In addition, subjection of the obtained (2*E*,4*Z*)-adduct **7A** to a stoichiometric amount of $TrClO_4$ (1.1 equiv) in THF in the presence of 10 equiv of MeOH led to the exclusive formation of **6A** in 81% yield (eq 4). The

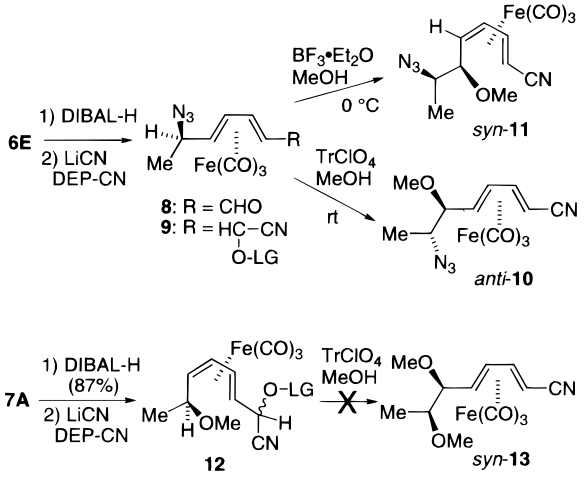


(4)

isomerization of **7A** into **6A** also proceeded with a catalytic amount of $TrClO_4$ (0.1 equiv), giving **6A** in 66% yield as a major product (**6A**/**7A** = 93:7). Based on these results, $TrClO_4$ and $AgClO_4$ are unique promoters of this reaction and seem to play an important role[12] in the catalytic isomerization of **7** to **6**, the mechanism of which is not clear at this stage.

In contrast to $TrClO_4$, other Lewis acids such as $LiClO_4$ and $TrBF_4$ afforded the 6-substituted (2*E*,4*Z*)-adducts **7E** exclusively

Scheme 3



by the reaction of **5** with $TMSN_3$ (Table 3, entries 1−4). Similarly, several ethers **7A,B** were synthesized by treatment of **5** with 10 equiv of the corresponding alcohols in the presence of 1.1 equiv of $LiClO_4$ in ether at room temperature, but the (2*E*,4*E*)-adducts **6A,B** always contaminated the reaction mixture as a minor product (entries 5 and 6). Therefore, reaction with a catalytic amount of BF_3·etherate in THF at 0 °C was the method of choice for the synthesis of **7A**−**C**, leading to the exclusive formation of the (2*E*,4*Z*)-isomers in comparable yields (entries 7−9). Similarly, reaction of **5** with 10 equiv of PhSH under the same reaction conditions afforded the corresponding sulfide **7D** stereoselectively in 54% yield (entry 10).

The stereochemistry of **6E** was unambiguously confirmed by chemical transformation of **6E** into **24** and X-ray crystallographic analysis of **28**, which had been derived from **6E**. The relative configuration of the remaining adducts **6B**−**D** and **7B**−**E** was elucidated by comparison of their spectra data with those of **6A**, **6E**, and **7A**.

We have succeeded in developing a method for synthesizing both (2*E*,4*E*)- and (2*E*,4*Z*)-adducts **6A**−**E** and **7A**−**E** in a stereoselective manner. This method would provide us an efficient tool for constructing both central chiralities of the C6 carbon adjacent to the (diene)$Fe(CO)_3$ group.

Construction of Contiguous Chiral Centers Using Iterative 1,2-Migration of $Fe(CO)_3$ Group and Determination of Their Stereochemistry. There are numerous biologically important 1,2-amino alcohols with a 1,2-*syn*- or 1,2-*anti*-configuration, such as sphingosine,[13] statin,[14] and so on. We assumed that both diastereomers of these compounds could be synthesized from the same chiral starting material by using iterative manipulation of the 1,5-nucleophilic substitution developed above (Scheme 3).

At first, we examined the possibility of iterative manipulation of this 1,5-substitution with the obtained azide **6E**. The requisite cyanophosphate **9** was easily prepared from **6E** in two steps. The reduction of **6E** with diisobutylaluminum hydride (DIBAL-H) gave the aldehyde **8** in 88% yield, which was efficiently converted to the desired cyanophosphate **9** by the same procedure described above. We undertook the second 1,5-

(12) (a) Mahler, J. E.; Pettit, R. *J. Am. Chem. Soc.* **1963**, *85*, 3955−3959. (b) Mahler, J. E.; Gibson, D. H.; Pettit, R. *J. Am. Chem. Soc.* **1963**, *85*, 3959−3963. (c) Pearson, A. J.; Ray, T. *Tetrahedron* **1985**, *41*, 5765−5770.

(13) A review of recent synthetic studies: Koskinen, P. M.; Koskinen, A. M. P. *Synthesis* **1998**, 1075−1091.

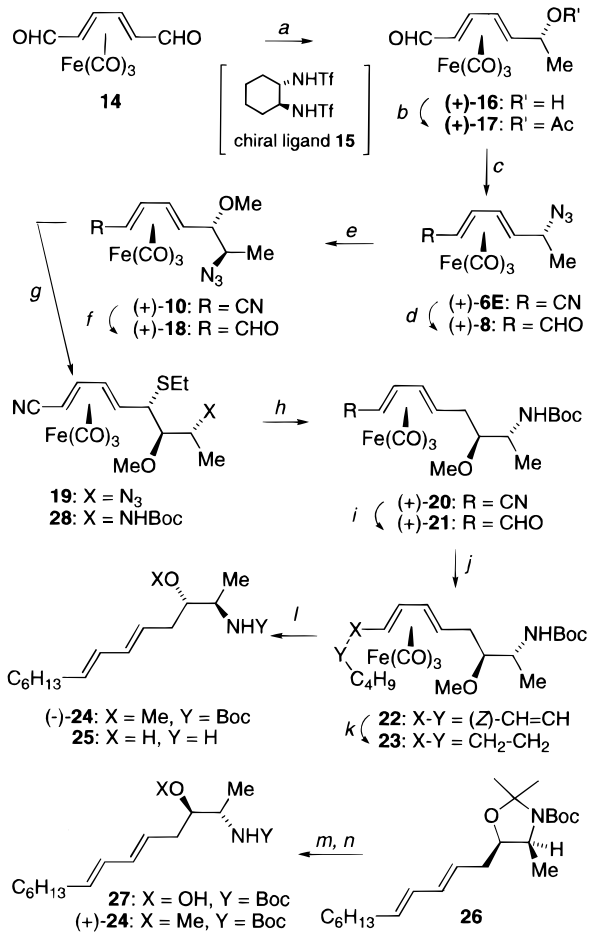
(14) A review of recent synthetic studies of statins: *Nachr. Chem. Tech. Lab.* **1988**, *36*, 756−758.

nucleophilic substitution of **9** under the reaction conditions of method A. The crude cyanophosphate **9** was subjected to 1.1 equiv of $TrClO_4$ and 10 equiv of methanol in THF at room temperature to afford the desired 6,7-disubstituted (2*E*,4*E*)-adduct *anti*-**10** in 52% yield from the aldehyde **8**. We could not detect other diastereomers by 500-MHz ^1H NMR. In a similar manner, the treatment of **9** with a catalytic amount of BF_3·etherate in methanol at 0 °C furnished the 6,7-disubstituted (2*E*,4*Z*)-adduct *syn*-**11** in 53% yield in two steps as the single isomer. Thus, it is revealed that, by the iterative manipulation, (1) the second nucleophiles were introduced regio- and stereoselectively with the 1,2-migration of the $Fe(CO)_3$ group without influence of the neighboring stereogenic functional group, i.e., the azide group at C7, and (2) both diastereomers with 1,2-*anti*- and 1,2-*syn*-configuration could be synthesized simply by switching the reaction conditions (methods A and B).

Having succeeded in the iterative use of **6E**, we next investigated the possibility of the (2*E*,4*Z*)-adduct **7A** for the iterative manipulation. The cyanophosphate **12** was prepared from **7A** by the same procedure as that used for **6E**. However, in contrast to **9**, 1,2-migration of **12** to *syn*-**13** did not occur by the reaction of **12** with methanol in the presence of $TrClO_4$ or BF_3·etherate, resulting in a complex mixture. These results indicate that **7A**−**E** bearing 6,7-*syn*-configuration cannot be used for further iterative manipulation; that is, synthesis of (2*E*,4*Z*)-isomers such as **7** and **11** means the termination of this iterative manipulation.

To determine the relative stereochemistry of **10** and **11** and also to extend this iterative method to the asymmetric synthesis of (2*R*,3*S*)-2-amino-5,7-tetradecadien-3-ol (**25**),[15] the iterative manipulation of the 1,5-nucleophilic substitution was applied to the chiral starting material (+)-**6E** (Scheme 4). The reaction of dialdehyde $Fe(CO)_3$ complex **14**[16] with 1.8 equiv of dimethylzinc and 1.8 equiv of titanium(IV) isopropoxide in the presence of (1*S*,2*S*)-*N*,*N*′-bis(trifluoromethanesulfonyl)-1,2-cyclohexyldiamine **15** (3 mol %) as a chiral ligand in toluene at 0 °C gave rise to monomethylated complex **16** in 71% yield with 96% ee.[17,18] After acetylation of **16**, an azide group was introduced stereoselectively by treatment of **17** with $TMSN_3$ and $Sc(OTf)_3$ in methylene chloride at room temperature to afford the nitrile (+)-**6E** in 92% yield with no racemization. Under these conditions, the aldehyde group of **17** was converted to a nitrile group simultaneously. This reaction is an uncommon but not unobserved occurrence.[19] With the target chiral azide complex **6E** in hand, we undertook the same manipulation developed above [DIBAL-H reduction, phosphorylcyanation, 1,2-migration of the $Fe(CO)_3$ group with MeOH and $TrClO_4$] with (+)-**6E** to obtain the *anti*-adduct (+)-**10** in a comparable yield. To next introduce a hydride as the third nucleophile together with 1,2-migration of the $Fe(CO)_3$ group, we first attempted the trialkylsilane reduction[20] of the *O*-phosphoryl cyanohydrin derived from (+)-**18** under various Lewis acidic conditions. The reaction, however, did not proceed cleanly regardless of the Lewis acids used, giving the desired product in less than 19% yield along with unidentified products. To avoid this step, we next tried the two-step sequence, that is, introduction of the sulfide group (**18** → **19**) and hydrogenolysis of the C−S bond (**19** → **20**). The introduction of an ethylsulfanyl group into the *O*-phosphoryl cyanohydrin derived from (+)-**18** using $TrClO_4$ and ethanethiol (method A) successfully afforded the desired (2*E*,4*E*)-adduct **19** as the single isomer in 61% yield (the relative stereochemistry of **19** was confirmed by X-ray crystallography of the racemic *N*-Boc derivative **28**; see Supporting Information). The hydrogenolysis of the C−S bond and concurrent reduction of the azide group of **19** were conducted by medium-pressure hydrogenation with 10% palladium-on-charcoal in the presence of di-*tert*-butyl dicarbonate, giving the 1,2-amino alcohol derivative **20** in good yield. The right-side chain of the nitrile **20** was elongated by a three-step sequence: DIBAL-H reduction (**21**, 78% yield), Wittig reaction with $C_5H_{10}{=}PPh_3$ (**22**, 73% yield), and subsequent hydrogenation over 10% palladium-on-charcoal (**23**, 81% yield). Finally, demetalation of **23** with trimethylamine oxide[21] gave rise to the *N*-Boc-*O*-methyl derivative (−)-**24** of (2*R*,3*S*)-2-amino-5,7-

