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Chemoselective and metal-free reduction of α,β-unsaturated ketones by *in situ* produced benzeneselenol from *O*-(*tert*-butyl) Se-phenyl selenocarbonate†

Andrea Temperini, [ID]*[a] Marco Ballarotto [ID][a] and Carlo Siciliano[b]

The carbon–carbon double bond of arylidene acetones and chalcones can be selectively reduced with benzeneselenol generated *in situ* by reacting *O*-(*tert*-butyl) Se-phenyl selenocarbonate with hydrochloric acid in ethanol. This mild, metal-free and experimentally simple reduction procedure displays considerable functional-group compatibility, products are obtained in good to excellent yields, and the use of toxic Se/CO mixture and NaSeH, or the smelly and air-sensitive benzeneselenol, is avoided.

Introduction

Organoselenium compounds have attracted considerable interest as intermediates and reagents in organic synthesis during the past years.[1] Among these reagents, benzeneselenol was utilized for the reductive cleavage of nitrogen-containing functional groups such as nitro, azo and hydrazino groups,[2] giving the corresponding amino group, or for the reductive amination of aldehydes,[3] and the reduction of aromatic aldehydes to the corresponding alcohols.[4]

Moreover, examples of reduction of the C–C double bond of α,β-unsaturated carbonyl compounds (Scheme 1(i)) by benzeneselenol under photochemical[5] or oxygen-induced activation[6] have seldom been reported. Besides, poisonous hydrogen selenide generated from Se/CO/H$_2$O[7] and Se/NaBH$_4$ mixtures[8] have been used for the selective reduction of the olefinic linkage of α,β-unsaturated ketones, esters, and acids. More recently reduction of chalcones with 3 equiv. of H$_2$Se produced from the reaction of elemental selenium, DMF and a base at 150 °C in the presence of water has been also proposed[9] (Scheme 1(ii)). These reduction systems possess limitation due to the use of poisonous elemental selenium and CO, the formation of highly toxic hydrogen selenide, handling of smelly and sensitive reagents, no selenium recovery, harsh reaction conditions as well as low chemoselectivity.

Other ways to reduce the carbon–carbon double bond of α,β-unsaturated ketones are known and most of them have their own merits and demerits. Transition-metal catalyzed transfer hydrogenation,[10] metal-catalyzed hydrogenation,[11] dissolving metal reduction,[12] use of hydrides[13] and metal-free reductive processes[14] are methods for selective reduction of the C–C double bond. Notwithstanding these methods suffer from their limitation as handling of sensitive reagents or catalysts, relatively expensive metal complexes, long reaction time, poor yields, and metal contamination of the products. Thus a simple, mild, efficient, and metal-free approach to the 1,4-chemoselective reduction of α,β-unsaturated ketones is still challenging.

For years, we have been engaged in the selenofunctionalization of organic molecules[15] and the development of new synthetic methodologies involving organoselenium species.[16] In continuation of our research on the preparation of potentially useful selenium derivatives, we recently described[17] the use of *O*-(*tert*-butyl) Se-phenyl selenocarbonate **1** as a safer, practical, and efficient reagent enabling the "*in situ*" generation of benzeneselenol under advantageous transition-metal free conditions. Furthermore, the nucleophilic benzeneselenol thus obtained can be trapped with different electrophiles, affording alkyl phenyl selenides, β-hydroxyselenides, β-phenylseleno carbonyl derivatives, and vinyl selenides (Scheme 2).

Results and discussion

We report a facile and selective reduction of the C–C double bond of arylidene acetones and chalcones by using benzeneselenol prepared *via* the acidic decomposition of *O*-(*tert*-butyl) Se-phenyl selenocarbonate **1** (Scheme 1B). Previous results from our laboratory[17] reported on the facile 1,4-addition of benzeneselenol to 1-phenyl-but-3-en-2-one, methyl vinyl ketone, and some alkylidene acetones with **1** in ethanol, at 95 °C, and under an inert atmosphere. Thus we initially exploited the reaction of
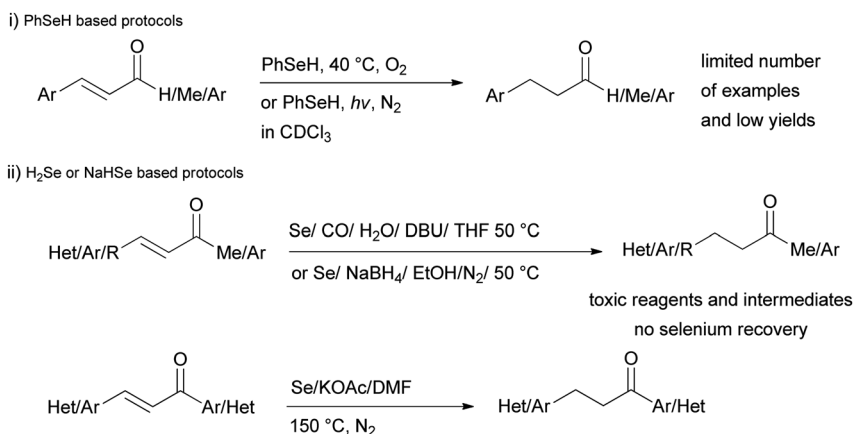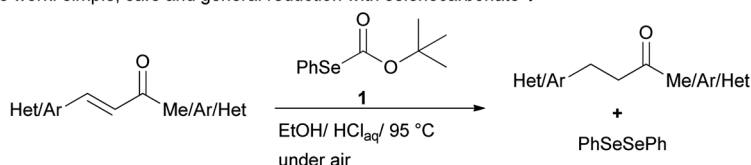
[a]Dipartimento di Scienze Farmaceutiche, Università di Perugia, Consorzio C.I.N.M.P.I.S., Via del Liceo 1, 06123 Perugia, Italy. E-mail: andrea.temperini@unipg.it

[b]Dipartimento di Farmacia e Scienze della Salute e della Nutrizione, Università della Calabria, Edificio Polifunzionale, 87030 Arcavacata di Rende, Cosenza, Italy

A) Previous works

i) PhSeH based protocols

PhSeH, 40 °C, O$_2$

or PhSeH, *hv*, N$_2$

in CDCl$_3$

limited number
of examples
and low yields

ii) H$_2$Se or NaHSe based protocols

Se/ CO/ H$_2$O/ DBU/ THF 50 °C

or Se/ NaBH$_4$/ EtOH/N$_2$/ 50 °C

toxic reagents and intermediates
no selenium recovery

Se/KOAc/DMF

150 °C, N$_2$

B) This work: simple, safe and general reduction with selenocarbonate 1

EtOH/ HCl$_{aq}$/ 95 °C
under air

**Scheme 1**   Methods for the selenium mediated selective reduction of enones.
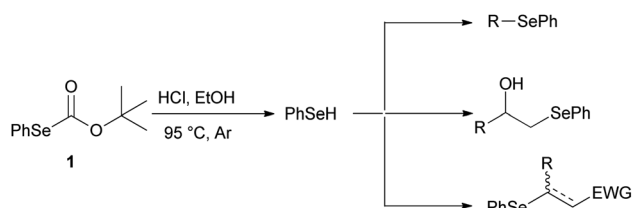
Scheme 2   Alkyl phenyl selenides, β-hydroxyselenides, β-phenyl-seleno carbonyl derivatives and vinyl selenides from *O*-(*tert*-butyl) Se-phenyl selenocarbonate (**1**).

