Synthesis of Allenes from Allylic Alcohol Derivatives Bearing a Bromine Atom Using a Palladium(0)/Diethylzinc System

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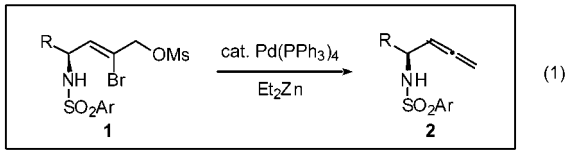
A general and efficient synthesis of allenes using a palladium(0)/diethylzinc system is described. Treatment of mesylates or trichloroacetates of (*E*)- or (*Z*)-2-bromoalk-2-en-1-ols with diethylzinc in the presence of a catalytic amount of palladium(0) affords allenes bearing an aminoalkyl, alkyl, or aryl substituent(s) in good to high yields. No transfer of chirality from the stereogenic center carrying the mesyloxy group to the allene was observed.

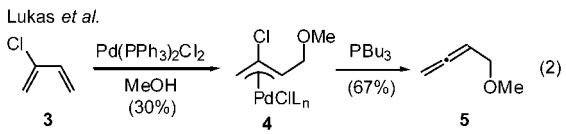
Introduction

Allenes are an important class of molecules with high chemical reactivity, due to their cumulated double bonds.[1] Owing to the recent development of synthesis and transition metal-catalyzed reactions of allenes,[1e,1f,2] they have become more versatile intermediates in organic synthesis. Among various substituted allenes, amino allenes have attracted considerable interest in recent years, since they are versatile substrates for constructing various azacycles.[2]

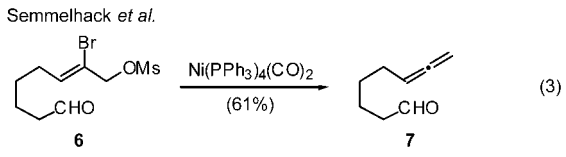
In the course of our study involving synthesis of ethynylaziridines,[3] we found that the allylic mesylate **1** can be converted into the amino allene **2** on treatment with diethylzinc in the presence of palladium(0) catalyst (eq 1).[4] Scanning the literature revealed that there have been some reports describing related synthesis of allenes.[5,6] In 1973, Lukas and co-workers reported that 2-chloro-1,3-diene **3** and palladium(II) chloride forms an allylpalladium(II) complex **4**, which undergoes an elimination reaction in the presence of tributylphosphine to yield the allene **5**, only in a single example (eq 2).[5a,b] Semmelhack and his associate observed formation of a monosubstituted allene **7** as an undesired product by treatment of an allylic mesylate **6** with 2.4 equiv of Ni(PPh$_3$)$_2$(CO)$_2$, also in one example.[5c] However, no systematic investigation involving the synthesis of allenes from such class of compounds has been carried out, and a catalytic synthesis of allenes[7] from such substrates is unknown as far as we are aware.



(1)



(2)



(3)

Recently, we have reported that internal allenes (1,3-disubstituted allenes) bearing an *N*-protected amino group could be readily synthesized from ethynylaziridines by treatment with organocopper reagents;[8] however,

† Deceased January 20, 2000.

(1) For reviews, see: (a) Brandsma, L.; Verkruijsse, H. D. In *Synthesis of Acetylenes, Allenes and Cumulenes*; Elsevier: New York, 1981. (b) Smadja, W. *Chem. Rev.* **1983**, *83*, 263. (c) Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805. (d) Marshall, J. A. *Chem. Rev.* **2000**, *100*, 3163. (e) Yamamoto, Y.; Radhakrishnan, U. *Chem. Soc. Rev.* **1999**, *28*, 199. (f) Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067. (g) Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2000**, *39*, 3590.

(2) (a) Ohno, H.; Toda, A.; Miwa, Y.; Taga, T.; Osawa, E.; Yamaoka, Y.; Fujii, N.; Ibuka, T. *J. Org. Chem.* **1999**, *64*, 2992. (b) Ohno, H.; Anzai, M.; Toda, A.; Ohishi, S.; Fujii, N.; Tanaka, T.; Takemoto, Y.; Ibuka, T. *J. Org. Chem.* **2001**, *66*, 4904, and references sited therein.

(3) (a) Ohno, H.; Toda, A.; Fujii, N.; Ibuka, T. *Tetrahedron: Asymmetry* **1998**, *9*, 3929. (b) Ohno, H.; Toda, A.; Takemoto, Y.; Fujii, N.; Ibuka, T. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2949.

(4) A portion of this study was reported in a preliminary communication: Ohno, H.; Toda, A.; Oishi, S.; Tanaka, T.; Takemoto, Y.; Fujii, N.; Ibuka, T. *Tetrahedron Lett.* **2000**, *41*, 5131.

(5) (a) Lukas, J.; Visser, J. P.; Kouwenhoven, A. P. *J. Organomet. Chem.* **1973**, *50*, 349. See also, (b) Lupin, M. S.; Powell, J.; Shaw, B. L. *J. Chem. Soc. A* **1966**, 1687. (c) Semmelhack, M. F.; Brickner, S. J. *J. Am. Chem. Soc.* **1981**, *103*, 3945. For other related synthesis of allenes, see: (d) Konoike, T.; Araki, Y. *Tetrahedron Lett.* **1992**, *33*, 5093. (e) Bhuvaneswari, N.; Venkatachalam, C. S.; Balasubramanian, K. K. *J. Chem. Soc., Chem. Commun.* **1994**, 1177. (f) Gabbutt, C. D.; Hepworth, J. D.; Heron, B. M.; Rahman, M. M. *J. Chem. Soc., Chem. Commun.* **1994**, 1733.

(6) Reverse reactions of our allene synthesis have been reported. For formation of π-allylpalladium(II) complexes by the reaction of allenes with a stoichiometric amount of Pd(II), see: (a) Lupin, M. S.; Shaw, B. L. *Tetrahedron Lett.* **1964**, *5*, 883. (b) Schultz, R. G. *Tetrahedron* **1964**, *20*, 2809, and see also, ref 5b. Bäckvall and co-workers reported the palladium(II)-catalyzed 1,2-oxidation of a certain allene with *p*-benzoquinone in the presence of LiBr affording, only in an isolated example, 2,3-dibromoprop-1-ene derivative, see: (c) Jonasson, C.; Karstens, W. F. J.; Hiemstra, H.; Bäckvall, J.-E. *Tetrahedron Lett.* **2000**, *41*, 1619. See also, (d) Jonasson, C.; Horváth, A.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **2000**, *122*, 9600.

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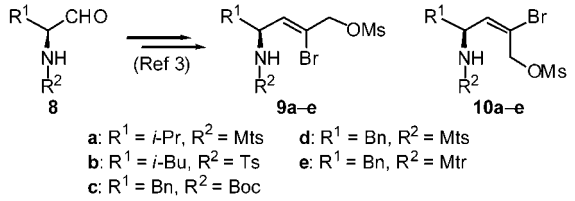
preparation of monosubstituted allenes of the type **2** without contaminating the corresponding acetylene by the use of organocopper chemistry has proven to be quite difficult. Although reliable synthetic methods of terminal allenes have been already developed,[9−11] some of these are unsuitable for the synthesis of allenes bearing a nitrogen functionality.[12] The potential utility of the synthesis of allenes by a palladium(0)/diethylzinc system (eq 1), especially for the synthesis of amino allenes, led us to a detailed investigation of this reaction. In this paper, we present a full account of our investigation into the synthesis of allenes from esters of 2-bromoalk-2-en-1-ols using diethylzinc and catalytic palladium(0).[4] The effect of the chirality of the mesyloxy group of the secondary substrates, on the axial chirality of the resulting internal allenes, is also described.

Results and Discussion

Synthesis of Esters of Allylic Alcohols Bearing a Bromine Atom. The requisite mesylates of brominated (*Z*)-allylic alcohols **9a**−**e** bearing a protected amino group were prepared in high yields starting from natural α-amino acids following the published procedure (Scheme 1).[3] The (*Z*)-mesylates **10a**−**e** were also synthesized via the same sequence of reactions (see the Supporting Information).

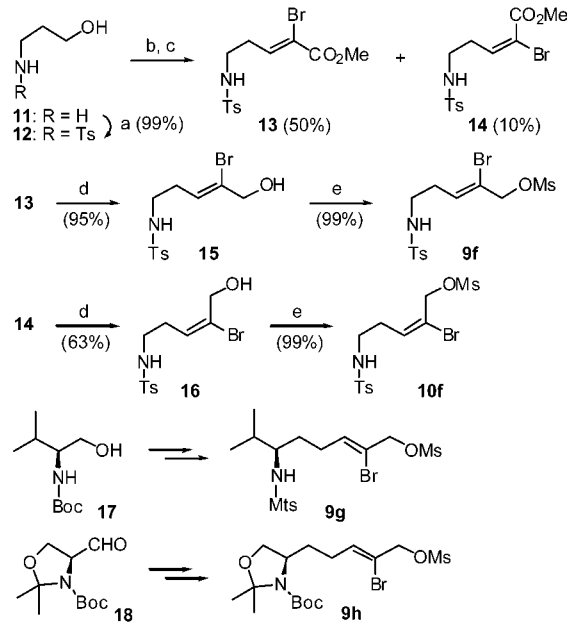
Mesylates **9f** and **10f** were synthesized as shown in Scheme 2. Thus, 3-amino-1-propanol **11** was treated successively with *p*-toluenesulfonyl chloride−DMSO−*N*,*N*-diisopropylethylamine, and a brominated ylide [$Ph_3P{=}C(Br)CO_2Me$][13] to afford a 5:1 mixture of the (*Z*)- and (*E*)-α-bromo-α,β-unsaturated esters **13** and **14** in a good combined yield, which were separated by flash chromatography. Reduction of the (*Z*)-enoate **13** with DIBAL-H yielded the allylic alcohol **15**, which can be readily converted into the mesylate **9f** following the standard procedure. The (*E*)-enoate **14** was also converted into the corresponding mesylate **10f**. In a similar manner, the allylic mesylates

Scheme 1[a]



[a] Abbreviations: Mts = 2,4,6-trimethylphenylsulfonyl; Mtr = 4-methoxy-2,3,6-trimethylphenylsulfonyl.

Scheme 2[a]



[a] Reagents: (a) TsCl, Et_3N; (b) $(COCl)_2$, DMSO, CH_2Cl_2, then $(i\text{-Pr})_2NEt$; (c) $Ph_3P{=}C(Br)CO_2Me$; (d) DIBAL-H; (e) MsCl, Et_3N.

(7) For transition metal-catalyzed synthesis of allenes, see: (a) Ogoshi, S.; Nishiguchi, S.; Tsutsumi, K.; Kurosawa, H. *J. Org. Chem.* **1995**, *60*, 4650. (b) Suginome, M.; Matsumoto, A.; Ito, Y. *J. Org. Chem.* **1996**, *61*, 4884. (c) Mikami, K.; Yoshida, A. *Angew. Chem., Int. Ed.* **1997**, *36*, 858. (d) Dixneuf, P. H.; Guyot, T.; Ness, M. D.; Roberts, S. M. *Chem. Commun.* **1997**, 2083. (e) Tsuji, Y.; Taniguchi, M.; Yasuda, T.; Kawamura, T.; Obora, Y. *Org. Lett.* **2000**, *2*, 2635. (f) Ogasawara, M.; Ikeda, H.; Hayashi, T. *Angew. Chem., Int. Ed.* **2000**, *39*, 1042. (g) Ogasawara, M.; Ikeda, H.; Nagano, T.; Hayashi, T. *J. Am. Chem. Soc.* **2001**, *123*, 2089.

