Received: 9 October 2018 | Revised: 19 November 2018 | Accepted: 20 November 2018

DOI: 10.1002/hc.21480

RESEARCH ARTICLE

WILEY Heteroatom Chemistry

Nitroselenation of carbon-carbon triple bond by PhSeSePh and NO/O_2 or NO_2

Yutaka Nishiyama | **Mari Sumida** | **Noboru Sonoda**

Faculty of Chemistry, Materials and Bioengineering, Kansai University, Suita, Osaka, Japan

Correspondence
Yutaka Nishiyama, Faculty of Chemistry, Materials and Bioengineering, Kansai University, Suita, Osaka, Japan.
Email: nishiya@kansai-u.ac.jp

Abstract

When alkynes were treated with diphenyl diselenide under an atmosphere of nitric oxide and oxygen, nitroselenation of the carbon-carbon triple bond proceeded with a high regioselectivity to give the corresponding 1-nitro-2-phenylseleno alkenes. Similarly, the nitroselenation of alkynes proceeded by the reaction of the alkynes with nitrogen dioxide. The stirring of the 1,2-bis(phenylseleno) alkenes under an atmosphere of nitric oxide and oxygen also gave the corresponding 1-nitro-2-phenylseleno alkenes.

1 | INTRODUCTION

Much attention has been paid to nitric oxide, which is known to have a free radical character, in the fields of medical science and biochemistry.[1] On the other hand, in organic synthesis, the use of nitric oxide as a reagent is quite limited because of the sparse information available on the chemical behavior of nitric oxide and the difficulty incurred in controlling its reactivity.[2]

It has known that homolytic cleavage of the selenium-selenium bond of diorganyl diselenide, such as diphenyl diselenide, easily occurred under thermal or visible light irradiation conditions and formed the corresponding seleno center radical as a labile species. Sonoda and Ogawa reported that the treatment of alkynes and diphenyl diselenide under thermal or visible light irradiation[4] conditions gave the corresponding[3] 1,2-bis(phenylseleno) alkenes in moderate yields. In their manuscripts, they suggested the reaction pathway that included the addition of the phenylseleno radical formed in situ on the carbon-carbon triple bond followed by the capture of the β-phenylseleno substituted vinyl carbon radical by the diphenyl diselenide (Scheme 1). Furthermore, they have developed the synthetic method of various organoselenium compounds using the addition of the phenylseleno radical to various unsaturated bonds, such as carbon-carbon and carbon-nitrogen bonds.[5]

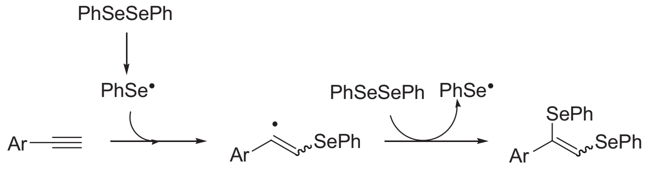
Our attention was the directed toward the use of nitric oxide, which has a radical character, on the synthesis of the 1-nitro-2-phenylseleno alkenes. We now found that the treatment of alkynes and diphenyl diselenide under an atmosphere of nitric oxide and oxygen or nitrogen dioxide gave the corresponding 1-nitro-2-phenylseleno alkenes in moderate to good yields. 1-Nitro-2-phenylseleno alkenes were also prepared by the stirring of 1,2-bis(phenylseleno) alkenes under an atmosphere of nitric oxide and oxygen (Scheme 2).

