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Hydrozirconation of Lithium Alkynylselenolate Anions. Generation and Reactions of α-Zirconated Vinyl Selenide Intermediates[†]

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Lithium alkynylselenolate anions react completely with 1.0 equiv of $Cp_2Zr(H)Cl$ in THF at room temperature to give exclusively the α-zirconated vinylselenolate intermediates **23**−**27**, which by treatment with an alkyl halide afforded the α-zirconated vinyl alkylselenide intermediates **29**−**33**. Reaction of **29**−**33** with butyltellurenyl bromide results in the formation of ketene telluro(seleno) acetals **35**−**39** with total control of the regio- and stereochemistry. The synthetic utility of the ketene telluro(seleno) acetals obtained here was demonstrated by reaction of **36** with butyllithium. This promotes the exclusive and stereospecific removal of the tellurium moiety and enables formation of the corresponding selenium-containing allylic alcohol of type **44**, α-(alkylseleno)-α,*β*-unsaturated aldehyde **45**, ester **46**, or carboxylic acid **47**, after reaction with different types of electrophiles.

Introduction

Over the past decades, numerous groups have investigated various aspects of organotellurium compounds, especially their preparation and use in organic synthesis.[1,2] This has been particularly true for tellurium-containing unsaturated systems.[1,3−8] Among various synthetic strategies, the tellurium/metal exchange reactions in vinylic tellurides, as represented by Te/Li,[4] Te/Cu,[5] Te/Zn,[6] Te/Mg,[7] Te/Ca,[7] and Te/Na[7] transmetalations, possess a number of ideal properties. These reactions may take place with regio- and stereospecificity. In combination with the hydrotelluration of alkynes[1,4c,e,g,i,8] or with the hydrozirconation[3c] (or hydroalumination[3b]) of acetylenic tellurides, these reactions permit the exclusive preparation of (*Z*)-vinylmetallic reagents that are often difficult to obtain by other methods.[9] Because of such merits, intensive efforts have been focused on creating new methods for the synthesis and synthetic transformations of vinylic tellurides,[1,3−8] tellurobutenynes,[3d,4e,g,j,k] and tellurobutadienes.[3b,4c,i,k,l,10]

Other synthetically important hydrometalation processes of terminal alkynes, i.e., hydroboration,[9,11] hydroalumination,[9,12] hydrozirconation,[9,13] or hydrostannylation,[9,14] afford the (*E*)-vinylic metal isomers.[9,11−14]

[†] Dedicated to Prof. Nicola Petragnani on the occasion of his 70th birthday and for his invaluable contributions in the field of organotellurium chemistry.

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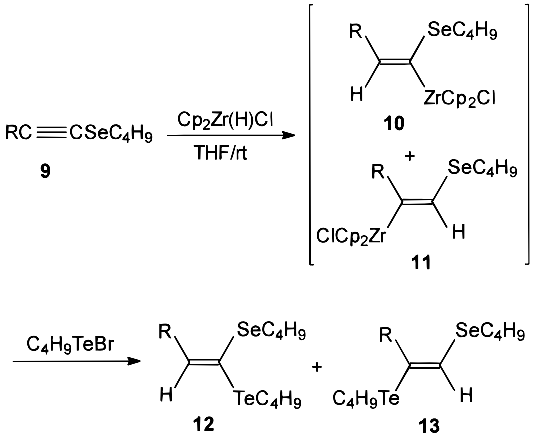
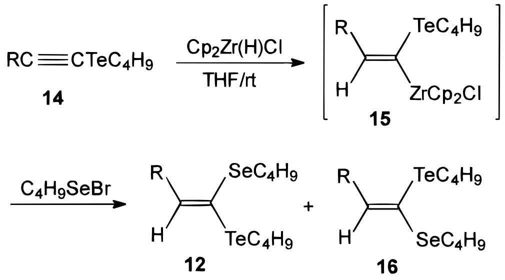
10.1021/jo991016e CCC: $19.00

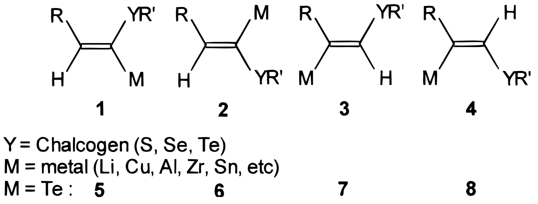
Scheme 1



Scheme 2

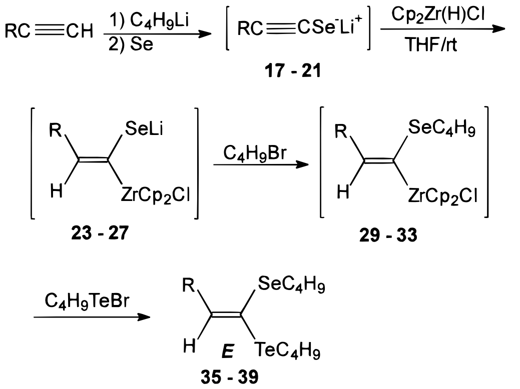


Preparation of highly functionalized vinylmetallic reagents is also of interest because carbon−carbon or carbon−heteroatom bond formation of these organometallics afford polyfunctionalized olefins.[9,15,16] The use of 1-(chalcogenovinyl)metallics **1** and **2** or 2-(chalcogenovinyl)metallics **3** and **4** could combine such processes with the specific chemistry of the vinyl chalcogenides.



