A Novel Stereoselective Preparation of Various Vinyl Sulfide Derivatives Using β-Alkylthioalkenylselenonium Salts

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Received April 25, 2000

The treatment of alkynylselenonium salt and various thiophenol derivatives with a catalytic amount of triethylamine gave β-arylthioalkenylselenonium salts in good yields. The alkenylselenonium salts thus prepared reacted with nucleophiles such as acetylides, thiolates, and alkoxides to produce (*Z*)-β-arylthio-α-functionalized ethenes in high yields. The vinylselenonium salts bearing a hydroxy group on a β-side chain caused intramolecular cyclization upon treatment with sodium hydride to produce medium-membered heterocyclic compounds containing sulfur and oxygen atoms. The reactions giving (*Z*)-β-arylthio-α-functionalized ethenes would proceed via the formation of selenurane intermediates followed by the ligand coupling reaction.

Introduction

Vinyl sulfides (α,β-unsaturated sulfides) have been generally accepted as useful intermediates in organic synthesis. They show very efficient behavior as acceptors in Michael addition and Peterson olefination sequences[1] and as synthetic equivalents of enolonium ions,[3] as well as in the preparation of carbonyl compounds by mercury(II)-promoted hydrolysis,[2] the synthesis of stereodefined alkenes by the cross-coupling reaction with Grignard reagents,[4] the formation of vinyl anion,[5] and a large range of cycloaddition reactions such as Diels−Alder and ene reactions.[6] However, even though there have been several reports on the regioselective synthesis of vinyl sulfides because of their versatility,[7] not many methods for the stereoselective synthesis of vinyl sulfides have been reported.[8] Therefore, the development of a novel method is needed.

We have reported the reactions of alkynylselenonium salts with some nucleophiles. Michael addition occurred in the reactions with benzenesulfinic acid[9] or sodium active methylenide.[10] On the other hand, aryllithium as a nucleophile mainly attacked the selenium atom of alkynylselenonium salts.[11] These results indicated that the soft nucleophile such as sulfinyl anion and carbanions generated from active methylene compounds caused the Michael-type addition to the carbon−carbon triple bond of the alkynylselenonium salts and the hard carbanion like phenyllithium attacked the selenium atom of the selenonium salts. Thiol derivatives as a nucleophile are more widely available and can be more easily prepared

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10.1021/jo000640k CCC: $19.00
Published on Web 12/06/2000

Table 1. Reactions of Alkynylselenonium Salt 1 with Thiols

entry	RSH (equiv)	conditions	products (% yield)	
1	PhSH (2)	rt, 24 h	**1** (20)[e]	**2a** (10)[e]
2	PhSH (5)	rt, 24 h		**2a** (38)
3[a]	PhSH (1.1)	rt, 30 min		**2a** (62)
4[b]	PhSH (1.1)	rt, 30 min		**2a** (65)
5	*p*-MeC_6H_4SH (5)	rt, 24 h	**1** (4)[e]	**2b** (8)[e]
6[a]	*p*-MeC_6H_4SH (1.1)	rt, 30 min		**2b** (55)
7	*p*-ClC_6H_4SH (5)	rt, 24 h		**2c** (48)
8[a]	*p*-ClC_6H_4SH (1.1)	rt, 30 min		**2c** (63)
9[c]	*o*-$HOOCC_6H_4SH$ (1.1)	rt, 30 min		**2d** (75)
10	*o*-$H_2NC_6H_4SH$ (1.2)	rt, 10 min		**2e** (90)
11[a]	*o*-$Me(O)CC_6H_4SH$ (1.1)	rt, 30 min		**2f** (78)
12[a]	*o*-HOC_6H_4SH (1.1)	rt, 30 min		**2g** (66)
13[a]	*o*-$HOCH_2C_6H_4SH$ (1.1)	rt, 30 min		**2h** (85)
14[a]	*o*-$OH(CH_2)_2C_6H_4SH$ (1.1)	rt, 30 min		**2i** (75)
15[a]	$PhCH_2SH$ (1.1)	rt, 12h	**1** (53)	
16[d]	$PhCH_2SH$ (1.5)	−10 °C, 5 min		**2j** (23)
17[d]	$HO(CH_2)_2SH$ (1.5)	−10 °C, 5 min		**2k** (15)

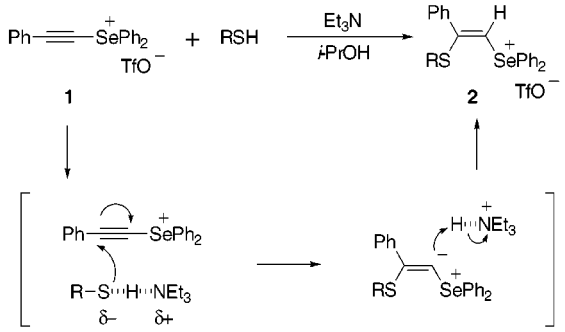
[a] 0.1 equiv of Et_3N was added. [b] 0.1 equiv of aniline was added. [c] 1.2 equiv of Et_3N was added against arenethiol. [d] Aqueous $NaHCO_3$ was added until the reaction mixture was neutral. [e] Determined by ^1H NMR.