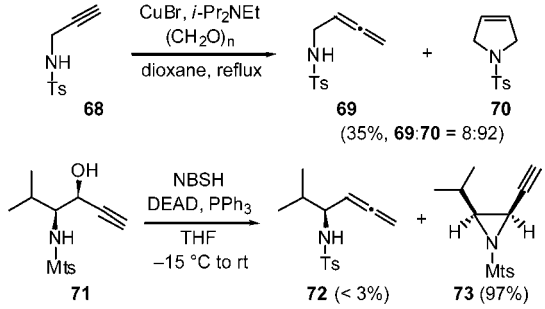
(8) (a) Ohno, H.; Toda, A.; Miwa, Y.; Taga, T.; Fujii, N.; Ibuka, T. *Tetrahedron Lett.* **1999**, *40*, 349. (b) Ohno, H.; Toda, A.; Fujii, N.; Takemoto Y.; Tanaka, T.; Ibuka, T. *Tetrahedron* **2000**, *56*, 2811.

(9) (a) Searles, S.; Li, Y.; Nassim, B.; Lopes, M.-T. R.; Tran, P. T.; Crabbé, P. *J. Chem. Soc., Perkin Trans. 1* **1984**, 747. (b) Myers, A. G.; Zheng, B. *J. Am. Chem. Soc.* **1996**, *118*, 4492. (c) Dunn, M. J.; Jackson, R. F. W.; Pietruszka, J.; Turner, D. *J. Org. Chem.* **1995**, *60*, 2210.

(10) For recent examples of racemic or achiral allene synthesis, see: (a) Brummond, K. M.; Dingess, E. A.; Kent, J. L. *J. Org. Chem.* **1996**, *61*, 6096. (b) Petasis, N. A.; Hu, Y.-H. *J. Org. Chem.* **1997**, *62*, 782. (c) Brody, M. S.; Williams, R. M.; Finn, M. G. *J. Am. Chem. Soc.* **1997**, *119*, 3429. (d) Nagaoka, Y.; Tomioka, K. *J. Org. Chem.* **1998**, *63*, 6428. (e) Sturla, S. J.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 1976. (f) Cunico, R. F.; Zaporowski, L. F.; Rogers, M. *J. Org. Chem.* **1999**, *64*, 9307. (g) Delouvrié, B.; Lacôte, E.; Fensterbank, L.; Malacria, M. *Tetrahedron Lett.* **1999**, *40*, 3565. (h) Varghese, J. P.; Knochel, P.; Marek, I. *Org. Lett.* **2000**, *2*, 2849. (i) Tius, M. A.; Pal, S. K. *Tetrahedron Lett.* **2001**, *42*, 2605.

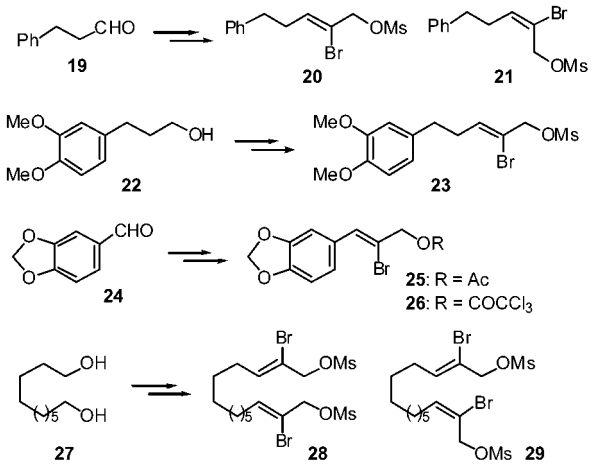
(11) For recent synthesis of enantiomerically enriched allenes, see: (a) Marshall, J. A.; Pinney, K. G. *J. Org. Chem.* **1993**, *58*, 7180. (b) Nishibayashi, Y.; Singh, J. D.; Fukuzawa, S.; Uemura, S. *J. Org. Chem.* **1995**, *60*, 4114. (c) Marshall, J. A.; Wolf, M. A.; Wallace, E. M. *J. Org. Chem.* **1997**, *62*, 367. (d) Naruse, Y.; Watanabe, H.; Ishiyama, Y.; Yoshida, T. *J. Org. Chem.* **1997**, *62*, 3862. (e) Noguchi, Y.; Takiyama, H.; Katsuki, T. *Synlett* **1998**, 543. (f) Node, M.; Nishide, K.; Fujiwara, T.; Ichihashi, S. *Chem. Commun.* **1998**, 2363. (g) Satoh, T.; Kuramochi, Y.; Inoue, Y. *Tetrahedron Lett.* **1999**, *40*, 8815. (h) Sweeney, Z. K.; Salsman, J. L.; Andersen, R. A.; Bergman, R. G. *Angew. Chem., Int. Ed.* **2000**, *39*, 2339. (i) Mikami, K.; Yoshida, A. *Tetrahedron* **2001**, *57*, 889. (j) Yamazaki, J.; Watanabe, T.; Tanaka, K. *Tetrahedron: Asymmetry* **2001**, *12*, 669. (k) Schultz-Fademrecht, C.; Wibbeling, B.; Fröhlich, R.; Hoppe, D. *Org. Lett.* **2001**, *3*, 1221. See also, refs 7c, 7d, 7g, and 8.

(12) For example, (1) when the protected propargylamine **68** was subjected to the Crabbé reaction,[9a] an intractable mixture of the desired allene **69** and pyrroline **70** (**69**:**70** = 8:92) was formed in 35% yield. (2) Reaction of protected amino alcohol **71** with *o*-nitrobenzenesulfonylhydrazine (NBSH) under Mitsunobu conditions (Myers' method[9b]) gave a trace amount of the desired allene **72** (<3%), and a considerable amount of the aziridine **73** (97%) was isolated. (3) Although the reaction of zinc/copper reagents with propargyl tosylate is a convenient method for a short synthesis of β-amino allenes,[9c] yields of some allenes are considerably low (14−67% in our case).[2b]



Abbreviations: NBSH = *o*-nitrobenzenesulfonylhydrazine; DEAD = diethyl azodicarboxylate.

Scheme 3

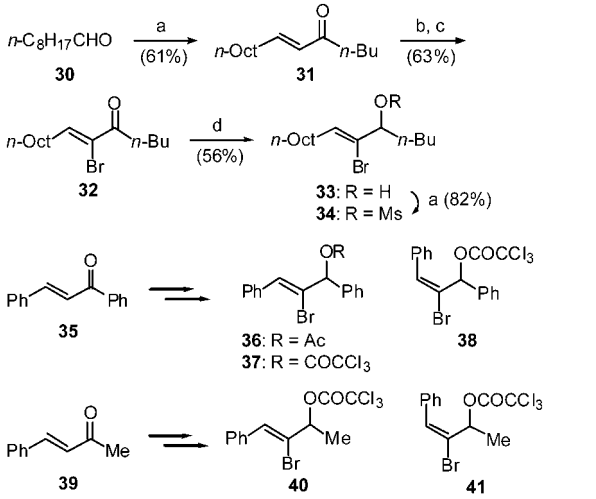


9g and **9h** were readily prepared from the *N*-Boc-valinol **17**[14] and Garner's aldehyde **18**,[15] respectively (see the Supporting Information).

The mesylates (**20** and **21**) and **23** (Scheme 3) were also prepared starting from 3-phenylpropanal **19** and the known alcohol **22**,[16] respectively, by use of the sequence of reactions similar to that depicted in Scheme 2. It should be noted that synthesis of the mesylate derived from piperonal **24** was quite difficult, presumably due to the conjugated system.[17] Accordingly, the corresponding acetate **25** and trichloroacetate **26** were prepared instead of the mesylate. From 1,10-decanediol **27**, (*Z*,*Z*)- and (*E*,*Z*)-bis(mesylate)s **28** and **29** were prepared in a similar manner. All the preparative methods and characterization for all the intermediates are detailed in the Supporting Information.

Scheme 4 shows preparation of secondary alcohol derivatives **34**, **36**−**38**, **40**, and **41**, which would be precursors of internal allenes. Typically, treatment of *n*-nonyl aldehyde **30** with $Ph_3P{=}CHC(O)n\text{-}Bu$[18] yielded unsaturated ketone **31**, which was brominated by the reaction with bromine in carbon tetrabromide followed by dehydrobromination with triethylamine to afford **32** as a single isomer, in 63% yield. Reduction and mesylation of **32** gave the desired mesylate **34**. Since the mesylate **34** is relatively unstable, crude **34** was used in the next reaction (Table 3) without further purification. Although the enone **32** would be also prepared by the reaction of **30** with bromo-ylide, the bromination−elimination protocol will be preferred for the synthesis of brominated enones in which preparation of various bromo-ylides is unnecessary. Especially, when inexpensive enones are available, this method is quite useful:

Scheme 4[a]



[a] Reagents: (a) $Ph_3P{=}CHC(O)n\text{-}Bu$; (b) Br_2; (c) Et_3N; (d) DIBAL-H; (e) MsCl, Et_3N, DMAP.

Table 1. Synthesis of Allene 42a from Bromo-mesylate 9a[a]

entry	catalyst	R_2Zn	reaction time (min)	yield[b] (%)
1	$Pd(PPh_3)_4$	Et_2Zn	60	86
2	$Pd(PPh_3)_4$	none	600	8
3	$Pd(PPh_3)_4$ (1 eq)	none	20	82
4	none	Et_2Zn	120	0
5	$Pd(PPh_3)_4$	Me_2Zn	600	9
6	$Pd(OAc)_2/4PPh_3$	Et_2Zn	60	85
7	$Pd(OAc)_2$	Et_2Zn	600	0
8	$Pd(OAc)_2/4PBu_3$	Et_2Zn	240	trace

[a] All reactions were carried out in THF at room temperature under argon using 10 mol % of catalyst and 2 equiv of R_2Zn. [b] Isolated yields.

chalcone **35** and benzylideneacetone **39** were easily converted into the corresponding esters (**36**−**38**, **40**, and **41**) in a similar manner (see the Supporting Information).[19]

Synthesis of Terminal Allenes Bearing a Protected Amino Group. We initiated our study to convert the mesylate **9a** into the allene **42a** under various reaction conditions. The results are summarized in Table 1. Treatment of the mesylate **9a** with $Pd(PPh_3)_4$ (10 mol %) and Et_2Zn (2 equiv)[20] in THF at room temperature gave the desired allene **42a** in 86% yield as the sole product (entry 1). When the mesylate **9a** was treated with $Pd(PPh_3)_4$ (10 mol %) in the absence of Et_2Zn, only 8% of **42a** was obtained, and 90% of the starting material was recovered (entry 2). In contrast, reaction of **9a** with a stoichiometric amount of $Pd(PPh_3)_4$ in the absence of Et_2Zn proceeded smoothly to give 82% yield of the allene

(13) (a) Denney, D. B.; Ross, S. T. *J. Org. Chem.* **1962**, *27*, 998. (b) For a recent synthesis of stabilized halo-ylides, see: Kayser, M. M.; Zhu, J.; Hooper, D. L. *Can. J. Chem.* **1997**, *75*, 1315.

(14) Quagliato, D. A.; Andrae, P. M.; Matelan, E. M. *J. Org. Chem.* **2000**, *65*, 5037.

(15) Garner, P.; Park, J. M. *J. Org. Chem.* **1987**, *52*, 2361.