benzylidene acetone **2a** under these standard conditions. The predominant formation of the 1,4-addition product **3a** (33% yield) together with minor amounts of the reduced product **4a** (15% yield), was observed (Scheme 3). Unreacted **2a** was also isolated from the reaction mixture. Modification of the stoichiometric amounts of selenocarbonate **1** (*e.g.* from 1.2 to 2 equiv.) resulted in only a mild enhancement in the yield of product **4a**. Similar results were previously observed for the 1,4-addition of pure benzeneselenol to **2a**, chalcone, and a β,β-dimethyl enone at room temperature and under air atmosphere.[18]

When the reaction was performed under air (closed glassware apparatus) the reduction was not complete, and **4a** was obtained as the major product in a 28% yield. This result was supposed due to the fact that the benzeneselenol intermediate, produced during the decomposition of **1**, might further be oxidized to diphenyl diselenide **5**. To our delight, when the reaction was carried out in the presence of 3 equiv. of selenocarbonate **1**, in no degassed ethanol and under air, compound **4a** was obtained in a maximal 48% yield.

To investigate the substrate scope of this carbon–carbon double bond selective reduction of β-aryl substituted enones, we first tested various (hetero)arylidene acetones under optimized conditions (Table 1). Good to excellent yields in the respective products were observed when electron-donating (Table 1, entries 1–3), electron-withdrawing (Table 1, entries 5 and 6), or both kinds of substituents (Table 1, entry 4) were placed on the aromatic ring of the arylidene acetone.

Satisfying yields and selectivity were observed starting from heteroarylidene acetones (Table 1, entries 7–9). Thiazole, benzothiophene, and indole containing enones gave the expected reduced products with total selectivity and in excellent yields. It should be underlined that our protocol resulted to be compatible with the presence of a methoxy group in the precursors,
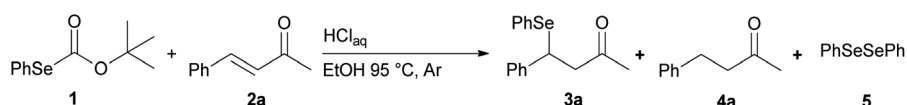
Scheme 3   Preliminary experiments.

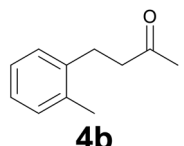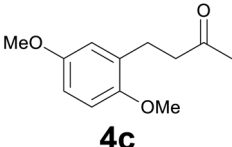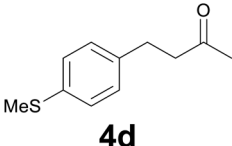**Table 1** Chemoselective double bond reduction of (hetero)arylidene acetones[a]
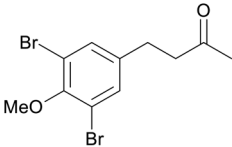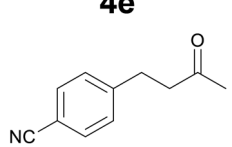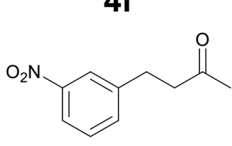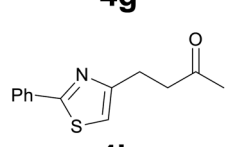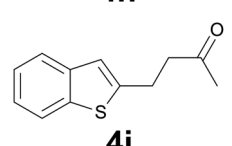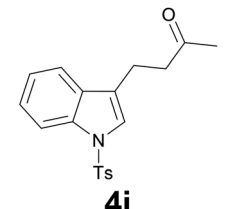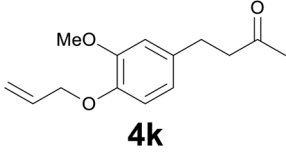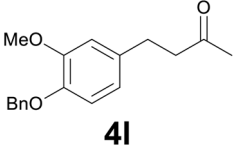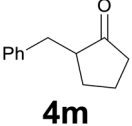
Entry	Enones 2	Time (h)	Products 4	Yield[a] (%)
1	**2b**	9	**4b**	77
2	**2c**	9	**4c**	89
3	**2d**	7	**4d**	93
4	**2e**	8	**4e**	79
5	**2f**	8	**4f**	90
6	**2g**	10	**4g**	78
7	**2h**	8	**4h**	86
8	**2i**	8	**4i**	85
9	**2j**	7	**4j**	91

Table 1 (*Contd.*)

Entry	Enones 2	Time (h)	Products 4	Yield[a] (%)
10	2k	6	**4k**	78
11	2l	6	**4l**	76
12	2m	8	**4m**	66

[a] Reaction scale: enone **2** (0.3 mmol), selenocarbonate **1** (0.9 mmol), 35% HCl (6 equiv.) in technical grade ethanol, 95 °C under air atmosphere.
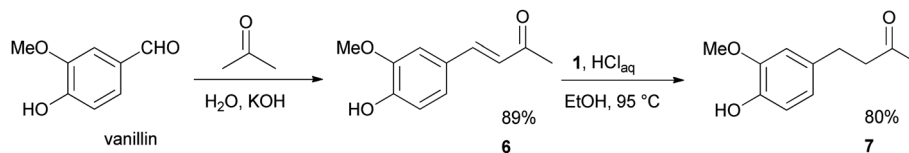
Scheme 4 The two steps synthesis of zingerone (**7**) from vanillin.

unlikely from the previously reported method,[14c] in which the demethylation products are unwantedly formed during the reduction process. Moreover, methylthio, cyano, nitro, and tosyl groups on the aromatic ring displayed high tolerance to the reaction conditions (Table 1, entries 3, 5, 6 and 9). Moreover, it was remarkable to observe that no cleavage of the allyl- and benzyl ether protecting groups occurred (Table 1, entries 10 and 11). The presence of an alkyl group at the C–C double bond α-position, as in the cyclic unsaturated ketone **2f**, resulted in a slight decrease in yield, proving that steric effects on the α-carbon might negatively influence this transformation.

We further desired to check the performance and robustness of our method in the simple two-step synthesis of 4-(4-hydroxy-3-methoxyphenyl)-2-butanone **7** (zingerone),[19] the spicy principle of ginger (Scheme 4). To fulfill our aim, this objective vanillin was condensed with acetone to afford the vanillylidenacetone **6** intermediate in 89% yield.[20] The chemoselective reduction of **6** with **1** under the optimized conditions, furnished zingerone **7** in 80% excellent yield.