than sulfinic acid derivatives. In addition, (*Z*)-*β*-sulfonylalkenylselenonium salts with two kinds of electron-withdrawing groups on the double bond, prepared from the above-mentioned reaction of alkynylselenonioum salts with benzenesulfinic acid, reacted with a variety of alkoxides to produce (*Z*)-*β*-alkoxyvinyl sulfones with retention of the configuration via a Michael-type addition/elimination process not to the vinylselenonium salt but to the vinyl sulfone.[9,12] Interestingly, if the sulfonyl group in *β*-sulfonylalkenylselenonium salts is replaced by an alkylthio group, the reactivity of the *β*-alkylthioalkenylselenonium salts against nucleophiles will be changed and it is anticipated that the Michael-type addition against the selenonio group would occur at only *β*-carbon. On the basis of this background, we have recently succeeded in the first synthesis of (*Z*)-*β*-alkylthioalkenylselenonium salts and investigated the reactions of the selenonium salts with nucleophiles.[13] The nucleophiles unexpectedly attacked the α-vinyl carbon of the alkenylselenonium salts. This paper provides a full description of the preliminary results of our extensive study.

Results and Discussion

First, the reactions of diphenylalkynylselenonium triflate **1** with various thiols in *i*-PrOH at room temperature were examined. The results are shown in Table 1. The reaction with 2 equiv of thiophenol for 24 h afforded an inseparable mixture of a Michael adduct **2a** and unreacted starting material **1** in 10% and 20% yields, respectively (entry 1). Using 5 equiv of thiophenol in this reaction exhausted **1**, and the yield of the adduct **2a** was increased in a 38% yield (entry 2). On the other hand, the intended product was scarcely obtained from the reaction with *p*-thiocresol (entry 5), and the reaction with *p*-chlorothiophenol for 12 h under the same conditions used for entry 2 produced vinylselenonium salt **2c** in a 48% yield (entry 7). These results showed that the more acidic arenethiol derivative gave a better yield of the

Scheme 1



vinylselenonium triflate **2** and that an increase of nucleophilicity of thiols was important for the reactions. Therefore, the reactions in the presence of a catalytic amount of Et_3N were examined, and yields were improved by the addition of a catalytic amount of Et_3N (Scheme 1). The reaction with 1.1 equiv of thiophenol in the presence of 0.1 equiv of Et_3N for only 30 min afforded **2a** in a 62% yield (entry 3). The use of aniline as weaker base than Et_3N also gave **2a** in 66% yield (entry 4). The reaction of thiosalicylic acid also proceeded in high yield using 1.2 equiv of Et_3N (entry 9). To confirm the effect of an amine, the reaction with *o*-aminothiophenol without triethylamine was carried out to afford the desired compound **2e** in a 90% yield only for 10 min (entry 10). The reaction with other arenethiol derivatives bearing neutral substituents such as a chloro, methyl, hydroxy, or acetyl group also produced vinylselenonium salts **2** in good yields (entries 6, 8, 11−14). From these findings it is very important that preparation of the *β*-arylthioalkenylselenonium salts is conducted in the presence of a small amount of a weak base. The base activates the nucleophilicity of thiols by the interaction between the base and a thiol group. In contrast to arenethiols, alkanethiols did not produce good results. The vinylselenonium salts were provided from the reactions with phenylmethanethiol and 2-mercaptoethanol in only 23% and 15% yields, respectively, after neutralization of the reaction mixture with aqueous $NaHCO_3$ (entries 16 and 17). However, the reaction of alkynylselenonium salt **1** with phenylmethanethiol in the presence of 0.1 equiv of Et_3N did not afford the desired alkenylselenonium salt, but alkynylselenonium salt **1** was recovered in 53% yield (entry 15). The (*Z*) stereochemistry of **2** was determined by the NOE technique, and the results were attributable to the *anti*-addition of thiols against alkynyl moiety. The NOE experiment of **2c** showed the enhancement between the *ortho*-protons of the *cis*-phenyl group and the vinyl proton and, moreover, no enhancement between the *ortho*-protons of the *p*-chlorophenyl group and the vinyl proton.

Next, we investigated the reactions of alkynylselenonium salt **1** with various thiolate ions bearing a hydroxy or another mercapto group (Scheme 2). The results are shown in Table 2. Treatment of **1** and 2-(hydroxymethyl)benzenethiol with NaH in THF at room temperature for 3 h produced alkynyl sulfide **3a** (40%) and 2-phenyl-5*H*-4,1-benzoxathiepine **5b** (29%) (entry 2). Product **5b** would be formed via intramolecular cyclization of a benzyl alcohol intermediate. The reaction with sodium 2-(hydroxyethyl)benzenethiolate afforded alkynyl sulfide **3b** (43%) together with α,*β*-diarylthiostyrene **6** (19%) instead of the corresponding cyclic com-

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Scheme 2

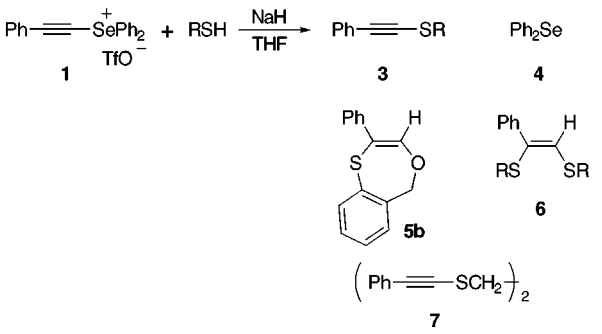


Table 2. Reactions of Alkynylselenonium Salt 1 with Sodium Thiolates

entry	RSNa (equiv)	condi-tions	products (% yield)		
1	*o*-HOC_6H_4SNa (1.1)	0 °C, 24 h	**4** (88)		
2	*o*-$HOCH_2C_6H_4SNa$ (1.1)	rt, 3 h	**3a** (40)	**4** (84)	**5b** (29)
3	*o*-$HO(CH_2)_2C_6H_4SNa$ (1.1)	rt, 3 h	**3b** (43)	**4** (74)	**6** (19)[a]
4	$HO(CH_2)_2SNa$ (1.0)	rt, 1 h	**3c** (73)	**4** (82)	
5	$HS(CH_2)_2SNa$ (1.0)	rt, 3 h		**4** (83)	**7** (48)[b]