We envisioned two alternative ways to reach most of the intermediates **1**−**4**. The first pathway (method 1) involves the direct hydrometalation of acetylenic species (Schemes 1−3).[3b,c,9,11−14] The second pathway (method 2) takes advantage of the higher expected reactivity in the chalcogen/metal exchange reaction for the organotellurium functionality in the presence of another organochalcogeno moiety (sulfur,[17] selenium,[3c,18] or even another tellurium[3c,4f,19] group) attached at the same double bond (Scheme 4) in compounds of type **5**−**8**. In this paper we disclose, in full, our studies on the scope and limitations in the generation of the zirconated vinylic selenides of type **1** (M = Zr) through the hydrozirconation of alkynylselenolate anions (method 1, Scheme 3). The transformation of these intermediates into the ketene telluro(seleno) acetals **5** was also achieved by the Zr/Te exchange reaction. In this paper, we also expand upon our initial Te/Li transmetalation investigations of functionalized vinylic tellurides and demonstrate that they are useful sources of highly functionalized vinyllithium intermediates. This allowed us to generate the lithiated vinylic selenides of type **1** (M = Li) by reaction with butyllithium (method 2, Scheme 4). In the accompanying paper,[20] we describe the synthesis and reactions of the ketene stannyl(telluro) acetals of type **2** (M = Sn and Y = Te). The total retention of the configuration in all steps is a critical issue in this chemistry.

Scheme 3



Results and Discussion

Hydrozirconation of terminal alkynes with $Cp_2Zr(H)Cl$ is a well-known reaction that results in exclusive formation of (*E*)-Zr-substituted alkenes. The Zr group is always added to the terminal carbon, and hydride is transferred to the internal carbon.[9,13] The same stereo- and regiochemistry was observed in the reaction of (trimethylsilyl)ethyne,[21] ethoxyethyne,[22] and (organylseleno)ethynes[3c,23] which were 100% regioselectively converted into the (*E*)-[2-(trimethylsilyl)ethenyl]zirconium, (*E*)-(2-ethoxyethenyl)zirconium, or (*E*)-[2-(arylseleno)ethenyl]zirconium derivatives, respectively, via hydrozirconation using

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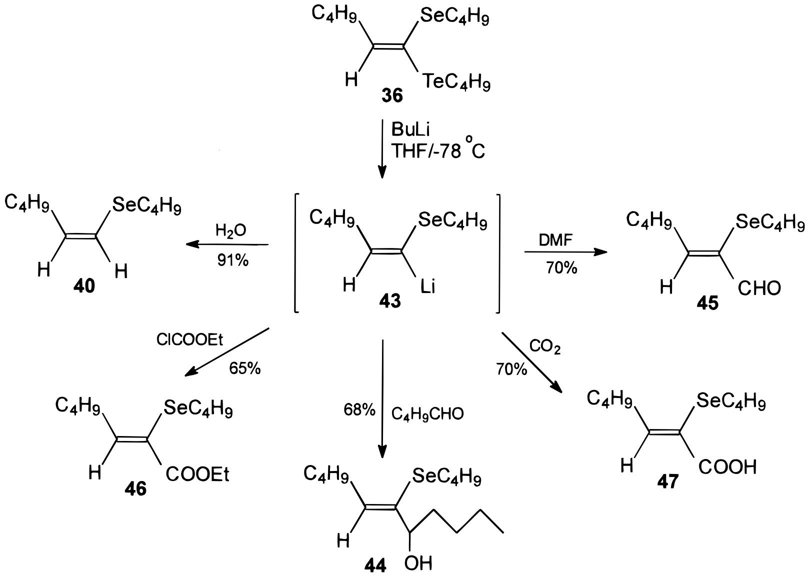
Scheme 4



Schwartz's reagent $Cp_2Zr(H)Cl$. Our studies with a wide range of internal selenoacetylenes have shown that the regioselectivity observed for the terminal (arylseleno)ethynes[23] is not general.[3c] For example, the disubstituted 1-(butylseleno)-2-phenylethyne derivative exhibits total inversion of the regiochemistry, affording only the corresponding α-zirconated vinyl selenide.[3c] Hydrozirconation of 1-(butylseleno)-2-alkylethynes **9**, however, resulted in a mixture of the α-zirconated vinyl selenide **10** and β-zirconated vinyl selenide **11**; these reacted with butyltellurenyl bromide to afford a mixture of telluro(seleno)alkenes **12** and **13**, as depicted in Scheme 1. The isomers of type **12** were the major products, indicating that the organoselenium moiety is responsible for the partial preference of the attachment of zirconium at the α position.[3c]