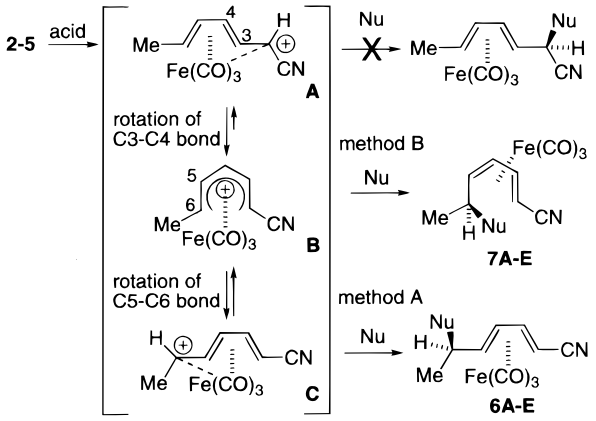
Scheme 4[a]



[a] Conditions: (a) Me_2Zn, $Ti(Oi\text{-}Pr)_4$, chiral ligand (**15**), −20 to 0 °C, toluene, 71%; (b) Ac_2O, pyridine, CH_2Cl_2, 80%; (c) $TMSN_3$, $Sc(OTf)_3$, CH_2Cl_2, 92%; (d) DIBAL-H, CH_2Cl_2, −78 °C, 88%; (e) $(EtO)_2P(O)CN$, LiCN, THF; $TrClO_4$, MeOH (10 equiv), THF, 52%; (f) DIBAL-H, CH_2Cl_2, −78 °C, 77%; (g) $(EtO)_2P(O)CN$, LiCN, THF; $TrClO_4$, EtSH (10 equiv), THF, 61%; (h) H_2 (5 atm),10% Pd/C, $(Boc)_2O$, MeOH, 85%; (i) DIBAL-H, CH_2Cl_2, −78 °C, 78%; (j) $C_5H_{11}PPh_3Br$, *n*-BuLi, toluene, −78 tp 0 °C, 73%; (k) H_2 (3 atm), 10% Pd/C, MeOH, 81%; (l) Me_3NO, benzene, 60 °C, 87%; (m) *p*-TsOH, MeOH, 82%; (n) MeI, Ag_2O, MeCN, reflux, 54%.

(15) Glanita, N. K.; Scheuer, P. J. *J. Org. Chem.* **1989**, *54*, 366−369.
(16) Roush, W. R.; Park, J. C. *Tetrahedron Lett.* **1990**, *31*, 4707−4710.
(17) (a) Takemoto, Y.; Baba, Y.; Noguchi, I.; Iwata, C. *Tetrahedron Lett.* **1990**, *31*, 4707−4710. (b) Takemoto, Y.; Baba, Y.; Honda, A.; Nakao, S.; Noguchi, I.; Iwata, C.; Tanaka, T.; Ibuka, T. *Tetrahedron* **1998**, *54*, 15567−15580.
(18) Takhashi, H.; Kawakita, T.; Ohno, M.; Yoshikawa, M.; Kobayashi, S. *Tetrahedron* **1992**, *48*, 5691−5700.
(19) Nishikawa, K.; Watanabe, A. *Chem. Lett.* **1984**, 773−774.
(20) Benvegnu, T.; Schio, L.; Le Floc'h, Y.; Grée, R. *Synlett* **1994**, 505−506.
(21) Shvo, Y.; Hazum, E. *J. Chem. Soc., Chem. Commun.* **1974**, 366−377.

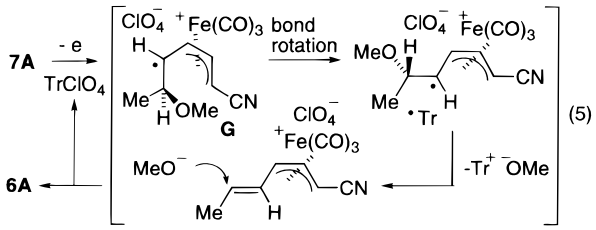
Scheme 5



tetradecadien-3-ol **25** in 87% yield. Alternatively, (+)-**24** was prepared from the authentic sample **26**, which had been synthesized as a synthetic intermediate of the natural product **25**[22] by deprotection of the acetonide of **26** and subsequent methylation of the hydroxy group of **27**. These two compounds **24** were identical to each other with respect to ^{1}H NMR, IR, mass, and $[\alpha]_D$, except for the opposite sign of the specific rotation. Based on these results, all substituents in **10** and **19** are revealed to possess the (6*R*,7*R*)-6,7-*anti*- and (6*R*,7*R*,8*R*)-6,7-*anti*-6,8-*syn*-configurations, which furthermore demonstrates that all nucleophiles would be introduced from the opposite side of the $Fe(CO)_3$ group in this iterative manipulation using method A.

Discussion

The formation of (2*E*,4*E*)- and (2*E*,4*Z*)-1,5-substituted products **6** and **7** is reasonably explained by the mechanism via *U*-shaped (η^5-pentadienyl)iron(1+) cation complexes (Scheme 5).[23] The first step is a formation of unstable *S*-shaped cation complex **A**, together with loss of the leaving group such as diethyl phosphate. It is well known that ψ-*exo* alcohol derivatives are more reactive to an acidic catalyst than ψ-*endo* ones, because the leaving group of the former can occupy the anti-periplanar position to the $Fe(CO)_3$ group more easily than that of the latter.[10,23,24] From the investigation of the leaving groups [AcO, DNBO, TCBO, $(EtO)_2P(O)O$] of the *O*-protected cyanohydrin $Fe(CO)_3$ complexes **3**−**5** in Table 1, we also observed moderately to quite different reactivity between the ψ-*exo* and ψ-*endo* isomers in terms of reaction time and chemical yield. Although only **3a** gave the desired product **6A** in a case of the acetate, the difference in reactivity between the diastereoisomers **3** and **4** becomes smaller as the ability of the leaving group becomes stronger. It is presumed that, due to the small steric bulkiness of the nitrile group, the ψ-*endo* complexes **4a**−**c** can adopt the anti-periplanar alignment of the leaving group to the $Fe(CO)_3$ group as easily as the ψ-*exo* complexes **3a**−**c**. However, it should be difficult to generate a cationic species on the C2-carbon bearing the nitrile group. Therefore, the ability of the leaving group to form the cation complex **A** would be most important in this 1,5-nucleophilic substitution. The sequential bond rotation of the C3−C4 bond of the *S*-shaped cation complex **A** gave the more stable *U*-shaped (η^5-pentadienyl)-iron(1+) cation **B**. This conversion from **A** to **B** relieves the electronic repulsion between the nitrile group and the C2-carbocation. Such electronic repulsion[10d] and configurational preference play a key role in determining the regio- and stereochemical outcomes of the 1,5-nucleophilic substitution with 1,2-migration of the $Fe(CO)_3$ group. Once the *U*-shaped cation **B** is generated in the presence of BF_3·etherate (method B), the nucleophilic attack of the heteroatomic nucleophiles such as alcohols, thiophenol, and trimethylsilyl azide at the C6 position occurs from the anti direction to the $Fe(CO)_3$ moiety of **B**, resulting in the exclusive formation of (2*E*,4*Z*)-adducts **7A**−**E**. Unlike the azide and thiol, if alcohols are employed as a nucleophile at a higher temperature or with a stoichiometric amount of the Lewis acid, the (2*E*,4*Z*)-adducts **7A**−**C** are equilibrated with the corresponding (2*E*,4*E*)-adducts **6A**−**C** via cation complexes **B** and **C**, affording the more stable (2*E*,4*E*)-adducts predominantly or exclusively, depending on the reaction temperature and acidic catalyst. Similarly, alcohols attack from the anti direction to the $Fe(CO)_3$ moiety of **C**, giving the (2*E*,4*E*)-adducts **6A**−**C** with high diastereoselectivity. Furthermore, we found that triphenylcarbenium perchlorate promotes the isomerization of **7A** to **6A** in the presence of methanol at room temperature (eq 4). Interestingly, this isomerization proceeded effectively with either a catalytic or stoichiometric amount of $TrClO_4$. The mechanism of the isomerization promoted by $TrClO_4$ is not clear, but judging from the facts that (1) this reaction occurs with a catalytic amount of $TrClO_4$ (or $AgClO_4$) and (2) Lewis acids such as $HClO_4$, $LiClO_4$, and $TrBF_4$ do not promote this reaction, their oxidation ability and perchlorate counteranion should play a key role in this isomerization. It is reasonable to speculate that the isomerization might proceed via a cation radical intermediate (eq 5). In other words,



(5)

7A was more easily oxidized by $TrClO_4$ than **6A**, resulting in the cation−radical complex **G**, which was converted into **6A** via the C4−C5 bond rotation and recombination of the methoxy group with inversion of the configuration.

By adding a stoichiometric amount of $TrClO_4$ in the presence of appropriate nucleophiles, several (2*E*,4*E*)-adducts **6A**−**E** could be synthesized from **5** in one step. The highly stereoselective synthesis of **6A**−**E** in this reaction would be strongly dependent on the ability of $TrClO_4$ to isomerize **7** to **6**.

