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ORIGINAL PAPER

Catalytic multicomponent reaction between nitroalkanes, elemental sulfur, and oxiranes

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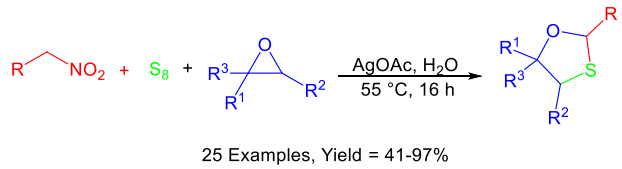
Abstract An efficient multicomponent reaction of nitroalkanes and elemental sulfur with oxiranes was developed with the aid of silver salt. This reaction procedure provides a novel and practical strategy for the rapid assembly of 1,3-oxathiolane skeletons. The reaction exhibited remarkable functional group tolerability and regio-selectivity so that only one regio-isomer formed during the ring opening of oxiranes.

Graphical abstract



25 Examples, Yield = 41-97%

Keywords Oxirane · Cyclization · Elemental sulfur · Nitroalkane · Catalytic multicomponent reaction

Introduction

Heterocyclic compounds are core skeletons of most pharmaceutical agents and bioactive compounds [1–4]. The addition and/or elimination of bonds to active carbon are the most privileged route for the synthesis of heterocyclic compounds [5–7]. The achievement of forming heterocyclic compounds in a multicomponent reaction has opened the door for expedient and diverse syntheses of these highly valuable building-blocks in only one single step [8–10]. Among the various types of heterocycles, organosulfur compounds are important intermediates for the synthesis of various biologically active molecules. 1,3-Oxathiolane derivatives have been shown to possess radioprotective activity [11]. Over the years, the increasing request for oxathiolanes resulted in the development of synthetic strategy for the syntheses of the structures in high purity and on large scale [12–14]. As result of promising biological activities, some of oxathiolane nucleosides have been licensed for the treatment of human immunodeficiency viruses (HIV-1 and HIV-2) and hepatitis B virus (HBV) infections [15, 16]. In addition, more studies are being conducted to evaluate antiretroviral activity of a number of other oxathiolane nucleosides [17].

A variety of oxathiolanes and oxathianes have been formed starting from epoxides and heterocomulenes [17–25]. However, a relatively limited number of reports on the reaction of oxiranes with elemental sulfur have appeared [26, 27]. Most of the transformation described above produced 1,3-oxathiolanes which contain C–N or C–S double bond at C-2 position.

Organic C–H acids typically have an adjacent electron-withdrawing group to polarize the C–H bond for site-selective addition and enhanced reactivity. In continuation of our report in catalysis [28–31], we examine the efficiency

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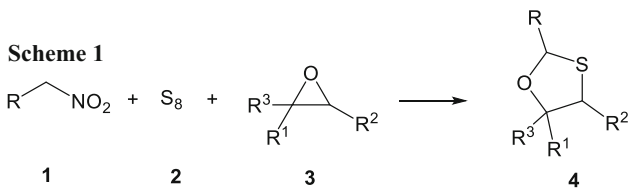
of nitroalkane, elemental sulfur, and oxiranes in preparation of 1,3-oxathiolane derivatives (Scheme 1).

Results and discussion

Preliminary attempt to promote the reaction between nitromethane (**1**), elemental sulfur (**2**), and methyl oxirane (**3a**) in the presence of $(i\text{-Pr})_2$MeN at 55 °C for the synthesis of 1,3-oxathiolane skeleton was unsuccessful. Therefore, the reaction was conducted with tetrabutylphosphonium acetate (TBPA) for 16 h and 4-methyl-1,3-oxathiolane (**4a**) was obtained in traces amount together with 1-[(nitromethyl)thio]propan-2-ol (**5**) in 41% yield (Table 1, entry 2). It should be noted that tetrabutylammonium acetate (TBAA) completely inhibited the reaction (Table 1, entry 3). Based on this finding, we examined the reaction under various conditions to improve the yield of **4a** (Table 1). As anticipated, Lewis acidity of the metal-cation should facilitate the ring opening and subsequent nucleophilic substitution on the carbon atom bound to the nitro group. As such, the reaction was conducted with a range of Lewis acids and the results are summarized in Table 1. While in most reactions trace amounts of the targeted 1,3-oxathiolane **4a** were detected (Table 1, entries 4–8), the use of Ag_2O led to a promising 51% yield (Table 1, entry 9). To our delight, the yield of **4a** increased to 96% yield when the reaction was performed in the presence of AgOAc (Table 1, entry 10). Other silver salts also promoted the reaction; however, the yields were comparatively lower (entries 11–13). Such substantial variations on the yield using AgOAc as the promoter could traduce the positive role displayed by releasing AcOH in the mild entries 10 vs. entry 11. To our surprise, the yield completely suppressed using $AgNO_3$ and $AgBF_4$ as the promoter (Table 1, entries 14 and 15). The results clearly exhibit the sensitivity of the reaction to the nature of both the metallic cation and the counter-ion. Attempts to use alternative solvents such as THF, DMF, toluene, and others proved less efficient affording **4a** in lower yields (Table 1, entries 15–20). It is worth mentioning that the desired product obtained in 93% yield when deionized water was used as the solvent using 1.5 mmol of nitromethane (**1a**) (Table 1, entry 21). Finally, a sulfur loading screen indicated that the yield remained almost unchanged by decreasing the amount of sulfur to 0.3 mmol; however, the yield was observed to decrease as the amount reduced further (Table 1, entries 22 and 23). There was no progress in the reaction after hours at room temperature (Table 1, entry 24).