2 | RESULTS AND DISCUSSION

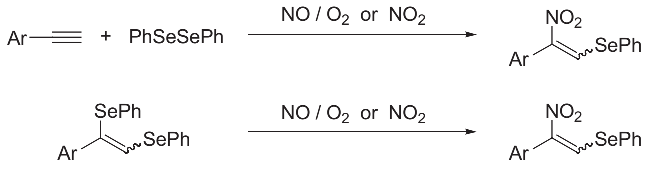
The reaction of phenylacetylene (**1a**) and diphenyl diselenide (**2**) was carried out under several reaction conditions, and these results are shown in Table 1. Treatment of **2** (0.5 mmol) and ten equivalent amounts of **1a** under an atmosphere of NO at 80°C for 5 hours, followed by oxidation in air at room temperature led to the formation of 1-nitro-1-phenyl-2-phenylselenoethylene (**3a**) in low yield along with a small amount of 1,2-bis(phenylseleno)-1-phenylethylene (**4a**) (Figure S1) (entry 1). For the nitroselenation of **1a**, a phenylseleno group was regioselectively introduced at the terminal position of **1a** and nitro group was introduced at the inner one of **1a**. The yield of **3a** was improved by increasing the amounts of **1a** (entries 1-5). At higher reaction temperatures (100 and 120°C), the yields of both **3a** and **4a** increased, but the selectivity of **3a** decreased (entries 4, 6 and 7). Surprisingly, when air and oxygen were introduced into the reaction solution, the yield of **3a** was dramatically increased (entries 8 and 9). When **1a** was allowed

---

A tribute to Professor Naomichi Furukawa on the Occasion of his 82nd birthday - By Invitation only



SCHEME 1 Reaction of alkyne and diphenyl diselenide.



SCHEME 2 Synthesis of 1-nitro-2-phenylseleno alkenes

to react with **2** under an atmosphere on NO and a small amount of oxygen at 80°C for 15 hours, **3a** was obtained in an 82% yield (entry 10). Similarly, the nitroselenation of the carbon-carbon triple bond of **1a** proceeded under an atmosphere of NO_2 to give **3a** in 77% yield (entry 11).

To determine the applicability of the nitroselenation of alkynes, various aryl substituted acetylenes was allowed to react with diphenyl diselenide (**2**) under a NO/O_2 atmosphere, and these results are shown in Scheme 3.[1] In the case of 4-methylphenyl acetylene **1b** and 4-methoxyphenyl acetylene **1c**, in which the electron donating groups were substituted on the aromatic ring, nitroselenation of the carbon-carbon triple bond proceeded with regioselectively to form the corresponding 1-aryl substituted 1-nitro-2-phenylseleno alkenes in 87% and 82% yields, respectively (Figure S2 and S3). Similarly, an electron withdrawing group, such as the fluorine, substituted aryl acetylene **1d**, was nitroselenated by PhSeSePh, NO and O_2 to give 1-(4-fluorophenyl)-1-nitro-2-phenylselenoethylene **3d** in 95% yield (Figure S4). However, in the case of alkyl substituted terminal and inner alkynes, the yields of phenylselenonitrated products were very low. 1-Aryl-1-nitro-2-phenylseleno alkenes were also prepared by the reaction of alkynes and **2** under NO_2 atmosphere in moderate to good yields (Scheme 4).

Figure 1 shows the time dependence curve for the reaction of phenylacetylene (**1a**) and diphenyl diselenide (**2**) at 80°C under an atmosphere of NO and a small amount of O_2. During an earlier stage of the reaction, the yield of **3a** was almost same as that of **4a**. After 5 hours, the yield of **3a** gradually increased; however, the yield of **4a** had not increased. From the result, it was suggested that **3a** was also produced through the formation of **4a**. In fact, when **4a** was stirred at 80°C for 5 hours, under an atmosphere of NO and a small amount of O_2, **3a** was formed in 80% yield (Equation 1).

It is shown that the bisphenylselenation of alkynes with diphenyl diselenide under visible light irradiation with a Hg lamp efficiently proceeded to give the corresponding 1,2-bis(phenylseleno)alkenes.[4] In order to decrease the amount of alkyne used, two-step procedures were next investigated. When the treatment of diphenyl diselenide and a 1.5 equivalent amount of phenylacetylene under visible light irradiation for 5 hours followed by stirring the reaction mixture under a NO/O_2 atmosphere at 80°C for 5 hours, 1-nitro-1-phenyl-2-phenylselenoethylene (**3a**) was obtained in 98% yield. Various 1-aryl- and 1-aryl-2-alkyl substituted 1-nitro-2-phenylselenoethylenes (Figure S5) were formed in moderate to good yields by using the two-step procedures (Scheme 5).