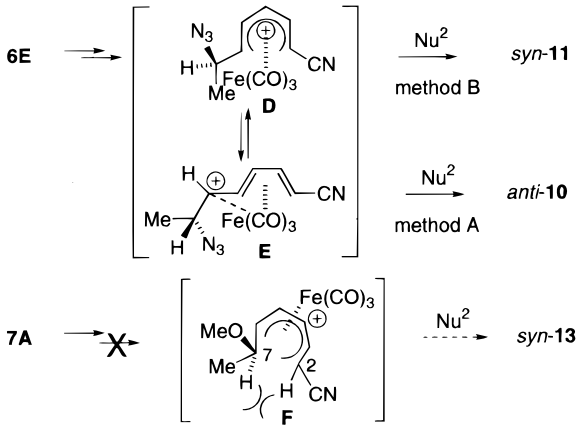
In the second nucleophilic substitution of **6E**, a similar reaction via η^5-(pentadienyl)cation complexes **D** and **E** occurs to afford the 6,7-disubstituted (2*E*,4*E*)- and (2*E*,4*Z*)-adducts **10** and **11**, dependent on the reaction conditions (method A and method B), respectively (Scheme 6). On the other hand, the same treatment of **7A** by methods A and B gave none of the desired products, resulting in a complex mixture. Perhaps the failure of the second substitution of **7A** would be attributed to instability of the η^5-(pentadienyl)cation complex **F** due to the severe steric hindrance between the C2−H and substituents of C7.

(22) Mori, K.; Matsuda, H. *Liebigs Ann. Chem.* **1992**, 131−137.

(23) (a) Gresham, D. G.; Kowalski, D. J.; Lillya, C. P. *J. Organomet. Chem.* **1978**, *144*, 71−79. (b) Bayoud, R. S.; Biehl, E. R.; Reeves, P. C. *J. Organomet. Chem.* **1978**, *150*, 75−83. (c) Donaldson, W. A. *J. Organomet. Chem.* **1990**, *395*, 187−193. (d) Quirosa-Guillou, C.; Lellouche, J.-P. *J. Org. Chem.* **1994**, *59*, 4693−4697. (e) Donaldson, W. A. *Aldrichimica Acta* **1997**, *30*, 17−24.

(24) (a) Uemura, M.; Minami, T.; Yamashita, Y.; Hiyoshi, K.; Hayashi, Y. *Tetrahedron Lett.* **1987**, *28*, 641−644. (b) Roush, W. R.; Wada, C. K. *J. Am. Chem. Soc.* **1994**, *116*, 2151−2152. (c) Roush, W. R.; Wada, C. K. *Tetrahedron Lett.* **1994**, *35*, 7347−7350.

Scheme 6



Conclusion

The reactions outlined herein demonstrate that the iron-mediated 1,5-nucleophilic substitution can be an effective method for constructing contiguous stereogenic centers in acyclic ligands. In addition, this is the first example in which the iterative 1,2-migration of a metal has been utilized in the multiple functionalization of acyclic compounds. The ability to construct both central chiralities (*R* and *S*) at each chiral center with excellent stereoselectivity by simply switching the reaction conditions (method A and method B) enhances the utility of this method.

Experimental Section

General. Melting points are uncorrected. IR spectra were obtained using a Horiba FT-210 spectrometer. ^{1}H NMR spectra were obtained using JEOL JNM-GX-500 (500 MHz) and JEOL JNM-LA-500 (500 MHz) spectrometers. ^{13}C NMR spectra were obtained using JEOL JNM-EX-270 (67.8 MHz) and JEOL JNM-AL-300 (75.5 MHz) spectrometers. Optical rotations were measured with a JASCO DIP-360 polarimeter. Mass spectra (MS) were measured with a Shimadzu GCMS-QP-1000 spectrometer. High-resolution mass spectra (HRMS) were measured with JEOL JMS-D300 and JEOL JMS-600 spectrometers. Chemical ionization mass spectra (CIMS) were measured with a JEOL JMS-D300 spectrometer. Column chromatography was carried out using Merck Kieselgel 60. Toluene and THF were distilled from sodium benzophenone ketyl radical under argon. Dichloromethane was freshly distilled from calcium hydride. Dry ether and acetonitrile were obtained from Kanto Chemicals. **(2*RS*,3*SR*,6*RS*,3*E*,5*E*)-Tricarbonyliron[(η^4-3−6)-2-hydroxyhepta-3,5-dienenitrile] (*endo*-2) and (2*RS*,3*SR*,6*SR*,3*E*,5*E*)-Tricarbonyliron[(η^4-3−6)-2-hydroxyhepta-3,5-dienenitrile] (*exo*-2).** To a stirred solution of **1** (550 mg, 2.33 mmol) in dry CH_2Cl_2 (15 mL) were added TMSCN (0.49 mL, 3.50 mmol) and $ZnCl_2$ (635 mg, 0.466 mmol) at 0 °C under a nitrogen atmosphere. After 1 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with CH_2Cl_2. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. A 10% HCl solution (50 μL) was added to a solution of the residue in MeOH (15 mL), and the mixture was stirred for 15 min. Ice−water was added, and the resulting mixture was extracted with CH_2Cl_2. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo to give crude **2** (610 mg, 100%, 2 setps) as a diastereomeric mixture. The crude mixture was purified by recrystallization from a mixture of benzene and hexane, giving ***exo*-2** as yellow crystals (240 mg, 39%). The diastereomerically pure ***endo*-2** (195 mg, 32%) was obtained by column chromatography (SiO_2, hexane/AcOEt = 7:1) of the mother liquid along with ***exo*-2** (100 mg, 16%). ***endo*-2**: yellow crystals, mp 95−96 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 0.97 (dd, 1H, J = 6.7, 7.9 Hz), 1.28 (dq, 1H, J = 9.1, 6.1 Hz), 1.46 (d, 3H, J = 6.1 Hz), 2.45 (d, 1H, J = 5.5 Hz), 4.33 (dd, 1H, J = 5.5, 6.7 Hz), 5.14 (dd, 1H, J = 4.9, 9.2 Hz), 5.31 (dd, 1H, J = 4.9, 7.9 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.0, 56.9, 59.2, 62.9, 79.5, 86.8, 118.7, 210.6; IR (KBr) 3408, 2048, 1975 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 236 (M^+ − CN, 7.2), 208 (29), 180 (73), 152 (100). Anal. Calcd for $C_{10}H_9FeNO_4$: C, 45.66; H, 3.45; N, 5.23. Found: C, 45.49; H, 3.45; N, 5.34. ***exo*-2**: yellow crystals, mp 101 °C (hexane/benzene); ^{1}H NMR ($CDCl_3$) δ 0.97 (dd, 1H, J = 7.9, 8.5 Hz), 1.37 (dq, 1H, J = 9.1, 6.1 Hz), 1.46 (d, 3H, J = 6.1 Hz), 2.41 (d, 1H, J = 6.7 Hz), 4.25 (dd, 1H, J = 6.7, 8.7 Hz), 5.13 (dd, 1H, J = 4.9, 9.2 Hz), 5.28 (dd, 1H, J = 4.9, 7.9 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.1, 55.1, 59.6, 63.7, 81.4, 87.5, 118.9, 210.2; IR (KBr) 3394, 2050, 1980 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 236 (M^+ − CN, 5.2), 208 (29), 180 (71), 152 (100). Anal. Calcd for $C_{10}H_9FeNO_4$: C, 45.66; H, 3.45; N, 5.23. Found: C, 45.73; H, 3.52; N, 5.25.

(1*RS*,2*RS*,5*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-3,5-dienyl] Acetate (3a) and (1*RS*,2*SR*,5*RS*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-3,5-dienyl] Acetate (4a). To a stirred solution of crude **2** (120 mg, 0.458 mmol) in dry CH_2Cl_2 (4.8 mL) were added Ac_2O (64.8 μL, 0.687 mmol) and dry pyridine (44.5 μL, 0.550 mmol) at room temperature under a nitrogen atmosphere. After 2 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with CH_2Cl_2. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 10:1) to give **4a** (62.8 mg, 45%) and **3a** (62.9 mg, 45%). **4a**: yellow crystals, mp 92−94 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 0.92 (dd, 1H, J = 7.3, 7.3 Hz), 1.32 (dq, 1H, J = 8.5, 6.1 Hz), 1.46 (d, 3H, J = 6.1 Hz), 2.17 (s, 3H), 5.09 (d, 1H, J = 7.3 Hz), 5.14 (dd, 1H, J = 5.5, 8.5 Hz), 5.31 (dd, 1H, J = 5.5, 7.3 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 19.1, 20.2, 52.3, 59.4, 62.8, 79.8, 87.0, 115.9, 168.7, 210.2; IR (KBr) 2052, 1984, 1977, 1755 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 249 (M^+ − 2CO, 18), 221 (55), 80 (100). Anal. Calcd for $C_{12}H_{11}FeNO_5$: C, 47.25; H, 3.63; N, 4.59. Found: C, 47.26; H, 3.59; N, 4.54. **3a**: yellow crystals, mp 96−98 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 0.90 (dd, 1H, J = 8.5, 8.5 Hz), 1.39 (dq, 1H, J = 7.3, 6.1 Hz), 1.46 (d, 3H, J = 6.1 Hz), 2.14 (s, 3H), 5.10 (dd, 1H, J = 4.9, 8.5 Hz), 5.17 (d, 1H, J = 8.5 Hz), 5.34 (dd, 1H, J = 4.9, 7.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.0, 20.4, 51.3, 59.7, 63.3, 81.8, 87.5, 116.0, 168.9, 210.0; IR (KBr) 2054, 1983, 1753 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 221 (M^+ − 3CO, 16), 80 (100). Anal. Calcd for $C_{11}H_{11}FeNO_4$: C, 47.25; H, 3.63; N, 4.59. Found: C, 47.21; H, 3.64; N, 4.58. **(1*RS*,2*SR*,5*RS*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-2,4-dienyl] 3,5-Dinitrobenzoate (4b).** To a stirred solution of ***endo*-2** (65.0 mg, 0.247 mmol) in dry CH_2Cl_2 (4 mL) were added 3,5-dinitrobenzoyl chloride (71.2 mg, 0.309 mmol) and dry pyridine (30.0 μL, 0.371 mmol) at room temperature under a nitrogen atmosphere. After 2 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 5:1) to give **4b** (109.4 mg, 97%) as yellow crystals: mp 113 °C (petroleum ether/toluene); ^{1}H NMR ($CDCl_3$) δ 1.09 (dd, 1H, J = 7.9, 7.9 Hz), 1.26−1.30 (m, 1H), 1.50 (m, 3H), 5.24 (m, 1H), 5.29 (d, 1H, J = 7.9 Hz), 5.45 (dd, 1H, J = 4.9, 7.9 Hz), 9.23 (d, 2H, J = 2.4 Hz), 9.32 (dd, 2H, J = 2.4, 2.4 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.1, 50.9, 60.6, 65.4, 80.1, 87.8, 115.0, 123.4, 129.7, 131.6, 148.8, 160.7, 210.0; IR (KBr) 2052, 1986, 1975, 1747, 1549, 1346 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 430 (M^+ + 1 − CO, 0.6), 402 (0.4), 374 (12), 79 (100). Anal. Calcd for $C_{17}H_{11}FeN_3O_9$: C, 44.67; H, 2.43; N, 9.19. Found: C, 44.57; H, 2.59; N, 9.14.

