Carboindation of Alkynes. Regio- and Stereoselective Allylation of Carbon–Carbon Triple Bonds of Alkynols by Allylic Indium Reagents

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Allylindium sesquihalides undergo smooth allylindation with terminal alkynes bearing a neighboring hydroxyl group at 100–140 °C to give allylalkenols. The coupling occurred regioselectively at the γ-carbon of the allylindium reagents via *syn*-addition, whereas the regioselectivity concerning the alkynol depends upon the structures of both allylindium and alkynol. The allylation of nonfunctionalized alkynes is less efficient, requiring higher reaction temperature (150–180 °C) and giving lower yields. Mechanistic considerations suggest a hydroxyl-assisted concerted process for the allylindation of alkynols, whereas a radical pathway is more likely for nonfunctionalized alkynes. Three monoterpene alcohols, *i.e.*, yomogi alcohol, achillenol, and isomyrcenol, were conveniently prepared via allylindation of appropriate alkynols.

Introduction

Carbometalation of alkenes and alkynes is an important synthetic method for construction of complex molecules. In particular, allylmetalation of carbon–carbon triple bonds by allylmetals is useful for the synthesis of 1,4-dienes that widely exist in naturally occurring compounds such as terpenoids. Various main group allylmetals, as well as allylic transition metals, have hitherto been utilized in such transformations.[1] However, the lack of general and facile methods of preparation of allylic organometallics has prevented their extensive use in allylmetalation.

In our continuous work on organoindium chemistry,[2] we have shown that allylic organoindium reagents are easily accessible in high yields by a direct reaction of indium metal with allylic halides. These allylic indium reagents were recently reported by us to undergo allylindation with alkynols regioselectively at the γ-carbon to give allylalkenols.[3] This is the first example of carboindation so far reported. In contrast to the well-known hydrometalation with boron- and aluminium hydrides, carbometalation with group 13 organometallics, in particular allylmetalation, is less common: allylboration and allylalumination have so far been reported only sporadically.[1] In this paper, we describe the full scope of the reaction of allylic indium reagents with alkynes. Furthermore, as a demonstration of the usefulness of allylindation in synthetic chemistry, its application to the synthesis of the monoterpene alcohols possessing a 1,4-diene structure is also disclosed.

Results

Allylic indium sesquihalides, prepared from indium powder and allylic halides in *N,N*-dimethylformamide (DMF),[2a] were treated with alkynols. No reaction occurred at room temperature, but at elevated temperature (100–140 °C) clean allylindation proceeded. After aqueous workup, allylalkenols were obtained in good to excellent yields (Scheme 1). Results are summarized in Table 1. The coupling occurred regiospecifically at the γ-terminus of allyllic indium reagents. On the other hand, the regioselectivity concerning the alkynol triple bond largely depends upon the structures of both the allylic indium reagents and the alkynols employed. With γ-unsubstituted allylindiums, alkynols were allylated selectively at the inner carbon to yield the Markovnikov-type adducts (terminal alkenes), whereas γ,γ-disubstituted allylindium reagents, such as prenyl- and geranylindium, tended to attack the terminal carbon of alkynols to give anti-Markovnikov products (inner alkenes). This tendency was particularly evident when branched alkynols were used. For example, 2-methyl-3-butyn-2-ol reacted with geranylindium to give exclusive formation of the anti-Markovnikov alkene **11**. γ-Monosubstituted allylindiums such as cinnamylindium gave an intermediate selectivity. Solvent polarity also affected the regioselectivity; for example, the reaction of 2-propyn-1-ol with cinnamylindium in DMF gave a ratio of 14/86 anti-Markovnikov (**5**)/Markovnikov (**6**), whereas the ratio was 94/6 in THF (57% combined yield). ^{1}H NMR coupling constants show that the configuration of all the anti-Markovnikov adducts is *E*, implying the addition process is *syn*. Some main group metals (Li, Mg, and Zn) are known to undergo carbometalation generally in an *anti*-fashion, others including group 13 organometallics (B and Al) in a *syn*-fashion.[1]

The present allylindation is quite sensitive to the structures of alkynols. Only terminal alkynols undergo allylindation; 3-butyn-1-ol, for example, did not give any allylindation products upon reaction with prenyl- and cinnamylindium reagents under the standard conditions. This is in sharp contrast to known carbometalation, in which addition to inner alkynes is very common, whereas only a few examples of addition to terminal alkynes are reported.[1] A hydroxyl group near the triple bond is essential for smooth allylindation; 2-propen-1-ol (entry 1) and 3-buten-1-ol (entry 2) gave high yields of the

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(1) For reviews, see: Normant, J. F.; Alexakis, A. *Synthesis* **1981**, 841–870. Oppolzer, W. *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 38–52.

(2) (a) Araki, S.; Ito, H.; Butsugan, Y. *J. Org. Chem.* **1988**, *53*, 1831–1833. Araki, S.; Shimizu, T.; Johar, P. S.; Jin, S.-J.; Butsugan, Y. *Ibid.* **1991**, *56*, 2538–2542. (b) Araki, S.; Yamada, M.; Butsugan, Y. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 1126–1129, and references cited therein.

(3) Araki, S.; Imai, A.; Shimizu, K.; Butsugan, Y. *Tetrahedron Lett.* **1992**, *33*, 2581–2582.

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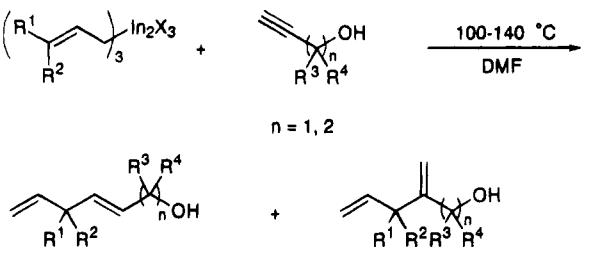
Scheme 1



prenylation products **1**–**4**, whereas 4-pentyn-1-ol was unsusceptible to prenylindation under similar reaction conditions. Furthermore, 3-methoxy-1-propyne did not react with prenylindium reagent, in contrast to the smooth reaction of 2-propyn-1-ol.