Possible pathways for the nitroselenation of the alkynes are shown in Scheme 6. As already disclosed, the initial step of the reaction was the addition of the phenylseleno radical, which was generated by the homolytic cleavage of the selenium-selenium bond of diphenyl diselenide (**2**), to the carbon-carbon triple bond to form the β-phenylseleno substituted vinyl carbon radical (**5**).[6] The vinyl radical, **5**, reacted nitrogen dioxide, which was generated by the oxidation of NO by O_2, to afford the 1-nitro-1-aryl-2-phenylselenoethylenes **3**. On another pathway, the 1,2-bis(phenylseleno) alkenes **4**, which was formed by the capture of **5** by **2**, reacted with nitric oxide or nitrogen dioxide to regenerate the vinyl radical **5**.[2] **5** then reacted with NO/O_2 or NO to give the corresponding 1-nitro-1-aryl-2-selenoethylenes **3**.[7,8]

3 | CONCLUSIONS

In summary, we developed a novel synthetic method of 1-nitro-2-phenylseleno alkenes by the reaction of alkyne and NO/O_2 or NO_2. 1-Nitro-2-phenylseleno alkenes were also prepared when 1,2-bis(phenylseleno) alkenes were treated with NO/O_2.

4 | EXPERIMENTAL

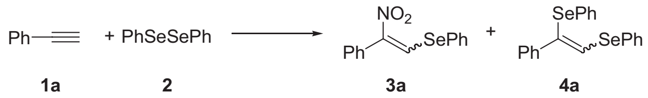
The FT-IR spectra were recorded by a JASCO FT/IR-4100 instrument. ^{1}H-NMR spectra were recorded at 400 MHz and ^{13}C-NMR spectra at 100 MHz by a JEOL JNM-ECS-400 or a JEOL JNM-AL400. Chemical shifts were reported in ppm relative to tetramethylsilane or the residual solvent as the internal standard. GLC mass spectral analyses were performed

---

[1] We could not determine the structure of geometric isomers and the ratio of geometric isomers.

[2] When 1,2-bis(phenylseleno) alkene was stirred under NO atmosphere, the formation of alkyne and diphenyl diselenide was observed. On the other hand, under NO_2 or O_2 atmosphene, alkyne and diphenyl diselenide were not formed. From these results, we proposed that deselenation of 1,2-bis(phenylseleno) alkene proceeded under NO or NO/O_2.

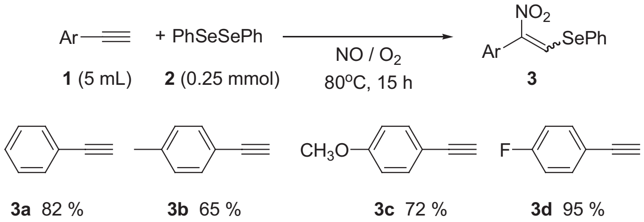
TABLE 1 Reaction of phenylacetylene (**1a**) and diphenyl diselenide (**2**)[a]



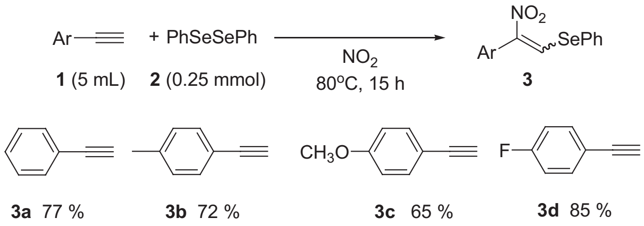
					Yield (%)[b]	
Entry	**Condition**	**1a**	**Temp. (°C)**	**Time (h)**	**3a**	**4a**
1	NO	5 mmol	80	5	5	Trace
2	NO	1 mL	80	5	10	2
3	NO	3 mL	80	5	15	5
4	NO	5 mL	80	5	18	6
5	NO	5 mL	50	5	4	Trace
6	NO	5 mL	100	5	13	10
7	NO	5 mL	120	5	10	27
8	NO/Air	5 mL	80	5	30	10
9	NO/O_2	5 mL	80	5	43	7
10	NO/O_2	5 mL	80	15	82	17
11	NO_2	5 mL	80	15	77	17

[a] Reaction conditions: **2** (0.25 mmol) was used.
[b] GLC yield based on **2**.