(1*RS*,2*RS*,5*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-3,5-dienyl] 3,5-Dinitrobenzoate (3b). The same treatment of ***exo*-2** (71.2 mg, 0.271 mmol) as described for the synthesis of **4b** gave the crude mixture, which was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give **3b** (111.3 mg, 90%) as yellow crystals: mp 142 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 1.05 (m, 1H), 1.27 (m, 1H), 1.51 (m, 3H), 5.16−5.19 (m, 1H), 5.46−5.49 (m, 2H), 9.17 (d, 2H, J = 1.8 Hz), 9.30 (dd, 2H, J = 1.8, 1.8 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.1, 49.7, 60.5, 65.9, 81.8, 88.1, 115.1, 123.3, 129.7, 131.8, 148.8, 161.0, 209.4; IR (KBr) 2054, 1986, 1975, 1745, 1549, 1346 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 430 (M^+ + 1 − CO, 0.6), 374

(3), 79 (100). Anal. Calcd for $C_{17}H_{11}FeN_3O_9$: C, 44.67; H, 2.43; N, 9.19. Found: C, 44.56; H, 2.68; N, 9.15.

(1*RS*,2*RS*,5*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-3,5-dienyl] 2,4,6-Trichlorobenzoate (3c) and (1*RS*,2*SR*,5*RS*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-1-cyanohexa-3,5-dienyl] 2,4,6-Trichlorobenzoate (4c). To a stirred solution of crude **2** (230 mg, 0.878 mmol) in dry CH_2Cl_2 (9.0 mL) were added 2,4,6-trichlorobenzoyl chloride (0.18 mL, 1.18 mmol) and dry pyridine (0.10 mL, 1.13 mmol) at room temperature under a nitrogen atmosphere. After 2 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with CH_2Cl_2. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 10:1) to give **4c** (156 mg, 38%) and **3c** (164 mg, 40%). **3c**: yellow oil; ^{1}H NMR ($CDCl_3$) δ 0.97 (dd, 1H, J = 8.1, 8.7 Hz), 1.37 (dq, 1H, J = 6.0, 9.0 Hz), 1.48 (d, 3H, J = 6.0 Hz), 5.14 (dd, 1H, J = 6.3, 9.0 Hz), 5.31 (d, 1H, J = 8.7 Hz), 5.41 (dd, 1H, J = 6.3, 8.1 Hz), 9.30 (m, 2H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 19.1, 50.1, 60.1, 65.5, 82.0, 88.2, 115.2, 128.2, 130.0, 132.9, 137.2, 162.3, 210.5; IR (KBr) 2056, 1988, 1755 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 422 (M^+ + 1 − CO, 1.6), 413 (M^+ − 2CO, 2.7), 385 (M^+ − 3CO, 62), 106 (100); HRMS calcd for $C_{17}H_{10}Cl_3FeNaNO_5$ 491.8872 (FAB, M + Na), found 491.8877. **4c**: yellow oil; ^{1}H NMR ($CDCl_3$) δ 0.88 (dd, 1H, J = 8.6, 8.6 Hz), 1.37 (dq, 1H, J = 6.9, 6.7 Hz), 1.41 (d, 3H, J = 6.7 Hz), 5.08 (dd, 1H, J = 6.9, 6.9 Hz), 5.29 (d, 1H, J = 8.6 Hz), 5.34 (dd, 1H, J = 6.9, 8.6 Hz), 7.31 (s, 2H); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 19.1, 50.1, 60.1, 65.4, 82.0, 88.2, 115.2, 128.2, 130.0, 133.0, 137.2, 168.9, 210.0; IR (KBr) 2056, 1986, 1755 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 413 (M^+ − 2CO, 1.5), 385 (M^+ − 3CO, 31), 106 (100); HRMS calcd for $C_{17}H_{10}Cl_3FeNaNO_5$ 491.8872 (FAB, M + Na), found 491.8854.

(2*RS*,5*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−4)-1-cyanohexa-2,4-diethyl] Diethyl Phosphate (5). To a stirred solution of **1** (201 mg, 0.851 mmol) in dry THF (8.5 mL) were added diethyl phosphorocyanidate (DEPC) (0.14 mL, 0.935 mmol) and LiCN (2.7 mg, 85.1 μmol) at room temperature under a nitrogen atmosphere. After 15 min, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo to give crude **5** (340 mg, 100%), which was used without further purification. **5**: a yellow oil; ^{1}H NMR ($CDCl_3$) δ 0.89 (m, 1/3H), 0.97 (m, 2/3H), 1.25−1.39 (m, 1H), 1.35−1.29 (m, 6H), 1.46 (d, 3H, J = 6.7 Hz), 4.10−4.24 (m, 4H), 4.69 (dd, 2/3H, J = 8.5, 8.5 Hz), 4.97 (dd, 1/3H, J = 6.1, 8.5 Hz), 5.11−5.15 (m, 1H), 5.33 (dd, 1/3H, J = 4.9, 7.3 Hz), 5.39 (dd, 2/3H, J = 4.9, 7.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 15.9, 16.0, 19.0, 19.1, 52.05, 52.10, 53.5, 53.6, 59.2, 59.9, 64.8, 67.3, 78.8, 81.8, 86.8, 88.0, 115.99, 116.07, 210.3; IR (KBr) 2219, 2051, 1974 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 260 (M^+ − $Fe(CO)_3$, 19), 161 (100).

General Procedure for Nucleophilic Substitution of the Cyano Esters 3a−d, 4a−d, and 5 (Table 1). A mixture of the cyano esters, Dowex 50W (26 mg), and dry MeOH (3 mL) was refluxed or stirred at 60 °C for the appropriate time under a nitrogen atmosphere. After the reaction mixture was filtered to remove the acidic catalyst, the filtrate was concentrated in vacuo, and the residue was purified by column chromatography (SiO_2, hexane/AcOEt = 7:1) to give **6A**.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-methoxyhepta-2,4-dienenitrile] (6A). Entry 1. The reaction of **3a** (38.1 mg, 0.125 mmol) and Dowex 50W (10 mg) according to the typical procedure gave **6A** (8.0 mg, 23%).

Entry 3. The reaction of **3b** (25.7 mg, 0.0562 mmol) and Dowex 50W (13 mg) according to the typical procedure gave **6A** (10.1 mg, 65%).

Entry 4. The reaction of **4b** (22.6 mg, 0.0494 mmol) and Dowex 50W (13 mg) according to the typical procedure gave **6A** (6.2 mg, 45%).

Entry 5. The reaction of **3c** (21.7 mg, 0.0461 mmol) and Dowex 50W (12 mg) according to the typical procedure gave **6A** (9.1 mg, 71%).

Entry 6. The reaction of **4c** (21.1 mg, 0.0448 mmol) and Dowex 50W (11 mg) according to the typical procedure gave **6A** (6.6 mg, 53%).

Entry 7. The reaction of **5** (77.8 mg, 0.195 mmol) according to the typical procedure, except a 54% solution of HBF_4 in ether (0.14 mL, 0.923 mmol) was used in the place of Dowex 50W, gave a 40:60 mixture of **6A** and **7A** (28.4 mg, 53%).

Entry 8. The reaction of **5** (21.7 mg, 0.0544 mmol) according to the typical procedure, except Nafion NR-50 was used in the place of Dowex 50W, gave **6A** (9.1 mg, 61%) as yellow crystals.

6A: mp 58 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 0.42 (d, 1H, J = 7.3 Hz), 1.17 (dd, 1H, J = 6.1, 8.5 Hz), 1.33 (d, 3H, J = 6.1 Hz), 3.24 (dq, 1H, J = 6.1, 6.1 Hz), 3.30 (s, 3H), 5.46 (dd, 1H, J = 4.9, 8.5 Hz), 5.90 (dd, 1H, J = 4.9, 7.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 21.9, 24.0, 56.0, 67.1, 77.2, 81.5, 86.4, 121.3, 203.4; IR (KBr) 2220, 2063, 1990 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 278.0 (M^+ + 1, 100). Anal. Calcd for $C_{11}H_{11}FeNO_4$: C, 47.69; H, 4.00; N, 5.06. Found: C, 47.80; H, 4.04; N, 5.10.

Isomerization of 7A to 6A. Equation 3. A mixture of **7A** (16.2 mg, 0.0585 mmol), Dowex 50W (22 mg), and dry MeOH (1.5 mL) was stirred at 60 °C under a nitrogen atmosphere. After 5 h, Dowex 50W (11 mg) was added to the reaction mixture, and the resulting mixture was stirred at 60 °C for 2 h. The reaction mixture was filtered to remove the acidic catalyst, the filtrate was concentrated in vacuo, and the residue was purified by column chromatography (SiO_2, hexane/AcOEt = 7:1) to give **6A** (8.8 mg, 54%).

Equation 4. *Stoichiometric Reaction.* To a stirred solution of **7A** (20.0 mg, 0.0722 mmol) in dry THF (0.75 mL) were added MeOH (0.03 mL, 0.752 mmol) and $TrClO_4$ (28.2 mg, 0.0827 mmol) at room temperature under a nitrogen atmosphere. After 4 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give **6A** (16.2 mg, 81%). *Catalytic Reaction.* To a stirred solution of **7A** (20.0 mg, 0.0722 mmol) in dry THF (0.75 mL) were added MeOH (0.03 mL, 0.752 mmol) and $TrClO_4$ (2.6 mg, 7.52 μmol) at room temperature under a nitrogen atmosphere. After 51 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give **6A**/**7A** = 93:7 (13.1 mg, 66%).

