aqueous layer was acidified with acetic acid and extensively extracted with chloroform. After evaporation in vacuo, 243 mg (64%) of **23** as a semisolid, homogeneous by TLC on three different solvent systems, was isolated. Further purification by TLC only led to decomposition. A similar experiment beginning with 45 mg of crude ester in 2 mL of dioxane and 1 mL of 2% aqueous sodium hydroxide for 3 h gave 39 mg (90%) of acid **23**: IR ($CHCl_3$) 3640–2500, 1675, 1608, 1502 cm^{-1}; UV (CH_3OH) λ_{max} (ϵ) 236 (17600), 275 nm (8780); NMR ($CDCl_3$) δ 7.52 (bs, 2 H), 7.28 (d, J = 8 Hz, 4 H), 6.88 (m, 1 H), 6.73 (d, J = 8 Hz, 4 H), 6.09 (m, 2 H), 5.02 (s, 1 H), 3.68 (s, 6 H), 3.44 (m, 1 H), 2.89 (dd, J = 18, 7 Hz, 1 H), 2.49 (dd, J = 18, 8 Hz, 1 H).

The above acid (130 mg, 0.36 mmol) was dissolved in 2 mL of 88% formic acid in an NMR tube and heated at 50 °C. Conversions of 24, 41, 59, and 62% were observed after 10, 25, 40, and 70 min. The tube was then heated at 60 °C for 30 min (74% completion) at which time the reaction mixture was evaporated to remove the formic acid and then partitioned between water and ether. The water was evaporated to give 84 mg of crude product. The product was dissolved in a minimum volume of distilled water, applied to a 1 × 21 cm ion retardation resin column (AG 11 A8 resin from Bio-Rad Laboratories), and eluted with water. Four fractions, 5, 20, 10, and 10 mL, were collected. The second fraction upon evaporation gave 56 mg of a white solid, mp 180–183 °C, which by UV analysis contained 28.5 mg (78% yield, based on 74% conversion) of (±)-gabaculine. The second and third fractions yielded 15 mg of solid which contained an additional 1.1 mg (2% yield) of (±)-gabaculine for a total yield of 80%. The (±)-gabaculine was recrystallized by dissolving it in a minimum volume of water, adding 1–2 drops of water, and placing the mixture in a closed chamber over acetone. After standing 24 h, the crystals were collected and had a melting point of 188–190 °C. A second recrystallization raised the melting point to 196–197 °C (lit.[11] mp 196–197 °C). IR, UV, and ^1H NMR spectra (in the presence of disodium acid phosphate buffer) are identical with those of an authentic sample: ^{13}C NMR (D_2O + Na_2HPO_4) δ 176.0, 133.0, 128.8, 128.3, 128.1, 45.4, 29.9. Anal. Calcd for $C_7H_9NO_2$: mol wt 139.0633. Found: mol wt 139.0635. The hydrochloride was prepared by dissolving the (±)-gabaculine in methanol and adding dry HCl. Recrystallization as described for (±)-gabaculine gave material of mp 197–199 °C (lit.[11] mp 198–200 °C). A mixture melting point (mp 198–200 °C) with an authentic sample was undepressed.

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Registry No. **2**, 19293-62-0; **3**, 70729-06-5; **4**, 70729-07-6; **5**, 70729-08-7; **6**, 70729-09-8; **7**, 70729-10-1; **8**, 70729-11-2; **9**, 2442-10-6; **10**, 70729-12-3; **11**, 70729-13-4; **12**, 70729-14-5; **13**, 70729-15-6; **14**, 70729-16-7; **15**, 62750-74-7; **17**, 61210-85-3; **18**, 70729-17-8; **18** formate, 70729-18-9; **19**, 70729-19-0; **20**, 70729-20-3; **20** formate, 70729-21-4; **21** isomer 1, 70729-22-5; **21** isomer 2, 70729-23-6; **22**, 70765-95-6; **23**, 70765-96-7; **24**, 59556-18-2; **24** HCl, 59556-17-1; **27**, 70729-24-7; **28**, 70729-25-8; (*E,E*)-sorbyl acetate, 57006-69-6; geranyl acetate, 105-87-3; neryl acetate, 141-12-8; 4,4′-dimethoxybenzophenone, 90-96-0; 4,4′-dimethoxybenzyhydryl chloride, 7525-23-7; (*E*)-7-methyl-2-octen-1-ol acetate, 70729-26-9; 7-methyl-1-octen-3-ol acetate, 70729-27-0.