[a] Isolated yield based on compound **6**. [b] Isolated yield based on compound **7**.

pound (entry 3). *o*-Hydroxybenzenethiolate gave a complex mixture besides **4** (entry 1), while the reaction with 2-mercaptoethanol afforded alkynyl sulfide **3c** in good yield (entry 4). 1,2-Ethanedithiol reacted with two molecules of selenonium salt **1** to give 1,2-(dialkynylthio)-ethane **7**.

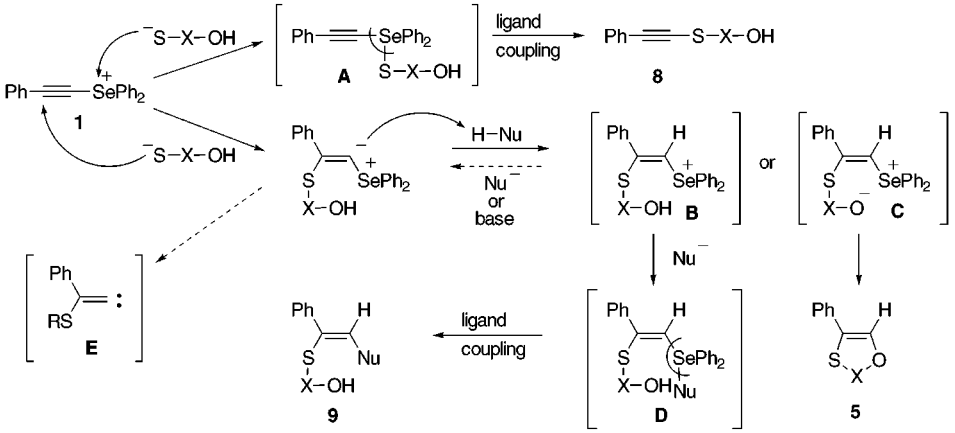
We propose a plausible mechanism for the reactions with sodium thiolates (Scheme 3). In one pathway, a thiolate anion attacks a selenium atom of **1** to form selenurane intermediate **A**, followed by ligand coupling to afford alkynyl sulfide **8**. In another pathway, a thiolate anion attacks the β-carbon of selenonium salt **1**. The resulting vinyl ylide is immediately protonated by a hydroxy or a mercapto group of the nucleophile NuH or the vinyl ylide to form an alkenylselenonium salt **B** or betaine **C**. The alkenylselenonium salt thus formed reacts with the nucleophile Nu^- to give compound **9** via the selenurane intermediate **D**. An intramolecular cyclization between the sp^2-C bearing the selenonio group and the alkoxide of **C** provides **5b**. The attack point of a thiolate ion in the first step would depend on its own nucleophilic property. The arenethiolate ions tend to attack the sp-C and the alkanethiolate ions tend to attack the positively charged selenium atom. A process via the alkylidene carbene intermediate **E** would be ruled out because formation of the alkylidene carbenes was not detected upon treating β-sulfonylalkenylselenonium salt with a base.[6a] If the above reaction proceeds via an alkenylselenonium salt intermediate **B**, it should react with the thiolate anion and alkoxide. Therefore, we carried out the reactions of alkenylselenonium salt **2** with various nucleophiles.

First, the reactions of alkenylselenonium salt **2a** with acetylides were conducted (Scheme 4, Table 3). The reaction of **2a** with lithium phenylethynylide, which was prepared from *n*-BuLi and phenylethyne, produced (*Z*)-4-phenyl-1-(phenylthio)-1-buten-3-yne **10a** in 74% yield in THF at −78 °C for 5 h (entry 1). The reactions with other acetylides such as 1-hexynylide and 3,3-dimethyl-1-butynylide also afforded desired compounds under the same conditions in good yields. The structures of **10a**−**c** were identified by spectral data. In particular, the ^1H NMR spectrum of **10b** showed the long-range coupling between a vinyl proton and protons of the 5-position (2 Hz). The (*Z*) stereochemistry of **10a**−**c** was established by observation of the NOE enhancement (10%) between the vinylic proton and *ortho*-protons of the *cis*-phenyl group in compound **10a**.