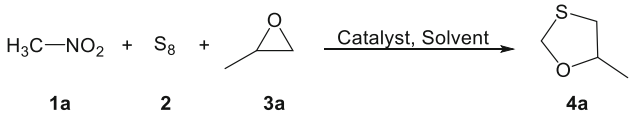
Scheme 1



Subsequently, we explored the scope of the cyclization reaction with oxirane derivatives **3** (Table 2). With the oxirane substituted by methyl group **3a**, a yield of 90% of the product was obtained (Table 2, entry 1). Other alkyl oxiranes could also be employed as facile substrates that provided the corresponding 1,3-oxathiolanes in good yields (Table 2, entries 2 and 3). Ethyl-substituted oxirane **3b** improved the reactivity of the reaction; in contrast, a modest decrease in yield occurred using 2-propyloxirane (**3c**) probably due to the steric hindrance for the incoming nucleophile. Sterically hindered oxirane **3d** proceeded in moderate success affording the corresponding products **4d** in 51% yield (Table 2, entry 4). When oxiranes containing oxymethyl motif were subjected to the reaction conditions, the desired heterocyclic products **4e**, **4f**, and **4g** were isolated in good yields (Table 2, entries 5–7). We found that ring opening of gem-di-substituted oxiranes **3h** and **3i** proceeded in excellent conversions (Table 2, entries 8 and 9). Electronically distinct group on the oxirane ring, such as chloride is also well tolerated (Table 2, entry 10). Higher yield was obtained for *tert*-butyl-substituted oxirane **3k** compared to their common alkyl analogues (Table 2, entry 11). Oxirane with allyl motif **3l** gave the corresponding product in acceptable yield (Table 2, entry 12). The presence of OH– and CF_3– in oxirane structure **3m** lowered the yield of its corresponding 1,3-oxathiolane (Table 2, entry 13). Taking phenyl-substituted oxiranes as an example (**3n**, **3o**, **3p**, and **3q**), the products yield decreased with increased electron density of the aryl moiety (Table 2, entries 14–17). Particularly noteworthy was that the reactions conducted with phenyl- and electron-rich arene-substituted oxirane formed the benzylic attacked product, exclusively. A modest increase in yield occurred when stilbene oxide (**3r**) was used as the substrate (Table 2, entry 18). Phenyl(3-phenyloxiran-2-yl)methanone (**3s**) was also transferred to the corresponding 1,3-oxathiolane in good yield (Table 2, entry 19). The fused bicyclic 1,3-oxathiolanes were also achieved in acceptable yields (Table 2, entries 20–22). Unfortunately, cyclopentene and cyclooctene oxides (**3w** and **3x**) did not undergo the desired cyclization reaction which is likely due to steric as well as electronic factors (Table 2, entries 23 and 24).

Finally, we extended this reaction to other types of nitroalkanes (Table 3). Under the similar conditions, the readily available nitroethane (**1b**) is converted to the desired 1,3-oxathiolane structure **4w** in 61% yield (Table 3, entry 1). Additionally, nitropropane (**1c**) also

Table 1 Optimization of reaction conditions



Entry	Catalyst	Solvent	Yield of **4a**/%
1	$(i\text{-Pr})_2$MeN	$MeNO_2$	–
2	TBPA	$MeNO_2$	Traces[a]
3	TBAA	$MeNO_2$	–
4	LiOTf	$MeNO_2$	17
5	$LiClO_4$	$MeNO_2$	11
6	$BF_3.Et_2O$	$MeNO_2$	–
7	$Sc(OTf)_3$	$MeNO_2$	Traces
8	$ZnCl_2$	$MeNO_2$	–
9	Ag_2O	$MeNO_2$	51
10	AgOAc	$MeNO_2$	96
11	AgOTf	$MeNO_2$	78
12	AgI	$MeNO_2$	34
13	AgCl	$MeNO_2$	26
14	$AgNO_3$	$MeNO_2$	17
15	AgBF4	$MeNO_2$	12
16	AgOAc	THF	38
17	AgOAc	DMF	40
18	AgOAc	Toluene	71
19	AgOAc	CH_2Cl_2	87
20	AgOAc	MeCN	38
21	AgOAc	H_2O	93[b]
22	AgOAc	H_2O	90[b,c]
23	AgOAc	H_2O	67[b,d]
24	AgOAc	H_2O	–[e]

For all entries except stated otherwise: **1a** (2.0 cm^3), **2** (1.0 mmol), **3a** (1.0 mmol), promoter (0.15 mmol) in solvent at 55 °C for 16 h in a sealed tube under N_2

[a]1-[(Nitromethyl)thio]propan-2-ol (**5**) was obtained in 41% yield

[b]Reaction conducted with 1.5 mmol of **1a**

[c]Reaction conducted with 0.3 mmol of **2**

[d]Reaction conducted with 0.2 mmol of **2**

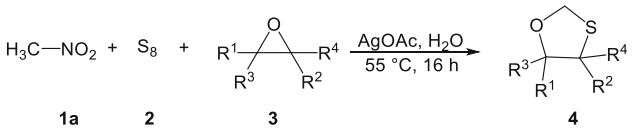
[e]Reaction conducted at 25 °C

proceeded smoothly to give the corresponding product **4x** in 52% yields (Table 3, entry 2). However, when 2-nitropropane (**1d**) was used, only a trace amount of the product **4y** was detected (Table 3, entry 3). These results indicated that the steric hindrance of alkyl groups disfavored the reaction obviously which indicates that the cyclization step proceeds through an SN2 pathway.