General Procedure for Nucleophilic Substitution of 5 with Perchlorate Salts (Table 2). The perchlorate salts $TrClO_4$ or $AgClO_4$ (1.1 equiv) and appropriate nucleophiles (2.5−10 equiv) were successively added to a stirred solution of **5** in dry THF or CH_2Cl_2 at 0 °C under a nitrogen atmosphere, and the mixture was allowed to warm slowly to room temperature. After being quenched with a saturated $NaHCO_3$ solution, the resulting mixture was extracted with AcOEt. The extract was washed with water and brine, dried over $MgSO_4$, and then concentrated in vacuo to give the crude mixture.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-methoxyhepta-2,4-dienenitrile] (6A). Entry 1. The reaction of **5** (91.7 mg, 0.230 mmol) with methanol according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 7:1) gave **6A** (31.2 mg, 49%).

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-ethoxyhepta-2,4-dienenitrile] (6B). Entry 2. The reaction of **5** (73.2 mg, 0.183 mmol) with EtOH according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **6B** (29.9 mg, 56%) as yellow crystals: mp 60 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 0.41 (d, 1H, J = 7.3 Hz), 1.17 (t, 3H, J = 7.1 Hz), 1.21 (m, 1H), 1.33 (d, 3H, J = 6.2 Hz), 3.34 (dq, 1H, J = 6.1, 6.2 Hz), 3.46 (q, 2H, J = 7.1 Hz), 5.48 (dd, 1H, J = 5.0, 8.8 Hz), 5.58 (dd, 1H, J = 5.0, 7.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 15.2, 22.4, 24.1, 63.9, 67.7, 75.5, 81.4, 86.5, 121.4, 206.0; IR (KBr) 2220, 2062, 1992 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 292.0 (M^+, 100). Anal. Calcd for $C_{12}H_{13}FeNO_4$: C, 49.52; H, 4.50; N, 4.82. Found: C, 49.59; H, 4.40; N, 4.80.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-benzyloxyhepta-2,4-dienenitrile] (6C). Entry 3. The reaction of **5** (59.2 mg, 0.148 mmol) with BnOH according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **6C** (20.5 mg, 39%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 0.30 (d, 1H, J = 7.6

Hz), 1.33 (m, 1H), 1.37 (d, 3H, $J = 5.9$ Hz), 3.70 (dq, 1H, $J = 5.6$, 5.9 Hz), 4.39 (d, 1H, $J = 12.0$ Hz), 4.63 (d, 1H, $J = 12.0$ Hz), 5.45 (dd, 1H, $J = 5.1$, 8.9 Hz), 5.55 (dd, 1H, $J = 5.0$, 7.6 Hz), 7.23−7.36 (m. 5H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 22.2, 23.4, 70.4, 70.6, 74.0, 80.7, 85.0, 121.6, 127.6, 127.7, 128.4, 137.9, 206.3; IR (KBr) 2218, 2062, 1990 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 325 ($M^+ - CO$, 3.5), 269 ($M^+ - 3CO$, 100); HRMS calcd for $C_{17}H_{16}FeNO_4$ 354.0429 (FAB, M + H), found 354.0421.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-phenylthiohepta-2,4-dienenitrile] (6D). Entry 4. The reaction of **5** (65.2 mg, 0.163 mmol) with PhSH (0.042 mL, 0.408 mmol) and $TrClO_4$ (61.2 mg, 0.179 mmol) in dry CH_2Cl_2 (1.6 mL) according to the typical procedure and purification by preparative TLC (hexane/CH_2Cl_2= 1:1 × 3) gave **6D** (14.4 mg, 25%) as yellow crystals: mp 124 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 0.43 (d, 1H, $J = 7.9$ Hz), 1.22−1.26 (m, 1H), 1.48 (d, 3H, $J = 7.3$ Hz), 2.90 (dq, 1H, $J = 3.7$, 7.3 Hz), 4.63 (dd, 1H, $J = 4.9$, 9.2 Hz), 5.36 (dd, 1H, $J = 4.9$, 7.9 Hz), 7.28−7.45 (m, 5H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 23.1, 24.4, 48.9, 69.1, 81.3, 86.6, 121.1, 128.8, 129.2, 132.9, 135.2, 205.1; IR (KBr) 2220, 2062, 1996 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 355 (M^+, 0.7), 327 (14), 299 (8), 271 (71), 161 (100). Anal. Calcd for $C_{16}H_{13}FeNO_3S$: C, 54.11; H, 3.69; N, 3.94; S, 9.03. Found: C, 54.09; H, 3.74; N, 3.93; S, 8.98.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-azidohepta-2,4-dienenitrile] (6E). Entry 5. The reaction of **5** (62.0 mg, 0.155 mmol) with $TMSN_3$ (206 μL, 1.55 mmol) and $TrClO_4$ (57.8 mg, 0.170 mmol) in THF according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 7:1) gave **6E** (25.1 mg, 56%).

Entry 6. The reaction of **5** (57.1 mg, 0.143 mmol) with $TMSN_3$ (48 μL, 0.358 mmol) and $AgClO_4$ (32.6 mg, 0.157 mmol) in CH_2Cl_2 at room temperature for 3 h according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 7:1) gave **6E** (17.9 mg, 43%).

Entry 7. The reaction of **5** (60.4 mg, 0.151 mmol) with $TMSN_3$ (50 μL, 0.378 mmol) and $TrClO_4$ (5.2 mg, 0.015 mmol) in THF according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 7:1) gave **7E** (20.4 mg, 47%).

Entry 8. The reaction of **5** (159 mg, 0.398 mmol) with $TMSN_3$ (134 μL, 1.01 mmol) and $AgClO_4$ (91.8 mg, 0.443 mmol) in CH_2Cl_2 at 0 °C for 10 min according to the typical procedure and purification by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **7E** (69.1 mg, 60%) as yellow crystals: mp 48 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 0.53 (d, 1H, $J = 8.1$ Hz), 1.12 (dd, 1H, $J = 7.5$, 8.6 Hz), 1.43 (d, 3H, $J = 7.0$ Hz), 3.33 (dq, 1H, $J = 7.5$, 7.0 Hz), 5.43 (dd, 1H, $J = 5.2$, 8.6 Hz), 5.65 (dd, 1H, $J = 5.2$, 8.1 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 21.7, 24.9, 60.1, 63.8, 82.9, 86.6, 120.8, 205.4. IR (KBr) 2220, 2100, 2067, 2003, 1986 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 289 (M^+, 53), 261 (14), 108 (100). Anal. Calcd for $C_{10}H_8FeN_4O_3$: C, 41.70; H, 2.80; N, 19.45. Found: C, 41.77 H, 2.87; N, 19.45.

General Procedure for Nucleophilic Substitution of 5 to 7A−E (Table 3). The appropriate nucleophile (10 equiv) and Lewis acid (1.1 or 0.1 equiv) were successively added to a stirred solution of **5** in dry ether or THF (0.10 M solution) at 0 °C under a nitrogen atmosphere, and the resulting mixture was allowed to warm slowly to room temperature. After 16 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo to give the crude mixture.

(2*RS*,5*RS*,6*RS*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-6-azidohepta-2,4-dienylnitrile] (7E). Entry 1. The reaction of **5** (51.9 mg, 0.130 mmol) with $TMSN_3$ (0.18 mL, 1.30 mmol) and $LiClO_4$ (15.5 mg, 0.143 mmol) according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **7E** (22.4 mg, 60%).

Entry 2. The reaction of **5** (40.1 mg, 0.100 mmol) with $TMSN_3$ (33 μL, 0.251 mmol) and $TrBF_4$ (36.3 mg, 0.110 mmol) according to the typical procedure and purification of the crude mixture by column chromatography gave a 90:10 mixture of **7E** and **6E** (6.2 mg, 22%).

Entry 3. The reaction of **5** (46.5 mg, 0.117 mmol) with $TMSN_3$ (39 μL, 0.291 mmol) and $HClO_4$ (1 M in ether solution, 0.05 mL) according to the typical procedure and purification of the crude mixture by column chromatography gave a 90:10 mixture of **7E** and **6E** (10.7 mg, 32%).

Entry 4. The reaction of **5** (43.7 mg, 0.109 mmol) with $TMSN_3$ (0.14 mL, 1.09 mmol) and $BF_3{\cdot}Et_2O$ (2.3 μL, 10.9 μmol) according to the typical procedure and purification of the crude mixture by column chromatography gave **7E** (18.3 mg, 58%) as yellow crystals: mp 73−74 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 1.37 (d, 3H, $J = 6.3$ Hz), 1.49 (d, 1H, $J = 7.3$ Hz), 2.72 (dd, 1H, $J = 7.5$, 7.5 Hz), 2.83 (dq, 1H, $J = 7.5$, 6.3 Hz), 5.40 (dd, 1H, $J = 6.4$, 7.5 Hz), 5.85 (dd, 1H, $J = 6.4$, 7.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 21.7, 25.5, 57.8, 61.6, 85.0, 93.2, 121.0, 205.5; IR (KBr) 2220, 2100, 2067, 2003, 1996 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 289.0 ($M^+ + 1$, 100). Anal. Calcd for $C_{10}H_8FeN_4O_3$: C, 41.70; H, 2.80; N, 19.45. Found: C, 41.74 H, 2.93; N, 19.46.

(2*RS*,5*RS*,6*RS*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-6-methoxyhepta-2,4-dienenitrile] (7A). Entry 5. The reaction of **5** (163 mg, 0.408 mmol) with methanol (0.17 mL, 4.08 mmol) and $LiClO_4$ (47.9 mg, 0.448 mmol) according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave an 84:16 mixture of **7A** and **6A** (56.4 mg, 51%).

Entry 7. The reaction of **5** (197 mg, 0.494 mmol) with methanol (0.20 mL, 4.94 mmol) and $BF_3{\cdot}Et_2O$ (6.3 μL, 49 μmol) according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **7A** (70.9 mg, 52%) as yellow crystals: mp 46 °C (hexane/AcOEt); ^{1}H NMR ($CDCl_3$) δ 1.35 (d, 3H, $J = 5.8$ Hz), 1.56 (d, 1H, $J = 7.9$ Hz), 2.60 (dd, 1H, $J = 8.1$, 9.7 Hz), 2.80 (dq, 1H, $J = 9.7$, 5.8 Hz), 3.23 (s, 3H), 5.38 (dd, 1H, $J = 5.3$, 8.1 Hz), 5.85 (dd, 1H, $J = 5.3$, 7.9 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 22.3, 24.7, 55.3, 63.2, 76.4, 86.5, 92.0, 121.4, 203.4; IR (KBr) 2220, 2064, 1998 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 278.0 ($M^+ + 1$, 71), 246.0 (100). Anal. Calcd for $C_{11}H_{11}FeNO_4$: C, 47.69; H, 4.00; N, 5.06. Found: C, 47.83; H, 4.00; N, 5.11.