Next, the reactions of alkenylselenonium salt **2** with thiolates and alkoxides were investigated and summarized in Table 4. The reactions of **2a** with *p*-methyl- and *p*-chlorobenzenethiolate in *i*-PrOH produced 1,2-(diarylthio)ethenes in good yields (entries 1 and 2). Alkanethiolates such as 2-hydroxy- and 2-aminoethanethiolates also provided compounds **10f** and **10g** in 67% and 70% yields, respectively (entries 3 and 4). These reactions were completely stereoselective since no *E*-isomer was detected by the NMR measurement at 400 MHz. The (*Z*) stereochemistry of **10f** was established by the observation of an NOE enhancement of the *ortho*-protons of the *cis*-phenyl group (9.9%) and the methylene protons of the geminal thiolate group (5.0%) on irradiation of the vinyl proton. The reaction of **2c** with isopropoxide in *i*-PrOH afforded 2-alkoxy-1-alkylthioethene **10h** in an 86% yield without a change in the configuration similarly to the reaction with thiolate ions (entry 5). To apply this reaction to various alcohols, an equimolar amount of an alkoxide in MeCN as an aprotic solvent was used, and good results were obtained in the case of both aliphatic and aromatic alkoxides (entries 6 and 7). The NOE experiment of **10h** showed enhancement of the *ortho*-protons of the *cis*-phenyl group and the methyne protons of the geminal 2-propoxy group on irradiation of the vinyl proton. In addition, we tried to prepare chiral β-alkoxylvinyl sulfides from the reactions with chiral alkoxides by reference to the method of preparation of chiral (*Z*)-β-alkoxy-α-phenylsulfonylstyrenes.[12] The reaction of **2a** with sodium (+)-1-phenylethanolate as an acyclic secondary alkoxide, which was prepared from the alcohol and NaH, gave a chiral β-alkoxylvinyl sulfide **10j** in a 74% yield at room temperature for 90 min. On the other hand, a sterically hindered secondary cyclic (−)-menthoxide prepared from (−)-menthol and PhLi also reacted with selenonium salt **2a** to produce the desired compound **10k** in good yield.

Owing to the success of the reactions of alkenylselenonium salts **2** with alkoxide in aprotic solvent, we decided to try the synthesis of medium-membered heterocyclic compounds containing sulfur and oxygen atoms via an intramolecular cyclization reaction (Scheme 5, Table 5). The reaction of alkenylselenonium salt **2g** with NaH in MeCN at −10 °C for 24 h produced a complex mixture, and the ring closure product **5a** was obtained in only a 17% yield (entry 1). On the other hand, the reaction of selenonium salt **2h** proceeded smoothly to afford the desired compound, 2-phenyl-5*H*-4,1-benzoxathiepine **5b** in a 67% yield (entry 2). 2-Phenyl-5,6-dihydro-4,1-benzoxathiocine **5c** was also prepared from **2i** in a 54% yield (entry 3). In contrast to the compound bearing a hydroxyphenylthio group **2g**, the compound with a hydroxyethyl side chain, **2k**, produced the cyclic product **5d** in a 51% yield. The syntheses of six- and seven-membered heterocycles including sulfur and oxygen atoms have been reported;[14] however, only two kinds of the compounds bearing 5*H*-4,1-benzoxathiepine struc-

Scheme 3



Scheme 4

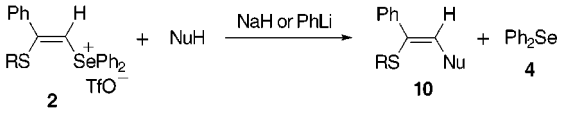


Table 3. Reactions of Alkenylselenonium Salt 2a with Lithium Acetylides

entry	NuLi (equiv)	conditions	products (% yield)	
1	PhC≡CLi (1.2)	−78 °C, 5 h	**10a** (74)	**4** (77)
2	*n*-BuC≡CLi (1.2)	−78 °C, 5 h	**10b** (82)	**4** (92)
3	*t*-BuC≡CLi (1.2)	−78 °C, 5 h	**10c** (78)	**4** (80)

ture have been prepared.[15] Furthermore, there is no report on the synthesis of 4,1-benzoxathiocine and related compounds. This new method preparing medium-membered heterocycles containing sulfur and oxygen atoms is expected to have a wide number of applications.

We have reported that the alkoxyselenurane as an intermediate, which was formed from the intramolecular cyclization reaction of vinylselenonium salt bearing an alkoxide, was isolated in the reactions of alkynylselenonium salt **1** with active methylenide.[10] Reaction mechanism to produce (*Z*)-vinyl sulfides consists of the processes of the formation of selenurane intermediate followed by the ligand coupling between Nu group and the alkenylcarbon with retention of configuration. If the acidity of the olefinic hydrogen was stronger than the hydrogen of the hydroxy group in the alkenylselenonium salt, α-elimination of the resulting vinyl ylide intermediate would occur to form the carbene intermediate. However, the alkyne derivatives formed by 1,2-migration of the alkylidene carbene were not detected in the reactions of vinylselenonium salts **2** with alkoxides or NaH. These results denied the formation of a carbene intermediate not only in the reaction of vinylselenonium salt **2** with a nucleophile but also in the reaction of alkynylselenonium salt **1** with thiolates bearing a hydroxy group.

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Conclusion

In summary, the first synthesis of (*Z*)-*β*-alkylthio or arylthioalkenylselenonium salts has been achieved from the reaction of the alkynylselenonium salt with thiols. In particular, the improvement of the yields of the above reactions by the addition of a catalytic amount of Et_3N makes the synthesis of polyfunctionalized alkenylselenonium salts much easier. It was found that the reaction point of the alkynylselenonium salt with a thiolate anion was selected on the basis of the property of the thiolate anion. Furthermore, we developed an easy way to prepare many types of (*Z*)-vinyl sulfides from the reaction of alkenylselenonium salt with nucleophiles via the selenurane intermediate. We have also succeeded in the synthesis of medium-membered heterocyclic compounds including sulfur and oxygen atoms using the alkenylselenonium salts bearing a hydroxy group. The first preparation of the 5,6-dihydro-4,1-benzoxathiocine skeleton was achieved by this method.