The mechanism is not clear at the present stage. Unfortunately, the exact role of silver salt and how do it catalyze this transformation is still unclear, but it should be noted that the reaction did not work well in absence of silver acetate. A plausible mechanism for the formation of the main product **4** is shown in Scheme 2. The reaction starts with initial formation of conjugate base of nitroalkane **5** by the action of AgOAc. The reaction of **5** with elemental sulfur forms the intermediated **6**, which attacks **3a** to afford ring-opened intermediate **7**. Finally, the ring closing of the intermediate **7** through an SN2 reaction gave the desired product **4**.

The structures of the products were confirmed by spectroscopic analyses. For example, the ^{1}H NMR spectrum of **4a** showed characteristic (AB)X spin system for

Table 2 Reaction scope with oxiranes

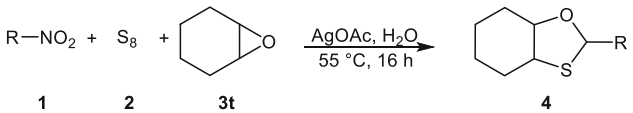


Entry	Epoxide	R^1, R^2, R^3, R^4	**4**, yield/%
1	**3a**	CH_3, H, H, H	**4a**, 90
2	**3b**	Et, H, H, H	**4b**, 92
3	**3c**	*n*-Pr, H, H, H	**4c**, 83
4	**3d**	CH_3, CH_3, CH_3, CH_3	**4d**, 48
5	**3e**	$(CH_3)_2CHOCH_2$, H, H, H	**4e**, 90
6	**3f**	$PhCH_2OCH_2$, H, H, H	**4f**, 92
7	**3g**	$PhOCH_2$, H, H, H	**4g**, 95
8	**3h**	CH_3, H, CH_3OCO, H	**4h**, 88
9	**3i**	*n*-Pr, H, CH_3, H	**4i**, 96
10	**3j**	$ClCH_2$, H, H, H	**4j**, 68
11	**3k**	$(CH_3)_3C$, H, H, H	**4k**, 95
12	**3l**	$CH_2CHCH_2OCH_2$, H, H, H	**4l**, 82
13	**3m**	$PhC(OH)(CF_3)$, H, H, H	**4m**, 62
14	**3n**	H, Ph, H, H	**4n**, 81[a]
15	**3o**	H, 4-Me_2N-C_6H_4, H, H	**4o**, 57[a]
16	**3p**	4-NO_2-C_6H_4, H, H, H	**4p**, 73
17	**3q**	H, 4-MeO-C_6H_4, H, H	**4q**, 66[a]
18	**3r**	Ph, Ph, H, H	**4r**, 79
19	**3s**	PhCO, Ph, H, H	**4s**, 70[a]
20	**3t**	$-(CH_2)_4-$, H, H	**4t**, 97
21	**3u**	$-(CH)_2(CH_2)_2-$, H, H	**4u**, 71
22	**3v**	$-(CH_2)_5-$, H, H	**4v**, 57
23	**3w**	$-(CH_2)_3-$, H, H	–
24	**3x**	$-(CH_2)_6-$, H, H	–

For all entries: **1a** (1.5 mmol), **2** (0.3 mmol), **3** (1.0 mmol), AgOAc (0.15 mmol) in 3 cm^3 H_2O at 55 °C for 16 h in a sealed tube under N_2

[a]The yield of the benzylic attacked product

Table 3 Reaction scope with nitroalkanes

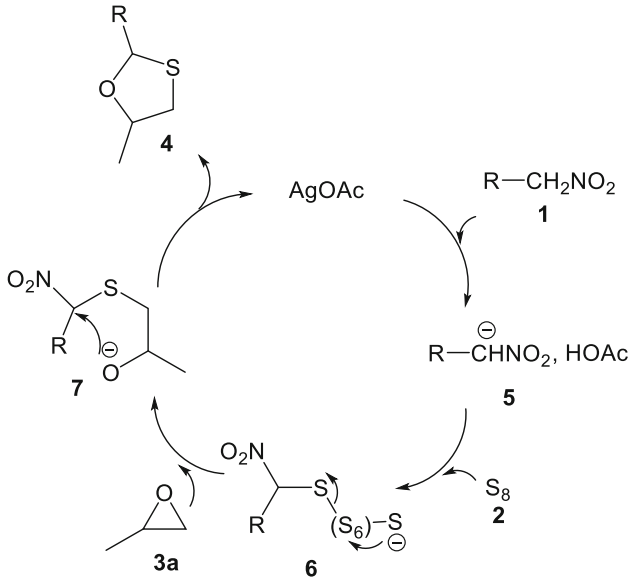


Entry	Nitroalkane	R	**4**, yield/%
1	**1b**	Et	**4w**, 61
2	**1c**	*n*-Pr	**4x**, 52
3	**1d**	*i*-Pr	Traces[a]

For all entries: **1** (1.5 mmol), **2** (0.3 mmol), **3t** (1.0 mmol), AgOAc (0.15 mmol) in 3 cm^3 H_2O at 55 °C for 16 h

[a]Determined by GC-Macc

Scheme 2



the CH_2-CH H-atoms, together with a doublet for the methyl group. The ^{13}C-NMR spectrum of **4a** exhibited four signals in agreement with the proposed structure.

In summary, we report on the catalytic multicomponent reaction for the synthesis of 1,3-oxathiolane skeletons. The presence of a silver salt is crucial for the success of the reaction. We have further shown that the steric hindrance of alkyl group on nitroalkane structure adversely affects the reaction outcome. The optimized reaction conditions given above were compatible with a wide variety of oxiranes. Use of this method offers an environmentally benign route for the synthesis of 1,3-oxathiolane skeletons from readily available starting materials and in good-to-excellent yields.