Supplementary Material Available: Mass spectral data (2 pages). Ordering information is given on any current masthead page.

Transition Metal Promoted Alkylations of Unsaturated Alcohols. Alkylation of Alkynols with Organoalanes Promoted by Group 4a Metal–Cyclopentadienyl Compounds

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Studies on the carbometalation of several alkynols, using bis(cyclopentadienyl)- and bis(methylcyclopentadienyl)titanium dichloride–organoalane systems, are reported. Alkynols of three types were examined: (1) $HO(CH_2)_nC{\equiv}CH$, n = 2, 3, 4; (2) $HOCHRCH_2C{\equiv}CH$, R = CH_3, C_2H_5; and (3) $HOCH_2CH_2C{\equiv}CR$, R = CH_3, C_2H_5. Additionally, 3-butyn-1-ol was examined with bis(cyclopentadienyl)zirconium dichloride–organoalanes. Finally, the carbometalation of the trimethylsilyl ether of 3-butyn-1-ol was studied with bis(cyclopentadienyl)titanium dichloride–diethylaluminum chloride. All substrates react to produce substituted olefinic alcohols.

There have been recent studies on the regulated carbometalation of alkynols[1] and alkynes,[2] using organoalanes with group 4 transition-metal compounds. Negishi and co-workers[2] have found that acetylenes react with organoalane–bis(cyclopentadienyl)zirconium dichloride reagents to produce alkenylmetals selectively in high yields. The system is characterized as providing "a novel, selective, and operationally simple route to trisubstituted olefins" with starting alkynes of the type $RC{\equiv}CH$. Also, preliminary investigations were reported[2d] for the alkylation of alkynes with a $Al(CH_3)_3$–(η^5-$C_5H_5)_2TiCl_2$ system which was described as one which would often be complementary to the $Al(CH_3)_3$–(η^5-$C_5H_5)_2ZrCl_2$ reagent. Rausch and Boon[3] reported that photolysis of a (η^5-$C_5H_5)_2Ti(CH_3)_2$–diphenylacetylene solution gave the *syn*-methyl-titanated product in 18% yield. Their work represents the "first definite example of the insertion of unsaturated hydro-

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carbons of the type of $RC\equiv CR$ into carbon–titanium σ bonds". Related to the work reported herein, McGuirk, Marfat, and Helquist[4] have reported the synthesis of homoallylic alcohols containing trisubstituted olefinic double bonds.

We have examined the ethylation via diethylaluminum chloride of several alkynols which were bound as alkynoxo ligands in *cis*-chloro(alkynoxy)bis(2,4-pentanedionato)titanium(IV) complexes.[1a,b] Selective carbometalation was observed for the alkynols with the unsaturation in the γ and δ positions although the yields were not optimal. Subsequent work with a limited number of alkynols showed that $(\eta^5\text{-}C_5H_5)_2TiCl_2\text{–}Et_2AlCl$–alkynol systems were capable of giving much better yields of carbometalated products with greater synthetic convenience.[1c] However, poor regioselectivity with terminal acetylenic alcohols was observed. In this paper, we wish to report primarily extended studies on the carbometalation of several alkynols using bis(cyclopentadienyl)- and bis(methylcyclopentadienyl)titanium dichloride–ethylaluminum systems.

Experimental Section

Materials. The alkynols were purchased from Farchan Research Laboratories and were used without further purification except for storage over Linde 3-A molecular sieves. Organoaluminum reagents were obtained from the Ethyl Corporation as neat liquids and used without further purification. Methylene chloride solutions of the organoalanes (ca. 1.5 M) were prepared in a drybox for use in the alkylation reactions. Methylene chloride was redistilled under nitrogen over phosphorus pentoxide and stored under nitrogen. All liquids were transferred using syringe and drybox techniques.