(16) Bode, J. W.; Doyle, M. P.; Protopopova, M. N.; Zhou, Q.-L. *J. Org. Chem.* **1996**, *61*, 9146.

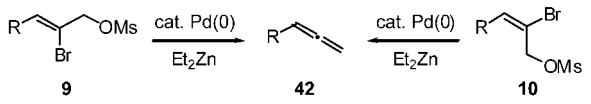
(17) When the allylic alcohol derived from **24** (precursor of **25** and **26**) was subjected to the standard mesylation conditions (MsCl, Et_3N, THF), the corresponding chloride was obtained in 35% yield. Although this chloride could be prepared in high yield by the reaction of the same alcohol with thionyl choride, the desired allene could not be obtained from this chloride by treatment with Pd(0) and Et_2Zn.

(18) Such ylides can be easily prepared from $Ph_3P{=}CHC(O)Me$ by the reaction with LDA and appropriate alkyl halides, see: Cooke, M. P., Jr. *J. Org. Chem.* **1973**, *38*, 4082.

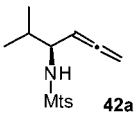
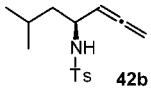
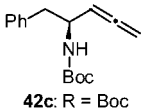
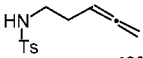
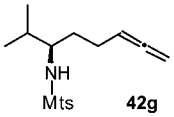
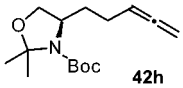
(19) Synthesis of some intermediates for **36**−**38**, **40**, and **41** has been already reported in the literature. For α-bromination of chalcone **35**, see: Blatt, A. H. *Org. Synth.* Coll. Vol. 1, John Wiley & Sons: New York, 1944; p 205. (b) Lutz, R. E.; Hinkley, D. F.; Jordan, R. H. *J. Am. Chem. Soc.* **1951**, *73*, 4647. For synthesis of (*Z*)-3-Bromo-4-phenylbut-3-en-2-ol from benzylideneacetone **39** by α-bromination and reduction, see: (c) Murphy, J. A.; Scott, K. A.; Sinclair, R. S.; Martin, C. G.; Kennedy, A. R.; Lewis, N. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2395.

(20) We used 2 equiv of Et_2Zn considering the acidity of the sulfonamide proton of **9**.

Table 2. Synthesis of Allenes Bearing a Protected Amino Group[a]



9 **42** **10**

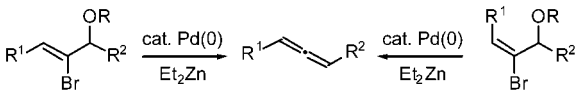
entry	mesylate (geometry)	reaction time (min)	allene	yield[b] (%)
1	**9a** (*Z*)	60	 **42a**	86
2	**10a** (*E*)	30		86
3	**9b** (*Z*)	40	 **42b**	86
4	**10b** (*E*)	40		87
5	**9c** (*Z*)	60	 **42c**: R = Boc **42d**: R = Mts **42e**: R = Mtr	82
6	**9d** (*Z*)	60		85
7	**9e** (*Z*)	60		83
8	**10c** (*E*)	60		83
9	**10d** (*E*)	60		90
10	**10e** (*E*)	20		80
11[c]	**9f** (*Z*)	30	 **42f**	69
12	**10f** (*E*)	60		66
13	**9g** (*Z*)	45	 **42g**	68
14	**9h** (*Z*)	60	 **42h**	69

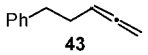
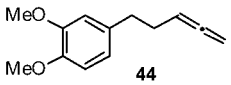
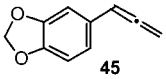
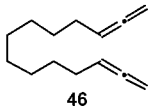
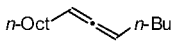
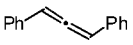
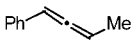
[a] Reactions were carried out in THF at room temperature under argon using $Pd(PPh_3)_4$ (10 mol %) and Et_2Zn (2 equiv), unless otherwise stated. [b] Isolated yields. [c] 4 mol % of $Pd(PPh_3)_4$ was used.

(entry 3). As we expected, when **9a** was treated with Et_2Zn in the absence of a palladium catalyst, **9a** was recovered unchanged (entry 4). Dimethylzinc was found to be ineffective for the present transformation (entry 5). Although $Pd(OAc)_2/4PPh_3$ gave a satisfactory result (entry 6), $Pd(OAc)_2$ alone or $Pd(OAc)_2-4PBu_3$ could not be used for the present transformation reaction (entries 7 and 8). From these results, use of $Pd(PPh_3)_4$ (10 mol %) and Et_2Zn (2 equiv) proved to be the optimized reaction conditions.

We next examined various substrates bearing an amino group for the palladium-catalyzed reduction. As shown in Table 2, both the (*Z*)- and (*E*)-mesylates **9a**−**e** and **10a**−**e** were converted into the corresponding α-amino allenes **42a**−**e** in good to high yields by exposure to $Pd(PPh_3)_4$ (10 mol %) and Et_2Zn (2 equiv) in THF for 20 to 60 min. It was found that neither the *N*-protecting group (Mts, Ts, Boc, or Mtr) nor the alkyl group on the carbon adjacent to the nitrogen atom (*i*-Pr, *i*-Bu, or Bn) has significant influence on the reaction. Similarly, *β*-amino allene **42f** and *γ*-amino allenes **42g** and **42h** were obtained in good yields from the corresponding mesylates. When the reaction is carried out in a relatively large scale, decreased loading of the palladium catalyst is recommended: starting from 4 g of **9f**, the allene **42f** was obtained in 69% yield using 4 mol % of $Pd(PPh_3)_4$ (entry 11). From these results, it is clear that a simple and efficient synthesis of terminal allenes bearing a protected amino group could be realized, irrespective of the (*E*)- or (*Z*)-geometry of the substrates.

Table 3. Synthesis of Allenes Bearing an Alkyl or Aryl Group[a]



entry	substrate (geometry)	R[b]	time (min)	allene	yield[b] (%)
1	**20** (*Z*)	Ms	60	 **43**	78
2	**21** (*E*)	Ms	60		62
3	**23** (*Z*)	Ms	120	 **44**	69
4[c]	**25** (*Z*)	Ac	90	 **45**	60
5	**26** (*Z*)	$COCCl_3$	30		69
6	**28** (*Z*,*Z*)	Ms	90	 **46**	77
7	**29** (*E*,*Z*)	Ms	90		74
8	**34** (*Z*)	Ms	15	 **47**	77
9[d]	**36** (*Z*)	Ac	120	 **48**	66
10	**37** (*Z*)	$COCCl_3$	30		83
11	**38** (*E*)	$COCCl_3$	15		47
12	**40** (*Z*)	$COCCl_3$	15	 **49**	53[e]
13	**41** (*E*)	$COCCl_3$	15		55[e]

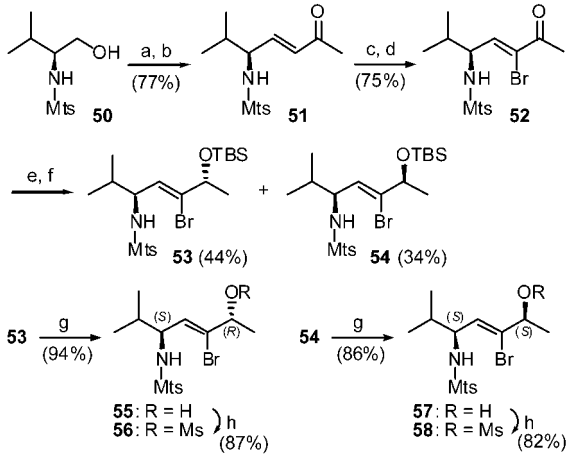
[a] All reactions were carried out in THF at room temperature under argon using 10 mol % of $Pd(PPh_3)_4$ and 2 equiv of Et_2Zn unless otherwise stated. [b] Isolated yields. [c] Reactions were conducted at 45 °C using 4 equiv of Et_2Zn. [d] Reactions were conducted at 60 °C using 5 equiv of Et_2Zn. [e] Relatively low yields of the allene **49** are due to its volatility.

Synthesis of Various Terminal and Internal Allenes. To expand the synthetic utility of the reaction, we next proceeded to the synthesis of various alkyl and aryl allenes lacking an amino group. The results are summarized in Table 3. Monoalkyl allenes **43** and **44** were synthesized in good yields from (*Z*)- or (*E*)-mesylates **20**, **21**, and **23**. When using the acetate **25**, the reaction proceeded quite slowly at room temperature, and prolonged reaction time was required. Upon heating at 45 °C, the reaction was completed within 90 min and the desired aryl allene **45** was obtained in 60% yield (entry 4). In contrast, when using the trichloroacetate **26**, the reaction was completed at room temperature within 30 min, and 69% of the aryl allene **45** was obtained (entry 5). Similarly, bis(mesylate)s **28** and **29** were converted into the bis(allene) **46** (entry 6, 7).[21]

Our allene synthesis is also applicable to the conversion of secondary alcohol derivatives into the corresponding internal allenes (entry 8−13). Thus, treatment of secondary mesylate **34** with Et_2Zn in the presence of palladium(0) yielded the corresponding internal allene

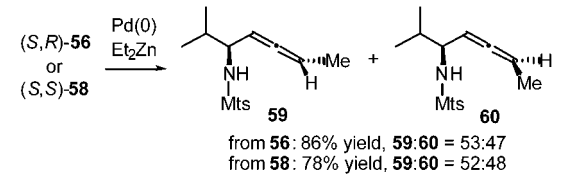
(21) For recent reports describing a useful ring-forming reaction of bis(allene)s, see: (a) Kang, S.-K.; Baik, T.-G.; Kulak, A. N.; Ha, Y.-H.; Lim, Y.; Park, J. *J. Am. Chem. Soc.* **2000**, *122*, 11529. (b) Kang, S.-K.; Ha, Y.-H.; Kim, D.-H.; Lim, Y.; Jung, J. *Chem. Commun.* **2001**, 1306.

Scheme 5[a]



[a] Reagents: (a) $(COCl)_2$, DMSO, CH_2Cl_2, then $(i\text{-}Pr)_2NEt$; (b) $Ph_3P{=}CHC(O)Me$; (c) Br_2; (d) DABCO; (e) DIBAL-H; (f) TBSCl, imidazole; (g) TBAF; (h) MsCl, Et_3N, DMAP.

Scheme 6[a]



47[22] in 77% yield (entry 8). In analogy with the synthesis of terminal aryl allene **45** (entries 4 and 5), the acetate **36** was less reactive than the trichloroacetates **37** (compare entries 9 and 10), and the reaction of the acetate **36** was completed in 2 h at 60 °C using 5 equiv of Et_2Zn, to afford 66% of diphenylallene **48**[23] (entry 9). The yields of the allene **49**[22,24] were relatively low (53 and 55%; entries 12 and 13), presumably due to the volatility of **49**. From these observations, it is obvious that our allene synthesis is useful for the synthesis of allenes bearing aminoalkyl, alkyl, and aryl group(s) including terminal, internal, and bis(allene)s. In all cases, no acetylenic compounds were detected.