At higher reaction temperature (150–180 °C), even nonfunctionalized alkynes such as 1-octyne and phenylacetylene underwent coupling with cinnamylindium (Scheme 2), but the yields were only modest (12–28%), accompanied by 1,4- and 1,6-diphenyl-1,5-hexadienes. It is interesting to note that, in contrast to the high γ-selectivity observed in the alkynol cases, cinnamylindium sesquibromide coupled with 1-octyne and phenylacetylene both at the α- and γ-carbons. This fact, together with the formation of 1,4- and 1,6-diphenyl-1,5-hexadienes, suggests that the allylindation of nonfunctionalized alkenes proceeds by a different mechanism (probably by a radical process) from that of alkynols (*vide infra*).

Discussion

Allylindium reagents are stable at ambient temperature, but upon heating they are pyrolyzed to give mixtures of biallyls (1,5-dienes). For example, heating of cinnamylindium sesquibromide in DMF at 100 °C for 4 h did not cause any decomposition, but 58% of the indium reagent was lost after 4 h at 130 °C (confirmed by titration with benzaldehyde). At 150 °C the reagent was completely decomposed within 4 h, giving a mixture of 1,4-diphenyl- and 1,6-diphenyl-1,5-hexadienes (37% yield). Therefore, it may be possible that the present allylindation is initiated by homolytic cleavage of the carbon–indium bond to produce allyl radical, which adds to alkynol triple bonds to give allylalkenols. This is probably the case for 1-octyne and phenylacetylene, because, as is described above, allylindation of these unactivated alkynes only proceeds above the decomposition temperature of cinnamylindium sesquibromide and is accompanied by the formation of the hexadienes.

In order to obtain further insights into the reaction mechanism of allylindation of alkynols, dehydrolinalool (**20**) was used as a radical probe. Dehydrolinalool (**20**), when treated with triphenylstannane and AIBN, is known to give a methylenecyclopentane cyclization product via a vinyl radical intermediate.[4] Therefore, if the allylindation of **20** proceeds via a radical pathway, cyclization products like **21** could be anticipated (Scheme 3). Prenylation of **20** with prenylindium reagent, however, gave the anti-Markovnikov alkene **22** in 60% yield with a small amount (8%) of cyclization products **23** and **24** (Scheme 4). No other products like **21** were found in the reaction mixture. It may be possible that the formation of **21** is unfavoured owing to a steric interaction between the adjacent two bulky substituents on the cyclopentane ring. However, even with less hindered allylindium sesquiiodide no cyclization products were formed, but only the Markovnikov adduct **25** was obtained (30% yield) together with **23** and **24** (20%). Although the products **23** and **24** are considered to be formed via a 5-*exo*-trigonal ring closure initiated by hydrogen radical generated from pyrolysis of prenylindium, the absence of cyclization products like **21** strongly suggests that a radical pathway is unlikely for allylindation of alkynols.

Quenching the reaction of dehydrolinalool (**20**) and prenylindium with D_2O or I_2 resulted in no deuterium- or iodine-incorporation. The prenylation of dehydrolinalool-1,*O*-d_2 followed by quench with H_2O gave a mixture of **22**-d_2, **22**-d, and **22**. The deuterium distribution analyzed by ^{1}H NMR revealed that C-4 and C-5 were deuterated (Scheme 5). The fact that only terminal alkynols undergo smooth allylindation may suggest initial metalation of the acetylenic hydrogen (indium acetylide formation) prior to allylindation of the triple bond. However, the above results clearly show that this process is less likely. The plausible reaction sequence for allylindation of alkynols is illustrated in Scheme 6. The high γ-selectivity and *syn*-addition mode of anti-Markovnikov addition are best interpreted in terms of a $[2_s + 4_2]$ process that is analogous to known allylboration.[5] The finding that only the alkynols bearing a neighboring hydroxyl group undergo smooth allylindation indicates that allylindation of alkynols is chelation assisted; the hydroxyl group coordinates to the indium atom and facilitates the coupling of alkynol and allylindium reagent.[6] It has to be emphasized here that the allylindium reagents are tolerant to protic functionalities such as a hydroxyl group.[2a,7] In the present allylindation of alkynols, therefore, the reaction is considered to proceed without formation of the indium alkoxides of alkynols.[8] The allyl group on the coordinated indium atom adds to the terminal carbon of alkynol and the indium to the inner carbon, thus leading to anti-Markovnikov addition. This type of an "intramolecular" coordination is sterically advantageous for propargylic (n = 1) and homopropargylic alcohols (n = 2), which form chelated four- and five-membered ring intermediates, respectively. On the other

(4) Nozaki, K.; Oshima, K.; Utimoto, K. *J. Am. Chem. Soc.* **1987**, *109*, 2547–2549.

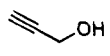
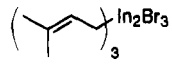
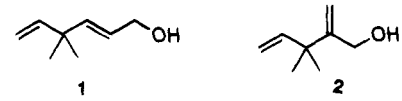
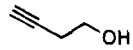
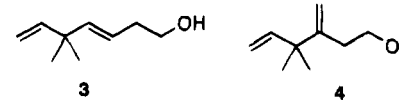
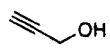
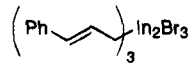
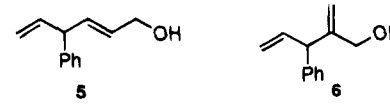
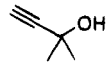
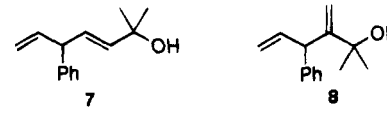
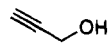
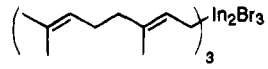
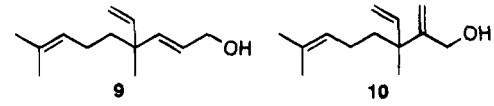
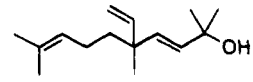
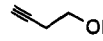
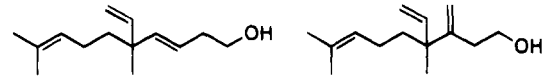
(5) Mikhailov, B. M. *Pure Appl. Chem.* **1974**, *39*, 505–523.