Bis(cyclopentadienyl)titanium dichloride was purchased from Alfa products and used as received. Bis(methylcyclopentadienyl)titanium dichloride was obtained as a gift from Hercules, Inc. Bis(cyclopentadienyl)zirconium dichloride was obtained from Apache Chemicals and used without further purification. Trimethylchlorosilane was used as purchased from Alfa Products. $(CH_3)_3SiOCH_2CH_2C\equiv CH$ was prepared by the method of Langer, Connell, and Wender.[5]

Representative Procedure for Alkynol Alkylations. For a typical reaction, 40 mmol of an organoalane in methylene chloride (1.5 M) was added to a 250-mL round-bottom three-necked flask equipped with a gas inlet, magnetic stirring bar, and 50-mL dropping funnel; the final concentration was adjusted to 0.75 M with additional solvent. The dropping funnel was charged with 20 mmol of alkynol and 25 mL of methylene chloride. The organoalane solution was cooled to 0 °C, and the alkynol solution was added dropwise to form the alkynoxy–organoalane system (solution I).

To a second 250-mL flask, equipped as described above, an appropriate amount of $(\eta^5\text{-}C_5H_5)_2TiCl_2$, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$, or $(\eta^5\text{-}C_5H_5)_2ZrCl_2$ was added followed by 50 to 100 mL of methylene chloride; the resulting solution was cooled to the desired temperature. Solution I was transferred to the dropping funnel and added dropwise. The reactions were terminated by the addition of 8 mL of methanol followed by 50 mL of a 5% sulfuric acid solution saturated with sodium chloride. The resulting solution was stirred over an oxygen atmosphere for 30–60 min, filtered over a bed of Celite, and then extracted with five 50-mL portions of diethyl ether. The ether extract was dried over magnesium sulfate and then filtered. The product solutions were reduced in volume, filtered, and analyzed by GLC.

Gas Chromatography. Yields were determined by GLC (HP 5750) with the internal standard technique, using an 8 ft. × $^1/_8$ in. XE-60 and/or a 6-10 ft. × $^1/_8$ in. Carbowax 20M column, and are corrected for response factors.[17] Samples were isolated for spectral investigation by preparative GLC, using 6 and 10 ft. × $^1/_4$ in. XE-60 and Carbowax 20M columns, respectively.

Spectra. NMR and IR spectra were taken with Perkin-Elmer R-20B and 457 spectrometers, respectively.

Product Characterization. The structure assignments for the products from the carbometalation of terminal alkynols were derived primarily from NMR and IR measurements.[6] The cis and trans alkenols are distinguished readily from the strong characteristic IR bands in the regions 665–730 and 960–980 cm^{-1}, respectively; a characteristic vinylidene absorption occurs from 885 to 895 cm^{-1}. In the proton NMR, $=CH_2$ groups absorb at substantially higher fields than $=CHR$ groups. The following products prepared from terminal alkynols in this study have been reported previously: (1) 3-ethyl-3-buten-1-ol;[7] (2) *trans*-3-hexen-1-ol;[8] (3) 4-ethyl-4-penten-1-ol;[9] (4) *trans*-4-hepten-1-ol;[10] (5) 5-octen-1-ol;[11] (6) 4-hepten-2-ol;[12] (7) 3-methyl-3-buten-1-ol;[13] and (8) *trans*-3-penten-1-ol.[14] Spectral measurements were all consistent with the assigned structures. Several product alkenols were not found in the literature; selected characterization data for these are presented. **(1) 5-Ethyl-5-hexen-1-ol**: IR (CCl_4) 3310 (OH), 3075, 1640, 890 cm^{-1} ($>C=CH_2$); ^1H NMR (CCl_4) δ 4.67 (s, $=CH_2$); GLC retention time 9.0 min; column 10% XE-60 on Chromosorb WHP (80-100 mesh), 8 ft × $^1/_8$ in. in series with 10% Carbowax 20M on Chromosorb WAW (80-100 mesh), 6 ft × $^1/_8$ in., column temperature 135 °C, carrier gas N_2, 30 mL/min. **(2) 4-Ethyl-4-penten-2-ol**: IR (CCl_4) 3400 (OH), 3080, 1645, 895 cm^{-1} ($>C=CH_2$); ^1H NMR (CCl_4) δ 4.76 (s, $=CH_2$); GLC retention time 3.02 min; column 10% XE-60 on Chromosorb WHP (80–100 mesh), 8 ft × $^1/_8$ in., column temperature 95 °C, carrier gas He, 30 mL/min. **(3) 5-Octen-3-ol**: IR (CCl_4) 3400 (OH), 3080, 965 cm^{-1} (*trans*-$CH=CH$); ^1H NMR (CCl_4) δ 5.45 (m, $-HC=CH-$); GLC retention time 3.67 min; conditions as those immediately above except for a column temperature of 110 °C. **(4) 5-Ethyl-5-hexen-3-ol**: IR (CCl_4) 3400 (OH), 3080, 885 cm^{-1} ($>C=CH_2$); ^1H NMR (CCl_4) δ 4.77 (s, $=CH_2$); GLC retention time 3.18 min; conditions are the same as those immediately above.