Stereochemical Course of the Reaction of Secondary Mesylates with Palladium(0) and Diethylzinc. Finally, the influence of the stereochemistry of the mesyloxy group, on the axial chirality of the resulting allenes, was investigated. For ease of stereochemical assignment, we planned to synthesize the mesylates **56** and **58** (Scheme 5), which would be precursors of known allenes. The amino aldehyde, derived from *N*-protected (*S*)-valinol **50**,[25] was allowed to react with $Ph_3P{=}CHC(O)Me$ to afford enone **51**. Bromination of **51** followed by dehydrobromination gave **52**, which was reduced with DIBAL-H to give a mixture of allylic alcohols. Since separation of the diastereomers was quite difficult at this stage, this mixture was directly silylated to give silyl ethers **53** and **54**, which were readily separated by flash

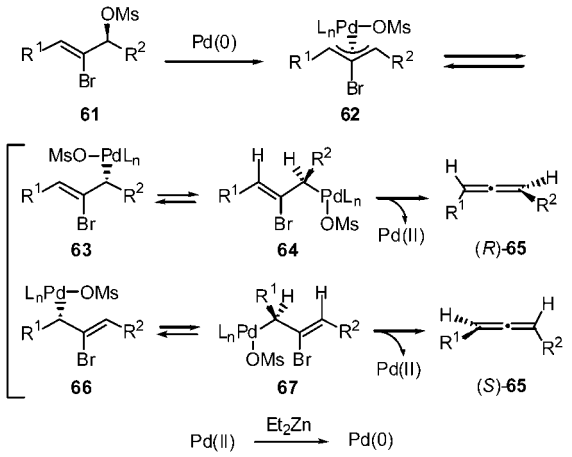


Figure 1.

chromatography. The stereochemistry of **54** was determined by degradation into a 1,2-propanediol derivative.[26] After **53** was desilylated with tetrabutylammonium fluoride, mesylation of the resulting alcohol **55** yielded the (*S*,*R*)-mesylate **56**. Similarly, **54** was converted into the (*S*,*S*)-mesylate **58**.

As shown in Scheme 6, reaction of the (*S*,*R*)-mesylate **56** with Et_2Zn in the presence of catalytic $Pd(PPh_3)_4$ afforded a mixture of known amino allenes **59** and **60**[8b] in 86% yield (**59**:**60** = 53:47). Similarly, the (*S*,*S*)-mesylate **58** also gave an almost equimolar mixture of **59** and **60** (78% yield, **59**:**60** = 52:48). From these results, it is apparent that the chirality of the substrates is not reflected to the axial chirality of the resulting allenes.

These results can be rationalized as follows (Figure 1): oxidative addition of **61** to palladium(0) will afford π-allylpalladium(II) intermediate **62** with inversion of configuration. While *syn*-1,2-elimination of palladium(II) from **64** would give (*R*)-**65**, elimination from **67** would give (*S*)-**65**. Since an almost 1:1 mixture of **59** and **60** was obtained from either **56** or **58** (Scheme 6), we speculate that both **64** and **67** are competent intermediates in the reaction. The generated palladium(II) species would be converted into palladium(0) by the action of Et_2Zn, which is well accepted in the literature.[27] Although Et_2Zn is not essential when 1 equiv of $Pd(PPh_3)_4$ was employed (entry 3, Table 1), another mechanism via transmetalation of the π-allylpalladium(II) intermediate with diethylzinc cannot be ruled out.[28]

Conclusion

In conclusion, we have established a reliable synthetic method of allenes including amino allenes by palladium-

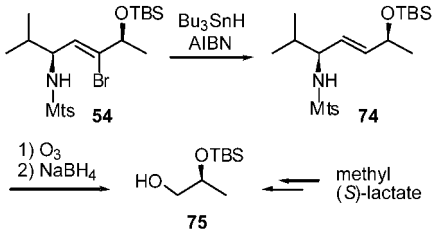
(22) Elsevier, C. J.; Vermeer, P. *J. Org. Chem.* **1989**, *54*, 3726.

(23) (a) Elsevier, C. J.; Vermeer, P. *J. Org. Chem.* **1985**, *50*, 3042. (b) Witt, O.; Mauser, H.; Friedl, T.; Wilhelm, D.; Clark, T. *J. Org. Chem.* **1998**, *63*, 959.

(24) (a) Caporusso, A. M.; Polizzi, C.; Lardicci, L. *J. Org. Chem.* **1987**, *52*, 3920. (b) Stemple, J. Z.; Peters, D. G. *J. Org. Chem.* **1989**, *54*, 5318.

(25) Ibuka, T.; Mimura, N.; Aoyama, H.; Akaji, M.; Ohno, H.; Miwa, Y.; Taga, T.; Nakai, K.; Tamamura, H.; Fujii, N.; Yamamoto, Y. *J. Org. Chem.* **1997**, *62*, 999.

(26) Reductive debromination of **54** with Bu_3SnH in the presence of AIBN gave **74**. Ozonolysis of **74** followed by reduction with $NaBH_4$ yielded (*S*)-**75**, the optical rotation of which was in good agreement with the authentic sample identically prepared from methyl (*S*)-lactate. For synthesis of (*R*)-**75** from methyl (*R*)-lactate, see: Pilli, R. A.; Victor, M. M.; de Meijere, A. *J. Org. Chem.* **2000**, *65*, 5910.



(27) For a recent review, see: Knochel, P.; Almene Perea, J. J.; Jones, P. *Tetrahedron* **1998**, *54*, 8275.

(0)-catalyzed reduction of 2-bromo-2-propen-1-ol derivatives, using diethylzinc. The reaction of the mesylates usually gives good to high yields of the corresponding allenes. For the synthesis of aryl allenes, however, trichloroacetates should be used because of difficulty in preparing the corresponding mesylates. Since both the (*Z*)- and (*E*)-substrates were efficiently converted into the corresponding allenes, it is unnecessary to separate these isomers for preparative use. It was found that the center chirality of the substrates is not reflected to the axial chirality of the resulting allenes. Utilizing this synthetic method, various allenes bearing aminoalkyl, alkyl, and aryl group(s) including terminal, internal, and bis(allene)s can be prepared from the corresponding aldehydes or enones.

Experimental Section

General Methods. Melting points are uncorrected. ^{1}H NMR spectra were recorded in $CDCl_3$. Chemical shifts are reported in parts per million downfield from internal Me_4Si (*s* = singlet, d = doublet, dd = double doublet, ddd = doublet of double doublet, t = triplet, q = quartet, m = multiplet). Optical rotations were measured in $CHCl_3$. For flash chromatography, silica gel 60 H (silica gel for thin-layer chromatography, Merck) or silica gel 60 (finer than 230 mesh, Merck) was employed.

The known compounds **9a**−**e**,[3] **50**,[25] and **75**[26] were synthesized according to the literature.

3-[*N*-(4-Methylphenylsulfonyl)amino]propan-1-ol (12). To a stirred mixture of the alcohol **11** (10.2 mL, 0.13 mol) and Et_3N (36 mL, 0.26 mol) in $CHCl_3$ (20 mL) was added a solution of TsCl (27.3 g, 0.14 mol) in $CHCl_3$ (30 mL) at 0 °C. The stirring was continued for 17 h at this temperature, followed by quenching with 5% $NaHCO_3$ (25 mL). The whole was extracted with EtOAc, and the extract was washed with 5% citric acid, water, 5% $NaHCO_3$, and brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with EtOAc gave **12** (30.5 g, 99% yield) as a colorless oil: ^{1}H NMR (270 MHz) δ 1.71 (quintet, J = 6.2 Hz, 2H), 2.00 (t, J = 4.9 Hz, 1H), 2.43 (s, 3H), 3.10 (dt, J = 6.2, 6.2 Hz, 2H), 3.73 (td, J = 6.2, 4.9 Hz, 2H), 5.14 (t, J = 6.2 Hz, 1H), 7.30−7.33 (m, 2H), 7.74−7.77 (m, 2H); MS (FAB) *m*/*z* 230 (MH^+, base peak), 212, 155, 139, 91, 74; HRMS (FAB) calcd $C_{10}H_{16}NO_3S$ (MH^+) 230.0851, found 230.0838.

General Procedure for the Synthesis of 2-Bromo-2-enoates: Synthesis of Methyl (*Z*)-2-Bromo-5-[*N*-(4-methylphenylsulfonyl)amino]pent-2-enoate (13) and Its (*E*)-Isomer (14). To a stirred solution of oxalyl chloride (3.13 mL, 32.7 mmol) in CH_2Cl_2 (15 mL) at −78 °C under argon was added dropwise a solution of DMSO (7.73 mL, 109 mmol) in CH_2Cl_2 (5 mL). After 30 min, a solution of the alcohol **12** (5.0 g, 21.8 mmol) in CH_2Cl_2 (20 mL) was added to the above stirred reagent at −78 °C, and the mixture was stirred for 50 min. Diisopropylethylamine (26.6 mL, 153 mmol) was added to the above mixture at −78 °C, and the mixture was stirred for 30 min with warming to 0 °C. The mixture was made acidic with saturated citric acid, and the whole was extracted with a mixed solvent of Et_2O−EtOAc (1:1). The extract was washed with water, 5% $NaHCO_3$, and brine, and dried over $MgSO_4$. Concentration under reduced pressure gave a crude aldehyde, which was dissolved in $CHCl_3$ (15 mL). A solution of $Ph_3P{=}C(Br)CO_2Me$ (9.9 g, 24.0 mmol) in $CHCl_3$ (15 mL) was added to the above stirred solution, and the mixture was stirred for 19 h at 0 °C. Concentration under reduced pressure gave a residual oil, which was purified by flash chromatography over silica gel with *n*-hexane−EtOAc (4:1) to give, in order of elution, the (*E*)-enoate **14** (777 mg, 10% yield) and (*Z*)-enoate **13** (3.96 g, 50% yield).

Compound **13**: colorless crystals; mp 81−84 °C (*n*-hexane−$CHCl_3$ = 1:3); ^{1}H NMR (270 MHz) δ 2.44 (s, 3H), 2.52 (dt, J = 7.0, 6.5 Hz, 2H), 3.14 (dt, J = 6.5, 6.5 Hz, 2H), 3.82 (s, 3H), 4.63 (br s, 1H), 7.22 (t, J = 7.0 Hz, 1H), 7.30−7.33 (m, 2H), 7.73−7.76 (m, 2H). Anal. Calcd for $C_{13}H_{16}BrNO_4S$: C, 43.11; H, 4.45; N, 3.87. Found: C, 42.93; H, 4.45; N, 3.60.

Compound **14**: colorless oil: ^{1}H NMR (270 MHz) δ 2.43 (s, 3H), 2.65 (dt, J = 7.8, 6.2 Hz, 2H), 3.09 (dt, J = 6.2, 6.2 Hz, 2H), 3.81 (s, 3H), 4.94 (m, 1H), 6.56 (t, J = 7.8 Hz, 1H), 7.30−7.33 (m, 2H), 7.72−7.76 (m, 2H); MS (FAB) *m*/*z* 364 (MH^+, ^{81}Br), 362 (MH^+, ^{79}Br), 242, 208, 155 (base peak), 139, 91; HRMS (FAB) calcd $C_{13}H_{17}BrNO_4S$ (MH^+, ^{79}Br) 362.0062, found 362.0058.