(6) Such coordinative assistance by a hydroxyl group is well-known in carbomagnesiation of alkenols, alkynols, and allenols. However, it should be noted that in contrast to our indium-based reaction the hydroxyl group is present as a magnesium salt in the Grignard reactions: see for example; (a) Eisch, J. J.; Husk, G. R. *J. Am. Chem. Soc.* **1965**, *87*, 4194–4195. Cherest, M.; Felkin, H.; Frajerman, C.; Lion, C.; Roussi, G.; Swierczewski, G. *Tetrahedron Lett.* **1966**, 875–879; Eisch, J. J.; Merkley, J. H. *J. Organomet. Chem.* **1969**, P27–P31. Felkin, H.; Kaeseberg, C. *Tetrahedron Lett.* **1970**, 4587–4590. Richey, H. G., Jr.; Wilkins, C. W., Jr.; Brown, B. S.; Moore, R. E. *Tetrahedron Lett.* **1976**, 723–726. Eisch, J. J.; Merkley, J. H.; Galle, J. E. *J. Org. Chem.* **1979**, *44*, 587–593. (b) Richey, H. G., Jr.; von Rein, F. W. *J. Organomet. Chem.* **1969**, P32–P35. von Rein, F. W.; Richey, H. G., Jr. *Tetrahedron Lett.* **1971**, 3777–3780. Miller, R. B.; Reichenbach, T. *Synth. Commun.* **1976**, *6*, 319–323. (c) Richey, H. G., Jr.; Szucs, S. S. *Tetrahedron Lett.* **1971**, 3785–3787.

(7) Li, C. J.; Chan, T. H. *Tetrahedron Lett.* **1991**, *32*, 7017–7020. Chan, T. H.; Li, C. J. *J. Chem. Soc., Chem. Commun.* **1992**, 747. Kim, E.; Gordon, D. M.; Schmid, W.; Whitesides, G. M. *J. Org. Chem.* **1993**, *58*, 5500–5507.

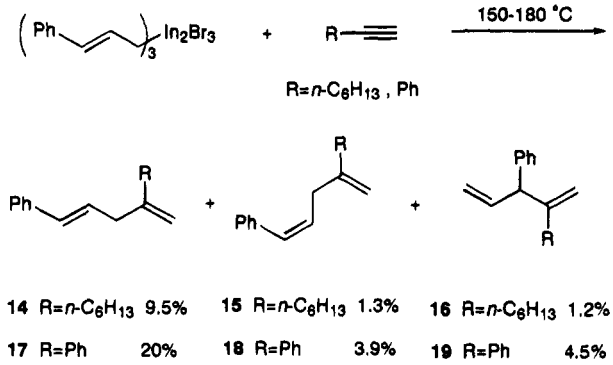
(8) In all the allylindation reactions reported in this paper, the molar ratio of allylic indium sesquihalide to alkynol is 0.5. Therefore, if alkynols are present as alkynol indium salts during the reaction, the theoretical yield of allylindation products based on alkynol does not exceed 50%, even if all three allyl groups in sesquihalide are used for the reaction.

Table 1. Carboindation of Alkynols by Allylic Indium Reagents[a]

Entry	Alkynol	Allylindium	Products	Yield/%[b]
1			 **1** **2**	91 (65:35)
2		"	 **3** **4**	85 (73:27)
3			 **5** **6**	56 (14:86)
4		"	 **7** **8**	68 (90:10)
5			 **9** **10**	59 (75:25)
6		"	 **11**	75 (100:0)
7		"	 **12** **13**	83 (77:23)

[a] All reactions were carried out in DMF at 100−140 °C. [b] Figures in parentheses refer to the ratio *anti*-Markovnikov:Markovnikov adducts.

Scheme 2

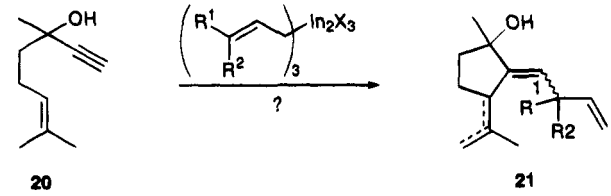


14 R=*n*-C_6H_{13} 9.5% **15** R=*n*-C_6H_{13} 1.3% **16** R=*n*-C_6H_{13} 1.2%

17 R=Ph 20% **18** R=Ph 3.9% **19** R=Ph 4.5%

hand, such intramolecularly coordinated cyclic addition is sterically impossible for Markovnikov addition. Alternatively, the "intermolecular" process, which is observed in allylmagnesiation of alkynols,[6b] may be dominant for Markovnikov addition; the coordinated indium atom may facilitate the allylation of the triple bond from an external allylindium reagent. Although there is, at present, no definitive evidence for the mechanism of Markovnikov addition,[9] we tentatively propose the reaction course depicted in Scheme 6, by analogy with known allymagnesiation of alkynols.[6b] The vinylindium species thus

Scheme 3



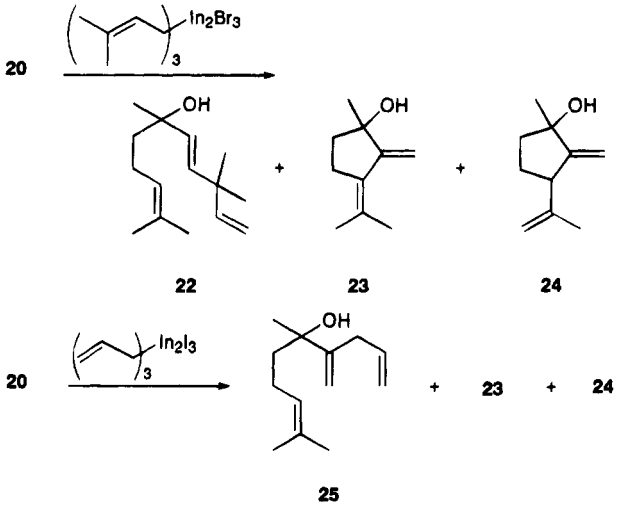
20 **21**

formed via allylindation are considered to be spontaneously protonated by the hydroxyl proton to furnish allylalkenol indium salts. The formation of **22**-4,5-d_2 and **22**-5-d can be reasonably explained by this reaction process, although considerable amounts of D−H scrambling takes place.