Experimental

Epoxides, elemental sulfur, nitroalkanes, catalysts, and solvents were obtained from Merck and were used without further purification. Melting points: Electrothermal-9100 apparatus. IR Spectra: Shimadzu IR-460 spectrometer. ^{1}H and ^{13}C NMR spectra: Bruker DRX-500 AVANCE instrument; in $CDCl_3$ at 500.1 and 125.7 MHz, resp; δ in ppm, J in Hz. EI-MS (70 eV): Finnigan-MAT-8430 mass spectrometer. Elemental analyses (C, H, N) were performed with a Heraeus CHN-O-Rapid analyzer. The results agreed favorably with the calculated values (see ESI for characterization data for all products). All known compounds gave satisfactory spectroscopic data and were consistent with that reported in the literature.

*General procedure for the preparation of **4***

To a mixture of 0.076 g elemental sulfur (0.3 mmol), oxirane (1.0 mmol), and 0.025 g AgOAc (0.15 mmol) in 3 cm^3 H_2O at 55 °C was gradually added nitroalkane (1.5 mmol). The resulting pale yellow mixture was then evacuated, back-filled with N_2 (3 times), and stirred for 16 h at 55 °C. After completion of the reaction, it was diluted by 5 cm^3 EtOAc and 5 cm^3 saturated NH_4Cl solution. The mixture was stirred for additional 30 min and the two layers were separated. The aqueous layer was then extracted with EtOAc (8 cm^3 × 3). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuum. The residue was purified by chromatography (silica gel, hexane:EtOAc) to give the desired product [32].

5-Methyl-1,3-oxathiolane (**4a**, C_4H_8OS)

The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 12/1, $R_f = 0.43$) affording 0.09 g (90%) of **4a** as a colorless oil. IR (KBr): $\bar{\nu} = 2981$, 2965, 1465, 1321, 1187, 1011 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.25$ (3H, d, $^3J = 6.1$ Hz, Me), 3.04 (1H, dd, $^2J = 12.1$ Hz, $^3J = 6.4$ Hz, CH), 3.12 (1H, dd, $^2J = 12.1$ Hz, $^3J = 10.2$ Hz, CH), 4.01 (1H, m, CH), 4.86 (1H, d, $^2J = 6.3$ Hz, CH), 4.92 (1H, d, $^2J = 6.3$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 22.5$ (Me), 48.3 (CH_2), 78.3 (CH_2), 85.1 (CH) ppm; EI-MS (70 eV): m/z (%) = 104 (M^+, 23), 89 (21), 74 (38), 62 (58), 58 (100), 42 (39).

5-Ethyl-1,3-oxathiolane (**4b**, $C_5H_{10}OS$)

The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 12/1, $R_f = 0.51$) affording 0.11 g (92%) **4b** as a colorless oil. IR (KBr): $\bar{\nu} = 2961$, 1465, 1323, 1050 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 0.93$ (3H, t, $^3J = 6.8$ Hz, Me), 1.53–1.56 (2H, m, CH_2), 2.98 (1H, dd, $^2J = 11.9$ Hz, $^3J = 5.9$ Hz, CH), 3.17 (1H, dd, $^2J = 11.9$ Hz, $^3J = 9.7$ Hz, CH), 4.08–4.11 (1H, m, CH), 4.92 (1H, d, $^2J = 6.1$ Hz, CH), 5.05 (1H, d, $^2J = 6.1$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 11.0$ (Me), 29.5 (CH_2), 47.1 (CH_2), 78.5 (CH_2), 89.9 (CH) ppm; EI-MS (70 eV): m/z (%) = 118 (M^+, 12), 89 (29), 88 (43), 73 (100), 63 (67), 56 (31).

5-Propyl-1,3-oxathiolane (**4c**, $C_6H_{12}OS$)

The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 12/1, $R_f = 0.56$) affording 0.11 g (83%) **4c** as a colorless oil. IR (KBr): $\bar{\nu} = 2986$, 2957, 1487, 1321 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 0.95$ (3H, t, $^3J = 6.0$ Hz, Me), 1.45–1.53 (4H, m, 2 CH_2), 3.11–3.21 (2H, m, 2 CH), 4.13–4.16 (1H, m, CH), 4.82 (1H, d, $^2J = 6.5$ Hz, CH), 4.99 (1H, d, $^2J = 6.5$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 15.8$ (Me), 20.1 (CH_2), 37.2 (CH_2), 48.3 (CH_2), 79.7 (CH_2), 87.6 (CH)

ppm; EI-MS (70 eV): *m/z* (%) = 132 (M^+, 7), 102 (44), 89 (15), 87 (100), 86 (32), 70 (68).

4,4,5,5-Tetramethyl-1,3-oxathiolane (**4d**, $C_7H_{14}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 10/1, $R_f = 0.39$) affording 0.07 g (48%) **4d** as a pale yellow oil. IR (KBr): $\bar{\nu} = 2979, 2954, 1478, 1312, 1046\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.29$ (6H, m, 2 CH_3), 1.48 (6H, m, 2 CH_3), 4.71 (2H, s, CH_2) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 22.4$ (2 CH_3), 24.1 (2 CH_3), 69.4 (CH_2), 70.1 (C), 97.5 (C) ppm; EI-MS (70 eV): *m/z* (%) = 146 (M^+, 2), 131 (23), 116 (59), 100 (100), 84 (87).