For the internal alkynol 3-pentyn-1-ol, only a single major product was observed: 4-methyl-3-hexen-1-ol. This product has been reported previously,[16] and the *Z* isomer has been characterized.[15,16] We tentatively assign the *E* configuration to our product as we have observed only syn addition for all terminal alkynols in this study and others.[1] With 3-hexyn-1-ol, two ethylation products were observed. The major product is tentatively assigned as 4-ethyl-3-hexen-1-ol by comparison with the 3-pentyn-1-ol reaction product and because of its greater GLC retention time (i.e., we have commonly observed the internal carbon alkylation products to have shorter retention times). These latter two products were isolated as a mixture by preparative GLC: IR (CCl_4) 3040 (OH), 1660 ($C=C$), 1050 (CO); ^1H NMR (CCl_4) δ 5.10 (m, $C=C$), 3.54 (t, $J = 6$ Hz, CH_2O), 2.80 (s, OH), ~2.10 (m, $-CH_2-$), 1.53 (t, $J \approx 7$ Hz, CH_3), 1.51 (t, $J \approx 7$ Hz, CH_3); GLC retention time 5.48 and 596 min; conditions are the same as those for 4-ethyl-4-penten-2-ol above except for the column temperature of 98 °C.

Results and Discussion

The results of the alkynol ethylation reactions with $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ are summarized in Tables I and II, respectively. Table III contains a summary of some ad-

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Table I. Alkynol Ethylations with Bis(η^5-cyclopentadienyl)titanium Dichloride and Diethylaluminum Chloride

alkynol	react cond temp, °C	react cond time, h	molar ratios of reactants (Ti:ROH:Al)[a]	products	total yield, %	product ratio[d] internal/terminal	% of starting alkynol, recov
3-butyn-1-ol	0	0.25	0.1:1:2.5	*trans*-3-hexen-1-ol (I) 3-ethyl-3-buten-1-ol (II)	60	50/50	25
	0	2	0.1:1:2.5	I and II	90		0
	0	6	0.1:1:1.0	I and II	10		40
4-pentyn-1-ol	0	4	0.1:1:2.0	*trans*-4-hepten-1-ol (III) 4-ethyl-4-penten-1-ol (IV)	50	63/37	20
	0	4	0.5:1:2.0	III and IV	70		0
5-hexyn-1-ol	0	4	0.1:1:2.0	*trans*-5-octen-1-ol (V) 5-ethyl-5-hexen-1-ol (VI)	10	44/56	60
	0	4	0.5:1:2.0	V and VI	70		0
4-pentyn-2-ol	0	4	0.1:1:2.0	*trans*-4-hepten-2-ol 4-ethyl-4-penten-2-ol	85	60/40	0
5-hexyn-3-ol	0	4	0.1:1:2.0	*trans*-5-octen-3-ol (VII) 5-ethyl-5-hexen-3-ol (VIII)	80	58/42	5
	0	4	0.5:1:2.0	VII and VIII	100		0
	0	4	0.75:1:2.0	VII and VIII	90		0
3-pentyn-1-ol	0	4	0.1:1:2.5	4-methyl-3-hexen-1-ol (IX)[b]	10	~7/93	
	0	6	0.25:1:2.5	IX	30		60
	0	6	0.25:1:2.0	IX	35		55
	0	6	0.25:1:2.0	IX	70		20
	0	6	0.75:1:2.0	IX	85		0
	20-25	6	0.5:1:2.5	IX	30		0
	20-25	14	0.5:1:2.5	IX	25		0
3-hexyn-1-ol	0	4	0.1:1:2.0	4-ethyl-3-hexen-1-ol (X)[c] 3-ethyl-3-hexen-1-ol (XI)		31/69	
	0	4	0.5:1:2.0	X and XI	50		30
	0	4	0.75:1:2.0	X and XI	70		0