Successively, we verified the versatility of the presented method by subjecting to the reduction of the C–C double bond various chalcones (Table 2). Reduction of chalcones successfully afforded the corresponding 1,3-diarylpropan-1-ones, which were obtained in good to excellent yields. Both electron-donating or -withdrawing substituents on the phenyl, or heteroaryl ring, had no significant influence on the yield. Substrates with thiophene, pyrazole, and benzothiazole rings were also suitable under the employed reaction conditions. Our protocol showed high chemoselectivity, as established when the carbon–carbon double bond in substrate **8c** was reduced selectivity in the presence of nitro group (Table 2, entry 3), unlikely the already reported reduction of *p*-nitrotoluene to *p*-toluidine with benzeneselenol.[2]

Noteworthy, in the case of chalcone **8d** bearing the *N*-acetyl group, the reduction was accompanied by hydrolysis of the amide function to afford the corresponding aniline derivative **9d** (Table 2, entry 4). The *N,N*-dimethylamino group was also well tolerated (Table 2, entry 6), although the reaction

Table 2 The chemoselective double bond reduction of chalcones **8**

Entry	Chalcones **8**	Time (h)	Products **9**	Yield[a] (%)
1	**8a**	3.5	**9a**	79
2	**8b**	8.5	**9b**	96
3	**8c**	3	**9c**	77
4	**8d**	3.5	**9d**	63[b]
5	**8e**	9	**9e**	72
6	**8f**	3	**9f**	86
7	**8g**	3.5	**9g**	89[c]
8	**8h**	3	**9h**	88
9	**8i**	3	**9i**	92

Table 2 (Contd.)

Entry	Chalcones 8	Time (h)	Products 9	Yield[a] (%)
10	**8j**	9	**9j**	74[d]
11	**8k**	9	**9k**	53

[a] Reaction scale: chalcone 8 (0.2 mmol), selenocarbonate 1 (0.6 mmol), 35% HCl (6 equiv.) in technical grade ethanol, 95 °C under air atmosphere. [b] The corresponding deacetylated product was isolated. [c] A gram scale reaction with 2.5 mmol of 8g was also carried out. [d] Selenocarbonate 1 (1.2 mmol) and 35% HCl (12 equiv.) were employed.

proceeded slower, and the addition of selenocarbonate 1, in four discrete portions, was necessary to obtain product 9f in excellent yield. Moreover, the reduction of dibenzylidene acetone 8j required the use of 6 equiv. of 1 to yield the corresponding saturated ketone 9j in good amounts. Another noteworthy result was obtained by treating the ene-dione 1,4-naphthoquinone 8k with selenocarbonate 1. The expected reduced product 1,4-naphthalenediol was not isolated. In its place, the 1-ethoxy-4-hydroxynaphthalene derivative 9k was obtained in an appreciable yield. Most probably the initially formed 1,4-naphthalenediol reacts with ethanol under acidic conditions to give 9k as previously reported by Laatsh.[21]

Finally, we checked the reduction procedure on a gram scale. In that case, the reaction was conducted, as usual, using 7.5 mmol of the reagent 1 and 2.5 mmol of the chalcone 8g obtaining the expected ketone 9g in an 82% yield. Moreover, although it was necessary to use 3 equiv. of 1, almost all of the phenylseleno unit was recovered as diphenyl diselenide at the end of the process (1.05 g, 89% yield), and recycled to prepare compound 1, demonstrating the atom economy of the procedure. We also tested the possibility to run the reduction of an

arylidenacetone in the presence of an α,β-unsaturated ester moiety, given the known difficulty preparation of an enone featuring the two above mentioned functional groups. Thus, an equimolar amount (0.2 mmol) of enone 2c and ethyl cinnamate was reacted with 3 equiv of 1 under the standard conditions (Scheme 5).

After 7 hours the reaction outcome was analyzed using GC-MS. The result indicated that the enone 2c was completely consumed to give the reduced product 4c whereas the ethyl cinnamate remained unchanged; only negligible amounts of 1,4-phenylseleno adduct to ethyl cinnamate and reduced ethyl cinnamate were observed by GC-MS analysis. Ketone 4c was then isolated in 81% yield confirming the mildness and selectivity of the proposed method.

A plausible mechanism of this oxygen-induced reduction of arylidenacetones and chalcones with benzeneselenol generated from 1 suggests the reaction to proceed via a free radical pathway in which the benzeneselenenyl radical might be formed in the reaction system by the reaction of benzeneselenol with oxygen accordingly to the mechanism previously described
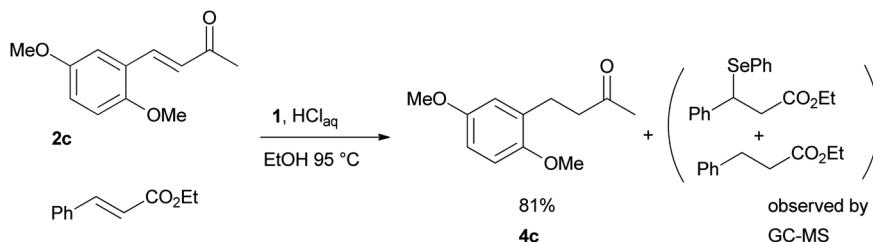
Scheme 5 Competitive reduction of the C−C double bond of α,β-unsaturated carbonyl compounds.
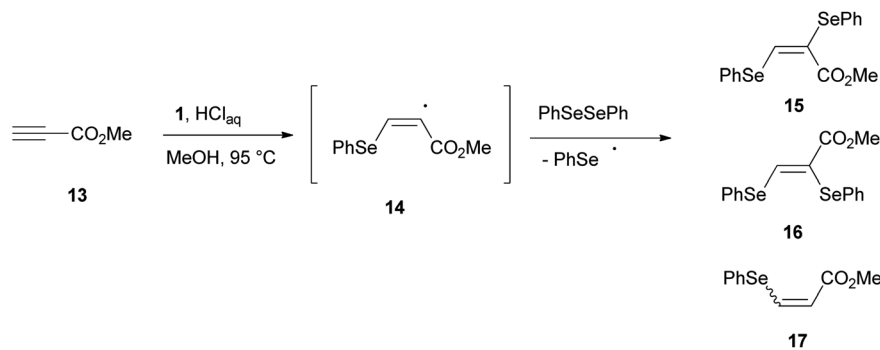
Scheme 6 Supporting benzeneselenenyl radical mediated mechanism experiment.

by Sonoda[6] for similar substrates working at 40 °C in 1,2,3,4-tetrahydronaphthalene.

The role played by a benzeneselenenyl radical in the reduction process was supported by the reaction of methyl propiolate **13** with **1**, in methanol under the proposed reaction conditions (Scheme 6). A 91 : 9 (*E/Z*) mixture of bis-selenides **15** and **16** contaminated by methyl β-phenylselenoacrylate **17** was isolated in a good amount. Bis-selenides **15** and **16** were firstly obtained by Back[22] through the photolysis of diphenyl diselenide, carried out in the presence of methyl propiolate, *via* a free-radical chain addition mechanism of benzeneselenenyl radical.

Most likely, the benzeneselenenyl radical, formed under our reaction conditions, gives addition to the triple bond of **13**, resulting in the formation of the alkenyl radical intermediate **14** (Scheme 6). This intermediate undergoes chain transfer to a molecule of diphenyl diselenide, formed in the reaction mixture by oxidation of benzeneselenol with oxygen, to afford the corresponding (*E*)-bis-selenide **15**. The formation of **16** suggests that the intermediate vinyl radical **14** is able to equilibrate prior to the chain-transfer step. Moreover, if the radical intermediate **14** abstracts an hydrogen atom from benzeneselenol, the β-phenylseleno derivative **17** can be formed.