The tellurium functionality in telluroalkynes **14** is responsible for the regiospecificity of the hydrozirconation reaction, affording **15** as an intermediate. Although it has been demonstrated that this reaction is stereospecific,[3c] the synthesis of ketene telluro(seleno) acetals by employing the hydrozirconation of telluroalkynes **14** followed by the Zr/Se exchange reaction results in the formation of a mixture of stereoisomers **12** and **16**. Thus, the Zr/Se exchange reaction occurs with a partial inversion of the configuration (Scheme 2).[3c] These facts compelled us to develop other methods to perform the exclusive synthesis of ketene telluro(seleno) acetals **12** or **16** with total control of the regio- and stereochemistry.

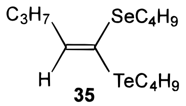
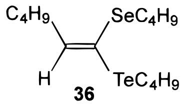
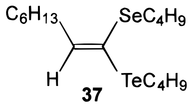
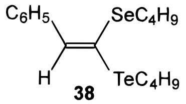
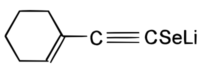
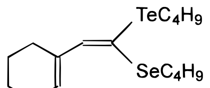
We are especially interested in the study of the reactivity of an organotellurium moiety in the presence of another vinyl organochalcogene group (Te, Se, S), because tellurium removal using several types of reagents is expected to be an extremely selective reaction. However, few compounds containing these difunctionalizations are known.[3c,4f,17−19] Previous attempts to prepare the 1-(phenylseleno)-2-(butyltelluro)alkenes **8** by the telluroalumination/selenenylation of acetylenes were unsuccessful.[3b] More recently, we described the synthesis of ketene butyltelluro(phenylseleno) acetals **12** by the Al/Te exchange reaction,[18b] showing that the addition of DIBAL-H to the carbon−carbon triple bond of acetylenic selenides is syn. Aluminum is always added to the carbon bearing the selenium moiety, and hydride is transferred to the adjacent carbon. The ketene telluro(seleno) acetals were obtained in low yields (22−50%) because the Al/Te exchange reaction is very slow in the α-aluminated vinyl selenide intermediates, and vinyl selenides of the *Z* configuration are formed as side products.[18b]

The hydrozirconation of the alkyl- or aryl-substituted lithium alkynylselenolate anions **17**−**21** (obtained in situ) with 1.0 equiv of $Cp_2Zr(H)Cl$ in THF at room temperature followed by treatment of the zirconated vinylselenolate intermediates **23**−**27** with butyl bromide results in the exclusive generation of the α-zirconated vinyl selenide intermediates **29**−**33**. Subsequently, intermediates **29**−**33** were treated with butyltellurenyl bromide, resulting in the formation of the ketene telluro(seleno) acetals **35**−**39** in good yields (Scheme 3 and Table 1). The stereochemistry for these compounds was confirmed by the measurement of the NOESY in the ^1H NMR spectra. An enhancement of the methylenic protons next to tellurium was observed as the vinylic proton of **36** was irradiated. There was no correlation between the vinylic proton and the CH_2 bonded to the selenium atom (see the Experimental Section). The correlation between the allylic protons and the CH_2 of the butylselenium group was also observed. The NOE results indicate that the vinylic hydrogen is situated close to the butyltellurium group (cis relation). No other regio- or stereoisomers were formed, as confirmed by the analytical methods employed (IR, MS, and ^1H and ^{13}C NMR) and by comparison with all other isomers and the authentic ones which were obtained previously by us using other methodologies.[3c,18b] All attempts to transform intermediate **22** (entry 6 in Table 1) into the corresponding ketene telluro(seleno) acetal by this method failed.

As an additional evidence of the stereospecific hydrozirconation and their use for the synthesis of vinylic selenides, in one experiment, after reaction of **24** (entry 2 in Table 1) with butyl bromide, the α-zirconated vinyl selenide intermediate **30** was treated with water at room temperature to provide exclusively the (*Z*)-vinylic selenide **40** in 95% yield (eq 1).