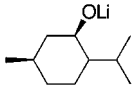
Experimental Section

Typical Procedure for the Preparation of Alkenylselenonium Salts (2a−i). To a stirred solution of alkynylselenonium salt **1** (97 mg, 0.20 mmol) and arenethiol (0.22 mmol, 1.1 equiv) in dry *i*-PrOH (2 mL) was added dropwise Et_3N (2 mg, 0.02 mmol, 0.1 equiv) at room temperature. The mixture was stirred at the same temperature for 30 min and extracted with $CHCl_3$. The organic layer was successively washed with dilute aqueous HCl and water and then dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, ether was added to the residue, and it was triturated. The crystalline solid was washed several times with ether and recrystallized from CH_2Cl_2−Et_2O. In the case of the reaction with thiosalicylic acid 1.2 equiv of Et_3N was used, and in the case of the reaction with *o*-aminothiophenol no Et_3N was used.

(*Z*)-Diphenyl-(*β*-phenylthiostyryl)selenonium Trifluoromethanesulfonate (2a). Colorless prisms; mp 136−137 °C; IR cm^{-1} (neat) 1280, 1260, 1030; ^1H NMR(400 MHz, $CDCl_3$) δ 6.92 (s, 1 H), 7.13−7.18 (m, 3 H), 7.26−7.34 (m, 5 H), 7.61−7.69 (m, 8 H), 7.83 (d, J = 8 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 117.1, 120.8, 128.8, 129.2, 129.4, 129.5, 129.6, 130.3, 131.3, 131.5, 132.0, 133.2, 134.3, 159.4; ^{77}Se NMR (76.1 MHz) δ 468.7; FAB MS *m*/*z* 445 [(M − TfO)$^+$]. Anal. Calcd for $C_{27}H_{21}F_3O_3S_2Se$: C, 54.64; H, 3.57. Found: C, 54.40; H, 3.63.

(*Z*)-Diphenyl-(*β*-benzylthiostyryl)selenonium Trifluoromethanesulfonate (2j). To a stirred solution of alkynylselenonium salt **1** (242 mg, 0.50 mmol) and phenylmethanethiol (93 mg, 0.75 mmol) in dry *i*-PrOH (5 mL) was added dropwise aqueous $NaHCO_3$ until the reaction mixture was neutral at −10 °C. The mixture was stirred at the same temperature for 5 min and extracted with $CHCl_3$. The organic

Table 4. Reactions of Alkenylselenonium Salt 2 with Metal Thiolates and Alkoxides at Room Temperature

entry	RPh_2Se^+	NuM (equiv)	solvent	time	products (% yield)	
1	**2a**	*p*-MeC_6H_4SNa (1.1)	*i*-PrOH	1.5 h	**10d** (76)	**4** (89)
2	**2a**	*p*-ClC_6H_4SNa (1.1)	*i*-PrOH	1.5 h	**10e** (68)	**4** (83)
3	**2a**	$HO(CH_2)_2SNa$ (1.1)	*i*-PrOH	30 min	**10f** (67)	**4** (69)
4	**2a**	$H_2N(CH_2)_2SNa$ (1.1)	*i*-PrOH	45 min	**10g** (70)	**4** (92)
5	**2c**	*i*-PrONa (1.0)	*i*-PrOH	3 h	**10h** (86)	**4** (92)
6	**2c**	*i*-PrONa (1.1)	MeCN	45 min	**10h** (79)	**4** (80)
7	**2a**	*p*-MeC_6H_4ONa (1.1)	MeCN	1 h	**10i** (80)	**4** (81)
8	**2a**	(+)-PhCH(Me)ONa (1.1)	MeCN	1.5 h	**10j** (74)	**4** (82)
9	**2a**	 (1.1)	THF	1.5 h	**10k** (56)	**4** (73)

Scheme 5

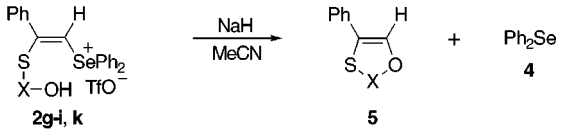
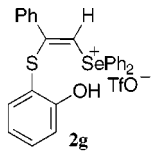
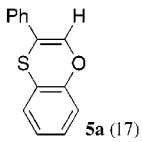
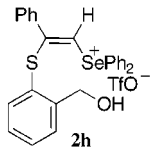
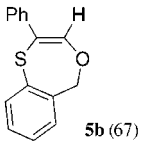
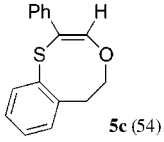
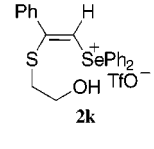
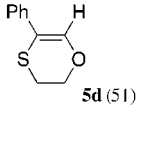