Conclusions

A mild, efficient, and high chemoselective C–C double bond reduction of (hetero)arylidene acetones and chalcones with *O*-(*tert*-butyl) Se-phenyl selenocarbonate **1** as the precursor of benzeneselenol was established. At the same time, this safer procedure uses ethanol as an environmentally friendly solvent, and successfully works at moderate temperature (95 °C), in the presence of air. This method showed high functional group tolerance, and a wide substrate scope representing a valuable choice in alternative to the known traditional methods.

Experimental section

General information

Reactions were performed under atmosphere. Compounds purification by column chromatography was executed on silica gel (Merck 60, 70–230 mesh), and analytical TLC was carried out on pre-coated silica gel plates (Merck 60 F254, 0.25 mm) using

UV light and 0.5% w/v $KMnO_4$ aqueous solution (followed by gentle heating) for visualisation. Melting points were measured on a hot plate apparatus and are uncorrected. Proton magnetic resonance (^{1}H-NMR) spectra were recorded at 200 and 400 MHz. Proton-decoupled carbon magnetic resonance (^{13}C-NMR) spectra were recorded at 50.3 and 100.6 MHz. Chemical shifts (δ) are reported in parts per million (ppm). The NMR spectra were calibrated using the proton or carbon signals of residual non-deuterated solvent peaks: δ_H 7.27 and δ_C 77.0 for $CDCl_3$. Infrared (IR) spectra were recorded with a FT-IR instrument, using a diamond ATR sample interface. Absorption maxima (ν_{max}) are reported in wavenumbers (cm^{-1}). GC-MS analysis were obtained with a gas chromatograph (HP-5MS capillary column 29.0 m, ID 0.25, film 0.25 μm) equipped with a mass selective detector at an ionising voltage of 70 eV. Combustion analyses were carried out on an elemental analyser. IUPAC names of compounds were generated with ACD/Name. When the *E* and *Z* isomers were not separated (compounds **15**, **16** and **17**), the relative spectra were assigned by comparison with previously reported data. The reported yields were calculated based on the amount of isolated products. Unless otherwise noted, all reagents and solvents were obtained commercially and used without further purification. Compound **1** was synthesized in gram-scale by the method described in the literature.[17,23] Enones **2b–2e** were synthesized by aldol condensation of the corresponding aldehyde with acetone, in accord with previously reported procedures.[24] The enones **2f–j** were prepared by Wittig reaction of the corresponding aldehydes with 1-(triphenylphosphoranylidene)propan-2-one.[25] The remaining α,β-unsaturated ketones **2k**,[26] **2l**,[27] **2m**,[28] **8b**,[29] **8c**,[30] **8e**,[31] **8f**,[32] and **8h**[33] were prepared according to literature procedures.

Preparation of ketones 8d and 8g (general procedure)

To an ethanolic solution (30 mL) of substituted aryl methyl ketone (2.2 mmol) and substituted aromatic aldehyde (2 mmol), 8.0 M aqueous potassium hydroxide (1 mL) was added dropwise with stirring at room temperature. After completion of the reaction (48 h), 2.0 M aqueous hydrochloric acid (5 mL) was added and the crude product was isolated by filtration and washed with water, dried, and purified by chromatography

using a petroleum ether–dichloromethane mixture (1 : 9) as eluant.

(E)-N-(3-(3-(2-Bromo-4-chlorophenyl)acryloyl)phenyl) acetamide (8d). Yield: 0.55 g (73%); yellow solid, mp: 155–157 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.07–8.01 (m, 2H), 7.85 (d, J = 6.3 Hz, 1H), 7.69–7.61 (m, 3H), 6.97.46–7.25 (m, 3H), 2.25 (s, 3H), 1.78 (br s, 1H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 189.6, 168.9, 142.1, 138.6, 138.3, 136.6, 133.3, 133.2, 129.4, 128.5, 128.1, 126.2, 124.7, 124.5, 124.3, 119.6, 24.6. FTIR ν_{max}/ cm^{-1} 3250, 3066, 1662, 1600, 1486, 1296, 973, 787; m/z (E/I): 379 (M$^+$, 12%), 298 (100), 256 (59), 207 (46), 193 (18), 136 (14), 92 (11). Found: C, 53.98; H, 3.68; N, 3.61. Calc. for C$_{17}$H$_{13}$BrClNO$_2$: C, 53.92; H, 3.46; N, 3.70.

(E)-1-(3-Bromophenyl)-3-(3-methyl-1-phenyl-1H-pyrazol-4-yl) prop-2-en-1-one (8g). Yield: 0.83 g (90%); yellow solid, mp 159–160 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) δ 8.23 (s, 1H), 8.14 (t, J = 1.8 Hz, 1H), 7.93 (d, J = 7.8 Hz, 1H), 7.82 (d, J = 15.6 Hz, 1H), 7.75–7.65 (m, 3H), 7.54–7.39 (m, 3H), 7.38–7.19 (m, 3H), 2.54 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 188.7, 151.2, 140.1, 139.2, 136.1, 135.4, 131.4, 130.2, 129.6 (2C), 127.4, 126.8, 122.9, 119.4, 119.1 (2C), 118.5, 13.1; FTIR ν_{max}/cm^{-1} 2922, 3125, 1652, 1560, 1200, 987, 790, 683; m/z (E/I): 366 (M$^+$, 95%), 351 (23), 287 (48), 211 (100), 183 (30), 158 (54), 115 (25), 77 (44). Found: C, 62.02; H, 4.27; N, 7.55. Calc. for C$_{19}$H$_{15}$BrN$_2$O: C, 62.14; H, 4.12; N, 7.63.

Preparation of ketone 8i

A mixture of benzothiazole-2-carboxaldehyde (0.49 g, 3 mmol) and acetophenone (0.36 g, 3.3 mmol) was dissolved in 50% aqueous sulfuric acid (25 mL) and then heated at 50 °C (oil bath). After 48 h the mixture was cooling down and water (50 mL) was added. The mixture was extracted three times with 20 mL of CH$_2$Cl$_2$. The combined extracts were washed with brine, dried (MgSO$_4$), filtered, and concentrated *in vacuo*. The crude mixture was purified by column chromatography on silica gel with a mixture of petroleum ether–dichloromethane mixture (2 : 8) as eluant.

(E)-3-(1,3-Benzothiazol-2-yl)-1-phenylprop-2-en-1-one (8i). Yield: 0.42 g (53%); orange solid, mp 109–111 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.14–8.03 (m, 3H), 7.96–7.86 (m, 3H), 7.68–7.39 (m, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 189.2, 163.8, 153.8, 137.1, 135.9, 135.3, 133.4, 128.8 (2C), 128.7 (2C), 128.6, 126.8, 126.5, 123.9, 121.8; FTIR ν_{max}/cm^{-1} 3062, 1663, 1608, 1267, 1013, 727, 680; m/z (E/I): 265 (M$^+$, 46%), 236 (100), 188 (18), 160 (27), 105 (14), 77 (24). Found: C, 72.58; H, 4.32; N, 5.37. Calc. for C$_{16}$H$_{11}$NOS: C, 72.43; H, 4.18; N, 5.28.