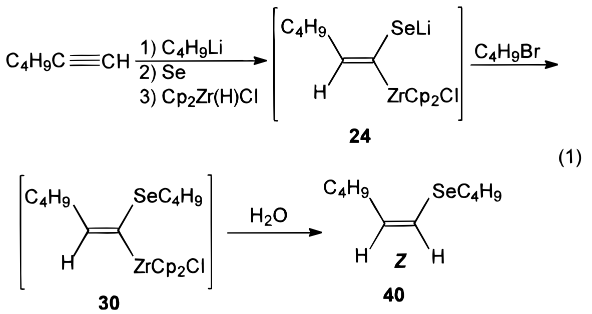
These facts show that for the preparation of vinylic selenides and other derivatives such as the ketene telluro(seleno) acetals hydrozirconation of lithium alkynylselenolates has several advantages over the hydrozir-

Table 1. Ketene Telluro(Seleno) Acetals Obtained from Alkynylselenolates

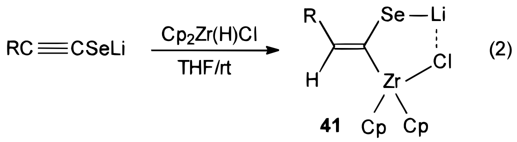
Entry	Alkynylselenolate Anion	Intermediates Formed	Product	Reaction time (min)[a]	Yield (%)
1	$C_3H_7C{\equiv}CSeLi$ **17**	**23** - **29**	 **35**	15	71
2	$C_4H_9C{\equiv}CSeLi$ **18**	**24** - **30**	 **36**	15	80
3	$C_6H_{13}C{\equiv}CSeLi$ **19**	**25** - **31**	 **37**	15	81
4	$C_6H_5C{\equiv}CSeLi$ **20**	**26** - **32**	 **38**	20	82
5	 **21**	**27** - **33**	 **39**	30	75
6	$CH_3OCH_2C{\equiv}CSeLi$ **22**	**28** - **34**	No product	-	-

[a] Hydrozirconation step.

conation of acetylenic selenides described previously:[3c] (a) lithium alkynylselenolate anions are formed in situ from terminal alkynes while acetylenic selenides must be prepared and isolated; (b) this hydrozirconation reaction is regio- and stereospecific, while the reaction of acetylenic selenides results in formation of regioisomer mixtures[3c] (Scheme 1); (c) hydrozirconation of lithium alkynylselenolate requires only 1.0 equiv of $Cp_2Zr(H)Cl$, while a similar reaction of acetylenic selenides or tellurides requires 2.0 equiv of this reagent to go to completion.[3c]



A very important observation is that only 1 equiv of Schwartz's reagent $Cp_2Zr(H)Cl$ is necessary for the total hydrozirconation of lithium selenolate anions. In this way a plausible mechanism to explain the exclusive formation of the α-zirconated vinylselenolate anions **23**−**27**, and the necessity of only 1.0 equiv of Schwartz's reagent, is based on the postulated formation of a cyclic five-membered intermediate **41** (eq 2). Cyclic intermediates could also be formed during the hydrozirconation of selenoacetylenes.[3c] However, these intermediates are not as efficient as those formed with the analogous tellurium compounds[3c] or with the lithium alkynylselenolate anion.



Recent reports by our group[3c,4h] and others[24] have shown that the Zr/Te exchange reaction on (*E*)-vinyl zirconates with organyltellurenyl halides occurs with total retention of the configuration, producing (*E*)-vinylic tellurides in good yields. In a previous paper we reported that vinylic tellurides of the *Z* configuration were obtained by us via hydrozirconation of acetylenic tellurides.[3c] The fact that only ketene telluro(seleno) acetals of the *E* configuration were obtained by treatment with C_4H_9TeBr is evidence that only intermediates of type **29**−**33** are formed, and total retention of the configuration occurs in Zr/Te exchange reactions with C_4H_9TeBr as the electrophile.

All attempts to perform hydrozirconation of the lithium alkynyltellurolate or lithium alkynylthiolate anions under similar conditions were unsuccessful. For example, after reaction of **42** with 1.0 equiv of $Cp_2Zr(H)Cl$ followed by addition of butyl bromide, the mixture was treated with water with the aim of obtaining the corresponding

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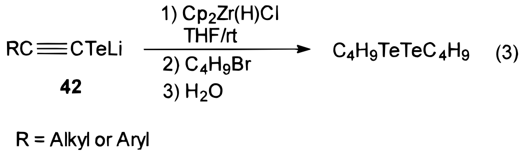
[24] Sung, J. W.; Lee, C. W.; Oh, D. Y. *Tetrahedron Lett.* **1995**, *36*, 1503.

vinylic telluride. However, only the formation of dibutyl ditelluride occurred (eq 3).



$$\mathrm{RC{\equiv}CTeLi} \xrightarrow[\substack{2)\ C_4H_9Br\\ 3)\ H_2O}]{\substack{1)\ Cp_2Zr(H)Cl\\ THF/rt}} \mathrm{C_4H_9TeTeC_4H_9} \quad (3)$$