5-(Isopropoxymethyl)-1,3-oxathiolane (**4e**, $C_7H_{14}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 11/1, $R_f = 0.43$) affording 0.15 g (90%) **4e** as a colorless oil. IR (KBr): $\bar{\nu} = 2976, 2961, 2932, 1461, 1289, 1044\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.21$ (6H, d, $^3J = 6.0$ Hz, 2 Me), 3.04–3.18 (2H, m, 2 CH), 4.11–4.17 (2H, m, CH_2), 4.43–4.58 (2H, m, 2 CH), 4.93 (1H, d, $^2J = 6.5$ Hz, CH), 5.11 (1H, d, $^2J = 6.5$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 21.2$ (2 Me), 43.7 (CH_2), 69.3 (CH_2), 72.8 (CH_2), 75.9 (CH), 87.1 (CH) ppm; EI-MS (70 eV): *m/z* (%) = 162 (M^+, 11), 103 (100), 89 (61), 73 (34), 64 (69), 59 (73).

5-(Benzyloxymethyl)-1,3-oxathiolane (**4f**, $C_{11}H_{14}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 9/1, $R_f = 0.40$) affording 0.19 g (92%) **4f** as a yellow oil. IR (KBr): $\bar{\nu} = 3077, 2978, 2960, 1541, 1462, 1290, 1035\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 2.97$–3.14 (2H, m, 2 CH), 3.92–4.16 (3H, m, 3 CH), 4.78–4.81 (2H, m, 2 CH), 4.95 (1H, d, $^2J = 6.2$ Hz, CH), 5.11 (1H, d, $^2J = 6.2$ Hz, CH), 7.29–7.37 (5H, m, 5 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 45.1$ (CH_2), 69.2 (CH_2), 75.1 (CH_2), 79.2 (CH_2), 88.1 (CH), 127.8 (CH), 128.2 (2 CH), 129.2 (2 CH), 136.8 (C) ppm; EI-MS (70 eV): *m/z* (%) = 210 (M^+, 1), 185 (17), 119 (47), 107 (29), 103 (41), 91 (100), 77 (47), 54 (38).

5-(Phenoxymethyl)-1,3-oxathiolane (**4g**, $C_{10}H_{12}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 8/1, $R_f = 0.52$) affording 0.19 g (95%) **4g** as a colorless oil. IR (KBr): $\bar{\nu} = 3069, 2982, 2969, 1562, 1474, 1296, 1056\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 2.96$ (1H, dd, $^2J = 12.3$ Hz, $^3J = 5.5$ Hz, CH), 3.12 (1H, dd, $^2J = 12.3$ Hz, $^3J = 9.9$ Hz, CH), 4.33–4.42 (2H, m, 2 CH), 4.71–4.74 (1H, m, 1 CH), 4.91 (1H, d, $^2J = 6.7$ Hz, CH), 5.10 (1H, d, $^2J = 6.7$ Hz, CH), 6.86 (2H, d, $^3J = 6.7$ Hz, 2 CH), 6.94 (1H, t, $^3J = 6.4$ Hz, CH), 7.25 (2H, t, $^3J = 6.4$ Hz, 2 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 43.7$ (CH_2), 68.1 (CH_2), 78.6 (CH_2), 86.1 (CH), 114.6 (2 CH), 121.7 (CH), 129.2 (2 CH), 159.6 (C) ppm; EI-MS (70 eV): *m/z* (%) = 196 (M^+, 4), 134 (52), 103 (61), 93 (38), 77 (100), 54 (49).

Methyl 5-methyl-1,3-oxathiolane-5-carboxylate (**4h**, $C_6H_{10}O_3S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 8/1, $R_f = 0.52$) affording 0.14 g (88%) **4h** as a colorless oil. IR (KBr): $\bar{\nu} = 3011, 2981, 1735, 1463, 1282, 1026\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.45$ (3H, s, CH_3), 3.14 (1H, d, $^2J = 10.9$ Hz, CH), 3.28 (1H, d, $^2J = 10.9$ Hz, CH), 3.78 (3H, s, OCH_3), 4.81 (1H, d, $^2J = 5.9$ Hz, CH), 4.93 (1H, d, $^2J = 5.9$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 21.8$ (CH_3), 47.2 (CH_2), 55.3 (CH_3), 79.2 (CH_2), 100.1 (C), 172.1 (C) ppm; EI-MS (70 eV): *m/z* (%) = 162 (M^+, 1), 131 (34), 103 (100), 100 (41).

5-Methyl-5-propyl-1,3-oxathiolane (**4i**, $C_7H_{14}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 11/1, $R_f = 0.32$) affording 0.14 g (96%) **4i** as a colorless oil. IR (KBr): $\bar{\nu} = 3274, 3260, 2975, 2249, 1567, 1168\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 0.93$ (3H, t, $^3J = 6.2$ Hz, CH_3), 1.21 (3H, s, CH_3), 1.35 (2H, m, CH_2), 1.64 (2H, t, $^3J = 6.2$ Hz, CH_2), 2.98 (1H, d, $^2J = 11.1$ Hz, CH), 3.19 (1H, d, $^2J = 11.1$ Hz, CH), 4.81–4.87 (2H, m, 2 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 13.2$ (CH_3), 16.1 (CH_2), 25.2 (CH_3), 40.1 (CH_2), 54.1 (CH_2), 78.8 (CH_2), 93.1 (C) ppm; EI-MS (70 eV): *m/z* (%) = 146 (M^+, 3), 131 (28), 103 (81), 100 (58), 84 (82).