Preliminary experiment for the reduction of 2a

Reaction conditions described in previous work[17] have been used. Thus aqueous 37% hydrochloric acid (0.1 mL, 1.2 mmol) was added to a solution of **1** (0.16 g, 0.6 mmol) and the α,β-unsaturated ketone **2a** (0.5 mmol) in 8 mL of degassed ethanol. The mixture was heated at 95 °C (oil bath) under argon atmosphere until the selenocarbonate **1** disappeared on TLC monitoring (5 h). After the addition of water (10 mL) the mixture was extracted three times with 10 mL of EtOAc. The combined

extracts were washed with brine, dried (MgSO$_4$), filtered, and concentrated *in vacuo*. The crude mixture was purified by column chromatography on silica gel with a 95 : 5 mixture of petroleum ether and ethyl ether as eluant to give the corresponding β-phenylseleno adduct **3a** and the reduced ketone **4a**.

4-Phenyl-4-(phenylseleno)butan-2-one (3a).[8] Yield: 50 mg (33%). ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.62–745 (m, 2H), 7.35–7.20 (m, 8H), 4.85 (dd, J = 8.5, 6.5 Hz, 1H), 3.30 (dd, J = 17.0, 8.5 Hz, 1H), 3.16 (dd, J = 17.0, 6.5 Hz, 1H), 2.14 (s, 3H).

4-Phenylbutan-2-one (4a). Yield: 12 mg (15%). Characterization data for the commercially available ketone **4a** matched the one reported for this compound; m/z (E/I): 148 (M$^+$, 100%), 133 (21), 105 (95), 91 (66), 77 (25).

General procedure for chemoselective reduction of (hetero) arylidene acetones 2a–o

A 25 mL round-bottom flask equipped with a stir bar and a condenser was charged with α,β-unsaturated ketone **2** (0.3 mmol), selenocarbonate **1** (0.24 g, 0.9 mmol) and ethanol (6 mL). The open end of the condenser was fitted with a rubber septum and then aqueous 37% hydrochloric acid (0.15 mL, 1.8 mmol) was added to the flask. The reaction mixture was stirred at 95 °C (oil bath) and the progress of the reaction was monitored by TLC (3–10 h). After cooling down, a saturated aqueous sodium hydrogencarbonate solution was carefully added dropwise (for ketone **4d**, saturated aqueous sodium carbonate solution was added). The mixture was extracted with three 10 mL portions of EtOAc. The combined extracts were washed with brine (10 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. The residue was then purified by flash chromatography on silica gel to provide the corresponding reduced product **4**.

4-(2-Methylphenyl)butan-2-one (4b).[10c] According to general procedure the title compound was obtained as colourless oil using a diethyl ether–hexane mixture (1 : 9) as eluent. Yield: 50 mg (77%); ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.18–7.08 (m, 4H), 2.96–2.82 (m, 2 H), 2.78–2.65 (m, 2H), 2.32 (s, 3H), 2.18 (s, 3H).

4-(2,5-Dimethoxyphenyl)butan-2-one (4c). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (4 : 6) as eluent to give **4c**. Yield: 56 mg (89%); colourless oil. ^{1}H NMR (200 MHz, CDCl$_3$) δ (ppm) 6.82–6.63 (m, 3H), 3.77 (s, 3H), 3.75 (s, 3H), 2.94–2.80 (m, 2H), 2.79–2.62 (m, 2H), 2.15 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 208.6, 153.3, 151.6, 130.4, 116.3, 111.2, 111.0, 55.7, 55.6, 43.6, 29.9, 25.1; FTIR ν_{max}/cm^{-1} 2938, 1712, 1498, 1220, 1039, 800, 712; m/z (E/I): 208 (M$^+$, 100%), 165 (31), 151 (51), 121 (24), 91 (13), 77 (15). Found: C, 68.97; H, 7.31. Calc. for C$_{12}$H$_{16}$O$_3$: C, 69.21; H, 7.04.

4-[4-(Methylthio)phenyl]butan-2-one (4d).[34] According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (1 : 9) as eluent to give **4d**. Yield: 52 mg (93%); ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.18 (d, J = 8.3, Hz, 2H), 7.10 (d, J = 8.3 Hz, 2H), 2.85 (t, J = 7.5 Hz, 2H), 2.73 (t, J = 7.5 Hz, 2H), 2.46 (s, 3H), 2.13 (s, 3H). m/z (E/I): 194 (M$^+$, 69%), 137 (100), 122 (15), 91 (9).

4-(3,5-Dibromo-4-methoxyphenyl)butan-2-one (4e). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (1 : 9) as eluent to give **4e**. Yield: 53 mg (79%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.32 (s, 2H), 3.85 (s, 3H), 2.90–2.65 (m, 4H), 2.16 (s, 3H); ^{13}C NMR (CDCl$_3$, 100 MHz) δ (ppm) 206.9, 152.3, 139.8, 132.5 (2C), 117.9 (2C), 60.5, 44.5, 30.0, 28.1; FTIR ν_{max}/cm^{-1} 2928, 1773, 1422, 1259, 993, 737; m/z (E/I): 336 (M$^+$, 100%), 278 (87), 266 (18), 214 (42), 185 (11), 118 (11). Found: C, 39.37; H, 3.84. Calc. for C$_{11}$H$_{12}$Br$_2$O$_2$: C, 39.32; H, 3.60.

4-(4-Isocyanophenyl)butan-2-one (4f). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (4 : 6) as eluent to give **4f**. Yield: 47 mg (90%); light yellow solid, mp 44–46 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.55 (d, J = 8.1 Hz, 2H), 7.29 (d, J = 8.1 Hz, 2H), 3.04–2.86 (m, 2H), 2.85–2.68 (m, 2H), 2.15 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 206.8, 146.7, 132.1 (2C), 129.1 (2C), 118.9, 109.8, 44.0, 29.9, 29.4; FTIR ν_{max}/cm^{-1} 2962, 2228, 1708, 1376, 1167, 827, 560; m/z (E/I): 173 (M$^+$, 100%), 130 (96), 116 (51), 103 (32), 89 (21), 77 (19). Found: C, 76.01; H, 6.60; N, 7.97. Calc. for C$_{11}$H$_{11}$NO: C, 76.28; H, 6.40; N, 8.09.

4-(3-Nitrophenyl)butan-2-one (4g).[35] According to general procedure the crude ketone was purified by chromatography using an ethyl acetate–hexane mixture (4 : 6) as eluent to give **4g**. Yield: 60 mg (78%). ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.13–7.95 (m, 2H), 7.62–7.3 (m, 2H), 3.06–2.92 (m, 2H), 2.90–2.78 (m, 2H), 2.17 (s, 3H).

4-(2-Phenyl-1,3-thiazol-4-yl)butan-2-one (4h). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (4 : 6) as eluent to give **4h**. Yield: 40 mg (86%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.01–7.82 (m, 2H), 7.50–7.37 (m, 3H), 6.92 (s, 1H), 3.28–3.01 (m, 2H), 3.00–2.85 (m, 2H), 2.19 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 207.9, 167.8, 156.6, 133.6, 129.9, 128.9 (2C), 126.4 (2C), 113.7, 42.8, 30.0, 25.5; FTIR ν_{max}/cm^{-1} 2918, 1713, 1356, 1159, 1003, 764, 690; m/z (E/I): 231 (M$^+$, 6%), 188 (100), 158 (12), 78 (20). Found: C, 67.39; H, 5.91; N, 5.90. Calc. for C$_{13}$H$_{13}$NOS: C, 67.50; H, 5.66; N, 6.06.