42

R = Alkyl or Aryl

It was our belief that greater preparative significance of the functionalized vinylic tellurides described here and in the preceding paper[20] could lay in their use as precursors for the formation of carbon−carbon bonds via functionalized alkenyllithium[4] or other alkenylmetal[5−7] intermediates or participation directly in transition-metal-catalyzed cross-coupling reactions as electrophilic reagents,[25] especially because these processes could occur with total retention of the geometry of the involved double bonds. Thus, to demonstrate the synthetic utility of the obtained ketene telluro(seleno) acetals, we studied the reaction of this type of compound with butyllithium because tellurium removal was expected to be favored over selenium removal. Compound **36** (entry 2 in Table 1) was taken as a representative example; after addition of butyllithium to **36** in THF at −78 °C, the reaction mixture was treated with different electrophiles, as shown in Scheme 4. Treatment of intermediate **43** with DMF resulted in formation of the α-(butylseleno)-α,β-unsaturated aldehyde **45** in 70% isolated yield, while the use of ethyl chloroformate and CO_2 as electrophiles permitted the synthesis of the α-(butylseleno)-α,β-unsaturated ethyl ester **46** and the corresponding carboxylic acid **47** in 65% and 70% yield, respectively.

In the same way, compounds **40** and **44** were obtained on reaction of intermediate **43** with water or pentanal as electrophiles, respectively. Although it seems clear from the protonation reaction of **43** and consequent formation of the *cis*-olefin **40** that the reaction of **43** with other electrophiles affords exclusively alkenes **44**−**47** of the *Z* configuration, an additional proof was obtained by the measurement of the NOESY in ^{1}H NMR spectra of **44** and **45** to demonstrate the *Z* configuration of the trisubstituted olefins **44**−**47**. This was inferred from the observation of NOE effects, from the allylic hydrogens to the CH_2 directly attached at the selenium atom (for **44** and **45**) and from the vinylic hydrogen to the CH of the carbinol group (for **44**) or to the aldehydic hydrogen (for **45**). These observations indicate that the selenium group is situated close to the alkyl group attached to the adjacent carbon (*Z* configuration). All compounds shown in Scheme 4 were obtained in a stereochemically pure form as determined by the analytical methods employed (^{1}H and ^{13}C NMR and GC/MS). The last results described here are evidence that the Te/Li exchange reaction is faster than the Se/Li exchange reaction in ketene telluro(seleno) acetals. The selective transmetalation occurs with total retention of the configuration at the double bond, and the stereochemically pure α-lithiated (*Z*)-vinyl selenide intermediates can be captured also with total retention of the double bond geometry.

Although the synthesis of several kinds of chalcogeno-substituted olefins described in the literature had been performed using Wittig-type reactions,[4i,19b,26] the employment of this approach is not useful for the synthesis of α-chalcogeno-substituted, α,β-unsaturated aldehydes, esters, or carboxylic acids because of the difficulty in preparing the α-chalcogeno aldehyde or carboxylic acid or the low reactivity of the α-chalcogenocarboethoxy Wittig-type reagent required. On the other hand, the synthesis of α-seleno-α,β-unsaturated aldehydes,[27] esters, or carboxylic acids described here is of considerable interest from a synthetic point of view because of the presence of a versatile functional group at the α center of the organylseleno moiety.

Conclusion

The first hydrozirconation reaction of an alkynylchalcogenate anion has been developed. The α-zirconated vinylic selenides **29**−**33** were generated by Se-alkylation of the α-zirconated vinylselenolate intermediates **23**−**27**. Highly functionalized and stereoisomerically pure ketene telluro(seleno) acetals **35**−**39** were obtained under mild conditions by the Zr/Te exchange reaction of **29**−**33** with butyltellurenyl bromide. When the Te/Li exchange reaction of **36** was carried out with butyllithium at −78 °C followed by treatment with an aldehyde, DMF, CO_2, or ethyl chloroacetate as the substrate, the corresponding selenium-containing allylic alcohol **44**, α-(alkylseleno)-α,β-unsaturated aldehyde **45**, ester **46**, or carboxylic acid **47** were obtained in good yields with the same double-bond geometry as that present in the original α-zirconated vinylic selenide intermediate **43**. Combined with the vinylic selenides chemistry, these mild, selective, and general methods disclosed here will be useful for the synthesis of a wide variety of other highly functionalized multisubstituted olefins.

Experimental Section

General Remarks. ^{1}H and ^{13}C NMR spectra of $CDCl_3$ solutions were recorded with a 200, 300, or 400 MHz spectrometer as noted. Chemical shifts are expressed as parts per million (ppm) with respect to tetramethylsilane as an internal standard. Mass spectra (EI) were obtained at 70 eV with a Hewlett-Packard EM/GC HP-5988A spectrometer. Elemental analyses were performed at the Instrumental Analysis Center, Chemistry Institute, São Paulo University. Reactions were conducted in oven-dried (120 °C) glassware under a nitrogen atmosphere. Analytical TLC of all reactions was performed using E. M. Merck prepared plates (silica gel 60 F-254 on aluminum). Merck silica gel (230−400 mesh) was used for flash chromatography. Tetrahydrofuran (THF) was distilled over sodium/benzophenone immediately before use. The 1-alkynes, butyllithium (2.5 M in hexanes), and Cp_2ZrCl_2 were purchased from Aldrich Chemical Co., Inc. Dibutyl ditelluride,[28] $Cp_2Zr(H)Cl$,[29] acetylenic tellurides,[30] and selenides[31] were prepared by methods reported in the literature.