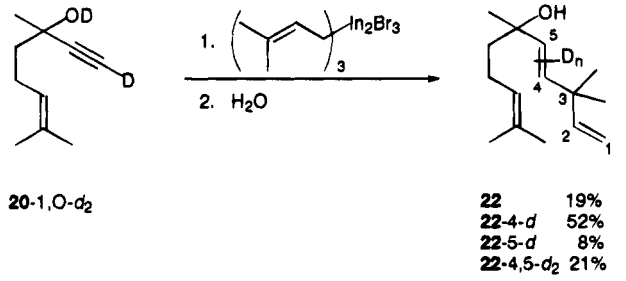
anti-Markovnikov/Markovnikov selectivity seems to depend primarily upon the steric factors of the transition states; when steric repulsion is present between the γ substituents (R^1 and R^2) of allylic indium and the propargylic substituents (R^3 and R^4) of alkynol, high anti-Markovnikov selectivity emerges. The selectivity also

(9) From the intermolecular Markovnikov mechanism, anti-addition would be anticipated. Attempts to determine whether Markovnikov addition is *syn* or *anti* were inconclusive; the reaction of dehydrolinalool-1,*O*-d_2 and allylindium sesquiiodide gave **25**, which surprisingly possessed no detectable amounts of deuterium. We have at present no satisfactory explanation for this result.

Scheme 4



Scheme 5



20-1,O-d_2

22	19%
22-4-*d*	52%
22-5-*d*	8%
22-4,5-d_2	21%

depends upon solvent polarity. Unfortunately, as allylic indium sesquihalides cannot be prepared in nonpolar solvents, a wide range of solvents could not be examined. However, THF, which is less polar than DMF, showed enhanced anti-Markovnikov selectivity. This solvent effect is not yet completely understood, but a similar tendency was also observed for the allylmagnesiation of alkynols.[6b]

Synthesis of Terpenic Alcohols

In order to examine the utility of our allylindation in the regioselective synthesis of alcoholic 1,4-pentadienes, we planned to synthesize some simple terpenic alcohols possessing a 1,4-pentadiene system. Yomogi alcohol (**26**),[10] an irregular monoterpene alcohol isolated from *Artemisia feddei* Lev. et Van., seemed to be a suitable compound for a demonstration of the usefulness of allylindation. Indeed, the reaction of 2-methyl-3-butyn-2-ol and prenylindium realized a one-pot synthesis of **26** in a high yield (83%) (Scheme 7). As is expected, the product is free from regio- and stereoisomers; only the anti-Markovnikov inner alkene **26** with *E*-configuration was formed exclusively. Achillenol (**27**)[11] and isomyrcenol (**28**)[12] were also synthesized via direct couplings of appropriate allylic indium reagents and alkynols. Again, the regioselectivity concerning the allylic indium reagents is excellent giving only γ-coupled products. However, the expected naturally occurring compounds **27** and **28** are unfortunately the minor products of both the reactions; the major ones are Markovnikov-type terminal alkenes **29** and **30**. Nevertheless, the present indium-based syntheses of these terpenic alcohols are unique and useful in respect to their short reaction sequences and simple reaction procedures.

Experimental Section

Material. 2-(Bromomethyl)-1,3-butadiene was prepared by the pyrolysis of 3-(bromomethyl)-2,5-dihydrothiophene 1,1-dioxide.[13] Other allylic bromides were prepared from the corresponding allylic alcohols. Allylic indium reagents were prepared according to the published procedure.[2a] All reactions were carried out under an argon atmosphere.

General Procedure for Allylindation of Alkynols with Allylic Indium Sesquibromides. Alkynol (1.0 mmol) was added to a solution of allylic indium sesquibromide, prepared from allylic bromide (1.5 mmol) and indium powder (1.0 mmol) in DMF (2 mL), and the mixture was heated at 100–140 °C for 3–6 h. After being cooled to room temperature, dilute hydrochloric acid was added, and the products were extracted with ether. The extracts were washed with brine and dried (Na_2SO_4). The solvent was evaporated, and the residue was column chromatographed on silica gel (CH_2Cl_2) to give a mixture of allylindation products. Separation of the isomeric 1,4-dienes was performed by preparative GLC (5% PEG 20MP, 5 mm × 1 m). Isomeric ratios were estimated by GLC analyses (OV-1, 50 m capillary column). The results are summarized in Table 1.

(*E*)-4,4-Dimethyl-2,5-hexadien-1-ol (1): IR (neat) 3350, 2970, 1636, 1460, 1410, 1378, 1360, 1088, 1016, 976, 910 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.12 (s, 6H), 1.70 (s, 1H), 4.11 (d, J = 5.2, 1H), 4.93 (dd, J = 10.4, 1.2, 1H), 4.96 (dd, J = 17.2, 1.2 1H), 5.58 (dt, J = 16.0, 5.2, 1H), 5.70 (d, J = 16.0, 1H), 5.82 (dd, J = 17.2, 10.4, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 26.7, 38.8, 63.7, 111.3, 125.4, 140.9, 146.6; Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.15; H, 11.32.

3,3-Dimethyl-2-methylene-4-penten-1-ol (2):[14] IR (neat) 3430, 2960, 1638, 1448, 1378, 1360, 1260, 1132, 910, 800 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.18 (s, 6H), 1.58 (s, 1H), 4.13 (s, 2H), 4.99 (dd, J = 17.3, 1.2, 1H), 5.02 (dd, J = 10.8, 1.2, 1H), 5.06 (d, J = 1.0, 1H), 5.17 (d, J = 1.0, 1H), 5.82 (dd, J = 17.3, 10.8, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 26.1, 40.9, 63.0, 108.5, 110.7, 146.6, 154.7.

(*E*)-5,5-Dimethyl-3,6-heptadien-1-ol (3): IR (neat) 3330, 2960, 1634, 1460, 1440, 1408, 1374, 1358, 1044, 970, 908 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.11 (s, 6H), 1.54 (s, 1H), 2.29 (dq, J = 7.2, 1.3, 2H), 3.63 (t, J = 7.2, 2H), 4.92 (dd, J = 10.0, 1.0, 1H), 4.95 (dd, J = 18.0, 1.0, 1H), 5.36 (dt, J = 16.0, 7.2, 1H), 5.57 (d, J = 16.0, 1H), 5.83 (dd, J = 18.0, 10.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 26.9, 35.9, 39.1, 62.0, 110.4, 121.1, 142.1, 147.1; HRMS $M^+ - H_2O$ calcd for C_9H_{14} 122.1095, found 122.1126. Anal. (for a mixture of **3** and **4**). Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 76.82; H, 11.73.