(2*RS*,5*RS*,6*RS*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-6-ethoxyhepta-2,4-dienenitrile] (7B). Entry 6. The reaction of **5** (83.6 mg, 0.209 mmol) with ethanol (0.12 mL, 2.09 mmol) and $LiClO_4$ (24.5 mg, 0.223 mmol) according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 5:1) gave an 83:17 mixture of **7B** and **6B** (32.1 mg, 53%).

Entry 8. The reaction of **5** (72.2 mg, 0.181 mmol) with EtOH (0.11 mL, 1.81 mmol) and $BF_3{\cdot}Et_2O$ (2.7 μL, 18.1 μmol) at 0 °C according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **7B** (28.4 mg, 54%) as yellow crystals: mp 46−47 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 1.12 (t, 3H, $J = 6.7$ Hz), 1.35 (d, 3H, $J = 6.1$ Hz), 1.60 (d, 1H, $J = 7.9$, Hz), 2.60 (dd, 1H, $J = 8.5$, 9.2 Hz), 2.81 (dq, 1H, $J = 9.1$, 6.1 Hz), 3.11 (dq, 1H, $J = 13.4$, 6.7 Hz), 3.53 (dq, 1H, $J = 13.4$, 6.7 Hz), 5.36 (dd, 1H, $J = 4.9$, 8.5 Hz), 5.84 (dd, 1H, $J = 4.9$, 7.9 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 15.2, 22.7, 24.5, 63.1, 63.8, 74.5, 86.3, 92.1, 121.5, 206.7; IR (KBr) 2206, 2065, 1992 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 292.0 (M^+, 25), 69.0 (100). Anal. Calcd for $C_{12}H_{13}FeNO_4$: C, 49.52; H, 4.50; N, 4.82. Found: C, 49.52; H, 4.52; N, 4.83.

(2*RS*,5*RS*,6*RS*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-6-benzyloxyhepta-2,4-dienenitrile] (7C). Entry 9. The reaction of **5** (80.0 mg, 0.200 mmol) with BnOH (0.21 mL, 2.00 mmol) and $BF_3{\cdot}Et_2O$ (2.5 μL, 20.0 μmol) at 0 °C according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt = 4:1) gave **7C** (29.6 mg, 42%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 1.39 (d, 1H, $J = 6.0$, Hz), 1.40 (d, 3H, $J = 6.0$ Hz), 2.65 (dd, 1H, $J = 7.7$, 9.2 Hz), 2.87 (dq, 1H, $J = 9.2$, 6.0 Hz), 4.23 (d, 1H, $J = 12.0$ Hz), 4.40 (d, 1H, $J = 12.0$ Hz), 5.38 (dd, 1H, $J = 6.2$, 7.7 Hz), 5.84 (dd, 1H, $J = 6.0$, 6.2 Hz), 7.23−7.36 (m. 5H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 22.6, 24.5, 63.5, 69.5, 73.7, 86.4, 92.1, 121.4, 127.7, 127.9, 128.5, 137.6, 207.3; IR (KBr) 2220, 2067, 1998 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 325 ($M^+ - CO$, 0.6), 297 (3.3), 269 (100). Anal. Calcd for $C_{17}H_{15}FeNO_4$: C, 57.82; H, 4.30; N, 4.00. Found: C, 57.92; H, 4.26; N, 4.08.

(2*RS*,5*RS*,6*RS*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-6-phenylthiohepta-2,4-dienenitrile] (7D). Entry 10. The reaction of **5** (62.6 mg, 0.157 mmol) with PhSH (0.16 mL, 1.57 mmol) and $BF_3{\cdot}Et_2O$ (2.0 μL, 15.7 μmol) at 0 °C according to the typical procedure and purification of the crude mixture by column chromatography (SiO_2, hexane/AcOEt =

8:1) gave **7D** (30.3 mg, 54%) as yellow crystals: mp 108 °C (hexane); ^{1}H NMR ($CDCl_3$) δ 1.23 (d, 1H, J = 7.0 Hz), 1.48 (d, 3H, J = 6.2 Hz), 2.58 (dq, 1H, J = 8.8, 6.2 Hz), 2.78 (dd, 1H, J = 7.1, 8.8 Hz), 4.72 (dd, 1H, J = 6.4, 7.1 Hz), 5.31 (dd, 1H, J = 6.4, 7.0 Hz), 7.50 (m, 5H);^{13}C NMR (75.5 MHz, $CDCl_3$) δ 22.3, 24.8, 46.4, 66.8, 84.2, 91.0, 121.3, 128.7, 129.0, 133.9, 135.0, 207.5; IR (KBr) 2219, 2063, 2007, 1984 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 356.0 (M^+ + 1, 73), 108.0 (100); HRMS calcd for $C_{16}H_{13}FeNO_3S$ 354.9966, found 354.9969.

(2*RS*,5*SR*,6*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-azidohepta-2,4-dienal] (8). To a stirred solution of **6E** (2.70 g, 9.37 mmol) in dry CH_2Cl_2 (50 mL) was added DIBAL-H (1.01 M in toluene, 12.1 mL, 12.19 mmol) at −78 °C under a nitrogen atmosphere. After 5 min, a saturated potassium sodium tartrate solution (15 mL) was added to the reaction mixture at −78 °C, and the resulting mixture was stirred at room temperature. The mixture was extracted with AcOEt, and the extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 5:1) to give **8** (2.40 g, 88%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 1.39 (m, 2H), 1.44 (d, 3H, J = 6.8 Hz), 3.35 (dq, 1H, J = 7.7, 6.8 Hz), 5.48 (dd, 1H, J = 6.6, 6.8 Hz), 5.89 (dd, 1H, J = 6.4, 6.6 Hz), 9.37 (d, 1H, J = 3.4 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 21.5, 55.0, 60.4, 64.0, 82.9, 86.4, 195.5, 207.2; IR (KBr) 2118, 2065, 2017, 1691 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 291 (M^+, 100). Anal. Calcd for $C_{10}H_9FeN_3O_4$: C, 41.27; H, 3.12; N, 14.44. Found: C, 41.16; H, 3.07; N, 14.62.

(2*RS*,5*RS*,6*RS*,7*SR*,2*E*,4*Z*)-Tricarbonyliron[(η^4-2−5)-7-azido-6-methoxyocta-2,4-dienenitrile] (*syn*-11). To a stirred solution of **8** (33.2 mg, 0.114 mmol) in dry THF (1.2 mL) were added DEPC (0.021 mL, 0.137 mmol) and LiCN (1.9 mg, 0.0570 mmol) at room temperature under a nitrogen atmosphere. After 15 min, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo to give the crude **9** as a yellow oil. To a stirred solution of **9** (51.2 mg, 0.114 mmol) in dry MeOH (1.2 mL) was added $BF_3{\cdot}Et_2O$ (1.4 μL, 11.4 μmol) at 0 °C under a nitrogen atmosphere. After 2 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give **11** (20.0 mg, 53%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 1.32 (d, 1H, J = 6.8 Hz), 1.35 (d, 3H, J = 6.8 Hz), 2.49 (dd, 1H, J = 3.4, 9.4 Hz), 2.74 (dd, 1H, J = 8.5, 9.4 Hz), 3.17 (s, 3H), 3.67 (dq, 1H, J = 3.4, 6.8 Hz), 5.45 (dd, 1H, J = 5.1, 6.8 Hz), 5.88 (dd, 1H, J = 5.1, 8.5 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 15.5, 24.8, 56.7, 57.3, 59.5, 82.3, 86.1, 92.5, 121.2; IR (KBr) 2220, 2116, 2065, 1998 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 276 (M^+ − 2CO, 33), 250 (M^+ − 3CO, 100); HRMS calcd for $C_{12}H_{12}FeN_4O_4$ 332.0206, found 332.0188.

(2*RS*,5*SR*,6*SR*,7*SR*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-7-azido-6-methoxyocta-2,4-dienenitrile] (*anti*-10). To a stirred solution of **9** (509 mg, 1.12 mmol) in dry THF (12 mL) were added MeOH (0.45 mL, 11.2 mmol) and $TrClO_4$ (419 mg, 1.31 mmol) at room temperature under a nitrogen atmosphere. After 2 h, a saturated $NaHCO_3$ solution was added to the reaction mixture, and the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give **10** (191 mg, 52%) as a yellow oil: ^{1}H NMR ($CDCl_3$) δ 0.42 (d, 1H, J = 7.1 H), 1.02 (dd, 1H, J = 4.1, 4.2 Hz), 1.26 (d, 3H, J = 5.7 Hz), 3.29 (dd, 1H, J = 4.1, 5.3 Hz), 3.40 (s, 3H), 3.70 (dq, 1H, J = 5.3, 5.7 Hz), 5.58 (dd, 1H, J = 4.2, 5.4 Hz), 5.63 (dd, 1H, J = 5.4, 7.1 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.1, 24.1, 57.6, 59.1, 60.2, 81.4, 83.3, 86.2, 121.2, 207.2; IR (KBr) 2218, 2109, 2056, 2011 cm^{-1}; MS (CI) *m*/*z* (relative intensity) 333.0 (M^+ + 1, 100); HRMS calcd for $C_{12}H_{13}FeN_4O_4$ 333.0286 (FAB, M + H), found 333.0288.