Table 5. Ring Closure Reaction of Alkenylselenonium Salt 2

entry	RPh_2Se^+	temp.	time	products (%yield)	
1	 **2g**	-10°C	24 h	 **5a** (17)	**4** (88)
2	 **2h**	r.t.	3 h	 **5b** (67)	**4** (93)
3	 **2i**	r.t.	20 h	 **5c** (54)	**4** (83)
4	 **2k**	r.t.	3 h	 **5d** (51)	**4** (72)

layer was dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was washed several times with ether and recrystallized from CH_2Cl_2–Et_2O to gave **2j** (70 mg, 23%) as colorless prisms: mp 81–83 °C; IR cm^{-1} (neat) 1280, 1260, 1030; ^1H NMR(400 MHz, $CDCl_3$) δ 3.87 (s, 2 H), 6.75 (s, 1 H), 7.02 (d, J = 7 Hz, 2 H), 7.17–7.28 (m, 3 H), 7.47–7.70 (m, 15 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 38.9, 118.2, 127.9, 128.8, 129.0, 129.1, 129.2, 129.4, 130.3, 131.4, 131.9, 133.1, 134.3, 135.2, 160.5; FAB MS m/z 459 [$(M - TfO)^+$]. Anal. Calcd for $C_{28}H_{13}F_3O_3S_2Se \cdot 1/2H_2O$: C, 54.54; H, 3.92. Found: C, 54.59; H, 3.95.

Reaction of Alkynylselenonium Salt 1 with Sodium 2-Hydroxythiophenolate. To a stirred solution of 2-hydroxythiophenol (28 mg, 0.22 mmol) in dry THF (3 mL) was added 60% NaH (9 mg, 0.22 mmol) at room temperature. After the mixture was stirred at the same temperature for 30 min, alkynylselenonium salt **1** (97 mg, 0.20 mmol) was added at 0 °C. The whole mixture was stirred at the same temperature for 24 h and extracted with ethyl acetate. The extract was washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was separated by preparative TLC (hexane/AcOEt, 3:1) to give **4** (41 mg, 88%) and an inseparable complex mixture.

Reaction of Alkynylselenonium Salt 1 with Sodium 2-Hydroxymethylthiophenolate. This reaction was conducted in a way similar to that with sodium 2-hydroxythiophenolate described above, using 2-hydroxymethylthiophenol[16] instead of 2-hydroxythiophenol. The crude products were separated by preparative TLC (hexane/AcOEt, 20:1 and 3:1) to give **3a** (19 mg, 40%) as pale yellow powder, **5b** (14 mg, 29%) as colorless oil, and **4** (39 mg, 84%). **3a**: mp 72–73 °C; IR cm^{-1} (KBr) 3500–3100, 2372; ^1H NMR(400 MHz, $CDCl_3$) δ 1.98 (brs, 1 H), 4.79 (s, 2 H), 7.28 (t, J = 7 Hz, 1 H), 7.31–7.37 (m, 4 H), 7.43 (d, J = 7 Hz, 1 H), 7.47–7.52 (m, 2 H), 7.79 (d, J = 7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 63.1, 75.6, 97.0, 122.8, 127.2, 128.3, 128.4, 128.6, 128.7, 128.8, 131.6, 131.8, 138.3; MS m/z 240 (M^+); HRMS calcd for $C_{15}H_{12}OS$ (M^+) 240.0609, found 240.0603. **5b**: IR cm^{-1} (KBr) 1606, 1149; ^1H NMR(400 MHz, $CDCl_3$) δ 5.46 (s, 2 H), 6.70 (s, 1 H), 7.20–7.40 (m, 6 H), 7.40–7.55 (m, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 71.7, 110.0, 127.8, 128.2, 128.3, 128.7, 129.5, 130.0, 130.6, 138.8, 139.2, 140.1, 145.4; MS m/z 240 (M^+); HRMS calcd for $C_{15}H_{12}OS$ (M^+) 240.0609, found 240.0612.

Reaction of Alkynylselenonium Salt 1 with Sodium 2-Hydroxyethylthiophenolate. This reaction was conducted similarly to that with sodium 2-hydroxythiophenolate using sodium 2-hydroxyethylthiophenolate prepared from 2-hydroxyethylthiophenol[17] and the equimolar amount of NaH. The crude products were separated by preparative TLC (hexane/AcOEt, 3:1) to give **3b** (22 mg, 43%) as pale yellow oil, **6** (15 mg, 19%) as pale yellow oil, and **4** (34 mg, 74%). **3b**: IR cm^{-1} (neat) 3500–3100, 2172; ^1H NMR(400 MHz, $CDCl_3$) δ 2.99(t, J = 7 Hz, 2 H), 3.90 (t, J = 7 Hz, 2 H), 7.20–7.37 (m, 6 H), 7.47–7.53 (m, 2 H), 7.77 (d, J = 7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.6, 62.1, 75.6, 97.5, 122.8, 126.9, 127.9, 128.0, 128.4, 128.6, 130.4, 131.8, 132.2, 135.9; MS m/z 254 (M^+); HRMS calcd for $C_{16}H_{14}OS$ (M^+) 240.0765, found 254.0759. **6**: IR cm^{-1} (neat) 3500–3100; ^1H NMR(400 MHz, $CDCl_3$) δ 3.07 (t, J = 7 Hz, 2 H), 3.13 (t, J = 7 Hz, 2 H), 3.81 (t, J = 7 Hz, 2 H), 3.97 (t, J = 7 Hz, 2 H), 7.00–7.10 (m, 3 H), 7.10–7.34 (m, 8 H), 7.49 (d, J = 7 Hz, 2 H), 7.55 (d, J = 7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 37.2, 37.6, 62.6, 63.0, 126.5, 126.8, 127.1, 127.8, 128.37, 128.41, 129.7, 130.0, 130.3, 130.7, 132.8, 133.7, 134.4, 136.1, 137.8, 138.7, 139.9; MS m/z 408 (M^+); HRMS calcd for $C_{24}H_{24}O_2S_2$ (M^+) 408.1218, found 408.1223.