General Procedure for the Synthesis of Allylic Alcohols: Synthesis of (*Z*)-2-Bromo-5-[*N*-(4-methylphenylsulfonyl)amino]pent-2-en-1-ol (15). To a stirred solution of the ester **13** (2.5 g, 6.91 mmol) in a mixed solvent of $CHCl_3$ (20 mL) and toluene (5 mL) under argon was added dropwise DIBAL-H (1.0 M solution in toluene; 24.2 mL, 24.2 mmol) at −78 °C, and the mixture was stirred for 2 h at this temperature. The mixture was quenched with a saturated NH_4Cl solution, and the mixture was made acidic with saturated citric acid. The whole was extracted with EtOAc, and the extract was washed with water, 5% $NaHCO_3$, and water and dried over $MgSO_4$. Usual workup followed by flash chromatography over silica gel with *n*-hexane−EtOAc (2:1) gave **15** (2.19 g, 95% yield) as a colorless oil: ^{1}H NMR (270 MHz) δ 2.38 (dt, J = 7.0, 6.5 Hz, 2H), 2.43 (s, 3H), 2.73 (m, 1H), 3.05 (dt, J = 6.5, 6.5 Hz, 2H), 4.16−4.23 (m, 2H), 5.17 (m, 1H), 6.00 (t, J = 7.0 Hz, 1H), 7.30−7.33 (m, 2H), 7.74−7.77 (m, 2H); MS (FAB) *m*/*z* 336 (MH^+, ^{81}Br), 334 (MH^+, ^{79}Br), 184 (base peak), 155, 139, 91; HRMS (FAB) calcd $C_{12}H_{17}BrNO_3S$ (MH^+, ^{79}Br) 334.0113, found 334.0117.

General Procedure for the Synthesis of Allylic Mesylates: Synthesis of (*Z*)-2-Bromo-5-[*N*-(4-methylphenylsulfonyl)amino]pent-2-en-1-yl Methylsulfonate (9f). To a stirred mixture of the alcohol **15** (1.0 g, 2.99 mmol) and Et_3N (2.07 mL, 15.0 mmol) in THF (10 mL) was added MsCl (0.81 mL, 10.5 mmol) at −78 °C. The stirring was continued for 2 h with warming to 0 °C, followed by quenching with 5% $NaHCO_3$ (3 mL). The whole was extracted with Et_2O−EtOAc (1:1), and the extract was washed with 5% citric acid, water, 5% $NaHCO_3$, and brine and dried over $MgSO_4$. Usual workup followed by flash chromatography over silica gel with *n*-hexane−EtOAc (1:1) gave **9f** (1.23 g, 99% yield) as a colorless oil: ^{1}H NMR (270 MHz) δ 2.42 (dt, J = 7.0, 6.8 Hz, 2H), 2.44 (s, 3H), 3.08 (dt, J = 7.0, 6.8 Hz, 2H), 3.09 (s, 3H), 4.67 (m, 1H), 4.81 (s, 2H), 6.16 (t, J = 7.0 Hz, 1H), 7.32 (m, 2H), 7.74 (m, 2H); MS (FAB) *m*/*z* 414 (MH^+, ^{81}Br), 412 (MH^+, ^{79}Br), 316, 184 (base peak), 155, 139, 91; HRMS (FAB) calcd $C_{13}H_{19}BrNO_5S_2$ (MH^+, ^{79}Br) 411.9888, found 411.9871.

General Procedure for the Synthesis of Allylic Acetates: Synthesis of (*Z*)-3-(1,3-Benzodioxol-5-yl)-2-bromoprop-2-en-1-yl Acetate (25). To a stirred mixture of (2*Z*)-3-(1,3-benzodioxol-5-yl)-2-bromoprop-2-en-1-ol (compound **S30** in the Supporting Information; 100 mg, 0.389 mmol) and pyridine (0.31 mL, 3.89 mmol) in THF (3 mL) was added acetic anhydride (0.18 mL, 1.95 mmol) at −78 °C. Then, 4-(dimethylamino)pyridine (4.8 mg, 0.039 mmol) was added at 0 °C, and the mixture was stirred at this temperature for 1.5 h. The mixture was quenched with saturated $NaHCO_3$, and the whole was extracted with Et_2O. The extract was washed with water, 1 N HCl, water, and brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with *n*-hexane−EtOAc (5:2) gave **25** (114 mg, 98% yield) as a colorless oil: IR (KBr) cm^{-1}: 1740, 1221; ^{1}H NMR (300 MHz) δ 2.15 (s, 3H), 4.88 (s, 2H), 5.99 (s, 2H), 6.80 (d, J = 8.1 Hz, 1H), 6.96 (s, 1H), 7.05 (dd, J = 8.1, 1.5 Hz, 1H), 7.33 (d, J = 1.5 Hz, 1H); ^{13}C NMR (75 MHz) δ 20.9, 70.2, 101.3, 108.1, 108.7, 117.2, 124.1, 128.4, 131.0, 147.4, 147.7, 170.3; MS (FAB) *m*/*z* (%) 323 (MNa^+, ^{81}Br, 4), 321 (MNa^+, ^{79}Br, 3), 154 (100); HRMS (FAB) calcd $C_{12}H_{11}BrNaO_4$ (MNa^+, ^{79}Br): 320.9738. Found 320.9735.

General Procedure for the Synthesis of Allylic Trichloroacetates: Synthesis of (2*Z*)-3-(1,3-Benzodioxol-5-yl)-2-

(28) For recent examples of such transmetalation, see: (a) Tamaru, Y.; Tanaka, A.; Yasui, K.; Goto, S.; Tanaka, S. *Angew. Chem., Int. Ed.* **1995**, *34*, 787. (b) Ollivier, J.; Girard, N.; Salaün, J. *Synlett*, **1999**, 1539. (c) Sakamoto, T.; Takahashi, K.; Yamazaki, T.; Kitazume, T. *J. Org. Chem*. **1999**, *64*, 9467.

bromoprop-2-en-1-yl 2,2,2-Trichloroacetate (26). To a stirred mixture of (2*Z*)-3-(1,3-benzodioxol-5-yl)-2-bromoprop-2-en-1-ol (compound **S30** in the Supporting Information; 70 mg, 0.272 mmol) and Et_3N (0.38 mL, 2.72 mmol) in THF (2 mL) was added trichloroacetyl chloride (0.15 mL, 1.36 mmol) at 0 °C, and the mixture was stirred at this temperature for 30 min. The mixture was quenched with saturated $NaHCO_3$, and the whole was extracted with Et_2O. The extract was washed with water, saturated NH_4Cl, water, and brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with *n*-hexane−EtOAc (10:1) gave **26** (82 mg, 75% yield) as a colorless oil. This compound is relatively unstable: ^{1}H NMR (300 MHz) δ 5.14 (s, 2H), 6.00 (s, 2H), 6.82 (s, J = 7.8 Hz, 1H), 7.07 (s, 1H), 7.09 (dd, J = 7.8, 1.5 Hz, 1H), 7.38 (d, J = 1.5 Hz, 1H).

(*E*)-Pentadec-6-en-5-one (31). To a stirred solution of nonyl aldehyde **30** (4.27 g, 30.0 mmol) in $CHCl_3$ (50 mL) was added $Ph_3P{=}CHC(O)n$-Bu (16.2 g, 45.0 mmol) at 0 °C. After the mixture was stirred for 7 h, the mixture was concentrated under reduced pressure to leave a residual oil, which was purified by column chromatography over silica gel with *n*-hexane−EtOAc (30:1) to give **31** (4.13 g, 61% yield) as a colorless oil: IR (KBr) cm^{-1}: 1678; ^{1}H NMR (300 MHz) δ 0.86−0.94 (m, 6H), 1.28−1.37 (m, 12H), 1.40−1.65 (m, 4H), 2.17−2.22 (m, 2H), 2.53 (t, J = 7.5 Hz, 2H), 6.09 (d, J = 15.6 Hz, 1H), 6.83 (dt, J = 15.6, 6.9 Hz, 1H); ^{13}C NMR (75 MHz) δ 13.7, 13.9, 22.3, 22.5, 26.3, 28.0, 29.1 (2C), 29.2, 31.7, 32.3, 39.7, 130.2, 147.1, 200.7; MS (FAB) *m*/*z* (%) 225 (MH$^+$, ^{79}Br, 100); HRMS (FAB) calcd $C_{15}H_{29}O$ (MH$^+$, ^{79}Br) 225.2218; found 225.2220.

General Procedure for the Bromination of Enones: Synthesis of (*Z*)-6-Bromopentadec-6-en-5-one (32). To a stirred solution of the enone **31** (100 mg, 0.45 mmol) in CH_2Cl_2 (2 mL) was added dropwise bromine (40 μL, 0.81 mmol) at −78 °C. After the mixture was stirred for 30 min at 0 °C, 1-hexene (0.07 mL, 0.54 mmol) was added to the mixture, and the mixture was stirred for 30 min at room temperature. The mixture was cooled to 0 °C, and Et_3N (0.23 mL, 1.65 mmol) in CH_2Cl_2 was added dropwise to the mixture with stirring. After the mixture was stirred for 90 min at 0 °C, saturated NH_4Cl was added. The whole was extracted with Et_2O, and the extract was washed with saturated $Na_2S_2O_3$, saturated NH_4Cl, and brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with *n*-hexane−EtOAc (40:1) gave **32** (85 mg, 63% yield) as a colorless oil: IR (KBr) cm^{-1}: 1691; ^{1}H NMR (300 MHz) δ 0.86−0.98 (m, 6H), 1.28−1.43 (m, 12H), 1.52−1.67 (m, 4H), 2.39 (td, J = 7.5, 7.2 Hz, 2H), 2.77 (t, J = 7.5 Hz, 2H), 7.14 (t, J = 7.2 Hz, 1H); ^{13}C NMR (75 MHz) δ 13.8, 14.1, 22.3, 22.6, 26.7, 27.6, 29.1, 29.3 (2C), 31.8, 32.5, 38.4, 127.3, 144.8, 194.4; MS (FAB) *m*/*z* (%) 305 (MH$^+$, ^{81}Br, 50), 303 (MH$^+$, ^{79}Br, 60), 225 (100); HRMS (FAB) calcd $C_{15}H_{28}BrO$ 303.1324; found 303.1319.

(*Z*)-6-Bromopentadec-6-en-5-ol (33). By a procedure identical with that described for the synthesis of **15**, the enone **32** (850 mg, 2.8 mmol) was converted into the alcohol **33** (476 mg, 56% yield): colorless oil; IR (KBr) cm^{-1}: 3354; ^{1}H NMR (300 MHz) δ 0.86−0.94 (m, 6H), 1.20−1.43 (m, 16H), 1.61−1.70 (m, 2H), 1.92 (d, J = 6.3 Hz, 1H), 2.20 (td, J = 7.2, 6.9 Hz, 2H), 4.04 (td, J = 6.3, 6.3 Hz, 1H), 5.95 (t, J = 6.9 Hz, 1H); ^{13}C NMR (75 MHz) δ 14.0, 14.1, 22.4, 22.6, 27.5, 28.3, 29.2 (2C), 29.4, 30.7, 31.8, 35.3, 76.7, 130.5, 131.4; MS (FAB) *m*/*z* (%) 305 (MH$^+$, ^{81}Br, 6), 303 (MH$^+$, ^{79}Br, 6), 137 (100); HRMS (FAB) calcd $C_{15}H_{29}BrNaO$ (MNa$^+$, ^{79}Br) 327.1299; found 327.1304.