[a] The numbers refer to $Al(C_2H_5)_2Cl$ as a monomeric species. [b] The major product as assigned from NMR and GLC observations. We presume that this product has the *E* configuration resulting from syn addition as observed in the above reactions. [c] X is assigned as the major product by comparison with the 3-pentyn-1-ol reaction and because of its greater GLC retention time. Again the *E* configuration is inferred. [d] No regular or significant changes in product ratios were observed from changes in stoichiometry.

Table II. Alkynol Ethylations with Bis(η^5-methylcyclopentadienyl)titanium Dichloride and Diethylaluminum Chloride

alkynol	react cond temp, °C	react cond time, h	molar ratios of reactants (Ti:ROH:Al)	products	total yield, %	product ratio internal/terminal	% of starting alkynol recov
3-butyn-1-ol	0	4	0.1:1:2.0	*trans*-3-hexen-1-ol 3-ethyl-3-buten-1-ol	100	56/44	0
4-pentyn-1-ol	0	4	0.1:1:2.0	*trans*-4-hepten-1-ol 4-ethyl-4-penten-1-ol	70	48/52	0
	0	4	0.5:1:2.0	*trans*-4-hepten-1-ol 4-ethyl-4-penten-1-ol	70		0
5-hexyn-1-ol	0	4	0.1:1:2.0	*trans*-5-octen-1-ol 5-ethyl-5-hexen-1-ol	80	66/34	0
	0	4	0.5:1:2.0	*trans*-5-octen-1-ol 5-ethyl-5-hexen-1-ol	95		0
4-pentyn-2-ol	0	4	0.1:1:2.0	*trans*-4-hepten-2-ol 4-ethyl-4-penten-2-ol	100	69/31	0
5-hexyn-3-ol	0	4	0.1:1:2.0	*trans*-5-octen-3-ol 4-ethyl-5-hexen-3-ol	85	68/32	0
3-pentyn-1-ol	0	4	0.1:1:2.0	4-methyl-3-hexen-1-ol	15	~5/95	78
	0	4	0.5:1:2.0	4-methyl-3-hexen-1-ol	65		30
3-hexyn-1-ol	0	4	0.1:1:2.0	4-ethyl-3-hexen-1-ol 3-ethyl-3-hexen-1-ol	10	19/81	90
	0	4	0.5:1:2.0	4-ethyl-3-hexen-1-ol 3-ethyl-3-hexen-1-ol	50		40

ditional reactions leading to the carbometalation of 3-butyn-1-ol.

We chose to study in some detail the carbometalation of alkynols with $(\eta^5\text{-}C_5H_5)_2TiCl_2$ and $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ because of the reported interest in cyclopentadienyltitanium compounds as components of Ziegler-Natta olefin polymerization catalysts.[18,19] In addition to any synthetic interest, it is our expectation that the investigation of the organometallic chemistry of regulated carbotitanation reactions will eventually provide basic information germane to a firm understanding of stereoregular multiple carbometalation processes involved in catalytic olefin polymerization. We extended investigations to $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ to obtain information about the effect of alkyl-substituted cyclopentadienyl complexes. Interactions of the methyl groups with substrates and ligands about titanium were expected to affect regioselectivity. Relative