(2*S*,5*R*,6*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-hydroxyhepta-2,4-dienal] (16). A solution of **15** (227 mg, 0.600 mmol) and Ti(O*i*-Pr)$_4$ (10.7 mL, 36.0 mmol) in dry toluene (50 mL) was stirred at 50 °C for 30 min under a nitrogen atmosphere. After the mixture was cooled to −78 °C, a 1.0 M solution of Me_2Zn (36 mL, 36 mmol) in hexane and a solution of **14** (5.0 g, 20.0 mmol) in dry toluene (90 mL) were successively added to the reaction mixture. The resulting mixture was allowed to warm slowly to 0 °C and stirried at 0 °C for 1 h. After being quenched with a 2 M aqueous HCl solution (80 mL), the mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and concentrated in vacuo. The crude residue was purified by column chromatography (SiO_2, $CHCl_3$/acetone = 20:1 to 10:1) to give **14** (0.59 g, 12%), a diastereomer of **16** (0.37 g, 7%), and **16** (3.82 g, 71%). **16**: yellow crystals; mp 72−73 °C (hexane/benzene); $[\alpha]^{25}_D$ +163.5 (c = 1.03, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 1.34 (dd, 1H, J = 4.3, 8.1 Hz), 1.42 (d, 3H, J = 6.0 Hz), 1.51−1.54 (m, 1H), 1.64 (d, 1H, J = 4.3 Hz), 3.78 (m, 1H), 5.55 (dd, 1H, J = 4.7, 9.0 Hz), 5.84 (dd, 1H, J = 4.7, 8.1 Hz), 9.32 (d, 1H, J = 4.3 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 25.7, 54.9, 68.8, 69.6, 82.4, 86.6, 196.2, 207.2; IR (KBr) 3398, 2059, 1988, 1673 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 238 (M^+ − CO, 8.5), 210 (19), 182 (32), 81 (100). Anal. Calcd for $C_{10}H_{10}FeO_5$: C, 45.15; H, 3.79. Found: C, 45.17; H,3.77. The diastereomer of **16**: a yellow oil; $[\alpha]^{26}_D$ +30.8 (c = 1.31, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 1.23 (dd, 1H, J = 4.3, 8.5 Hz), 1.41 (d, 3H, J = 6.0 Hz), 1.47 (d, 1H, J = 3.4 Hz), 1.62 (dd, 1H, J = 6.0, 8.6 Hz), 3.97−4.01 (m, 1H), 5.49 (dd, 1H, J = 5.1, 8.6 Hz), 5.84 (dd, 1H, J = 5.1, 8.5 Hz), 9.32 (d, 1H, J = 4.3 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 26.5, 54.5, 68.4, 72.5, 81.1, 85.0, 196.0, 208.4; IR (KBr) 3453, 2973, 2057, 1996, 1678 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 266 (M^+, 5.4), 238 (7.2), 210 (16), 182 (21), 81 (100); HRMS calcd for $C_{10}H_{10}FeO_5$ 265.9877, found 265.9890.

(2*S*,5*R*,6*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-acetoxyhepta-2,4-dienal] (17). To a stirred solution of **14** (3.47 g, 13.04 mmol) in a mixture of pyridine (6 mL) and CH_2Cl_2 (6 mL) were added (dimethylamino)pyridine (79.7 mg, 0.652 mmol) and Ac_2O (1.48 mL, 15.65 mmol) at 0 °C under a nitrogen atmosphere. After the resulting mixture was stirred at room temperature for 2.5 h, solvents were evaporated. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 5:1 to 3:1) to give **17** (3.21 g, 80%) as yellow crystals: mp 54−55 °C (hexane); $[\alpha]^{25}_D$ +170 (c = 1.84, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 1.36 (dd, 1H, J = 4.3, 8.5 Hz), 1.40−1.44 (m, 1H), 1.43 (d, 3H, J = 6.1 Hz), 2.05 (s, 3H), 4.81 (dq, 1H, J = 8.5, 6.1 Hz), 5.68 (dd, 1H, J = 4.9, 8.5 Hz), 5.82 (dd, 1H, J = 4.9, 8.5 Hz), 9.34 (d, 1H, J = 4.3 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 21.3, 22.1, 55.1, 64.0, 71.9, 82.7, 87.4, 170.4, 195.7, 209.2; IR (KBr) 2062, 1986, 1731, 1681 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 280 (M^+ − CO, 6.4), 224 (100). Anal. Calcd for $C_{12}H_{12}FeO_6$: C, 46.78; H, 3.93. Found: C, 47.07; H, 3.96.

(2*S*,5*R*,6*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-azidohepta-2,4-dienenitrile] (+)-6E. To a stirred solution of **17** (3.21 g, 10.42 mmol) in dry CH_2Cl_2 (22 mL) were added $TMSN_3$ (2.9 mL, 20.84 mmol) and $Sc(OTf)_3$ (512.8 mg, 1.042 mmol) at 0 °C under a nitrogen atmosphere. The resulting mixture was stirred at 0 °C for 1.5 h and at room temperature for 20 min. After water (20 mL) was added to the reaction mixture, the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 5:1) to give (+)-**6F** (2.76 g, 92%): $[\alpha]^{26}_D$ +91.7 (c = 0.84, $CHCl_3$).

(2*S*,5*R*,6*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-6-azidohepta-2,4-dienal] (+)-8. The chiral nitrile (+)-**6E** was treated by the same procedure as described for the racemic **6E** to give (+)-**8** (4.60 g, 88%) as a yellow oil: $[\alpha]^{25}_D$ +183.6 (c = 1.13, $CHCl_3$).

(2*S*,5*R*,6*R*,7*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-7-azido-6-methoxyocta-2,4-dienylnitrile] ((+)-10). The chiral aldehyde (+)-**8** was treated by the same procedure as described for the racemic **8** to give (+)-**10** (1.04 g, 52%) as a yellow oil. $[\alpha]^{25}_D$ +61.6 (c = 0.95, $CHCl_3$).

(2*S*,5*R*,6*R*,7*R*,2*E*,4*E*)-Tricarbonyliron[(η^4-2−5)-7-azido-6-methoxyocta-2,4-dienal] ((+)-18). The same treatment of (+)-**10** (286 mg, 0.861 mmol) as described for **8** gave an oily residue, which was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give (+)-**18** (221 mg, 77%) as a yellow oil: $[\alpha]^{25}_D$ +108 (c = 0.75, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 1.26−1.35 (m, 2H), 1.30 (d, 3H, J = 6.8 Hz), 3.29 (dd, 1H, J = 2.6, 5.1 Hz), 3.42 (s, 3H), 3.68 (dq, 1H, J = 2.6, 6.8 Hz), 5.62 (dd, 1H, J = 5.1, 8.6 Hz), 5.88 (dd, 1H, J = 5.1, 8.2 Hz), 9.34 (d, 1H, J = 4.0 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 13.8, 54.7, 57.6, 59.5, 60.3, 81.8, 83.9, 86.3, 195.9, 208.3; IR (KBr) 2106, 2060, 1990,

1687 cm^{-1}; MS (EI) *m/z* (relative intensity) 335 (M^+, 62), 306 (100). Anal. Calcd for $C_{12}H_{13}FeN_3O_5$: C, 43.01; H, 3.91; N, 12.54. Found: C, 43.31; H, 4.04; N, 12.60.

(2*S*,5*R*,6*R*,17*R*,8*R*,2*E*,4*E*)-Tricarbonyliron[(η⁴-2−5)-8-azido-6-ethylthio-7-methoxynona-2,4-dienenitrile] ((+)-19). The same treatment of (+)-**18** (114 mg, 0.34 mmol) with DEPC (0.078 mL, 0.512 mmol) and LiCN (5.6 mg, 0.171 mmol) as described for ***syn*-11** gave the crude cyanophosphate, which was subjected to EtSH (0.25 mL, 3.40 mmol) and $TrClO_4$ (128 mg, 0.374 mmol). Similar workup of the reaction mixture and purification by column chromatography (SiO_2, hexane/AcOEt = 6:1) afforded (+)-**19** (83.4 mg, 61%) as yellow crystals: mp 42 °C (petroleum ether/benzene); $[\alpha]^{25}_D$ +71.0 (c = 1.14, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.53 (d, 1H, J = 7.9 Hz), 1.28 (t, 3H, J = 7.3 Hz), 1.44 (d, 3H, J = 6.7 Hz), 1.61 (dd, 1H, J = 9.2, 9.2 Hz), 2.63 (dq, 1H, J = 4.9, 7.9 Hz), 2.70 (dq, 1H, J = 4.9, 7.9 Hz), 2.82 (dd, 1H, J = 3.1, 9.2 Hz), 3.14 (dd, 1H, J = 3.1, 7.9 Hz), 3.48 (s, 3H), 3.96 (dq, 1H, J = 7.9, 6.7 Hz), 5.48 (dd, 1H, J = 4.9, 9.2 Hz), 5.57 (dd, 1H, J = 4.9, 7.2 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.5, 15.8, 24.6, 26.5, 44.9, 58.0, 60.0, 63.6, 81.6, 86.9, 88.4, 121.1, 207.2; IR (KBr) 2218, 2109, 2056, 2011 cm^{-1}; MS (EI) *m/z* (relative intensity) 350 (M^+ − 2CO, 37), 322 (47), 191 (100); HRMS calcd for $C_{13}H_{18}FeN_4O_2S$ (M^+ − 2CO) 350.0499, found 350.0495.

(2*S*,5*R*,7*S*,8*R*,2*E*,4*E*)-Tricarbonyliron[(η⁴-2−5)-8-(*tert*-butoxycarbonylamino)-7-methoxynona-2,4-dienenitrile] ((+)-**20**). A mixture of (+)-**19** (20.0 mg, 0.0492 mmol), 10% Pd/C (12.5 mg), Boc_2O (33.9 μL, 0.148 mmol), and dry MeOH (1 mL) was vigorously stirred at room temperature under a medium-pressured hydrogen atmosphere (5 atm) for 24 h. The reaction mixture was filtered off throuth a pad of Celite, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give (+)-**20** (17.6 mg, 85%) as yellow crystals: mp 143 °C (hexane/benzene); $[\alpha]^{25}_D$ +98.0 (c = 0.98, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.49 (d, 1H, J = 7.1 Hz), 1.09 (d, 3H, J = 6.8 Hz), 1.44 (s, 10H), 1.60 (ddd, 1H, J = 5.8, 8.7, 14.3 Hz), 1.96 (ddd, 1H, J = 5.5, 5.7, 14.3 Hz), 3.29 (m, 1H), 3.37 (s, 3H), 3.75 (m, 1H), 4.59 (br, 1H), 5.25 (dd, 1H, J = 4.5, 5.5 Hz), 5.57 (dd, 1H, J = 5.5, 7.1 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 15.3, 24.1, 28.3, 34.3, 47.7, 58.5, 60.1, 79.5, 81.6, 84.5, 88.9, 121.3, 155.2, 207.7; IR (KBr) 3356, 2220, 2060, 1994, 1701 cm^{-1}; MS (EI) *m/z* (relative intensity) 365 (M^+ + 1 − 2CO, 1.3), 337 (M^+ + 1 − 3CO, 23), 59 (100). Anal. Calcd for $C_{18}H_{24}FeN_2O_6$: C, 51.45; H, 5.76; N, 6.67. Found: C, 51.71; H, 5.80; N, 6.66.