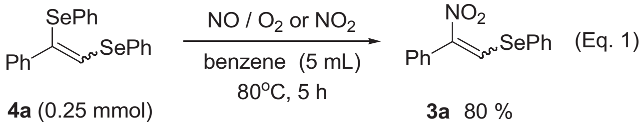
by a Shimadzu GCMS-QP5050A with CBP-M25-025. High mass spectral analyses were performed by a JEOL (JMS-T200GC). Nitric oxide, nitrogen dioxide, and oxygen were all purchased from commercial sources. Diphenyl diselenide, alkynes, and benzene were commercially available and were used without further purification.



SCHEME 3 Reaction of 1-aryl substituted acetylenes and 2 under NO/NO_2.



SCHEME 4 Reaction of 1-aryl substituted acetylenes and 2 under NO.



4.1 | Procedure: general procedure for reaction of alkyne with PhSeSePh under NO and O_2

Diphenyl diselenide (0.5 mmol, 0.157 g) and the alkyne (5 mL) were stirred under an atmosphere of NO and small amount of O_2 at 80°C for 15 hours. After the reaction was complete, H_2O was added to the reaction mixture and extracted with ethyl acetate. The organic layer was dried using $MgSO_4$. The resulting mixture was filtered, and the filtrate was concentrated. Purification of the residue by silica gel column chromatography (elute: mixture of C_6H_{14} and ethyl acetate) afforded the 1-nitro-2-phenylseleno alkenes. The structures of the products were assigned by their ^1H and ^{13}C-NMR, IR and high-resolution mass spectra analysis.

4.2 | Two steps procedure for reaction of alkyne with PhSeSePh under NO and O_2

Diphenyl diselenide (2.0 mmol, 0.628 g) and the alkyne (3 mmol) were stirred under irradiation of tungsten lamp at 500 W and 40°C for 24 hours. After the reaction was complete, benzene (5 mL) was added to the reaction mixture and the mixture was stirred under an atmosphere of NO and a small amount of O_2 at 80°C for 5 hours, then extracted with ethyl acetate. The organic layer was dried using $MgSO_4$. The resulting mixture was filtered, and the filtrate was