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(25) (a) Uemura, S.; Fukuzawa, S. *Tetrahedron Lett.* **1982**, *23*, 1181. (b) Dabdoub, M. J.; Dabdoub, V. B.; Marino, J. P. Results to be published.

(26) (a) Lee, C. W.; Koh, Y. J.; Oh, D. Y. *J. Chem. Soc., Perkin Trans. 1* **1994**, 717. (b) Silveira, C. C.; Perin, G.; Braga, A. L. *J. Chem. Res. (S)* **1994**, 492. (c) Silveira, C. C.; Perin., G.; Braga, A. L.; Petragnani, N. *Synlett* **1995**, 58. (d) Silveira, C. C.; Begnini, M. L.; Boeck, P.; Braga, A. L. *Synthesis* **1997**, 221.

(27) In a recent paper,[16] a very interesting and novel approach for the synthesis of α-seleno(or thio)-α,β-unsaturated aldehydes by the α-chalcogeno-substituted formylolefinations of ketones and aldehydes followed by acid treatment was described.

(28) Cava, M.; Engman, L. *Synth. Commun.* **1982**, *12*, 163.

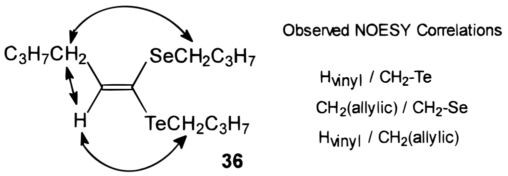
(29) Purchased from Aldrich Chemical Co., Inc., or prepared as described by: Buchwald, S. L.; LaMarie, S. J.; Nielsen, R. B.; Watson, B. T.; King, S. M. *Tetrahedron Lett.* **1987**, *28*, 3895.

(30) Dabdoub, M. J.; Comasseto, J. V. *Organometallics* **1988**, *7*, 84.

(31) Lang, H.; Keller, H.; Imhof, W.; Martin, S. *Chem. Ber.* **1990**, *123*, 417 and references therein.

General Procedure for the Synthesis of Ketene Telluro(Seleno) Acetals via Alkynylselenolate Anions. To a solution of the freshly distilled terminal alkyne (1.0 mmol) in THF (5.0 mL) under a nitrogen atmosphere was added butyllithium (1.0 mmol, 0.5 mL, 2.0 M in hexanes) at 0 °C, and the solution was stirred for 15 min. The mixture was allowed to reach room temperature, and elemental selenium (0.079 g, 1.0 mmol) was added. After total dissappearance of selenium, the solid $Cp_2Zr(H)Cl$ (0.257 g, 1.0 mmol) was added rapidly. The resulting mixture was stirred for the time indicated in Table 1, butyl bromide (0.21 mL, 2.0 mmol) was added, and the reaction was stirred at room temperature for an additional 1 h. Then, a solution of butyltellurenyl bromide (1.0 mmol) prepared separately as described in the preceding paper[20] was transferred with a syringe. The stirring was continued for an additional 30 min, and the mixture was transferred to an Erlenmeyer flask and diluted with ethyl acetate (10 mL), 95% ethanol (15 mL), and water (100 mL). Butyl bromide (1 mL) and finally $NaBH_4$ (until the solution turned pale yellow) were added to transform dibutyl ditelluride to the corresponding telluride which is more easily removed by distillation. After this treatment, the product was extracted with ethyl acetate and washed with water, the organic phase was dried over anhydrous $MgSO_4$, and the solvent was evaporated under vacuum. Dibutyl telluride was removed by distillation of the crude product using a Kugelrohr apparatus. The residue contained the ketene telluro(seleno) acetals described below, which were obtained as yellow liquids after purification by flash chromatography using hexane as the eluent in all cases.

(*E*)-1-(Butyltelluro)-1-(butylseleno)-1-hexene (36): yield 0.32 g (80%); MS/GC *m/z* 406 (4.23), 404 (5.40), 81 (100.00), 57 (36.07); ^{1}H NMR (300 MHz) (δ in $CDCl_3$) 0.85−0.95 (m, 9H), 1.3−1.5 (m, 8H), 1.62 (quint, J = 7.3 Hz, 2H), 1.78 (quint, J = 7 Hz, 2H), 2.33 (q, J = 7.3 Hz, 2H), 2.73 (t, J = 7.3 Hz, 2H), 2.79 (t, J = 7.3 Hz, 2H), 6.68 (t, J = 7.3 Hz, 1H); ^{13}C NMR 10.8, 14.7, 14.2, 14.5, 22.8, 23.5, 25.7, 31.8, 33.0, 34.2, 35.0, 98.4, 152.3. Anal. Calcd for $C_{14}H_{28}TeSe$: C, 41.73; H, 7.00. Found: C, 41.99; H, 6.67.