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Table III. Other Reactions Leading to the Alkylation of 3-Butyn-1-ol

carbometalation system	react cond		products	total yield, %	product ratio internal/ terminal	% of starting material recov
	temp, °C	time, h				
3-butyn-1-ol + $Al_2(C_2H_5)_6$ + 0.5$(\eta^5\text{-}C_5H_5)_2ZrCl_2$	20–25	8	*trans*-3-hexen-1-ol (I) 3-ethyl-3-buten-1-ol (II)	67[a]	63/37	20
3-butyn-1-ol + $Al_2(CH_3)_6$ + $\eta^5\text{-}C_5H_5)_2ZrCl_2$	20–25	14	*trans*-3-penten-1-ol (XIII) 3-methyl-3-buten-1-ol (XI)	66	91/9	26
3-butyn-1-ol + $Al_2(CH_3)_6$ + 0.1$(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$	0	4	XIII XIV	50	72/28	39
3-butyn-1-ol + $Al_2(CH_3)_6$ + 0.1$(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$	20–25	4	XIII XIV	75	74/26	5
$(CH_3)_3SiOCH_2CH_2C{\equiv}CH$ + $Al_2Et_4Cl_2$ + 1$(\eta^5\text{-}C_5H_5)_2TiCl_2$[b]	−25	4	I II	87	39/61	1
$(CH_3)_3SiOCH_2CH_2C{\equiv}CH$ + $Al_2Et_4Cl_2$ + 0.5$(\eta^5\text{-}C_5H_5)_2TiCl_2$[b]	0	4	I II	43	5/95	0

[a] The use of 100 mol % $(\eta^5\text{-}C_5H_5)_2ZrCl_2$ did not increase the yield under these conditions. [b] The $Al(C_2H_5)_2Cl$ and $(CH_3)_3SiOCH_2CH_2C{\equiv}CH$ were added together to a solution of the titanium compound. The trimethylsilyl ethers are hydrolyzed to the product alcohols under the conditions of the workup.

to $(\eta^5\text{-}C_5H_5)_2TiCl_2$, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ is less easily reduced. Thus, we anticipated improved yields in certain cases since reduction to a titanium(III) species in $(\eta^5\text{-}C_5H_5)_2TiCl_2\text{–}Al(C_2H_5)_xCl_{3-x}$ catalyst systems causes loss of polymerization activity and presumably loss of carbometalation activity in our systems. We have observed with $TiCl_4\text{–}Al(C_2H_5)_2Cl$ ethylations of 3-buten-1-ol that reduction to the 3+ valence state terminates carbometalation activity.[20] Finally, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ has greater solubility in nonpolar solvents relative to $(\eta^5\text{-}C_5H_5)_2TiCl_2$.

We specifically chose to emphasize the alkylation reactions with ethyl- as opposed to methylaluminum reagents for two reasons. First, the presence of a β-hydrogen in metal–ethyl linkages could lead to undesirable side reactions with respect to the goal of effecting a smooth metal–ethyl addition to the triple bond. For example, formation of titanium–ethyl groups via exchange could lead to β-hydride elimination (plus ethylene) with the formation of a titanium–hydride species which could add to the -yne functionality or cause rapid reduction to inactive titanium(III). Also, the ethylene produced could be inserted in other titanium–ethyl bonds diminishing the availability of these groups to carbometalate the alkynols. Thus, our view was that if the ethylation reactions proceeded smoothly, extension to other alkyl groups, e.g., methyl and propyl, should be possible. Second, we were influenced to study ethylaluminum compounds because of the ubiquity of their use as components of titanium–aluminum based Ziegler-Natta catalysts.