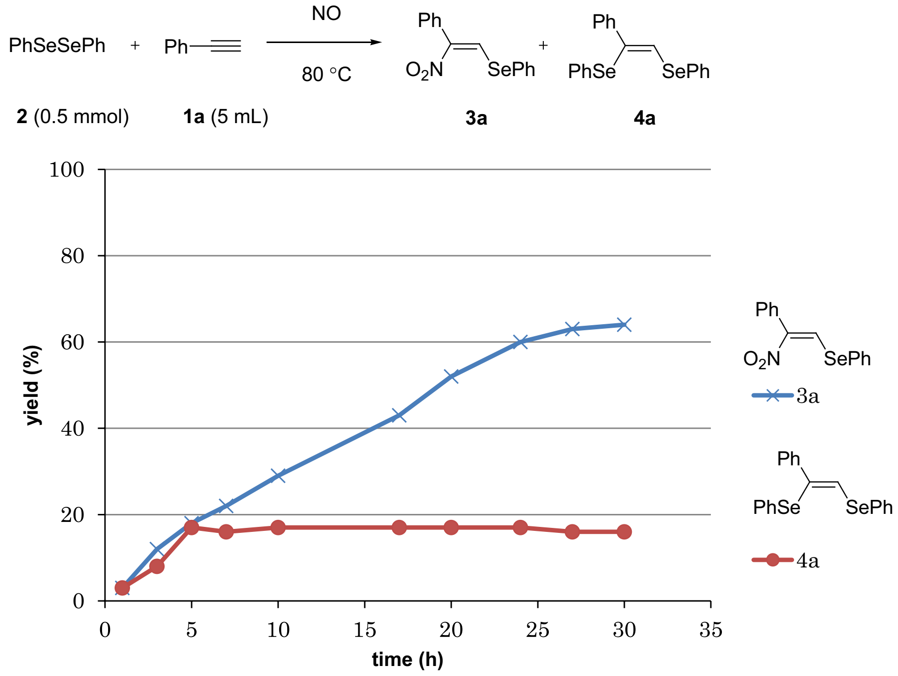
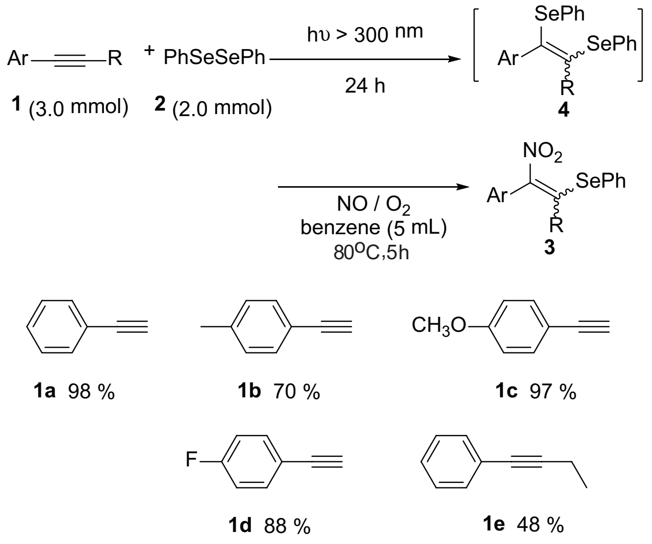


FIGURE 1 Time dependent curve for the reaction of phenylacetylene and diphenyl diselenide.

concentrated. Purification of the residue by silica gel column chromatography (elute: mixture of C_6H_{14} and ethyl acetate) afforded the 1-nitro-2-phenylseleno alkenes.



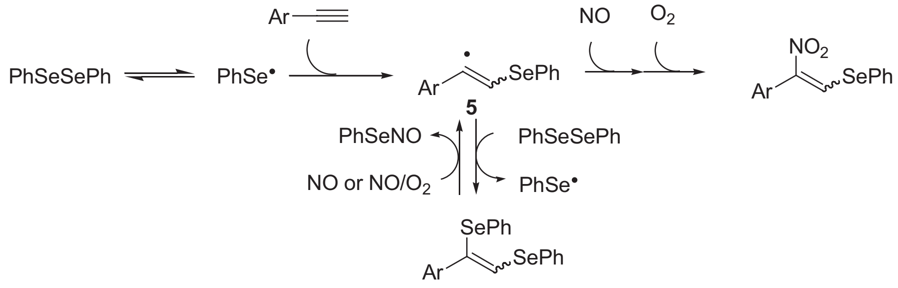
SCHEME 5 Time step synthetic method of 1-nitro-2-phenylseleno alkenes.

4.2.1 | 1-Nitro-1-phenyl-2-phenylselenoethylene (3a)

^{1}H-NMR (400 MHz, $CDCl_3$) δ 8.35 (d, $J = 7.2$ Hz, 1H); 7.85 (d, $J = 6.0$ Hz, 1H), 7.66 (t, $J = 7.2$ Hz, 1H), 7.60 (s, 1H), 7.56-7.50 (m, 3H), 7.32 (d, $J = 7.2$ Hz, 1H), 7.14-6.97 (m, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 136.4, 133.9, 130.6, 130.5, 130.3, 129.6, 129.0, 128.6, 128.4, 128.4, 127.3, 126.5, 125.8, 100.1; IR (neat) 3059, 1654, 1596, 1574, 1557, 1449, 1424, 1322, 1243, 893, 769, 725, 683, 652 cm^{-1}; MS: *m/z* Calcd. for $C_{14}H_{11}NO_2Se$: 304.9955; Found: 304.9942.