5-(Allyloxymethyl)-1,3-oxathiolane (**4l**, $C_7H_{12}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 11/1, $R_f = 0.28$) affording 0.13 g (82%) **4l** as a colorless oil. IR (KBr): $\bar{\nu} = 2991, 2963, 1543, 1462, 1287, 1036\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 3.16$ (1H, dd, $^2J = 11.1$ Hz, $^3J = 6.3$ Hz, CH), 3.29 (1H, dd, $^2J = 11.1$ Hz, $^3J = 9.6$ Hz, CH), 4.16–4.35 (3H, m, 3 CH), 4.52–4.63 (2H, m, 2 CH), 4.73 (1H, d, $^2J = 6.0$ Hz, CH), 4.86 (1H, d, $^2J = 6.0$ Hz, CH), 5.64–5.72 (2H, m, 2 CH), 6.28–6.36 (1H, m, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 42.1$ (CH_2), 68.3 (CH_2), 71.2 (CH_2), 77.3 (CH_2), 86.1 (CH), 116.2 (CH_2), 137.9 (CH) ppm; EI-MS (70 eV): *m/z* (%) = 160 (M^+, 5), 119 (24), 103 (100), 98 (38), 89 (76), 41 (81).

2,2,2-Trifluoro-1-(1,3-oxathiolan-5-yl)-1-phenylethan-1-ol (**4m**, $C_{11}H_{11}F_3O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 5/1, $R_f = 0.38$) affording 0.16 g (62%) **4m** as a pale yellow oil. IR (KBr): $\bar{\nu} = 3328, 3075, 2974, 1572, 1435, 1311, 1052\ cm^{-1}$; ^1H NMR (500.1 MHz, $CDCl_3$): $\delta = 3.11$–3.24 (2H, m, 2 CH), 4.69 (1H, d, $^2J = 6.5$ Hz, CH), 4.83 (1H, d, $^2J = 6.5$ Hz, CH), 5.14–5.22 (1H, m, CH), 6.16 (1H, br s, OH), 7.22

(2H, t, $^3J = 6.7$ Hz, 2 CH), 7.32 (1H, t, $^3J = 6.7$ Hz, CH), 7.61 (2H, d, $^3J = 6.9$ Hz, 2 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 39.1$ (CH_2), 78.7 (CH_2), 86.9 (CH), 90.1 (C, q, $^2J = 32.2$ Hz), 125.0 (CH), 129.3 (2 CH), 129.9 (2 CH), 133.9 (CF_3, q, $^1J = 270.9$ Hz), 138.1 (C, q, $^3J = 9.1$ Hz) ppm; EI-MS (70 eV): *m/z* (%) = 264 (M^+, 2), 195 (43), 194 (23), 105 (76), 77 (100), 54 (44).

4-Phenyl-1,3-oxathiolane (**4n**, $C_9H_{10}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 9/1, $R_f = 0.40$) affording 0.13 g (81%) **4n** as a colorless oil. IR (KBr): $\bar{\nu} = 3053$, 2978, 1548, 1436, 1320, 1051 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 4.21$–4.24 (1H, m, CH), 4.47 (1H, dd, $^2J = 10.8$ Hz, $^3J = 6.0$ Hz, CH), 4.58 (1H, dd, $^2J = 10.8$ Hz, $^3J = 9.0$ Hz, CH), 4.76 (1H, d, $^2J = 6.4$ Hz, CH), 4.89 (1H, d, $^2J = 6.4$ Hz, CH), 7.27–7.36 (5H, m, 5 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 65.2$ (CH), 76.2 (CH_2), 81.7 (CH_2), 127.8 (2 CH), 128.8 (CH), 129.1 (2 CH), 138.2 (C) ppm; EI-MS (70 eV): *m/z* (%) = 166 (M^+, 12), 120 (60), 104 (81), 89 (57), 77 (100), 54 (38).

N,N-Dimethyl-4-(1,3-oxathiolan-4-yl)aniline (**4o**, $C_{11}H_{15}NOS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 5/1, $R_f = 0.29$) affording 0.12 g (57%) **4o** as a pale yellow solid. M.p.: 57–59 °C; IR (KBr): $\bar{\nu} = 3042$, 2951, 1557, 1458, 1344, 1127, 1015 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 3.11$ (6H, s, 2 CH_3), 4.10–4.17 (1H, m, CH), 4.42 (1H, dd, $^2J = 11.2$ Hz, $^3J = 6.2$ Hz, CH), 4.57 (1H, dd, $^2J = 11.2$ Hz, $^3J = 9.7$ Hz, CH), 4.76 (1H, d, $^2J = 6.1$ Hz, CH), 4.93 (1H, d, $^2J = 6.1$ Hz, CH), 6.79 (2H, d, $^3J = 7.1$ Hz, CH), 7.11 (2H, d, $^3J = 7.1$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 47.6$ (2 CH_3), 63.0 (CH), 71.9 (CH_2), 81.5 (CH_2), 112.1 (2 CH), 126.7 (C), 129.7 (2 CH), 147.6 (C) ppm; EI-MS (70 eV): *m/z* (%) = 209 (M^+, 6), 165 (17), 120 (100), 96 (72), 89 (83), 77 (43).

5-(4-Nitrophenyl)-1,3-oxathiolane (**4p**, $C_9H_9NO_3S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 3/1, $R_f = 0.22$) affording 0.15 g (73%) **4p** as a yellow solid. M.p.: 101–103 °C; IR (KBr): $\bar{\nu} = 3025$, 2946, 1567, 1537, 1455, 1381, 1333, 1211, 1044 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 3.32$–3.44 (2H, m, 2 CH), 4.68–4.81 (2H, m, 2 CH), 5.06–5.09 (1H, m, CH), 7.71 (2H, d, $^3J = 6.7$ Hz, 2 CH), 8.24 (2H, d, $^3J = 6.7$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 42.1$ (CH_2), 72.4 (CH_2), 95.2 (CH), 128.7 (2 CH), 133.2 (2 CH), 145.1 (C), 148.9 (C) ppm; EI-MS (70 eV): *m/z* (%) = 211 (M^+, 7), 165 (34), 149 (64), 122 (22), 89 (100), 54 (31).