Representative alkynols of three types were examined: (1) $HO(CH_2)_nC{\equiv}CH$, $n = 2$, 3, and 4; (2) $HOCH(R)CH_2C{\equiv}CH$, R = CH_3, C_2H_5; and $HOCH_2CH_2C{\equiv}CR$, R = CH_3, C_2H_5. With the primary terminal alkynols, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ functions catalytically (10 mol % relative to alkynol) to give good combined yields of carbometalated products. In contrast, with 10 mol % $(\eta^5\text{-}C_5H_5)_2TiCl_2$, only 3-butyn-1-ol gave a high yield of products; respectable yields could be obtained with 4-pentyn-1-ol and 5-hexyn-1-ol, using 50 mol % of $(\eta^5\text{-}C_5H_5)_2TiCl_2$. These observations may be due to the more rapid reduction of the $(\eta^5\text{-}C_5H_5)_2TiCl_2$[18,21] giving an inactive species before all of the substrate has been carbometalated. (Indeed, the use of the more strongly reducing $Al(C_2H_5)_3$ with $(\eta^5\text{-}C_5H_5)_2TiCl_2$ gives no carbometalated products under similar conditions.) On the other hand, both $(\eta^5\text{-}C_5H_5)_2TiCl_2$ and $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ at 10 mol % gave good product yields with 4-pentyn-2-ol and 5-hexyn-3-ol. Overall, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ seems to give better total yields and function better at catalytic quantities. Unfortunately, neither titanium compound leads to highly regioselective reactions; however, $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$ gives a greater proportion of the internally substituted product except with 4-pentyn-1-ol. The changes in regioselectivity between the two compounds and the results of our previous carbometalation work with $\{TiCl(OR)(C_5H_7O_2)_2\}$ complexes suggest that suitable modification of ligand environments may well lead to control of the direction of addition. Interestingly, the ethylation of 3-buten-1-ol with $(\eta^5\text{-}C_5H_5)_2TiCl_2\text{–}Al(C_2H_5)_2Cl$ gives almost exclusively the internal product 3-methyl-1-pentanol.[22] For all of the terminal alkynols, addition of the ethyl group to the terminal carbon resulted in isolated products having the *E* configuration. This is consistent with syn addition of metal–ethyl groups as observed in other related titanium and zirconium work.[2,3]

Neither of the disubstituted alkynols, 3-pentyn-1-ol or 3-hexyn-1-ol, are extensively ethylated with 10 mol % of $(\eta^5\text{-}C_5H_5)_2TiCl_2$ and $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$. In order to obtain respectable yields with these substrates, it is necessary to use nearly stoichiometric quantities of the titanium compounds. The reason for this change relative to terminal alkynols is not clear.

Inspection of Table III shows that 3-butyn-1-ol can be methylated in good yields with $Al(CH_3)_3$ and 10 mol % $(\eta^5\text{-}C_5H_4CH_3)_2TiCl_2$; however, the reaction proceeds better at room temperature rather than at 0 °C. Again, syn addition occurs with the internal product dominant. 3-Butyn-1-ol with both the $Al(CH_3)_3$– and the $Al(C_2H_5)_3\text{–}(\eta^5\text{-}C_5H_5)_2ZrCl_2$ systems is alkylated with respectable yields; the methylation gives mostly the internal product. It appears that $(\eta^5\text{-}C_5H_5)_2ZrCl_2$ favors somewhat internal addition relative to $(\eta^5\text{-}C_5H_5)_2TiCl_2$. These ob-

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servations are consistent with the work of Negishi et al.,[2] who found recently internal addition favored in the $(\eta^5\text{-}C_5H_5)_2ZrCl_2$ promoted alkylation of alkynes. Finally, it was observed that the trimethylsilyl ether of 3-butyn-1-ol could be ethylated at −25 °C in high yield to give products I and II; at 0 °C, the overall yield was much lower; however, the product was nearly all *trans*-3-hexen-1-ol. Thus, it appears that the use of trimethylsilyl ether derivatives of alkynols may under certain conditions be used to modify carbometalation selectivity. Alexakis, Normant, and Villieras[23] have investigated the addition of alkylcopper–magnesium bromide reagents to the trimethylsilyl derivatives of 2-propynol and 3-butyn-1-ol. Compared with other analogous 2-propynyl and 3-butynyl systems, they found that "steric crowding on the heteroatom... enhances the ratio of branched to linear product". This substantial difference relative to our system (which favors the linear product) is not surprising at this point since the chemistry of organotitanium–aluminum systems is often quite different from that of organocopper reagents, e.g., olefin polymerization reactions.