4-(1-Benzothien-2-yl)butan-2-one (4i). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (2 : 8) as eluent to give **4i**. Yield: 36 mg (85%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.77 (dd, J = 6.9, 1.6 Hz, 1H), 7.68 (dd, J = 6.6, 2.1 Hz, 2H), 7.38–7.21 (m, 2H), 7.03 (s, 1H), 3.20 (t, J = 7.2 Hz, 2H), 2.89 (t, J = 7.2 Hz, 2H), 2.19 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 207.0, 144.6, 140.0, 139.2, 124.2, 123.6, 122.8, 122.1, 121.1, 44.5, 30.1, 24.6; FTIR ν_{max}/cm^{-1} 2914, 1712, 1354, 1097, 813, 749, 484; m/z (E/I): 204 (M$^+$, 51%), 161 (100), 147 (59), 128 (20), 115 (12). Found: C, 70.45; H, 5.90. Calc. for C$_{12}$H$_{12}$OS: C, 70.55; H, 5.92.

4-{1-[(4-Methylphenyl)sulfonyl]-1H-indol-3-yl}butan-2-one (4j). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (4 : 6) as eluent to give **4j**. Yield: 64 mg (91%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.98 (d, J = 8.3 Hz, 1H), 7.74 (d, J = 8.4 Hz, 2H), 7.48 (d, J = 8.3 Hz, 1H), 7.37–7.13 (m, 5H), 3.01–2.89 (m, 2H), 2.88–2.67 (m, 2H), 2.39 (s, 3H), 2.16 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 207.5, 144.8, 135.2, 135.1, 130.6, 129.8 (2C), 126.7 (2C), 124.7, 123.0, 122.7, 121.9, 119.3, 113.7, 42.6, 38.0, 21.5, 18.7; FTIR ν_{max}/cm^{-1} 3106, 2921, 1706, 1370, 1169, 1129, 752, 702, 607, 534; m/z (E/I): 341 (M$^+$, 100%), 298 (45), 284 (48), 186 (25), 155 (47), 144 (77), 115 (16), 91 (49), 65 (139). Found: C, 66.68; H, 5.87; N, 4.15. Calc. for C$_{19}$H$_{19}$NO$_3$S: C, 66.84; H, 5.61; N, 4.10.

4-[4-(Allyloxy)-3-methoxyphenyl]butan-2-one (4k). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–dichloromethane mixture (1 : 99) as eluent to give **4k**. Yield: 54 mg (78%); colourless oil. ^{1}H NMR (200 MHz, CDCl$_3$) δ (ppm) 6.79 (d, J = 8.1 Hz, 1H), 6.71 (d, J = 2.0 Hz, 1H), 6.68 (dd, J = 8.1, 2.0 Hz, 1H), 6.13–6.01 (m, 1H), 5.38 (dq, J = 17.3, 1.5 Hz, 1H), 5.26 (dq, J = 10.5, 1.5 Hz, 1H), 4.58 (dt, J = 5.4, 1.5 Hz, 2H), 3.85 (s, 3H), 2.88–2.79 (m, 2H), 2.78–2.70 (m, 2H), 2.13 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 208.1, 149.3, 146.2, 134.0, 133.4, 119.9, 117.8, 113.5, 111.9, 69.9, 55.8, 45.3, 30.1, 29.3; FTIR ν_{max}/cm^{-1} 2925, 1713, 1512, 1139, 1020, 803; m/z (E/I): 234 (M$^+$, 88%), 193 (100), 161 (25), 151 (15), 133 (61), 119 (79), 102 (21), 91 (36), 77 (21). Found: C, 71.22; H, 7.84. Calc. for C$_{14}$H$_{18}$O$_3$: C, 71.37; H, 7.74.

4-[4-(Benzyloxy)-3-methoxyphenyl]butan-2-one (4l). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–dichloromethane mixture (1 : 99) as eluent to give the known[36] ketone **4l**. Yield: 40 mg (71%). ^{1}H NMR (CDCl$_3$, 400 MHz) δ (ppm) 7.46–7.40 (m, 2H), 7.39–7.33 (m, 2H), 7.32–7.26 (m, 1H), 6.79 (d, J = 8.1 Hz, 1H), 6.74 (d, J = 2.0 Hz, 1H), 6.65 (dd, J = 8.1, 2.0 Hz, 1H), 5.13 (s, 2H), 3.88 (s, 3H), 2.87–2.79 (m, 2H), 2.77–2.71 (m, 2H), 2.13 (s, 3H); ^{13}C NMR (CDCl$_3$, 100 MHz) δ (ppm) 208.2, 149.5, 146.4, 137.3, 134.2, 128.5, 127.7, 127.2, 120.0, 114.1, 112.1, 71.1, 55.9, 45.3, 30.1, 29.3.

2-Benzylcyclopentanone (4m).[28] According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (3 : 97) as eluent to give the commercially available ketone **4m**. Yield: 38 mg (66%).

Two steps synthesis of zingerone 7.[19]

To a solution of vanillin (0.5 g, 3.3 mmol) in 2 mL of acetone was added gradually 2.5 M aqueous sodium hydroxide (2 mL) at room temperature. The mixture was stirred for 48 h and then diluted with 2.0 M aqueous hydrochloric acid (5 mL) and EtOAc (10 mL). The organic and aqueous layers were separated, and the aqueous layer was extracted with EtOAc (3× 20 mL). The combined extracts were washed with brine (10 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. Purification by silica gel column chromatography using an ethyl ether–hexane mixture (6 : 4) as eluent afforded the known[20] (3*E*)-4-(4-hydroxy-3-methoxyphenyl)but-3-en-2-one (**6**) intermediate (0.56 g, 89% yield). m/z (E/I): 192 (M$^+$, 92%), 177 (100), 145 (81), 117 (37), 89 (26), 77 (18).

Then compound **6** (0.3 mmol) was reduced as reported above for other arylidene acetones. After 7 h the mixture was cooling down and water (10 mL) was added. The mixture was extracted with three 10 mL portions of EtOAc. The combined extracts were

washed with brine (10 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. The crude ketone was purified by chromatography using a ethyl ether–hexane mixture (1 : 9) as eluent to furnish the commercially available ketone 4-(4-hydroxy-3-methoxyphenyl)butan-2-one (**7**). Yield: 47 mg (80%).