4-(4-Methoxyphenyl)-1,3-oxathiolane (**4q**, $C_{10}H_{12}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 7/1, $R_f = 0.34$) affording 0.13 g (66%) **4q** as a yellow solid. M.p.: 53–55 °C; IR (KBr): $\bar{\nu} = 3061$, 2988, 1562, 1453, 1320, 1176, 1023 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 3.76$ (3H, s, OCH_3), 4.03–4.08 (1H, m, CH), 4.36 (1H, dd, $^2J = 11.1$ Hz, $^3J = 5.8$ Hz, CH), 4.49 (1H, dd, $^2J = 11.1$ Hz, $^3J = 9.7$ Hz, CH), 4.78–4.86 (2H, m, 2 CH), 6.90 (2H, d, $^3J = 6.9$ Hz, CH), 7.27 (2H, d, $^3J = 6.9$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 57.1$ (CH_3), 63.2 (CH), 73.7 (CH_2), 82.2 (CH_2), 114.1 (2 CH), 127.5 (2 CH), 130.1 (C), 160.1 (C) ppm; EI-MS (70 eV): *m/z* (%) = 166 (M^+, 12), 165 (23), 150 (38), 134 (76), 107 (100), 89 (87).

4,5-Diphenyl-1,3-oxathiolane (**4r**, $C_{15}H_{14}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 5/1, $R_f = 0.38$) affording 0.19 g (79%) **4r** as a colorless solid. M.p.: 111–113 °C; IR (KBr): $\bar{\nu} = 3053$, 2978, 1548, 1436, 1320, 1051 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 4.59$ (1H, d, $^3J = 10.5$ Hz, CH), 4.64 (1H, d, $^2J = 6.1$ Hz, CH), 4.86 (1H, d, $^2J = 6.1$ Hz, CH), 5.38 (1H, d, $^3J = 10.5$ Hz, CH), 7.25–7.33 (10H, m, 10 CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 60.2$ (CH), 75.3 (CH_2), 100.1 (CH), 125.6 (CH), 126.7 (2 CH), 127.1 (CH), 127.8 (2 CH), 128.4 (2 CH), 129.2 (2 CH), 137.1 (C), 139.7 (C) ppm; EI-MS (70 eV): *m/z* (%) = 242 (M^+, 1), 165 (24), 180 (81), 88 (47), 77 (100), 54 (56).

Phenyl(4-phenyl-1,3-oxathiolan-5-yl)methanone (**4s**, $C_{16}H_{14}O_2S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 4/1, $R_f = 0.56$) affording 0.19 g (70%) **4s** as a colorless solid. M.p.: 81–84 °C; IR (KBr): $\bar{\nu} = 3050$, 2971, 1711, 1554, 1447, 1338, 1034 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 4.47$ (1H, d, $^3J = 10.1$ Hz, CH), 4.73 (1H, d, $^2J = 8.2$ Hz, CH), 4.93 (1H, d, $^2J = 8.2$ Hz, CH), 5.59 (1H, d, $^3J = 10.1$ Hz, CH), 7.17–7.40 (5H, m, 5 CH), 7.59–7.68 (3H, m, 3 CH), 8.11 (2H, d, $^3J = 6.9$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 57.1$ (CH), 79.4 (CH_2), 108.4 (CH), 124.7 (CH), 126.2 (2 CH), 129.1 (2 CH), 130.2 (2 CH), 131.8 (2 CH), 133.2 (CH), 136.2 (C), 137.6 (C), 196.1 (C) ppm; EI-MS (70 eV): *m/z* (%) = 270 (M^+, 4), 193 (35), 165 (51), 105 (100), 77 (76), 54 (68).

Hexahydrobenzo[d][1,3]oxathiole (**4t**, $C_7H_{12}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 10/1, $R_f = 0.36$) affording 0.14 g (97%) **4t** as a colorless oil. IR (KBr): $\bar{\nu} = 3008$, 2976, 1546, 1313, 1019 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.38$–2.01 (8H, m, 8 CH), 2.85–2.94 (1H, m, CH),

4.07–4.18 (1H, m, CH), 4.78 (1H, d, $^2J = 6.0$ Hz, CH), 4.93 (1H, d, $^2J = 6.0$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 25.6$ (CH_2), 26.4 (CH_2), 33.5 (CH_2), 34.8 (CH_2), 51.7 (CH), 75.3 (CH_2), 89.0 (CH) ppm; EI-MS (70 eV): m/z (%) = 144 (M^+, 5), 114 (33), 98 (69), 88 (43), 83 (100), 56 (26).

3a,4,5,7a-Tetrahydrobenzo[d][1,3]oxathiole (**4u**, $C_7H_{10}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 10/1, $R_f = 0.29$) affording 0.10 g (71%) **4u** as a colorless oil. IR (KBr): $\bar{\nu} = 3051$, 2917, 1531, 1312, 1023 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.95$–2.11 (4H, m, 4 CH), 3.01–3.09 (1H, m, CH), 4.19–4.23 (1H, m, CH), 4.67 (1H, d, $^2J = 6.8$ Hz, CH), 4.82 (1H, d, $^2J = 6.8$ Hz, CH), 5.46 (1H, t, $^3J = 6.4$ Hz, CH), 5.68–5.79 (1H, m, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 27.1$ (CH_2), 29.0 (CH_2), 51.3 (CH), 72.4 (CH_2), 87.5 (CH), 128.3 (CH), 130.4 (CH) ppm; EI-MS (70 eV): m/z (%) = 142 (M^+, 17), 112 (35), 96 (53), 88 (33), 83 (100), 80 (86), 52 (20).