4,4-Dimethyl-3-methylene-5-hexen-1-ol (4): IR (neat) 3330, 2960, 1628, 1460, 1408, 1370, 1358, 1138, 1040, 1012, 908, 892 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.17 (s, 6H), 1.55 (s, 1H), 2.30 (dt, J = 7.2, 1.0, 2H), 3.73 (t, J = 7.2, 2H), 4.84 (s, 1H), 5.00 (dd, J = 10.0, 1.0, 1H), 5.02 (dd, J = 18.0, 1.0, 1H), 5.05 (s, 1H), 5.78 (dd, J = 18.0, 10.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.9, 34.6, 42.5, 61.8, 11.4, 109.3, 146.5, 151.6; HRMS M^+ calcd for $C_9H_{16}O$ 140.1199, found 140.1161.

(*E*)-4-Phenyl-2,5-hexadien-1-ol (5):[15] IR (neat) 3325, 3060, 2870, 1632, 1599, 1492, 1449, 1081, 993, 973, 915, 753, 700 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 1.41 (s, 1H), 4.07 (t, J =

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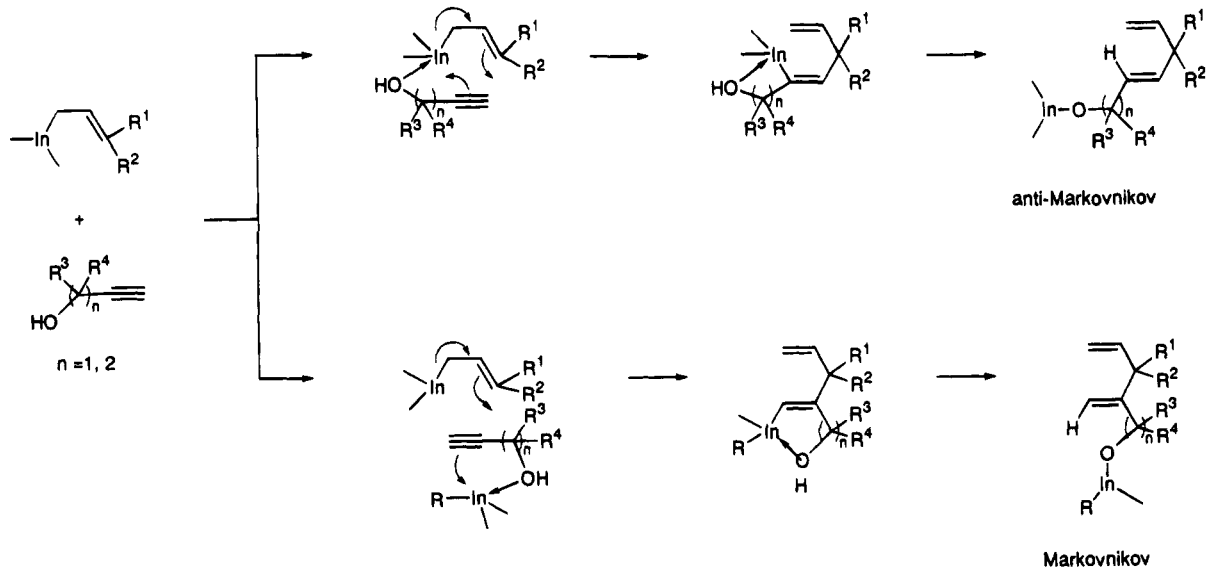
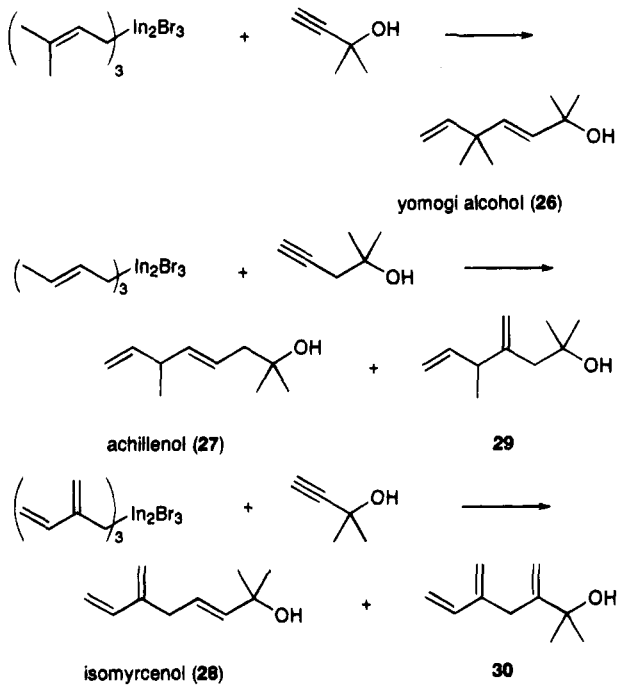
Scheme 6



Scheme 7



7.2, 1H), 4.14 (d, J = 5.4, 2H), 5.08 (bd, J = 18.0, 1H), 5.12 (bd, J = 9.0, 1H), 5.69 (dt, J = 15.3, 5.4, 1H), 5.82 (dd, J = 15.3, 7.2, 1H), 6.04 (ddd, J = 15.3, 9.0, 7.2, 1H), 7.03–7.43 (m, 5H).

2-Methylene-3-phenyl-4-penten-1-ol (6): IR (neat) 3300, 3080, 2860, 1632, 1599, 1490, 1448, 1403, 1050, 1029, 997, 913, 756, 699 cm^{-1}; ^{1}H NMR (90 MHz, $CDCl_3$) δ 1.48 (s, 1H), 3.92 (s, 2H), 4.08 (d, J = 7.5, 1H), 4.78–5.30 (m, 4H), 6.08 (ddd, J = 16.5, 10.5, 7.5, 1H), 7.07–7.41 (m, 5H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 52.3, 65.1, 111.7, 116.0, 126.5, 128.2, 128.4, 139.3, 141.0, 150.2. Anal. Calcd for $C_{12}H_{14}O$: C, 82.66; H, 8.10. Found: C, 82.70; H, 8.22.