General procedure for chemoselective reduction of chalcones 8a–l and naphthoquinone 8m

A 25 mL round-bottom flask equipped with a stir bar and a condenser was charged with chalcone **8** (0.2 mmol), seleno-carbonate **1** (0.16 g, 0.6 mmol) and ethanol (4 mL). The condenser was fitted with a rubber septum and then aqueous 37% hydrochloric acid (0.1 mL, 1.2 mmol) was added to the flask. The reaction mixture was stirred at 95 °C (oil bath) and the progress of the reaction was monitored by TLC (3–9 h). After cooling down to room temperature, a saturated aqueous sodium hydrogencarbonate solution was carefully added drop-wise (for chalcone **8d**, saturated aqueous sodium carbonate solution was added). To obtain ketone **9f** in high yield it was necessary to dissolve the selenocarbonate **1** in ethanol (1 mL) and then added this solution in four portions during the first six hours and finally quenched the reaction with saturated aqueous sodium carbonate solution. The mixture was extracted with three 10 mL portions of EtOAc. The combined extracts were washed with brine (10 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. The residue was then purified by flash chromatography on silica gel to provide the corresponding ketone **9**.

1,3-Diphenylpropan-1-one (9a). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (6 : 94) as eluent to give the commercially available ketone **9a**. Yield: 33 mg (79%).

1-(4-Chlorophenyl)-3-(4-methoxyphenyl)propan-1-one (9b).[37] According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (15 : 85) as eluent to give ketone **9b**. Yield: 53 mg (95%). ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.92–7.86 (m, 2H), 7.46–7.40 (m, 2H), 7.20–7.13 (m, 2H), 6.88–6.82 (m, 2H), 3.80 (s, 3H), 3.24 (t, J = 7.5 Hz, 2H), 3.00 (t, J = 7.5 Hz, 2H).

3-(2-Naphthyl)-1-(4-nitrophenyl)propan-1-one (9c). According to general procedure the crude ketone was purified by chromatography using a dichloromethane–hexane mixture (1 : 1) as eluent to give **9c**. Yield: 47 mg (77%); light yellow solid, mp 132–134 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.30 (d, J = 8.8 Hz, 2H), 8.10 (d, J = 8.8 Hz, 2H), 7.89–7.73 (m, 3H), 7.72 (s, 1H), 7.55–7.34 (m, 3H), 3.52–3.37 (m, 2H), 3.35–3.20 (m, 2H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 197.5, 150.2, 114.1, 138.0, 133.5, 132.1, 129.0 (2C), 128.3, 127.6, 127.4, 126.9, 126.6, 125.5, 123.8 (2C), 40.9, 29.9; FTIR ν_{max}/cm^{-1} 3113, 2897, 1784, 1517, 1319, 1195, 807, 476; *m/z* (E/I): 305 (M$^+$, 81%), 155 (100), 141 (62), 115 (19), 104 (139), 76 (10). Found: C, 74.78; H, 4.89; N, 4.35. Calc. for C$_{19}$H$_{15}$NO$_3$: C, 74.74; H, 4.95; N, 4.59.

1-(3-Aminophenyl)-3-(2-bromo-4-chlorophenyl)propan-1-one (9d). According to general procedure the crude ketone was purified by chromatography using an ethyl acetate–dichloromethane mixture (4 : 96) as eluent to give **9d**. Yield: 42 mg (63%); light yellow oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.56 (d, J = 1.6 Hz, 1H), 7.40–7.16 (m, 5H), 6.91 (d, J = 7.8 Hz, 1H), 7.30 (br s, 2H), 3.31–3.20 (m, 2H), 3.19–3.08 (m, 2H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 198.7, 146.2, 139.1, 137.7, 132.6, 132.3, 131.5, 129.5, 127.7, 124.5, 120.0, 118.7, 114.1, 38.3, 30.1; FTIR ν_{max}/cm^{-1} 3468, 3364, 2932, 1683, 1585, 1469, 1313, 1037, 732, 684; *m/z* (E/I): 339 (M$^+$, 29%), 258 (89), 120 (100), 92 (53), 65 (29). Found: C, 52.93; H, 3.99; N, 4.25. Calc. for C$_{15}$H$_{13}$BrClNO: C, 53.20; H, 3.87; N, 4.14.

3-(5-Bromo-2-thienyl)-1-(4-chlorophenyl)propan-1-one (9e). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (14 : 86) as eluent to give **9e**. Yield: 48 mg (72%); yellow solid, mp < 40 °C. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.89 (d, J = 8.8 Hz, 2H), 7.44 (d, J = 8.8 Hz, 2H), 6.85 (d, J = 3.7 Hz, 1H), 6.62 (d, J = 3.7 Hz, 1H), 3.32–3.26 (m, 2H), 3.24–3.18 (m, 2H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 196.9, 145.3, 139.7, 134.8, 129.5, 129.4 (2C), 129.0 (2C), 125.2, 109.4, 40.0, 24.4; FTIR ν_{max}/cm^{-1} 2896, 1699, 1587, 1206, 1090, 962, 796, 473; *m/z* (E/I): 330 (M$^+$, 54%), 330 (54), 177 (56), 139 (100), 111 (40). Found: C, 47.17; H, 3.28. Calc. for C$_{13}$H$_{10}$BrClOS: C, 47.37; H, 3.06.

3-[4-(Dimethylamino)phenyl]-1-(2-thienyl)propan-1-one (9f). According to general procedure the crude ketone was purified by chromatography using a dichloromethane–hexane mixture (8 : 2) as eluent to give **9f**. Yield: 45 mg (86%); light yellow oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.70 (dd, J = 3.8, 1.1 Hz, 1H), 7.63 (d, J = 4.9, 1.1 Hz, 1H), 7.22–7.08 (m, 3H), 6.78 (d, J = 8.6 Hz, 2H), 3.30–3.13 (m, 2H), 3.08–2.90 (m, 2H), 2.94 (s, 6H); ^{13}C NMR (CDCl$_3$, 100 MHz) δ (ppm) 192.5, 148.8, 144.2, 133.4, 131.7, 129.7, 129.1 (2C), 128.0, 113.4 (2C), 41.6, 41.1 (2C), 29.5; FTIR ν_{max}/cm^{-1} 3089, 2907, 1652, 1519, 1415, 1347, 1203, 811, 723; *m/z* (E/I): 259 (M$^+$, 49%), 134 (100), 118 (14), 111 (10). Found: C, 69.38; H, 6.89; N, 5.55. Calc. for C$_{15}$H$_{17}$NOS: C, 69.46; H, 6.61; N, 5.40.

1-(3-Bromophenyl)-3-(3-methyl-1-phenyl-1*H*-pyrazol-4-yl)propan-1-one (9g). According to general procedure the crude ketone was purified by chromatography using dichloromethane as eluent to give **9g**. Yield: 66 mg (89%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.10 (t, J = 1.7 Hz, 1H), 7.89 (d, J = 7.8 Hz, 1H), 7.74–7.55 (m, 4H), 7.48–7.15 (m, 4H), 3.24 (t, J = 7.1 Hz, 2H), 2.92 (t, J = 7.1 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 197.7, 149.0, 140.0, 138.4, 136.0, 131.0, 130.2, 129.3 (3C), 126.5, 125.7 (2C), 123.0, 120.2, 118.4 (2C), 39.2, 17.9, 11.9; FTIR ν_{max}/cm^{-1} 2922, 1687, 1503, 1197, 754, 729, 688, 677; *m/z* (E/I): 368 (M$^+$, 55%), 185 (35), 171 (100), 158 (28), 77 (25). Found: C, 61.68; H, 4.84; N, 7.46. Calc. for C$_{19}$H$_{17}$BrN$_2$O: C, 61.80; H, 4.64; N, 7.59.