4.2.2 | Mixture of (*E*)- and (*Z*)-1-nitro-1-(4-methylphenyl)-2-phenyl-selenoethylene (3b)

^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.68 (d, $J = 6.4$ Hz, 1H), 7.43-7.57 (m, 2H), 7.28-7.00 (m, 6H), 6.88 (s, 0.67H), 6.58 (s, 0.33 H), 2.38 (s, 2H), 2.19 (s, 1H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 160.9, 156.8, 140.0, 139.3, 136.4, 136.4, 136.1, 133.6, 131.5, 131.5, 131.2, 130.4, 130.3, 129.2, 128.7, 128.6, 128.4, 128.2, 127.4, 126.0, 21.5, 21.2; IR (neat) 3056, 3026,



SCHEME 6 Plausible reaction pathways.

2919, 1607, 1591, 1557, 1514, 1477, 1438, 1318, 1258, 1183, 1021, 976, 804, 742, 690 cm^{-1}; MS: *m/z* Calcd. for $C_{15}H_{13}NO_2Se$: 319.0112; Found: 319.0128.

4.2.3 | 1-Nitro-1-(4-methoxyphenyl)-2-phenylselenoethylene (3c)

^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.58 (s, 1H), 7.36 (s, 2H), 7.23-7.15 (m, 2H), 7.07 (t, $J = 7.6$ Hz, 1H), 6.94 (d, $J = 8.8$ Hz, 2H), 6.60 (d, $J = 8.4$ Hz, 2H), 3.69 (s, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 160.6, 160.3, 136.0, 133.5, 130.3, 128.7, 128.7, 128.4, 128.2, 126.7, 113.3, 55.2; IR (neat) 3075, 2932, 2837, 1603, 1556, 1508, 1477, 1438, 1316, 1252, 1174, 1111, 1030, 899, 834, 805, 790, 741, 691, 658, 628, 558 cm^{-1}: *m/z* Calcd. for $C_{15}H_{13}NO_3Se$: 335.0061; Found: 335.0038.

4.2.4 | 1-Nitro-1-(4-fluorophenyl)-2-phenylselenoethylene (3d)

^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.67-6.60 (m, 10H); ^{13}C-NMR (100 MHz, $CDCL_3$) δ 164.0, 159.3, 136.3, 136.2, 133.8, 130.6, 130.5, 130.4, 130.3, 129.0, 128.8, 127.7, 115.1, 114.8; IR (neat) 3078, 1601, 1562, 1505, 1478, 1438, 1318, 1259, 1230, 1157, 1096, 1000, 899, 838, 805, 740, 690, 655, 627, 544 cm^{-1}: *m/z* Calcd. for $C_{14}H_{10}FNO_2Se$: 322.9861; Found: 322.9874.

4.2.5 | Mixture of (*E*)- and (*Z*)-1-nitro-2-phenylseleno-1-phenyl-1-butene (3e)

^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.25-6.82 (m, 10H), 3.01 (q, $J = 7.6$ Hz, 0.4H), 2.45 (q, $J = 7.6$ Hz, 1.6H), 1.25 (t, $J = 7.6$ Hz, 0.6H), 1.00 (t, $J = 7.6$ Hz, 2.4H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 154.3, 146.6, 136.8, 136.8, 136.0, 135.5, 129.6, 128.7, 128.5, 128.4, 128.2, 128.1, 128.0, 127.7, 127.7, 127.7, 127.6; IR (neat) 3054, 2967, 2933, 1568, 1522, 1474, 1457, 1438, 1428, 1294, 1273, 1052, 1023, 891, 755, 740. 704, 692 cm^{-1}: *m/z* Calcd. for $C_{16}H_{15}NO_2Se$: 333.0268; Found: 333.0285.