In conclusion, we have found that the carbometalation of selected alkynols can be accomplished under mild conditions with transition metal–organoalane systems. It seems reasonable to expect that further studies with a variety of transition-metal species will lead to systems capable of giving stereo- and regioselective carbometalations of unsaturated substrates.

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Registry No. I, 928-97-2; II, 1708-98-1; III, 24469-79-2; IV, 59518-08-0; V, 64275-74-7; VI, 71097-17-1; VII, 71097-18-2; VIII, 71097-19-3; IX, 63714-11-4; X, 71097-20-6; XI, 71097-21-7; XIII, 764-37-4; XIV, 763-32-6; 4-ethyl-4-penten-6-ol, 63714-12-5; *trans*-4-hepten-2-ol, 58927-81-4; 3-butyn-1-ol, 927-74-2; 4-pentyn-1-ol, 5390-04-5; 5-hexyn-1-ol, 928-90-5; 4-pentyn-2-ol, 2117-11-5; 5-hexyn-3-ol, 19780-84-8; 3-pentyn-1-ol, 10229-10-4; 3-hexyn-1-ol, 1002-28-4; bis(η^5-cyclopentadienyl)titanium dichloride, 1271-19-8; diethylaluminum chloride, 96-10-6; bis(η^5-methylcyclopentadienyl)titanium dichloride, 1282-40-2; triethylaluminum dimer, 15203-25-5; trimethylaluminum dimer, 15632-54-9; 3-butyn-1-ol trimethylsilyl ether, 17869-75-9; diethylaluminum chloride dimer, 51466-48-9; bis(η^5-cyclopentadienyl)zirconium dichloride, 1291-32-3.

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Mercuric Trifluoroacetate Mediated Brominative Cyclizations of Dienes. Total Synthesis of *dl*-3β-Bromo-8-epicaparrapi Oxide

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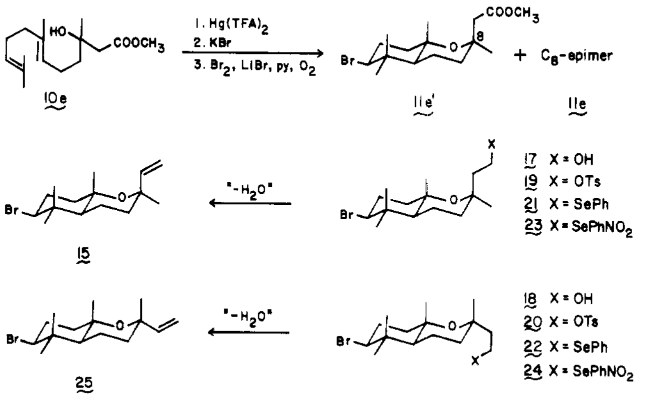
Mercuric trifluoroacetate induces the electrophilic cyclization of homogeranic acid and diene alcohols **10** with concomitant carbon–carbon bond formation to generate the bicyclic organomercury compounds **2** and **12**. The mercury substituent can be stereospecifically replaced by bromine with either retention or inversion of configuration to give the bromides **1** or **4** and **11** or **14**, respectively. Application of this net brominative cyclization to a synthesis of *dl*-3β-bromo-8-epicaparrapi oxide (**15**) in seven steps and 12% yield from geranylacetone is described.

The widespread occurrence of bromine-containing natural products from marine organisms[1] has prompted a number of investigations designed to establish methods for incorporation of a bromine atom into cyclic substrates via, formally, bromonium ion initiated polyolefin cyclizations.[2] Reagent systems that have been used successfully in this endeavor include *N*-bromosuccinimide,[3a–c] bromine in the presence of Lewis acids such as $AlBr_3$ and $SnBr_4$,[3d] bromine in the presence of silver(I) ion,[3d] and 2,4,4,6-tetrabromocyclohexa-2,5-dienone in the presence of Lewis acids.[3e,f] We recently reported an extensive investigation of the brominative cyclization of homogeranic acid to generate the trans-fused bromo lactone **1**.[4] The most efficient conditions for this cyclization appeared to

Scheme I



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