3-(3-Methyl-1-phenyl-1*H*-pyrazol-4-yl)-1-(2-thienyl)propan-1-one (9h). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–dichloromethane mixture (1 : 99) as eluent to give **9h**. Yield: 53 mg (88%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.78–7.68 (m, 2H), 7.67–7.52 (m, 3H), 7.47–7.33 (m, 2H), 7.27–7.16 (m, 1H), 7.13 (dd, J = 5.0, 3.8 Hz, 1H), 3.20 (t, J = 7.2 Hz, 2H), 2.93 (t, J = 7.2 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (CDCl$_3$, 50 MHz) δ (ppm) 192.0, 149.0, 144.1, 140.0, 132.6, 131.8, 129.3 (2C), 128.1, 125.7, 125.6, 120.2, 118.4 (2C), 39.8, 18.4, 11.9; FTIR ν_{max}/

cm^{-1} 3100, 2922, 1652, 1503, 1415, 1221, 1058, 724; m/z (E/I): 296 (M$^+$, 86%), 185 (30), 171 (100), 158 (35), 111 (24), 77 (30). Found: C, 68.65; H, 5.70; N, 9.33. Calc. for C$_{17}$H$_{16}$N$_2$OS: C, 68.89; H, 5.44; N, 9.45.

3-(1,3-Benzothiazol-2-yl)-1-phenylpropan-1-one (9i).[38] According to general procedure the crude ketone was purified by chromatography using dichloromethane as eluent to give **9i**. Yield: 50 mg (92%); light yellow oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.10–7.80 (m, 4H), 7.65–7.25 (m, 5H), 3.75–3.48 (m, 4H); FTIR ν_{max}/cm^{-1} 2928, 1679, 1449, 1240, 1112, 760, 687.

1,5-Diphenylpentan-3-one (9j). According to general procedure the crude ketone was purified by chromatography using a diethyl ether–hexane mixture (1 : 9) as eluent to give the commercially available ketone **9j**. Yield: 35 mg (74%).

4-Ethoxy-1-naphthol (9k).[39] According to general procedure the crude ketone was purified by chromatography using dichloromethane as eluent to give **9k**. Yield: 40 mg (53%); colourless oil. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.27–8.25 (m, 1H), 8.13–8.11 (m, 1H), 7.60–7.40 (m, 2H), 6.72 (d, J = 8.1 Hz, 1H), 6.64 (d, J = 8.1 Hz, 1H), 5.03 (bs, 1H), 4.14 (q, J = 7.0 Hz, 2H), 1.51 (t, J = 7.0 Hz, 3H).

Gram scale synthesis of 9g. In an round-bottom flask selenocarbonate **1** (1.93 g, 7.5 mmol) and chalcone **8g** (0.92 g, 2.5 mmol) were dissolved with reagent grade ethanol (50 mL). Aqueous 37% hydrochloric acid (1.25 mL, 15 mmol) was added and the resulting mixture was refluxed (95 °C, oil bath) as described above until the chalcone **8g** disappeared (7 h). After cooling to room temperature a saturated aqueous sodium hydrogencarbonate solution was carefully added dropwise. The mixture was extracted with three 40 mL portions of EtOAc. The combined extracts were washed with brine (20 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. The product was purified by chromatography using dichloromethane as eluent to give **9g** (0.75 g, 82% yield) as a colourless oil. Diphenyl diselenide was also recovered as a yellow solid (1.05 g, 89% yield).

Competitive Michael-addition experiment

According to general procedure an aqueous 37% hydrochloric acid solution (0.1 mL, 1.2 mmol) was added to a solution of **2c** (41 mg, 0.2 mmol), ethyl cinnamate (34 mL, 0.2 mmol) and the selenocarbonate **1** (0.16 g, 0.6 mmol) in 4 mL of ethanol. The mixture was heated at 95 °C (oil bath) under atmosphere (condenser fitted with a rubber septum) and the progress of the reaction was monitored by TLC (7 h). After cooling to room temperature a saturated aqueous sodium hydrogencarbonate solution was carefully added dropwise. The mixture was extracted with three 10 mL portions of EtOAc. The combined extracts were washed with brine (5 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. Purification of the crude product by chromatography (SiO$_2$, diethyl ether/hexane 4 : 6) afforded 34 mg (81% yield) of ketone **4c**.

Benzeneselenenyl radical-mediated addition of diphenyldiselenide to alkyne 13

A 50 mL round-bottom flask equipped with a stir bar and a condenser was charged with methyl propiolate **13** (0.2 mmol),

selenocarbonate **1** (0.16 g, 0.6 mmol) and methanol (4 mL). In this experiment methanol was employed to eliminate the potential transesterification reaction of methyl propiolate with ethanol. The condenser was fitted with a rubber septum and then aqueous 37% hydrochloric acid (0.1 mL, 1.2 mmol) was added to the flask. The reaction mixture was stirred at 95 °C (oil bath) and the progress of the reaction was monitored by TLC. Reaction quenching was achieved after 4 h by simply adding a saturated aqueous sodium hydrogencarbonate solution. The mixture was extracted with three 10 mL portions of EtOAc. The combined extracts were washed with brine (10 mL), dried (MgSO$_4$), filtrated and concentrated *in vacuo*. The residue was then purified by flash chromatography on silica gel using a diethyl ether/hexane 5 : 95 mixture as eluant. Unfortunately an inseparable 91 : 9 (E/Z) mixture of bis-selenides **15** and **16** respectively (60 mg, 75% yield) contaminated by β-phenylselenoacrylate **17** was isolated.

Methyl-(2E)-2,3-bis(phenylseleno)acrylate (15).[22] Major isomer. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.90 (s, 1H), 7.50–7.44 (m, 4H), 7.33–7.23 (m, 6H), 3.82 (s, 3H). m/z (E/I): 398 (M$^+$, 100%), 240 (25), 209 (41), 182 (51), 157 (92), 116 (23), 102 (41), 77 (61).

Methyl-(2Z)-2,3-bis(phenylseleno)acrylate (16).[22] Minor isomer. ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.90 (s, 1H), 7.63–7.55 (m, 4H), 7.41–7.32 (m, 6H), 3.70 (s, 3H).

Another fraction containing β-phenylselenoacrylate **17** (95 : 5 Z/E stereoisomeric mixture) was also obtained (10 mg, 20% yield).

Methyl 3-(phenylseleno)acrylate (17).[40] Mixture of isomers. Major isomer (Z)-**17**: ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 7.78 (d, J = 9.5 Hz, 1H), 7.65–7.55 (m, 2H), 7.40–7.30 (m, 3H), 6.38 (d, J = 9.5 Hz, 1H), 3.80 (s, 3H). Minor isomer (E)-**17**: ^{1}H NMR (CDCl$_3$, 200 MHz) δ (ppm) 8.16 (d, J = 15.5 Hz, 1H), 7.65–7.55 (m, 2H), 7.40–7.30 (m, 3H), 5.87 (d, J = 15.5 Hz, 1H), 3.70 (s, 3H). m/z (E/I): 242 (M$^+$, 100%), 211 (33), 183 (96), 157 (57), 131 (41), 102 (22), 77 (46).

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

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