(*E*)-2-Methyl-5-phenyl-3,6-heptadien-2-ol (7): IR (neat) 3380, 2990, 1636, 1600, 1497, 1453, 1364, 1154, 978, 916, 702 cm^{-1}; ^{1}H NMR (90 MHz, $CDCl_3$) δ 1.33 (s, 6H), 1.63 (bs, 1H), 4.05 (bt, J = 7.1, 6.4, 1H), 5.09 (dd, J = 17.2, 1.3, 1H), 5.15 (dd, J = 10.4, 1.3, 1H), 5.71 (d, J = 15.8, 1H), 5.84 (dd, J = 15.8, 6.4, 1H), 6.03 (ddd, J = 17.2, 10.4, 7.1, 1H), 7.10–7.50 (m, 5H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 29.7, 51.5, 70.7, 115.1, 126.3, 127.8, 128.4, 128.5, 138.9, 140.2, 142.6; HRMS M$^+$ – H_2O calcd for $C_{14}H_{16}$ 184.1251, found 184.1264. Anal. (for a mixture of **7** and **8**). Calcd for $C_{14}H_{18}O$: C, 83.12; H, 8.97. Found: C, 82.12; H, 8.93.

2-Methyl-3-methylene-4-phenyl-5-hexen-2-ol (8): IR (neat) 3420, 2990, 1633, 1598, 1496, 1452, 1363, 1152, 1001, 960, 918, 751, 702 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.33 (s, 3H), 1.35 (s, 3H), 1.56 (bs, 1H), 4.44 (bd, J = 6.7, 1H), 4.85 (dt, J = 17.3, 1.2, 1H), 4.94 (bs, 1H), 5.12 (dt, J = 10.0, 1.2, 1H), 5.40 (bs, 1H), 6.11 (ddd, J = 17.3, 10.0, 6.7, 1H), 7.10–7.50 (m, 5H); HRMS M$^+$ – H_2O calcd for $C_{14}H_{16}$: 184.1251, found 184.1270.

(*E*)-4,8-Dimethyl-4-vinyl-2,7-nonadien-1-ol (9): IR (neat) 3330, 2970, 2920, 1630, 1448, 1412, 1374, 1083, 1001, 976, 912 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.11 (s, 3H), 1.32–1.48 (m, 2H), 1.58 (s, 3H), 1.67 (s, 3H), 1.74–2.10 (m, 3H), 4.14 (d, J = 5.0, 2H), 4.97 (dd, J = 17.6, 1.5, 1H), 5.03 (dd, J = 10.8, 1.5, 1H), 5.08–5.14 (m, 1H), 5.62 (dd, J = 15.6, 5.0, 1H), 5.66 (d, J = 15.6, 1H), 5.80 (dd, J = 17.6, 10.8, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 17.5, 22.9, 23.0, 25.6, 40.9, 42.0, 63.9, 111.8, 124.5, 126.4, 131.2, 139.9, 145.5. Anal. Calcd for $C_{13}H_{22}O$: C, 80.36; H, 11.41. Found: C, 79.91; H, 11.60.

3,7-Dimethyl-2-methylene-3-vinyl-6-octen-1-ol (10): IR (neat) 3340, 2980, 2940, 2870, 1634, 1450, 1413, 1378, 1044, 913, 835 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.18 (s, 3H), 1.40–1.60 (m, 2H), 1.59 (s, 3H), 1.69 (s, 3H), 1.78–2.00 (m, 3H), 4.13 (s, 2H), 5.04 (dd, J = 18.0, 1.2, 1H), 5.06 (d, J = 1.0, 1H), 5.07 (dd, J = 11.2, 1.2, 1H), 5.10 (dd, J = 7.2, 1.4, 1H), 5.26 (d, J = 1.0, 1H), 5.82 (dd, J = 18.0, 11.2, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 17.5, 22.9, 23.0, 25.6, 38.1, 44.2, 63.1, 109.7, 112.2, 124.5, 131.3, 145.8, 153.4. Anal. Calcd for $C_{13}H_{22}O$: C, 80.36; H, 11.41. Found: C, 80.29; H, 11.41.

(*E*)-2,5,9-Trimethyl-5-vinyl-3,8-decadien-2-ol (11): IR (neat) 3360, 2970, 2920, 1628, 1452, 1376, 1128, 980, 910 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.07 (s, 3H), 1.30 (s, 6H), 1.30–1.45 (m, 2H), 1.50 (bs, 1H), 1.57 (s, 3H), 1.66 (s, 3H), 1.80–2.00 (m, 2H), 4.96 (dd, J = 17.7, 1.2, 1H), 5.00 (dd, J = 11.0, 1.2, 1H), 5.09 (t, J = 7.2, 1H), 5.57 (d, J = 16.0, 1H), 5.60 (d, J = 16.0, 1H), 5.80 (dd, J = 17.7, 11.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 17.5, 23.0, 23.1, 25.6, 29.9, 41.0, 41.5, 70.7, 113.0, 124.7, 131.1, 134.1, 135.4, 145.9. Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.78. Found: C, 80.72; H, 11.89.

(*E*)-5,9-Dimethyl-5-vinyl-3,8-decadien-1-ol (12): IR (neat) 3330, 2980, 2940, 1635, 1450, 1412, 1378, 1050, 980, 916, 840 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.08 (s, 3H), 1.30–1.45 (m, 2H), 1.47 (bs, 1H), 1.58 (s, 3H), 1.67 (s, 3H), 1.89 (dt, J = 9.2, 7.2, 2H), 2.30 (dt, J = 6.8, 6.6, 2H), 3.64 (t, J = 6.6, 2H), 4.96 (dd, J = 17.6, 1.7, 1H), 5.00 (dd, J = 10.8, 1.7, 1H), 5.02–5.18 (m, 1H), 5.37 (dt, J = 16.0, 6.8, 1H), 5.53 (d, J = 16.0, 1H), 5.80 (dd, J = 17.6, 10.8, 1H); HRMS M$^+$ calcd for $C_{14}H_{24}O$

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208.1826, found 208.1859. Anal. (for a mixture **12** and **13**) Calcd for $C_{14}H_{24}O$: C, 80.71; H, 11.61. Found: C, 80.60; H, 11.71.

4,8-Dimethyl-3-methylene-4-vinyl-7-nonen-1-ol (13): IR (neat) 3325, 2970, 2920, 1630, 1450, 1410, 1374, 1043, 911, 898, 836, 733 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.15 (s, 3H), 1.32–1.58 (m, 2H), 1.56 (s, 1H), 1.59 (s, 3H), 1.68 (s, 3H), 1.86 (m, 2H), 2.28 (t, J = 7.1, 2H), 3.75 (t, J = 7.1, 2H), 4.91 (s, 1H), 4.96 (s, 1H), 5.03 (dd, J = 17.5, 1.2, 1H), 5.05 (d, J = 11.0, 1.2, 1H), 5.12 (dd, J = 6.4, 1.4, 1H), 5.77 (dd, J = 17.5, 11.0, 1H); HRMS M^+ calcd for $C_{14}H_{24}O$ 208.1826, found 208.1831.