General Procedure for the Synthesis of Allenes from Activated Allylic Alcohols by a Et_2Zn/Pd(0) System. Synthesis of (4*S*)-5-Methyl-4-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hexa-1,2-diene (42a) from the Mesylate (9a) (Table 2, entry 1). To a stirred solution of the mesylate **9a** (70.3 mg, 0.15 mmol) and $Pd(PPh_3)_4$ (17.3 mg, 10 mol %, 0.015 mmol) in dry THF (1 mL) under argon was added Et_2Zn (1.1 M in toluene; 0.273 mL, 0.3 mmol) at room temperature. The mixture was stirred for 1 h at this temperature followed by quenching with saturated aqueous NH_4Cl (1 mL). The whole was extracted with Et_2O, and the extract was washed with water and dried over $MgSO_4$. Usual workup followed by flash chromatography over silica gel with *n*-hexane−EtOAc (10:1) gave **42a** (38 mg, 86% yield): colorless crystals; mp 61 °C (*n*-hexane); $[\alpha]^{30}_D$ −3.44 (*c* 0.524, $CHCl_3$); ^{1}H NMR (270 MHz) δ 0.84 (d, J = 6.8 Hz, 3H), 0.88 (d, J = 7.0 Hz, 3H), 1.75−1.87 (m, 1H), 2.30 (s, 3H), 2.63 (s, 6H), 3.56−3.66 (m, 1H), 4.57 (d, J = 8.6 Hz, 1H), 4.63 (dd, J = 6.8, 2.7 Hz, 2H), 4.93 (dt, J = 6.8, 6.8 Hz, 1H), 6.94 (s, 2H); ^{13}C NMR (67.8 MHz) δ 18.2, 18.3, 21.1, 23.4 (2C), 33.4, 57.6, 78.1, 90.1, 132.1 (2C), 135.0, 139.1 (2C), 142.2, 207.4. Anal. Calcd for $C_{16}H_{23}NO_2S$: C, 65.49; H, 7.90; N, 4.77. Found: C, 65.20; H, 7.91; N, 4.67.

(4*S*)-6-Methyl-4-[*N*-(4-methylphenylsulfonyl)amino]-hepta-1,2-diene (42b) (Table 2, entry 3). The mesylate **9b** (45.4 mg, 0.1 mmol) was converted into **42b** (24 mg, 86% yield) by treatment with Et_2Zn−Pd(0) at room temperature for 40 min: colorless oil; $[\alpha]^{27}_D$ −42.5 (*c* 0.221, $CHCl_3$); ^{1}H NMR (270 MHz) δ 0.84 (d, J = 6.2 Hz, 3H), 0.86 (d, J = 6.2 Hz, 3H), 1.25−1.45 (m, 2H), 1.64−1.79 (m, 1H), 2.43 (s, 3H), 3.79−3.92 (m, 1H), 4.46 (d, J = 8.9 Hz, 1H), 4.60 (ddd, J = 10.8, 6.2, 2.7 Hz, 1H), 4.67 (ddd, J = 10.8, 7.0, 2.7 Hz, 1H), 4.93 (ddd, J = 7.0, 6.8, 6.2 Hz, 1H), 7.27−7.30 (m, 2H), 7.73−7.76 (m, 2H); ^{13}C NMR (67.8 MHz) δ 21.7, 22.2, 22.7, 24.6, 45.6, 50.9, 78.3, 92.7, 127.5 (2C), 129.7 (2C), 138.3, 143.4, 207.0; MS (FAB) *m*/*z* 280 (MH$^+$), 240 (base peak), 222, 174, 155, 109, 91; HRMS (FAB) calcd $C_{15}H_{22}NO_2S$ (MH$^+$) 280.1371; found: 280.1377.

(4*S*)-4-[*N*-(*tert*-Butoxycarbonyl)amino]-5-phenylpenta-1,2-diene (42c) (Table 2, entry 5). The mesylate **9c** (65.1 mg, 0.15 mmol) was converted into **42c** (32 mg, 82% yield) by treatment with Et_2Zn−Pd(0) at room temperature for 1 h: colorless needles; mp 48 °C (*n*-hexane); $[\alpha]^{26}_D$ +20.0 (*c* 0.274, $CHCl_3$); ^{1}H NMR (270 MHz) δ 1.42 (s, 9H), 2.85 (dd, J = 13.5, 7.0 Hz, 1H), 2.88−2.97 (m, 1H), 4.42 (br s, 1H), 4.57 (br s, 1H), 4.84 (dd, J = 6.5, 3.2 Hz, 1H), 5.21 (dt, J = 6.5, 6.5 Hz, 1H), 7.20−7.33 (m, 5H); ^{13}C NMR (75 MHz) δ 28.3 (3C), 41.6, 49.5, 78.5, 79.4, 92.3, 126.4, 128.3 (2C), 129.6 (2C), 137.5, 155.1, 206.8. Anal. Calcd for $C_{16}H_{21}NO_2$: C, 74.10; H, 8.16; N, 5.40. Found: C, 74.02; H, 8.12; N, 5.34.

(4*S*)-5-Phenyl-4-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]penta-1,2-diene (42d) (Table 2, entry 7). The mesylate **9d** (103 mg, 0.2 mmol) was converted into **42d** (58 mg, 85% yield) by treatment with Et_2Zn−Pd(0) at room temperature for 1 h: colorless crystals; mp 51 °C (*n*-hexane−Et_2O = 3:1); $[\alpha]^{24}_D$ −15.2 (*c* 0.316, $CHCl_3$); ^{1}H NMR (270 MHz) δ 2.28 (s, 3H), 2.52 (s, 6H), 2.76−2.91 (m, 2H), 3.91−4.02 (m, 1H), 4.56−4.68 (m, 1H), 4.70 (dd, J = 6.8, 3.0 Hz, 2H), 5.09 (dt, J = 6.8, 6.8 Hz, 1H), 6.87 (s, 2H), 7.03−7.08 (m, 2H), 7.17−7.24 (m, 3H); ^{13}C NMR (67.8 MHz) δ 21.1, 23.2 (2C), 42.4, 53.1, 78.7, 92.1, 126.9, 128.7 (2C), 129.6 (2C), 132.1 (2C), 134.2, 136.7, 139.2 (2C), 142.2, 207.0. Anal. Calcd for $C_{20}H_{23}NO_2S$: C, 70.35; H, 6.79; N, 4.10. Found: C, 70.23; H, 6.80; N, 3.95.

(4*S*)-5-Phenyl-4-[*N*-(4-methoxy-2,3,6-trimethylphenylsulfonyl)amino]penta-1,2-diene (42e) (Table 2, entry 9). The mesylate **9e** (109 mg, 0.2 mmol) was converted into **42e** (62 mg, 83% yield) by treatment with Et_2Zn−Pd(0) at room temperature for 1 h: colorless oil; $[\alpha]^{24}_D$ −25.1 (*c* 0.693, $CHCl_3$); ^{1}H NMR (270 MHz) δ 2.07 (s, 3H), 2.33 (s, 3H), 2.63 (s, 3H), 2.81 (dd, J = 13.8, 7.3 Hz, 1H), 2.86 (dd, J = 13.8, 6.5 Hz,1H), 3.84 (s, 3H), 3.88−3.99 (m, 1H), 4.57 (d, J = 7.0 Hz, 1H), 4.73 (dd, J = 6.8, 3.0 Hz, 2H), 5.14 (dt, J = 6.8, 6.8 Hz, 1H), 6.53 (s, 1H), 7.00−7.07 (m, 2H), 7.16−7.22 (m, 3H); ^{13}C NMR (67.8 MHz) δ 12.2, 18.0, 24.7, 42.3, 53.1, 55.7, 78.7, 92.4, 112.1, 125.3, 126.9, 128.6 (2C), 129.2, 129.6 (2C), 136.8, 139.0, 139.1, 159.4, 207.1; MS (FAB) *m*/*z* 372 (MH$^+$), 280, 230 (base peak), 213, 149, 143, 119, 91; HRMS (FAB) calcd $C_{21}H_{26}NO_3S$ (MH$^+$) 372.1633; found 372.1642.

5-[*N*-(4-Methylphenylsulfonyl)amino]penta-1,2-diene (42f) (Table 2, entry 11). The mesylate **9f** (4.0 g, 9.71 mmol) was converted into the allene **42f** (1.58 g, 69% yield) by treatment with $Pd(PPh_3)_4$ (448 mg, 0.388 mmol; 4 mol %) and Et_2Zn (1.0 M solution in hexane; 17.6 mL, 17.6 mmol) in THF (40 mL) at room temperature for 30 min: colorless oil; ^{1}H NMR (270 MHz) δ 2.15 (dtt, J = 6.8, 6.8, 3.0 Hz, 2H), 2.43 (s, 3H), 3.05 (dt, J = 6.8, 6.8 Hz, 2H), 4.58−4.65 (m, 1H), 4.69 (dt, J = 6.8, 3.0 Hz, 2H), 4.99 (tt, J = 6.8, 6.8 Hz, 1H), 7.31 (m, 2H),

7.75 (m, 2H); ^{13}C NMR (67.8 MHz) δ 21.7, 28.4, 42.4, 70.1, 86.6, 127.2 (2C), 129.9 (2C), 137.1, 143.6, 208.9; MS (FAB) *m*/*z* 238 (MH^+, base peak), 237, 184, 155, 139, 86, 83, 82; HRMS (FAB) calcd $C_{12}H_{16}NO_2S$ (MH^+) 238.0902; found 238.0908.

(6*S*)-7-Methyl-6-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]octa-1,2-diene (42g) (Table 2, entry 13). The mesylate **9g** (25 mg, 0.05 mmol) was converted into **42g** (11 mg, 68% yield) and 2-(1-bromovinyl)-5-isopropyl-*N*-(2,4,6-trimethylphenylsulfonyl)pyrrolidine (3 mg, 15% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 45 min: colorless crystals; mp 53 °C (*n*-hexane); $[\alpha]^{24}_D$ −2.66 (*c* 0.601, $CHCl_3$); ^{1}H NMR (270 MHz) δ 0.72 (d, J = 6.8 Hz, 3H), 0.79 (d, J = 6.8 Hz, 3H), 1.30−1.57 (m, 2H), 1.61−2.02 (m, 3H), 2.30 (s, 3H), 2.64 (s, 6H), 3.14 (ddt, J = 8.9, 8.9, 4.3 Hz, 1H), 4.35 (d, J = 8.9 Hz, 1H), 4.64 (dt, J = 6.5, 3.2 Hz, 2H), 4.94 (tt, J = 6.5, 6.5 Hz, 1H), 6.94 (s, 2H); ^{13}C NMR (67.8 MHz) δ 17.8, 18.4, 21.1, 23.4 (2C), 24.4, 31.2, 31.5, 58.6, 75.6, 89.4, 132.1 (2C), 135.5, 138.7 (2C), 142.0, 208.5; MS (CI) *m*/*z* 322 (MH^+, base peak), 254, 139, 123; HRMS (CI) calcd $C_{18}H_{28}NO_2S$ (MH^+) 322.1840; found 322.1831. **(5*S*)-2-(1-Bromovinyl)-5-isopropyl-*N*-(2,4,6-trimethylphenylsulfonyl)pyrrolidine:** colorless oil; ^{1}H NMR (270 MHz) δ 0.69 (d, J = 6.8 Hz, 3H), 0.82 (d, J = 6.8 Hz, 3H), 1.95 (m, 4H), 2.30 (s, 3H), 2.67 (s, 6H), 3.65 (td, J = 6.5, 3.8 Hz, 1H), 4.43 (t, J = 7.6 Hz, 1H), 5.35 (d, J = 1.4 Hz, 1H), 5.76 (d, J = 1.4 Hz, 1H), 6.93 (s, 2H); MS (CI) *m*/*z* 402 (MH^+, ^{81}Br; base peak), 400 (MH^+, ^{79}Br), 356, 322, 321, 218, 183; HRMS (CI) calcd $C_{18}H_{27}BrNO_2S$ (MH^+, ^{79}Br) 400.0946; found 400.0950.