(2*S*,5*R*,7*S*,8*R*,2*E*,4*E*)-Tricarbonyliron[(η⁴-2−5)-8-(*tert*-butoxycarbonylamino)-7-methoxynona-2,4-dienal] ((+)-21). The same treatment of (+)-**20** (51.5 mg, 0.121 mmol) with DIBAL-H (1.0 M in toluene, 0.303 mL, 0.303 mmol) as described for **8** gave the crude mixture, which was purified by column chromatography (SiO_2, hexane/AcOEt = 4:1) to give (+)-**21** (40.5 mg, 78%) as yellow crystals: mp 118 °C (hexane); $[\alpha]^{25}_D$ +137.9 (c = 0.98, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 1.10 (d, 3H, J = 6.0 Hz), 1.44 (s, 11H), 1.66−1.69 (m, 1H), 1.99−2.04 (m, 1H), 3.23 (m, 1H), 3.40 (s, 3H), 3.81 (m, 1H), 4.66 (br, 1H), 5.31 (dd, 1H, J = 4.7, 8.6 Hz), 5.81 (dd, 1H, J = 4.7, 8.6 Hz), 9.31 (d, 1H, J = 3.4 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 15.0, 28.4, 34.5, 47.9, 54.7, 58.5, 60.4, 79.4, 81.7, 84.6, 88.8, 155.2, 195.9, 208.9; IR (KBr) 3348, 2055, 1988, 1687 cm^{-1}; MS (EI) *m/z* (relative intensity) 339 (M^+ − 3CO, 67), 59 (100). Anal. Calcd for $C_{18}H_{25}FeNO_7$: C, 51.08; H, 5.95; N, 3.31. Found: C, 51.01; H, 5.89; N, 3.36.

(2*R*,3*S*,5*R*,8*S*,5*E*,7*E*,9*Z*)-Tricarbonyliron[(η⁴-5−8)-2-(*tert*-butoxycarbonylamino)-3-methoxytetradodeca-5,7,9-triene] ((−)-22). A 1.5 M solution of *n*-BuLi in hexane (0.022 mL, 0.0325 mmol) was added to a stirred suspension of $C_5H_{11}PPh_3Br$ (13.4 mg, 0.0325 mmol) in dry toluene (0.25 mL) at 0 °C under a nitrogen atmosphere. After 5 min, a solution of (+)-**21** (5.5 mg, 0.0130 mmol) in dry toluene (0.5 mL) was added to the mixture at −78 °C, and the resulting mixture was stirred at −78 °C for 30 min and at 0 °C for 30 min. After being quenched with water at 0 °C, the resulting mixture was extracted with AcOEt. The extract was washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 7:1) to give (−)-**22** (4.5 mg, 73%) as a yellow oil: $[\alpha]^{25}_D$ −296 (c = 1.02, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.92 (t, 3H, J = 6.8 Hz), 1.09 (d, 3H, J = 6.4 Hz), 1.25−1.39 (m, 5H), 1.45 (s, 10H), 1.98−2.12 (m, 4H), 3.23 (m, 1H), 3.39 (s, 3H), 3.83 (m, 1H), 4.73 (br, 1H), 5.03 (dd, 1H, J = 5.1, 8.6 Hz), 5.16 (dd, 1H, J = 5.1, 8.6 Hz), 5.36−5.37 (m, 2H); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.0, 14.7, 22.4, 22.7, 28.4, 31.4, 34.6, 47.8, 56.7, 57.7, 58.4, 79.2, 82.9, 84.4, 84.7, 130.1, 132.2, 155.2, 212.0; IR (KBr) 3448, 2038, 1971, 1708, 1646 cm^{-1}; MS (EI) *m/z* (relative intensity) 422 (M^+ + 1 − 2CO, 3.2), 394 (26), 348 (18), 320 (100); HRMS calcd for $C_{21}H_{35}FeNO_4$ (M^+ − 2CO) 421.1915, found 421.1915.

(2*R*,3*S*,5*R*,8*S*,5*E*,7*E*)-Tricarbonyliron[(η⁴-5−7)-2-(*tert*-butoxycarbonylamino)-3-methoxytetradodeca-5,7-diene] ((+)-23). A mixture of (−)-**22** (18.3 mg, 0.0383 mmol), 10% Pd/C (4.1 mg), and dry MeOH (1 mL) was vigorously stirred at room temperature under a medium-pressured hydrogen atmosphere (3 atm) for 12 h. The reaction mixture was filtered off through a pad of Celite, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 8:1) to give (+)-**23** (14.9 mg, 81%) as a yellow oil: $[\alpha]^{24}_D$ +27.1 (c = 0.81, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.89 (t, 3H, J = 6.8 Hz), 1.07 (d, 3H, J = 6.6 Hz), 1.25−1.35 (m, 10H), 1.45 (s, 9H), 1.60−1.96 (m, 4H), 3.17 (m, 1H), 3.37 (s, 3H), 3.81 (m, 1H), 4.77 (br, 1H), 5.01 (m, 2H); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.1, 14.5, 22.6, 28.4, 29.0, 31.6, 32.1, 34.3, 34.5, 47.7, 56.8, 58.1, 64.8, 79.2, 84.0, 84.6, 84.7, 156.2, 212.3. IR (KBr): 3450, 2038, 1965, 1716 cm^{-1}; MS (EI) *m/z* (relative intensity) 424 (M^+ + 1 − 2CO, 0.6), 396 (33), 350 (12), 322 (100); HRMS calcd for $C_{21}H_{37}FeNO$ (M^+ − 2CO) 423.2071, found 423.2076.

(2*R*,3*S*,5*E*,7*E*)-2-(*tert*-Butoxycarbonylamino)-3-methoxytetradodeca-5,7-diene ((−)-24). A mixture of (+)-**23** (7.8 mg, 0.0163 mmol), anhydrous Me_3NO (9.8 mg, 0.130 mmol), and dry benzene (0.8 mL) was stirred at 60 °C for 1 h under a nitrogen atmosphere. The reaction mixture was filtered through a pad of Celite, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 8:1) to give (−)-**24** (4.8 mg, 87%) as a pale yellow oil: $[\alpha]^{26}_D$ −5.8 (c = 0.21, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.88 (t, 3H, J = 6.8 Hz), 1.06 (d, 3H, J = 6.4 Hz), 1.26−1.30 (m, 8H), 1.45 (s, 9H), 2.03−2.10 (m, 3H), 2.40 (ddd, 1H, J = 7.3, 7.3, 7.3 Hz), 3.26 (m, 1H), 3.39 (s, 3H), 3.75 (m, 1H), 4.80 (br, 1H), 5.50 (ddd, 1H, J = 7.3, 7.3, 14.6 Hz), 5.59 (ddd, 1H, J = 7.2, 7.2, 14.6 Hz), 5.97 (dd, 1H, J = 10.3, 14.6 Hz), 6.06 (dd, 1H, J = 10.3, 14.6 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.1, 14.3, 22.6, 28.4, 28.9, 29.3, 31.7, 32.6, 33.9, 48.3, 58.2, 79.1, 83.1, 126.6, 129.9, 133.1, 133.7, 155.3; IR (KBr): 3375, 1713, 1660 cm^{-1}; MS (EI) *m/z* (relative intensity) 340 (M^+ + 1, 0.9), 309 (2.1), 267 (7), 253 (100), 239 (10); HRMS calcd for $C_{20}H_{38}NO_3$ 340.2852 (FAB, M + H), found 340.2849.

(2*R*,3*S*,5*E*,7*E*)-2-(*tert*-Butoxycarbonylamino)-3-methoxytetradodeca-5,7-diene ((+)-24). To a stirred solution of (+)-**26** (30.0 mg, 0.0821 mmol) in dry MeOH (0.5 mL) was added *p*-TsOH·H_2O (1.6 mg, 0.0821 mmol) at room temperature under a nitrogen atmosphere. After 13 h, the solvent was concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 6:1 to 2:1) to give the recovered starting material **26** (3.8 mg, 13%) and **27** (18.9 mg, 71%) as colorless crystals. **27**: mp 91−92 °C (hexane); $[\alpha]^{25}_D$ −15.4 (c = 0.95, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 0.88 (t, 3H, J = 6.7 Hz), 1.11 (d, 3H, J = 6.77 Hz), 1.25−1.41 (m, 8H), 1.44 (s, 9H), 2.05 (dd, 1H, J = 7.3, 14.0 Hz), 2.10 (m, 4H), 3.69 (m, 2H), 4.76 (br, 1H), 5.55 (ddd, 1H, J = 7.3, 7.3, 14.6 Hz), 5.62 (ddd, 1H, J = 7.3, 7.3, 14.6 Hz), 6.01 (dd, 1H, J = 10.4, 14.6 Hz), 6.10 (dd, 1H, J = 10.4, 14.6 Hz); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 14.2, 14.7, 22.7, 28.5, 29.0, 29.3, 31.8, 32.7, 37.2, 50.3, 73.7, 79.4, 126.7, 129.6, 133.8, 134.1, 155.6; IR (KBr) 3351, 1682 cm^{-1}; MS (FAB) 326 (M + H); HRMS calcd for $C_{19}H_{36}NO_3$ 326.2695 (FAB, M + H), found 326.2708.

To a solution of (−)-**27** (24.4 mg, 0.0750 mmol) in dry MeCN (1 mL) were added MeI (0.047 mL, 0.750 mmol) and Ag_2O (40.0 mg, 0.188 mmol), and the resulting mixture was refluxed for 6 h under a nitrogen atmosphere. The reaction mixture was filtered through a pad of Celite, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (SiO_2, hexane/AcOEt = 8:1) to give (+)-**24** (11.1 mg, 44%), along with the recovered starting material **27** (4.3 mg, 18%). (+)-**24**: pale yellow oil; $[\alpha]^{24}_D$ +4.2 (c = 0.12, $CHCl_3$).

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Supporting Information Available: ^{1}H NMR spectra of **6A**, **6D**, **6E**, **7A**, **7D**, **7E**, **10**, **11**, **19**, (−)-**24**, and (+)-**24**, and X-ray structural information of the racemic *N*-Boc derivative **28** (PDF). An X-ray crystallographic file, in CIF format, is also available. This material is available free of charge via the Internet at http://pubs.acs.org.

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