Reactions of Cinnamylindium Sesquibromide with 1-Octyne and Phenylacetylene. Cinnamylindium, prepared from cinnamyl bromide (3.0 mmol) and indium (2.0 mmol) in DMF (8 mL), was treated with 1-octyne (2.0 mmol) at 150 °C for 4 h. Aqueous workup and column chromatography (SiO_2/hexane) gave a mixture of **14–16** (57 mg, 12% yield; **14**:**15**:**16** = 79:11:10) and 1,4- and 1,6-diphenyl-1,5-hexadienes (102 mg, 29%). Pure samples of **14–16** were obtained by preparative GLC (5% PEG 20MP, 5 mm × 1 m). The reaction with phenylacetylene was similarly carried out at 180 °C for 4 h to give **17–19** (**17**:**18**:**19** = 70:14:16) in 28% combined yield.

(*E*)-4-Hexyl-1-phenyl-1,4-pentadiene (14): IR (neat) 3100, 3040, 2980, 2950, 2880, 1650, 1605, 1580, 1500, 1470, 1455, 1440, 1380, 1300, 1080, 1030, 980, 970, 900, 743, 698 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 0.88 (t, J = 7.5, 3H), 1.29 (s, 6H), 1.45 (quin, J = 7.5, 2H), 2.08 (t, J = 7.5, 2H), 2.91 (d, J = 7.5, 2H), 4.79 (s, 2H), 6.24 (dt, J = 15.0, 7.5, 1H), 6.41 (d, J 15.0, 1H), 7.12–7.42 (m, 5H). Anal. Calcd for $C_{17}H_{24}$: C, 89.41; H, 10.59. Found: C, 89.49; H, 10.52.

(*Z*)-4-Hexyl-1-phenyl-1,4-pentadiene (15): IR (neat) 3100, 3040, 2970, 2950, 2870, 2850, 1650, 1600, 1500, 1470, 1450, 1400, 1380, 1080, 1030, 920, 892, 810, 770, 700 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 0.87 (t, J = 7.5, 3H), 1.20–1.45 (m, 8H), 2.05 (t, J = 7.5, 2H), 2.98 (d, J = 7.5, 2H), 4.82 (m, 2H), 5.75 (dt, J = 11.6, 7.5, 1H), 6.56 (d, J = 11.6, 1H), 7.22–7.38 (m, 5H). Anal. Calcd for $C_{17}H_{24}$: C, 89.41; H, 10.59. Found: C, 89.69; H, 10.77.

4-Hexyl-3-phenyl-1,4-pentadiene (16): IR (neat) 3090, 3040, 2960, 2940, 2860, 2330, 1640, 1600, 1495, 1465, 1450, 1405, 1380, 1075, 1030, 1000, 918, 900, 835, 760, 700 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 0.86 (t, J = 7.5, 3H), 1.10–1.31 (m, 6H), 1.42 (m, 2H), 1.86–2.00 (m, 2H), 3.99 (d, J = 7.5, 1H), 4.84–5.00 (m, 3H), 5.11 (dt, J = 10.5, 1.2, 1H), 6.11 (ddd, J = 17.5, 10.5, 7.5, 1H), 7.13–7.38 (m, 5H). Anal. Calcd for $C_{17}H_{24}$: C, 89.41; H, 10.59. Found: C, 89.40; H, 10.86.

(*E*)-1,4-Diphenyl-1,4-pentadiene (17): ^1H NMR (200 MHz, $CDCl_3$) δ 3.40 (d, J = 7.5, 2H), 5.16 (s, 1H), 5.42 (s, 1H), 6.31 (dt, J = 15.0, 7.5, 1H), 6.47 (d, J = 15.0, 1H), 7.09–7.41 (m, 10H).

(*Z*)-1,4-Diphenyl-1,4-pentadiene (18): ^1H NMR (200 MHz, $CDCl_3$) δ 3.49 (d, J = 7.5, 2H), 5.20 (s, 1H), 5.42 (s, 1H), 5.79 (dt, J = 10.5, 7.5, 1H), 6.58 (d, J = 10.5, 1H), 7.10–7.52 (m, 10H).

2,3-Diphenyl-1,4-pentadiene (19): ^1H NMR (200 MHz, $CDCl_3$) δ 4.63 (d, J = 6.0, 1H), 4.95 (dt, J = 17.5, 1.2, 1H), 5.14 (d, J = 1.2, 1H), 5.17 (dt, J = 10.0, 1.2, 1H), 5.57 (d, J = 1.2, 1H), 6.18 (ddd, J = 17.5, 10.0, 6.0, 1H), 7.08–7.44 (m, 10H).

Reaction of Dehydrolinalool (29) with Prenylindium. Prenylindium sesquibromide, prepared from prenyl bromide (1.5 mmol) and indium (1.0 mmol) in DMF (1 mL), was heated with dehydrolinalool (**20**) (152 mg, 1.0 mmol) at ca. 110 °C for 5 h. Aqueous workup and column chromatography (SiO_2/CH_2Cl_2) gave **22** (132 mg, 60%) and a mixture of **23** and **24** (12 mg, 8%). Pure samples of **23** and **24** were isolated by preparative GLC (5% PEG 20MP, 5 mm × 1 m).

(*E*)-3,3,6,10-Tetramethyl-1,4,9-undecatrien-6-ol (22): IR (neat) 3400, 2980, 1638, 1452, 1376, 1360, 1110, 980, 914 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.12 (s, 6H), 1.26 (s, 3H), 1.52 (m, 3H), 1.59 (s, 3H), 1.68 (s, 3H), 2.00 (m, 2H), 4.92 (dd, J = 10.5, 1.5, 1H), 4.94 (dd, J = 17.7, 1.5, 1H), 5.12 (bt, J = 7.5, 1H), 5.45 (d, J = 15.7, 1H), 5.60 (d, J = 15.7, 1H), 5.82 (dd, J = 17.7, 10.5, 1H): ^{13}C NMR (50 MHz, $CDCl_3$) δ 18.2, 23.5, 26.3, 27.7, 28.9, 39.3, 43.2, 73.6, 111.1, 125.1, 132.3, 134.0, 136.7, 147.8. Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.79. Found: C, 80.58; H, 11.98.