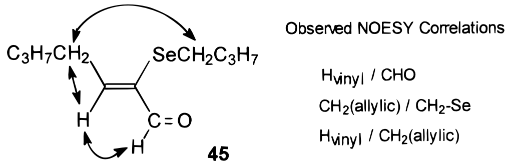


36

(*Z*)-1-(Butylseleno)-1-hexene (40).[3c] The α-zirconated hexenyl butyl selenide intermediate **30** obtained as described above was treated with water, affording (*Z*)-1-(butylseleno)-1-hexene (**40**): reaction scale 1.0 mmol; yield 0.208 g (95%); GC/MS *m/z* 220 (7.39), 218 (26.79), 161 (100.00); ^{1}H NMR (400 MHz) (δ in $CDCl_3$) 0.90 (t, J = 7.2 Hz, 3H), 0.92 (t, J = 7.2 Hz, 3H), 1.2−1.5 (m, 6H), 1.6−1.8 (m, 2H), 2.10 (dq, J = 7.2 and 1.3 Hz, 2H), 2.66 (t, J = 7.2 Hz, 2H), 5.86 (dt, J = 8.9 and 6.8 Hz, 1H), 6.20 (dt, J = 8.9 and 1.3 Hz, 1H); ^{13}C NMR 13.5, 13.9, 22.3, 22.8, 26.2, 29.9, 31.0, 33.1, 120.1, 133.1.

Te/Li Exchange Reaction on Compound 36. Preparation and Use of the α-Lithiated Vinyl Selenide 43. To a solution of 1-(butyltelluro)-1-(butylseleno)-1-hexene (**36**; 0.40 g, 1.0 mmol) in THF (5.0 mL) under nitrogen at −78 °C was added butyllithium (0.47 mL, 1.0 mmol, 2.1 M in hexanes), followed by immediate addition of the electrophile. The reaction was stirred for the time indicated in the specific procedure described below. Total transformation of the starting material was confirmed following the reaction by TLC on SiO_2 using hexane as the eluent. Then, the reaction mixture was treated with water, diluted with ethyl acetate, and washed with a saturated solution of ammonium chloride and water. The organic phase was dried over anhydrous $MgSO_4$ and the solvent evaporated under reduced pressure. After purification as indicated below, the products were obtained as yellow oils.

(*Z*)-2-(Butylseleno)-2-hepten-1-al (45). To the solution of α-butyl selenide hexenyllithium intermediate **43** obtained as described above was added dimethylformamide (0.07 mL, 1.0 mmol) at −78 °C. After 5 min the reaction was allowed to reach room temperature and stirred for an additional $^1/_2$ h. After workup as described above and purification by flash chromatography using a mixture of hexane/ethyl acetate (8:2), the corresponding (*Z*)-2-(butylseleno)-2-hepten-1-al (**45**) was obtained: yield 0.17 g (70%); MS *m/z* 248 (77.68), 246 (42.65), 81 (87.67), 57 (47.15), 41 (100.00); ^{1}H NMR (200 MHz) (δ in $CDCl_3$) 0.80 (t, J = 7.2 Hz, 3H), 0.87 (t, J = 7.2 Hz, 3H), 1.2−1.6 (m, 8H), 2.55 (q, J = 7.2 Hz, 2H), 2.76 (t, J = 7.2 Hz, 2H), 7.01 (t, J = 7.2 Hz, 1H), 9.29 (s, 1H); ^{13}C NMR 13.4, 13.8, 22.2, 22.8, 25.4, 30.3, 32.3, 32.7, 153.6, 162.2, 191.6. Anal. Calcd for $C_{11}H_{20}SeO$: C, 53.44; H, 8.15. Found: C, 53.83; H, 7.97.