Reaction of Alkynylselenonium Salt 1 with Sodium 2-Hydroxyethanethiolate. The reaction was conducted similarly to the above description using sodium 2-hydroxyethanethiolate. The crude products were separated by preparative TLC (hexane/AcOEt, 5:1) to give **3c** (26 mg, 73%) as colorless oil and **4** (38 mg, 82%). **3c**: IR cm^{-1} (neat) 3600–3100, 2166; ^1H NMR(400 MHz, $CDCl_3$) δ 2.29 (brs, 1 H), 2.96(t, J = 6 Hz, 2 H), 3.98 (brt, J = 6 Hz, 2 H), 7.28–7.35 (m, 3 H), 7.38–7.42 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 38.5, 60.5, 77.8, 93.0,

(16) Arnoldi, A.; Carughi, M. *Synthesis* **1988**, 155–157.

(17) (a) Bordwell, F. G.; Fried, H. E. *J. Org. Chem.* **1991**, *56*, 4218–4223. (b) Stacy, G. W.; Eck, D. L.; Wollner, T. E. *J. Org. Chem.* **1970**, *35*, 3495–3499.

123.0, 128.3, 131.5; MS *m*/*z* 178 (M^+); HRMS calcd for $C_{10}H_{10}OS$ (M^+) 178.0452, found 178.0442.

Reaction of Alkynylselenonium Salt 1 with 1,2-Ethanedithiol Monosodium Salt. The reaction was conducted using 1,2-ethanedithiol and equimolar NaH. The crude products were separated by preparative TLC (hexane/AcOEt, 5:1) to give **7** (14 mg, 48%) as colorless oil and **4** (39 mg, 83%). **7**: IR cm^{-1} (neat) 2167; ^1H NMR(400 MHz, $CDCl_3$) δ 3,20 (s, 4 H), 7.27−7.34 (m, 6 H), 7.38−7.43 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 35.1, 77.8, 94.2, 123.0, 128.3, 131.6; MS *m*/*z* 294 (M^+); HRMS calcd for $C_{18}H_{14}S_2$ (M^+) 294.0537, found 294.0524.

Reaction of Alkenylselenonium Salt 2a with Lithium Phenylethynylide. To a stirred solution of 98% phenylethyne (25 mg, 0.24 mmol) in dry THF (2 mL) was added 1.4 mol/L *n*-BuLi (0.17 mL, 0.24 mmol) at −78 °C. After being stirred at the same temperature for 30 min, the mixture was added to a THF solution (7 mL) of alkenylselenonium salt **2a** (119 mg, 0.20 mmol) at −78 °C. The whole mixture was stirred at the same temperature for 5 h, after which ether was added to it. The resulting mixture was washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was separated by preparative TLC (hexane/AcOEt, 5:1) to give **10a** (46 mg, 74%) as white powder and **4** (36 mg, 77%). **10a**: mp 107−108 °C; IR cm^{-1} (neat) 2191; ^1H NMR(400 MHz, $CDCl_3$) δ 6.32 (s, 1 H), 7.04 (t, J = 8 Hz, 1 H), 7.11 (t, J = 8 Hz, 2 H), 7.18−7.24 (m, 5 H), 7.26−7.30 (m, 3 H), 7.44 (dd, J = 8 Hz, 3 Hz, 2 H), 7.52 (dd, J = 8 Hz, 3 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 87.6, 98.3, 112.2, 123.3, 126.3, 127.9, 128.2, 128.3, 128.6, 130.4, 131.6, 134.4, 138.3, 147.1; MS *m*/*z* 312 (M^+). Anal. Calcd for $C_{22}H_{16}S$: C, 84.57; H, 5.16. Found: C, 84.56; H, 5.35.

Reaction of Alkenylselenonium Salt 2a with Sodium 4-Methylbenzenethiolate. To a stirred solution of 4-methylbenzenethiol (21 mg, 0.17 mmol) in dry *i*-PrOH (3 mL) was added 60% NaH (7 mg, 0.17 mmol) at room temperature. After the mixture was stirred at the same temperature for 30 min, alkenylselenonium salt **2a** (89 mg, 0.15 mmol) was added to it at room temperature. The resulting mixture was stirred at the same temperature for 1.5 h, poured into water, and extracted with ethyl acetate. The extracts were washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was separated by preparative TLC (hexane) to give **10d** (38 mg, 76%) as colorless oil and **4** (31 mg, 89%). **10d**: IR cm^{-1} (neat) 1581, 1540, 1490, 1440; ^1H NMR(270 MHz, $CDCl_3$) δ 2.34 (s, 3 H), 7.06 (t, J = 8 Hz, 1 H), 7.15−7.26 (m, 10 H), 7.39 (d, J = 8 Hz, 2 H), 7.53 (d, J = 8 Hz, 2 H); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 21.1, 125.8, 126.7, 127.5, 128.2, 128.3, 128.5, 128.8, 130.0, 131.0, 131.6, 134.8, 137.6, 137.8, 138.8; MS *m*/*z* 334 (M^+). Anal. Calcd for $C_{21}H_{18}S_2$: C, 75.40; H, 5.42. Found: C, 75.27; H, 5.61.