3-Isopropylidene-1-methyl-2-methylenecyclopentanol (23):[16] ^1H NMR (200 MHz, $CDCl_3$) δ 1.33 (s, 3H), 1.50 (s, 1H), 1.60–1.85 (m, 2H), 1.79 (s, 3H), 1.94 (s, 3H), 2.07–2.55 (m, 2H), 5.10 (s, 1H), 5.24 (s, 1H).

3-Isopropenyl-1-methyl-2-methylenecyclopentanol (24):[17] (3:2 mixture of diastereomers) ^1H NMR (200 MHz, $CDCl_3$) δ 1.34 (s, 3H), 1.55 (s, 1H), 1.58 (s, 1.8H), 1.63 (s, 1.2H), 1.64–2.04 (m, 4H), 3.37 (tt, J = 10, 2.5, 1H), 4.79 (s, 1H), 4.80 (s, 1H), 4.89 (d, J = 2.5, 1H), 5.25 (d, J = 2.5, 1H).

Reaction of dehydrolinalool (20) with allylindium sesquiiodide was similarly carried out, giving **25** (46 mg, 30%) and a mixture of **23** and **24** (29 mg, 20%).

5,9-Dimethyl-4-methylene-1,8-decadien-5-ol (25): IR (neat) 3450, 2980, 2940, 1640, 1450, 1432, 1376, 1120, 1000, 914 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.32 (s, 3H), 1.59 (m, 3H), 1.60 (s, 3H), 1.68 (s, 3H), 1.96 (m, 2H), 2.80 (d, J = 7.5, 2H), 4.89 (d, J = 1.5, 1H), 5.02–5.18 (m, 4H), 5.84 (ddt, J = 17.0, 9.0, 7.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 18.3, 23.4, 26.3, 28.6, 36.9, 41.1, 76.4, 110.5, 116.9, 124.9, 132.6, 137.6, 153.6. Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.09; H, 11.24.

Synthesis of Yomogi Alcohol. To a solution of prenylindium sesquibromide, prepared from indium powder (115 mg, 1 mmol) and prenyl bromide (116 mg, 1.5 mmol) in DMF (2 mL), was added 2-methyl-3-butyn-2-ol (84 mg, 1 mmol), and the mixture was heated at 110 °C for 3 h. The reaction was quenched with dilute hydrochloric acid and the product was extracted with ether. The solvent was evaporated and the residue was chromatographed on silica gel (eluent: CH_2Cl_2) yielding a colorless oil of Yomogi alcohol (128 mg, 83%).

(*E*)-2,4,4-Trimethyl-3,6-heptadien-2-ol (Yomogi alcohol) (26):[10] IR (neat) 3370, 2975, 1640, 1460, 1375, 1360, 1230, 1135, 980, 910 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.15 (s, 6H), 1.32 (s, 6H), 1.58 (s, 1H), 4.95 (dd, J = 10.0, 2.4, 1H), 4.96 (dd, J = 16.8, 2.4, 1H), 5.60 (d, J = 16.0, 1H), 5.63 (d, J = 16.0, 1H), 5.86 (dd, J = 16.8, 10.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 26.9, 29.8, 38.4, 70.7, 110.5, 134.3, 135.2, 147.0.

Synthesis of Achillenol. The reaction of crotylindium sesquibromide and 2-methyl-4-pentyn-2-ol[17] was sililarly carried out at 60 °C for 4 h. Column chromatography (SiO_2/CH_2Cl_2) gave a mixture of **27** and **29** (**27**:**29** = 21:79, 62% combined yield). Pure samples of **27** and **29** were isolated by preparative GLC. **(*E*)-2,6-Dimethyl-4,7-octadien-2-ol (Achillenol) (27)**:[11] IR (neat) 3390, 2985, 1640, 1455, 1377, 1155, 975, 913 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.10 (d, J = 7.2, 3H), 1.20 (s, 6H), 1.55 (s, 1H), 2.18 (m, 2H), 2.88 (m, 1H), 4.95, −5.08 (m, 2H), 5.48–5.56 (m, 2H), 5.82 (m, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.8, 28.9, 40.3, 46.8, 70.4, 112.7, 124.1, 138.5, 142.7. **2,5-Dimethyl-4-methylene-6-hepten-2-ol (29)**: IR (neat) 3410, 2990, 1638, 1462, 1379, 1225, 1210, 1155, 1128, 998, 910 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.14 (d, J = 6.8, 3H), 1.24 (s, 6H), 1.45 (s, 1H), 2.26 (s, 2H), 2.88 (m, 1H), 4.93–5.18 (m, 4H), 5.73 (m, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.0, 29.6, 44.2, 48.5, 70.5, 112.6, 113.5, 142.6, 150.0; Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.34; H, 11.63.

Synthesis of Isomyrcenol. The reaction of 2-methylene-3-butenylindium sesquibromide and 2-methyl-3-butyn-2-ol was similarly carried out at 80 °C for 4 h. Column chromatography (SiO_2/CH_2Cl_2) gave a mixture of **28** and **30** (**28**:**30** = 26:74, 46% combined yield). Pure samples of **28** and **30** were isolated by repeated column chromatography. **(*E*)-2-Methyl-6-methylene-3,7-octadien-2-ol (Isomyrcenol) (28)**:[12] IR (neat) 3375, 2975, 1592, 1370, 1230, 1147, 989, 972, 899 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.33 (s, 6H), 1.41 (s, 1H), 2.96 (bd, J =

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7.5, 2H), 5.00–5.36 (m, 4H), 5.70–5.74 (m, 2H), 6.43 (dd, J = 18.0, 11.2, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 29.6, 34.0, 70.6, 113.6, 116.5, 124.2, 138.5, 139.7, 144.7. **2-Methyl-3,5-dimethylene-6-hepten-2-ol (30)**: IR (neat) 3375, 2980, 1639, 1592, 1360, 1127, 990, 959, 897 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.41 (s, 6H), 1.49 (s, 1H), 3.07 (bs, 2H), 4.82 (bs, 1H), 5.05–5.31 (m, 5H), 6.43 (dd, J = 18.0, 11.2, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 29.3, 34.1, 73.3, 109.4, 114.0, 118.4, 138.2, 144.4, 152.7. Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 78.60; H, 10.66.

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Supplementary Material Available: Copies of ^1H NMR spectra of **4**, **8**, **13**, **17**, **18**, and **19** (6 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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