ACKNOWLEDGMENTS

Dedicated to 82nd birthday of Professor Naomichi Furukawa.

ORCID

Yutaka Nishiyama https://orcid.org/0000-0001-5687-5699

REFERENCES

[1] For recent reviews concerning the chemistry of NO in the fields of medical science and biochemistry, see: a) In Nitric Oxide; Biology and Pathobiology (Eds: L. Ignarro, B. Fieeman), Academic Press, **2017**; b) In Nitric Oxide (Eds: J.-L. Balligand, B. Mayer), Springer, New York **2000**.

[2] For recent reviews concerning the use of NO in the organic chemistry, see: J. Hartung, *Chem. Rev.* **2009**, *109*, 4500.

[3] a) A. Ogawa, N. Takami, M. Sekiguchi, H. Yokoyama, H. Kuniyasu, I. Ryu, N. Sonoda, *Chem. Lett.* **1991**, *20*, 2241; b) T. G. Back, M. V. Krishna, *J. Org. Chem.* **1988**, *53*, 2533.

[4] A. Ogawa, H. Yokoyama, K. Yokoyama, T. Masawaki, N. Kambe, N. Sonoda, *J. Org. Chem.* **1991**, *56*, 5721.

[5] a) A. Ogawa, in Main Group Metals in Organic Synthesis, Vol. *2* (Eds: H. Yamamoto, K. Oshima), Wilet-VCH: Weinheim, Germany **2004**, 813; b) A. Ogawa, in Comprehensive Organic Synthesis II (Ed: P Knochel), Elsevier, 4.06 **2014**, 392; c) A. Nomoto, S. Hayashi, T. Fujiyama, T. Ikeda, K. Hirata, J. Tohoma, K. Kakiuchi, W. Nakanishi, A. Ogawa, *Bull. Chem. Soc. Jpn.* **2014**, *87*, 550; d) Y. Kobiki, S. Kawaguchi, A. Ogawa, *Tetrahedron Lett.* **2013**, *54*, 5453; e) Y. Kobiki, S. Kawaguchi, T. Ohe, A. Ogawa, *Beil. J. Org. Chem.* **2013**, *117*, 1141; f) T. Tamai, A. Nomoto, K. Tsuchii, Y. Minamida, T. Mitamura, M. Sonoda, A. Ogawa, *Tetrahedron* **2012**, *68*, 10516; g) A. Ogawa, T. Tamai, T. Mitamura, A. Nomoto, *Pure Appl. Chem.* **2013**, *85*, 785 and references therein.

[6] The formation of β-phenylseleno substituted vinyl carbon radical by the addition of carbon-carbon triple bond of acetylene appears to be the rate-determining step. See: a) O. Ito, *J. Am. Chem. Soc.* **1983**, *105*, 850; b) G. A. Russell, H. Tashtoush, *J. Am. Chem. Soc.* **1983**, *105*, 1398.

[7] It is shown that nitrosothiols selectively decompose via S,N homolysis upon photoexcitation or thermal activation to give the corresponding disulfides and nitric oxide. See: a) D. L. H. Williams, *Acc. Chem. Res.* **1999**, *32*, 869; b) M. D. Bartberger, K. N. Houk, S. C. Powell, L. D. Mannion, K. Y. Lo, J. S. Stamler, E. J. Toone, *J. Am. Chem. Soc.* **2000**, *122*, 5889.

[8] Goto and Kawashima have reported the isolation of Se-nitrososeleno. See: K. Shimada, K. Goto, T. Kawashima, N. Takagi, Y.-K. Choe, S. Nagase, *J. Am. Chem. Soc.* **2004**, *126*, 13238.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Nishiyama Y, Sumida M, Sonoda N. nitroselenation of carbon-carbon triple bond by PhSeSePh and NO/O_2 or NO_2. *Heteroatom Chem.* 2018;29:e21480. https://doi.org/10.1002/hc.21480