Reaction of Alkenylselenonium Salt 2c with Sodium Isopropoxide in *i*-PrOH. The reaction was conducted using sodium isopropoxide prepared from dry *i*-PrOH and NaH. The products were separated by preparative TLC (hexane/AcOEt, 100:1) to give **10h** (39 mg, 86%) as colorless oil and **4** (32 mg, 92%). **10h**: IR cm^{-1} (neat) 1614, 1202; ^1H NMR(400 MHz, $CDCl_3$) δ 1,29 (d, J = 6 Hz, 6 H), 4.16−4.26 (m, 1 H), 7.06 (s, 1 H), 7.10 (d, J = 9 Hz, 2 H), 7.14 (d, J = 9 Hz, 2 H), 7.17 (t, J = 7 Hz, 1 H), 7.25 (t, J = 7 Hz, 2 H), 7.47 (d, J = 7 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.5, 76.6, 108.8, 126.5, 126.7, 128.4, 128.57, 128.63, 130.7, 135.4, 137.9, 151.1; MS *m*/*z* 304 (M^+); HRMS calcd for $C_{17}H_{17}ClOS$ (M^+) 304.0689, found 304.0682.

Reaction of Alkenylselenonium Salt 2c with Sodium Isopropoxide in MeCN. To a stirred solution *i*-PrOH (10 mg, 0.17 mmol) in dry MeCN (5 mL) was added 60% NaH (7 mg, 0.17 mmol) at room temperature. After the mixture was stirred at the same temperature for 30 min, alkenylselenonium salt **2c** (94 mg, 0.15 mmol) was added to it at room temperature. The mixture was stirred at the same temperature for 1 h, poured into water, and extracted with ethyl acetate. The extracts were washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was separated by preparative TLC (hexane/AcOEt, 100:1) to give **4** (28 mg, 80%) and **10h** (36 mg, 79%).

Reaction of Alkenylselenonium Salt 2a with Lithium (−)-Menthoxide. To a stirred solution of (−)-menthol (94 mg, 0.22 mmol) in dry THF (2 mL) was added 0.85 mol/L PhLi (0.26 mL, 0.22 mmol) at room temperature. After the mixture was stirred at the same temperature for 160 min, it was added to the THF solution (3 mL) of alkenylselenonium salt **2a** (119 mg, 0.20 mmol) at room temperature. The resulting mixture was stirred at the same temperature for 1.5 h, poured into water, and extracted with ethyl acetate. The extracts were washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was purified by column chromatography (chloroform) to give **10k** (41 mg, 56%) as white powder and **4** (34 mg, 73%). **10k**: mp 53−57 °C; $[\alpha]^{22}_D$ −2.0 (*c* 0.80, $CHCl_3$); IR cm^{-1} (neat) 1616, 1196; ^1H NMR(400 MHz, $CDCl_3$) δ 0.73 (d, J = 7 Hz, 3 H), 0.81−0.5 (m, 4 H), 0.85−1.04 (m, 4 H), 1.14 (q, J = 12 Hz, 1 H), 1.35−1.45 (m, 2 H), 1.64−1.69 (m, 2 H), 1.93−2.06 (m, 2 H), 3.67 (dt, J = 11 Hz, 4 Hz, 1 H), 7.02 (t, J = 7 Hz, 1 H), 7.10−7.18 (m, 4 H), 7.20−7.27 (m, 4 H), 7.50 (d, J = 7 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.2, 20.6, 22.0, 23.4, 25.5, 31.6, 34.0, 41.6, 47.2, 84.0, 108.2, 117.0, 124.7, 126.4, 127.0, 128.2, 128.4, 137.1, 138.5, 151.8; FABMS *m*/*z* 367 (M^+ + H); HRFAB MS calcd for $C_{24}H_{31}OS$ (M^+ + H) 367.2096, found 367.2087.

Reaction of Alkenylselenonium Salt 2g with Sodium Hydride. To a stirred solution of alkenylselenonium salt **2g** (91 mg, 0.15 mmol) in dry MeCN (5 mL) was added 60% NaH (6 mg, 0.15 mmol) at 0 °C. The mixture was stirred at the same temperature for 24 h, poured into water, and extracted with ethyl acetate. The extracts were washed with brine and dried over $MgSO_4$. After the solvent was evaporated under reduced pressure, the residue was purified by preparative TLC (hexane/AcOEt, 100:1) to give **5a** (8 mg, 17%) as colorless oil and **4** (26 mg, 88%). **5a**: IR cm^{-1} (neat) 1469, 1215; ^1H NMR(400 MHz, $CDCl_3$) δ 5.82 (s, 1 H), 6.94−7.02 (m, 3 H), 7.08−7.14 (m, 1 H), 7.30−7.40 (m, 3 H), 7.59 (d, J = 7 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 94.3, 117.6, 119.6, 124.2, 124.9, 126.6, 127.9, 128.5, 128.6, 133.3, 150.0, 152.0; MS *m*/*z* 226 (M^+); HRMS calcd for $C_{14}H_{10}OS$ (M^+) 226.0452, found 226.0456.

Acknowledgment. This work was supported in part by a Grant-in-Aid for Scientific Research (no. 11771388) from the Ministry of Education, Science, Sports and Culture, Japan.

Supporting Information Available: Spectroscopic data and experimental details of **2b**−**i**, **2k**, **5c**, **5d**, **10b**, **10c**, **10e**−**g**, **10i**, and **10j**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO000640K