5-[(4*R*)-*N*-(*tert*-Butoxycarbonyl)-2,2-dimethyl-1,3-oxazolidin-4-yl]penta-1,2-diene (42h) (Table 2, entry 14). The mesylate **9h** (40 mg, 0.090 mmol) was converted into **42h** (16.8 mg, 69% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 1 h: colorless oil; $[\alpha]^{21}_D$ −19.7 (*c* 0.811, $CHCl_3$); ^{1}H NMR (270 MHz) δ 1.48 (m, 9H), 1.50−2.05 (m, 10H), 3.73−3.96 (m, 3H), 4.68 (m, 2H), 5.07−5.15 (m, 1H); ^{13}C NMR (75 MHz, 323 K) δ 25.4 (2C), 27.4, 28.8 (3C), 33.2, 57.4, 67.3, 75.2, 80.0, 89.5, 93.8, 152.3, 209.0; MS (FAB) *m*/*z* 268 (MH^+), 252, 212, 168, 154, 57 (base peak), 55; HRMS (FAB) calcd $C_{15}H_{26}NO_3$ (MH^+) 268.1913; found 268.1936.

5-Phenylpenta-1,2-diene (43) (Table 3, entry 1). The mesylate **20** (160 mg, 0.50 mmol) was converted into **43** (56 mg, 78% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 1 h: colorless oil; ^{1}H NMR (270 MHz) δ 2.26−2.37 (m, 2H), 2.73 (t, J = 8.1 Hz, 2H), 4.67 (dt, J = 6.8, 3.5 Hz, 2H), 5.15 (tt, J = 13.5, 6.8 Hz, 1H), 7.16−7.31 (m, 5H); ^{13}C NMR (67.8 MHz) δ 30.2, 35.6, 75.4, 89.6, 126.1, 128.5 (2C), 128.7 (2C), 142.0, 208.8; MS (CI) *m*/*z* 145 (MH^+, base peak), 91, 61; HRMS (CI) calcd $C_{11}H_{13}$(MH^+) 145.1017; found 145.1019.

5-(3,4-Dimethoxyphenyl)penta-1,2-diene (44) (Table 3, entry 3). The mesylate **23** (200 mg, 0.53 mmol) was converted into **44** (74 mg, 69% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 2 h: colorless oil; ^{1}H NMR (270 MHz) δ 2.24−2.35 (m, 2H), 2.68 (t, J = 8.4 Hz, 2H), 3.86 (s, 3H), 3.87 (s, 3H), 4.68 (dt, J = 6.5, 3.2 Hz, 2H), 5.15 (tt, J = 6.5, 6.5 Hz, 1H), 6.72−6.81 (m, 3H); ^{13}C NMR (67.8 MHz) δ 30.4, 35.2, 56.0, 56.1, 75.3, 89.6, 111.3, 112.0, 120.4, 134.6, 147.4, 148.9, 208.7; MS (CI) *m*/*z* 205 (MH^+, base peak), 204, 151; HRMS (CI) calcd $C_{13}H_{17}O_2$ (MH^+) 205.1228; found 205.1233.

(2*Z*)-3-(1,3-Benzodioxol-5-yl)propa-1,2-diene (45) (Table 3, entry 5). The trichloroacetate **26** (80 mg, 0.199 mmol) was converted into **45** (22 mg, 69%) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 30 min: colorless oil; IR (KBr) cm^{-1}: 1942, 1240; ^{1}H NMR (300 MHz) δ 5.12 (d, J = 6.9 Hz, 2H), 5.93 (s, 2H), 6.09 (t, J = 6.9 Hz, 1H), 6.70−6.76 (m, 2H), 6.83 (s, 1H); ^{13}C NMR (75 MHz) δ 79.0, 93.8, 101.0, 106.6, 108.3, 120.3, 127.9, 146.6, 148.0, 209.3; MS (EI) *m*/*z* (%) 160 (M^+, 100); HRMS (EI) calcd $C_{10}H_8O_2$ (M^+) 160.0524; found 160.0586.

Tetradeca-1,2,12,13-tetraene (46) (Table 3, entry 6). The mesylate **28** (200 mg, 0.37 mmol) was converted into **46** (54 mg, 77% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 1.5 h: colorless oil; ^{1}H NMR (270 MHz) δ 1.28−1.47 (m, 12H), 1.94−2.04 (m, 4H), 4.65 (dt, J = 6.8, 3.0 Hz, 4H), 5.09 (tt, J = 6.8, 6.8 Hz, 2H); ^{13}C NMR (67.8 MHz) δ 28.5 (2C), 29.27 (2C), 29.32 (2C), 29.6 (2C), 74.7 (2C), 90.3 (2C), 208.7 (2C); MS (CI) *m*/*z* 191 (MH^+), 189, 135, 121, 109, 95 (base peak), 81; HRMS (CI) calcd $C_{14}H_{23}$ (MH^+) 191.1799; found: 191.1805.

Pentadeca-5,6-diene (47) (Table 3, entry 8). To a stirred mixture of the alcohol **33** (50.0 mg, 0.164 mmol) and Et_3N (0.11 mL, 0.820 mmol) in THF (3 mL) were added MsCl (0.025 mL, 0.328 mmol) and 4-(dimethylamino)pyridine (20 mg, 0.164 mmol) at −78 °C. The stirring was continued for 12 h at 40 °C, followed by quenching with saturated $NaHCO_3$. The whole was extracted with Et_2O, and the extract was washed with water, 1 N HCl, water, and brine and dried over $MgSO_4$. Concentration under reduced pressure gave a crude mesylate **34** (51.5 mg, 82% yield), which was used without further purification due to its instability toward silica gel. According to the general procedure, the crude mesylate **34** (50 mg, 0.130 mmol) was converted into **47** (26.1 mg, 77% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 15 min: colorless oil; ^{1}H NMR (300 MHz) δ 0.88 (t, J = 7.2 Hz, 3H), 0.90 (t, J = 7.2 Hz, 3H), 1.25−1.46 (m, 16H), 1.93−2.02 (m, 4H), 5.03−5.09 (m, 2H); ^{13}C NMR (75 MHz) δ 13.9, 14.1, 22.2, 22.7, 28.7, 29.0, 29.1, 29.2, 29.3, 29.4, 31.4, 31.9, 90.8, 90.9, 203.8; all the data for **47** were in good agreement with the literature.[22]

1,3-Diphenylpropa-1,2-diene (48) (Table 3, entry 10). The trichloroacetate **37** (26 mg, 0.058 mmol) was converted into **48** (9.1 mg, 83% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 30 min: colorless oil; ^{1}H NMR (300 MHz) δ 6.50 (s, 2H), 7.10−7.28 (m, 10H); ^{13}C NMR (75 MHz) δ 98.4 (2C), 127.0 (4C), 127.3 (2C), 128.7 (4C), 133.6 (2C), 207.8: this compound appeared to be unstable when exposed to air and light; all the data for **48** were in good agreement with the literature.[23]

4-Phenylbuta-2,3-diene (49) (Table 3, entry 12). The trichloroacetate **40** (100 mg, 0.268 mmol) was converted into **48** (18 mg, 53% yield) by treatment with $Et_2Zn-Pd(0)$ at room temperature for 15 min: colorless oil; ^{1}H NMR (300 MHz) δ 1.78 (dd, J = 6.9, 3.0 Hz, 3H), 5.53 (qd, J = 6.9, 6.6 Hz, 1H), 6.09 (dq, J = 6.6, 3.0 Hz, 1H), 7.14−7.32 (m, 5H); ^{13}C NMR (75 MHz) δ 14.1, 89.6, 93.9, 126.6 (3C), 128.5 (2C), 135.0, 206.1; all the data for **49** were in good agreement with the literature.[22,24]

(5*S*,3*E*)-6-Methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)-amino]hept-3-en-2-one (51). To a stirred solution of oxalyl chloride (3.74 mL, 39.0 mmol) in CH_2Cl_2 (45 mL) at −78 °C under argon was added dropwise a solution of DMSO (10.6 mL, 150 mmol) in CH_2Cl_2 (15 mL). After 30 min, a solution of the alcohol **50** (8.55 g, 30.0 mmol) in CH_2Cl_2 (15 mL) was added to the above stirred reagent at −78 °C, and the mixture was stirred for 1 h. Diisopropylethylamine (36.6 mL, 210 mmol) was added to the above mixture at −78 °C, and the mixture was stirred for 30 min with warming to 0 °C. The mixture was made acidic with 1 N HCl, and the whole was extracted with Et_2O. The extract was washed with water and brine, and dried over $MgSO_4$. Concentration under reduced pressure gave a crude aldehyde. To a stirred solution of the aldehyde in $CHCl_3$ (50 mL) was added $Ph_3P{=}CHC(O)Me$ (12.4 g, 39.0 mmol), and the mixture was stirred at 0 °C overnight. Concentration under reduced pressure gave a residual oil, which was purified by column chromatography over silica gel with *n*-hexane−EtOAc (11:4) to give **51** (7.43 g, 77% yield): colorless crystals; mp 91 °C (*n*-hexane−EtOAc); $[\alpha]^{28}_D$ −36.4 (*c* 1.03, $CHCl_3$); IR (KBr) cm^{-1}: 3284, 1678, 1325; ^{1}H NMR (270 MHz) δ 0.84 (d, J = 7.0 Hz, 3H), 0.92 (d, J = 7.0 Hz, 3H), 1.72−1.88 (m, 1H), 2.02 (s, 3H), 2.27 (s, 3H), 2.62 (s, 6H), 3.62−3.70 (m, 1H), 4.93 (d, J = 7.8 Hz, 1H), 5.83 (dd, J = 16.2, 1.1 Hz, 1H), 6.31 (dd, J = 16.2, 7.2 Hz, 1H), 6.92 (s, 2H); ^{13}C NMR (67.5 MHz) δ 18.4, 18.5, 20.9, 23.1 (2C), 27.2, 32.7, 60.5, 131.4, 131.8 (2C), 134.4, 138.7 (2C), 142.2, 143.4, 197.1. Anal. Calcd for $C_{17}H_{25}NO_3S$: C, 63.13; H, 7.79; N, 4.33. Found: C, 62.97; H, 7.66; N, 4.28.

(5*S*,3*Z*)-3-Bromo-6-methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-3-en-2-one (52). By a procedure identical with that described for the synthesis of **32** except that DABCO (3.36 g, 221 mmol) was used instead of Et_3N for dehydrobromination, **51** (5.50 g, 17.0 mmol) was converted into the alcohol **52** (3.28 g, 75% yield): colorless crystals; mp 158

°C (*n*-hexane−$CHCl_3$); $[\alpha]^{24}_D$ +37.2 (*c* 1.03, $CHCl_3$); IR (KBr) cm^{-1}: 3296, 1693, 1323; ^1H NMR (270 MHz) δ 0.92 (d, J = 7.0 Hz, 3H), 0.97 (d, J = 7.0 Hz, 3H), 1.88−2.01 (m, 1H), 2.21 (s, 3H), 2.27 (s, 3H), 2.64 (s, 6H), 4.08 (ddd, J = 8.9, 7.6, 5.7 Hz, 1H), 5.16 (d, J = 7.6 Hz, 1H), 6.67 (d, J = 8.9 Hz, 1H), 6.92 (s, 2H); ^{13}C NMR (67.5 MHz) δ 18.1, 18.8, 20.9, 23.1 (2C), 26.1, 32.6, 60.2, 127.1, 131.9 (2C), 133.7, 139.2 (2C), 142.4, 143.1, 190.9. Anal. Calcd for $C_{17}H_{24}BrNO_3S$: C, 50.75; H, 6.01; N, 3.48. Found: C, 50.82; H, 5.96; N, 3.47.