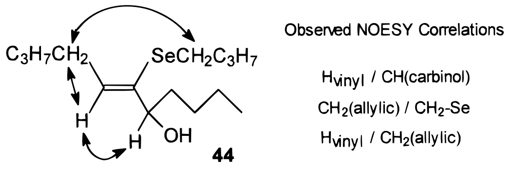


45

(*Z*)-Ethyl 2-(Butylseleno)-2-hepten-1-oate (46). To the solution of α-butyl selenide hexenyllithium intermediate **43** obtained as described above was added ethyl chloroformate (0.20 mL, 2.0 mmol) at −78 °C. After 5 min the reaction was allowed to reach room temperature and stirred for an additional 1h. After workup as described above and purification by flash chromatography using a mixture of hexane/ethyl acetate (8:2), the corresponding (*Z*)-ethyl 2-(butylseleno)-2-hepten-1-oate (**46**) was obtained: yield 0.19 g (65%); GC/MS *m/z* 292 (23.27), 81 (100.00); ^{1}H NMR (200 MHz) (δ in $CDCl_3$) 0.89 (t, J = 7.3 Hz, 3H), 0.95 (t, J = 7.3 Hz, 3H), 1.32 (t, J = 7.2 Hz, 3H), 1.3−1.7 (m, 8H), 2.44 (q, J = 7.3 Hz, 2H), 2.77 (t, J = 7.3 Hz, 2H), 4.27 (q, J = 7.3 Hz, 2H), 7.19 (t, J = 7.3 Hz, 1H); ^{13}C NMR 13.5, 13.9, 14.2, 22.4, 22.8, 27.0, 30.6, 61.5, 123.5, 151.8. Anal. Calcd for $C_{13}H_{24}SeO_2$: C, 53.41; H, 8.20. Found: C, 53.40; H, 8.30.

(*Z*)-2-(Butylseleno)-2-hepten-1-oic Acid (47). CO_2 was bubbled through the reaction mixture containing the α-butyl selenide hexenyllithium intermediate **43** obtained as described above for 1 h at room temperature. The reaction mixture was subsequently treated with a (10%) HCl solution (3 mL), extracted with ethyl acetate, and washed with water. After workup as described above and purification by flash chromatography using a mixture of hexane/ethyl acetate (8.5:1.5), the corresponding (*Z*)-2-(butylseleno)-2-heptenoic acid (**47**) was obtained: yield 0.18 g (70%); GC/MS *m/z* 266 (10.83), 264 (55.84), 262 (25.82), 81 (100.00), 57 (46.46), 41 (94.47); ^{1}H NMR (400 MHz) (δ in $CDCl_3$) 0.89 (t, J = 7.0 Hz, 3H), 0.93 (t, J = 7.0 Hz, 3H), 1.2−1.7 (m, 8H), 2.50 (q, J = 7.0 Hz, 2H), 2.80 (t, J = 7.0 Hz, 2H), 7.41 (t, J = 7.0 Hz, 1H), 10.78 (br s, 1H); ^{13}C NMR 13.5, 13.8, 26.7, 27.2, 29.6, 31.3, 32.4, 32.8, 122.7, 155.6. Anal. Calcd for $C_{11}H_{20}SeO_2$: C, 50.19; H, 7.66. Found: C, 50.29; H, 7.61.

(*Z*)-6-(Butylseleno)-6-undecen-5-ol (44). To the solution of α-butyl selenide hexenyllithium intermediate **43** obtained as described above was added pentanal (0.11 mL, 1.0 mmol) at −78 °C, and after 5 min the reaction was allowed to reach room temperature and stirred for an additional 15 min. After the workup described above and purification by flash chromatography using a mixture of hexane/ethyl acetate (9:1), the corresponding (*Z*)-6-(butylseleno)-6-undecen-5-ol (**44**) was obtained: yield 0.207 g (68%); GC/MS *m/z* 303 (4.90), 301 (2.50), 57 (61.32), 55 (62.50), 41 (100.00); ^{1}H NMR (300 MHz) (δ in $CDCl_3$) 0.86 (m, 9H), 1.28 (m, 10H), 1.57 (m, 4H), 2.10 (d, J =



44

7.0 Hz, 1H), 2.31 (q, $J = 7.0$ Hz, 2H), 2.61 (t, $J = 7.0$ Hz, 2H), 3.97 (q, $J = 7.0$ Hz, 1H), 5.91 (t, $J = 7.0$ Hz, 1H); ^{13}C NMR 13.5, 13.8, 22.3, 22.5, 22.8, 27.3, 27.9, 31.2, 32.7, 36.4, 136.0, 137.2. Anal. Calcd for $C_{15}H_{30}SeO$: C, 59.00; H, 9.90. Found: C, 59.30; H, 9.99.

Acknowledgment. This research was supported by a Grant in Aid for Scientific research from FAPESP. Thanks are due to Professor Antonio Gilberto Ferreira (UFSCar) for providing NMR facilities and to Mr. Djalma Batista Gianetti for assistance in obtaining infrared and mass spectra. Acknowledgments are also made to Dr. Joseph Gardner for revision of the manuscript.

Supporting Information Available: Lists of spectral data of compounds **35** and **37**−**39**. Copies of the ^{1}H NMR, ^{13}C NMR, and mass spectra of compounds **35**−**40** and **44**−**47**. NOESY experiments of compounds **36**, **44**, and **45**. This material is available free of charge via the Internet at http://pubs.acs.org.

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