(2*R*,5*S*,3*Z*)-3-Bromo-*O*-*tert*-butyldimethylsilyl-6-methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-3-en-2-ol (53) and Its (2*S*,5*S*,3*Z*)-Isomer (54). By a procedure identical with that described for the synthesis of **15**, the enone **52** (300 mg, 0.75 mmol) was converted into an inseparable mixture of diastereomeric alcohols (247 mg, 82% yield). To a stirred solution of this diastereomixture of the alcohols (1.70 g, 4.2 mmol) in a mixed solvent of $CHCl_3$ (20 mL) and DMF (20 mL) were successively added imidazole (1.15 g, 16.8 mmol) and *tert*-butyldimethylsilyl chloride (1.89 g, 12.6 mmol) at 0 °C, and the mixture was stirred for 3 h at room temperature. Water was added to the mixture, and the whole was extracted with Et_2O. The extract was washed with 1 N HCl, water, and brine and dried over $MgSO_4$. Usual workup followed by flash chromatography over silica gel with *n*-hexane−EtOAc (20:1) gave, in order of elution, **54** (0.73 g, 34%) and **53** (0.94 g, 44%).

Compound **53**: colorless crystals; mp 102 °C (*n*-hexane); $[\alpha]^{24}_D$ +46.3 (*c* 1.03, $CHCl_3$); IR (KBr) cm^{-1}: 3273, 1323; ^1H NMR (300 MHz) δ −0.02 (s, 3H), 0.00 (s, 3H), 0.85 (s, 9H), 0.88 (d, J = 6.9 Hz, 3H), 0.89 (d, J = 6.9 Hz, 3H), 1.08 (d, J = 6.3 Hz, 3H), 1.80−1.91 (m, 1H), 2.26 (s, 3H), 2.62 (s, 6H), 3.97 (ddd, J = 9.0, 7.5, 5.1 Hz, 1H), 4.06 (q, J = 6.3 Hz, 1H), 4.60 (d, J = 7.5 Hz, 1H), 5.69 (d, J = 9.0 Hz, 1H), 6.90 (s, 2H); ^{13}C NMR (75 MHz) δ −5.0, −4.9, 18.0, 18.1, 18.2, 20.9, 23.1 (2C), 23.3, 25.7 (3C), 53.1, 58.9, 72.7, 125.7, 131.9 (2C), 134.3, 134.7, 139.0 (2C), 142.0. Anal. Calcd for $C_{23}H_{40}BrNO_3SSi$: C, 53.27; H, 7.77; N, 2.70. Found: C, 53.52; H, 7.68; N, 2.70.

Compound **54**: colorless crystals; mp 59 °C (*n*-hexane); $[\alpha]^{25}_D$ +36.4 (*c* 1.03, $CHCl_3$); IR (KBr) cm^{-1}: 3302, 1323; ^1H NMR (300 MHz) δ −0.03 (s, 3H), 0.00 (s, 3H), 0.85 (s, 9H), 0.91 (d, J = 6.6 Hz, 6H), 1.00 (d, J = 6.3 Hz, 3H), 1.81−1.92 (m, 1H), 2.26 (s, 3H), 2.63 (s, 6H), 4.02 (ddd, J = 9.0, 8.1, 5.4 Hz, 1H), 4.09 (qd, J = 6.3, 1.2 Hz, 1H), 4.65 (d, J = 8.1 Hz, 1H), 5.76 (dd, J = 9.0, 1.2 Hz, 1H), 6.90 (s, 2H); ^{13}C NMR (75 MHz) δ −5.2, −5.1, 18.0 (2C), 18.1, 20.8, 22.7, 23.1 (2C), 25.6 (3C), 33.2, 59.1, 72.2, 124.2, 132.0 (2C), 133.2, 134.6, 138.9 (2C), 141.8; MS (FAB) *m*/*z* (%) 542 (MNa^+, ^{81}Br, 100), 540 (MNa^+, ^{79}Br, 88); HRMS (FAB) calcd $C_{23}H_{40}BrNNaO_3SSi$ (MNa^+, ^{79}Br) 540.1579; found 540.1602.

(2*R*,5*S*,3*Z*)-3-Bromo-6-methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-3-en-2-ol (55). To a stirred solution of **53** (200 mg, 0.386 mmol) in THF (2 mL) was added tetrabutylammonium fluoride (1.0 M in THF; 2.7 mL, 2.7 mmol), and the mixture was stirred for 4 h with warming to room temperature. The mixture was made acidic with 1 N HCl, and the whole was extracted with Et_2O. The extract was washed with water, saturated $NaHCO_3$, and brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with *n*-hexane−EtOAc (5:3) gave **55** (146 mg, 94% yield): colorless crystals; mp 105 °C (*n*-hexane−EtOAc); $[\alpha]^{27}_D$ +92.7 (*c* 0.28, $CHCl_3$); IR (KBr) cm^{-1}: 3471, 3313, 1319; ^1H NMR (300 MHz) δ 0.88 (d, J = 6.9 Hz, 3H), 0.92 (d, J = 6.9 Hz, 3H), 1.17 (d, J = 6.0 Hz, 3H), 1.76−1.87 (m, 1H), 1.88 (d, J = 4.5 Hz, 1H), 2.30 (s, 3H), 2.65 (s, 6H), 3.96−4.13 (m, 2H), 4.94 (d, J = 7.8 Hz, 1H), 5.65 (d, J = 8.7 Hz, 1H), 6.95 (s, 2H); ^{13}C NMR (75 MHz) δ 18.1, 18.3, 20.8, 21.7, 23.1 (2C), 32.9, 59.4, 72.3, 125.9, 131.8 (2C), 133.9, 134.8, 139.4 (2C), 142.2; MS (FAB) *m*/*z* (%) 406 (MH^+, ^{81}Br, 4), 404 (MH^+, ^{79}Br, 6), 119 (100); HRMS (FAB) calcd $C_{17}H_{27}BrNO_3S$ (MH^+, ^{79}Br) 404.0895; found 404.0899.

(2*R*,5*S*,3*Z*)-3-Bromo-6-methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-3-en-2-yl Methylsulfonate (56). By a procedure identical with that described for the synthesis of **9f**, the alcohol **55** (40 mg, 0.099 mmol) was converted into the mesylate **56** (42 mg, 87% yield): colorless oil; $[\alpha]^{24}_D$ +68.4 (*c* 0.83, $CHCl_3$); IR (KBr) cm^{-1}: 3334, 1356, 1157; ^1H NMR (300 MHz) δ 0.93 (d, J = 6.9 Hz, 3H), 0.95 (d, J = 7.2 Hz, 3H), 1.28 (d, J = 6.3 Hz, 3H), 1.82−1.93 (m, 1H), 2.29 (s, 3H), 2.63 (s, 6H), 2.97 (s, 3H), 3.96 (ddd, J = 9.0, 8.7, 5.7 Hz, 1H), 4.93−4.99 (m, 2H), 5.88 (d, J = 9.0 Hz, 1H), 6.93 (s, 2H); ^{13}C NMR (75 MHz) δ 17.9, 18.4, 20.2, 20.8, 23.0 (2C), 32.8, 39.1, 58.9, 80.6, 126.5, 132.0 (2C), 133.3, 134.1, 139.1 (2C), 142.2; MS (FAB) *m*/*z* (%) 484 (MH^+, ^{81}Br, 1), 482 (MH^+, ^{79}Br, 1), 136 (100); HRMS (FAB) calcd $C_{18}H_{29}BrNO_5S_2$ (MH^+, ^{79}Br) 482.0671; found 482.0658.

(5*S*,a*S*)-6-Methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-2,3-diene (59) and Its (5*S*,a*R*)-Isomer (60). According to the general procedure for the synthesis of allenes, the mesylate **56** (40 mg, 0.083 mmol) was converted into a mixture of the allenes **59** and **60** (22 mg, 86% yield; **59**:**60** = 53:47) by treatment with $Pd(PPh_3)_4$ (12.0 mg, 0.010 mmol) and Et_2Zn (1.02 M in hexane; 0.20 mL, 0.204 mmol) at room temperature for 30 min. ^1H NMR spectra of this diastereomeric mixture was in good agreement with those of the authentic samples.[8b]

(2*S*,5*S*,3*E*)-*O*-*tert*-Butyldimethylsilyl-6-methyl-5-[*N*-(2,4,6-trimethylphenylsulfonyl)amino]hept-3-en-2-ol (74). To a stirred solution of **54** (200 mg, 0.386 mmol) in benzene (5 mL) were successively added *n*-Bu_3SnH (0.62 mL, 2.32 mmol) and AIBN (19 mg, 0.116 mmol) at room temperature, and the mixture was heated under reflux for 16 h. Aqueous 10% KF was added to the mixture, and the resulting precipitate was filtered and washed with Et_2O. The filtrate was concentrated under reduced pressure to leave an oily residue, which was purified by column chromatography over silica gel with *n*-hexane−EtOAc (5:2) to give **74** (86.2 mg, 52%): colorless solid; mp 44−47 °C; IR (KBr) cm^{-1}: 3292, 1323; ^1H NMR (270 MHz) δ −0.02 (s, 3H), 0.00 (s, 3H), 0.82−0.89 (m, 15H), 0.94 (d, J = 6.2 Hz, 3H), 1.71−1.81 (m, 1H), 2.28 (s, 3H), 2.63 (s, 6H), 3.52−3.59 (m, 1H), 4.05−4.14 (m, 1H), 4.49 (d, J = 7.6 Hz, 1H), 5.28−5.31 (m, 2H), 6.91 (s, 2H); ^{13}C NMR (67.5 MHz) δ −4.8, −4.7, 18.0, 18.2, 18.5, 20.9, 23.2 (2C), 23.9, 25.8 (3C), 33.1, 60.6, 67.6, 124.7, 131.8 (3C), 137.3, 138.5 (2C), 141.6; MS (FAB) *m*/*z* (%) 462 (MNa^+, 60), 73 (100); HRMS (FAB) calcd $C_{23}H_{41}NNaO_3SSi$ (MNa^+) 462.2474; found 462.2459.

(2*S*)-2-(*tert*-Butyldimethylsilyloxy)propan-1-ol (75). Ozone was bubbled through a solution of **74** (40.0 mg, 0.091 mmol) in CH_2Cl_2 (3 mL) until blue color persisted (ca. 30 min). A solution of $NaBH_4$ (25.8 mg, 0.683 mmol) in a mixed solvent of EtOH−H_2O (1:1) was added to the mixture, and the mixture was stirred for 1.5 h. Concentration under reduced pressure gave an oily residue. Aqueous 1 N HCl was added, and the whole was immediately extracted with Et_2O. The extract was washed with brine and dried over $MgSO_4$. Usual workup followed by column chromatography over silica gel with *n*-hexane−EtOAc (7:2) gave **75** (1.6 mg, 9%). All the spectroscopic data were in good agreement with the authentic sample of **75**, which was identically prepared from methyl (*S*)-lactate.[26]

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Supporting Information Available: Synthetic procedures and characterization for **9c**, **9g**, **9h**, **10a**−**f**, **16**, **20**, **21**, **23**, **28**, **29**, **36**−**38**, **40**, **41**, **57**, and **58**; ^1H NMR spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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