Hexahydro-4H-cyclohepta[d][1,3]oxathiole (**4v**, $C_8H_{14}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 10/1, $R_f = 0.44$) affording 0.09 g (57%) **4v** as a colorless oil. IR (KBr): $\bar{\nu} = 3051$, 2917, 1631, 1312, 1123 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.22$–1.97 (10H, m, 10 CH), 2.86–2.89 (1H, m, CH), 3.93–4.03 (1H, m, CH), 4.74 (1H, d, $^2J = 6.2$ Hz, CH), 4.92 (1H, d, $^2J = 6.2$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 27.1$ (CH_2), 28.4 (CH_2), 28.8 (CH_2), 31.4 (CH_2), 34.1 (CH_2), 54.9 (CH), 75.1 (CH_2), 91.3 (CH) ppm; EI-MS (70 eV): m/z (%) = 158 (M^+, 4), 128 (35), 112 (60), 97 (100), 88 (43), 64 (43), 63 (20).

2-Methylhexahydrobenzo[d][1,3]oxathiole (**4w**, $C_8H_{14}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 10/1, $R_f = 0.49$) affording 0.10 g (61%) **4w** as a colorless oil. IR (KBr): $\bar{\nu} = 3000$, 2986, 1541, 1322, 1023 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.42$–2.12 (11H, m, 8 CH, CH_3), 2.89–2.97 (1H, m, CH), 4.03–4.08 (1H, m, CH), 4.93 (1H, q, $^3J = 6.2$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 21.0$ (CH_3), 24.5 (CH_2), 27.1 (CH_2), 33.4 (CH_2), 37.2 (CH_2), 50.1 (CH), 86.2 (CH), 87.5 (CH) ppm; EI-MS (70 eV): m/z (%) = 158 (M^+, 3), 114 (25), 98 (53), 78 (67), 83 (100), 82 (67).

2-Ethylhexahydrobenzo[d][1,3]oxathiole (**4x**, $C_9H_{16}OS$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 13/1, $R_f = 0.31$) affording 0.09 g (52%) **4x** as a colorless oil. IR (KBr): $\bar{\nu} = 2989$, 2956, 1562, 1325, 1033 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 0.92$ (3H, t, $^3J = 6.2$ Hz, CH_3), 1.24–2.17 (10H, m, 8 CH, CH_2), 2.89–2.94 (1H, m, CH), 3.85–3.96 (1H, m, CH), 4.83 (1H, t, $^3J = 6.4$ Hz, CH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 9.7$ (CH_3), 25.3 (CH_2), 25.9 (CH_2), 29.3 (CH_2), 30.8 (CH_2), 36.0 (CH_2), 50.2 (CH), 88.1 (CH), 91.2 (CH) ppm; EI-MS (70 eV): m/z (%) = 172 (M^+, 5), 141 (26), 114 (27), 98 (45), 92 (58), 83 (100).

1-[(Nitromethyl)thio]propan-2-ol (**5**, $C_4H_9NO_3S$)
The crude product was purified by column chromatography (SiO_2; hexane/EtOAc 2/1, $R_f = 0.28$) affording 0.06 g (41%) of **5** as a yellow solid. M.p.: 81–84 °C; IR (KBr): $\bar{\nu} = 3287$, 2941, 1546, 1453, 1372, 1301, 1287, 1024 cm^{-1}; ^{1}H NMR (500.1 MHz, $CDCl_3$): $\delta = 1.19$ (3H, d, $^3J = 5.7$ Hz, Me), 2.45–2.52 (2H, m, 2 CH), 3.81–3.90 (1H, m, CH), 5.79 (2H, s, CH_2), 6.34 (1H, br s, OH) ppm; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 24.6$ (Me), 48.1 (CH_2), 69.1 (CH), 91.4 (CH_2) ppm; EI-MS (70 eV): m/z (%) = 151 (M^+, 1), 133 (43), 91 (22), 61 (14), 58 (100).

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References

1. Aitken RA, Power LA (2008) In: Joule JA (ed) Comprehensive heterocyclic chemistry III, vol 4, 3rd edn. Elsevier, p 841
2. Martins P, Jesus J, Santos S, Raposo LR, Roma-Rodrigues C, Baptista PV, Fernandes AR (2015) Molecules 20:16852
3. Bandyopadhyay D, Banik BK (2017) Curr Med Chem. doi:10.2174/0929867324666170223152137
4. Chen YH, Sun XL, Guan HS, Liu YK (2017) J Org Chem 82:4774
5. Zhang S, Cheng B, Wang SA, Zhou L, Tung CH, Wang J, Xu Z (2017) Org Lett 19:1072
6. Wdowik T, Chemler SR (2017) J Am Chem Soc 139:11493
7. Rossi R, Lessi M, Manzini C, Marianetti G, Bellina F (2017) Curr Org Chem 21:964
8. Ganem B (2009) Acc Chem Res 42:463
9. Zhu Q, Yuan Q, Chen M, Guo M, Huang H (2017) Angew Chem Int Ed 56:5101
10. Rotstein BH, Zaretsky S, Rai V, Yudin AK (2014) Chem Rev 114:8323
11. Robbe Y, Fernandez JP, Dubief R, Chapat JP, Sentenac-Roumanou H, Fatome M, Laval JD, Subra G (1982) Eur J Med Chem 17:235
12. Chu CK (ed) (2003) Antiviral nucleosides: chiral synthesis and chemotherapy. Elsevier, Amsterdam
13. Cihlar T, Ray AS (2010) Antivir Res 85:39
14. Romeo G, Chiacchio U, Corsaro A, Merino P (2010) Chem Rev 110:3337
15. Férir G, Kaptein S, Neyts J, De Clercq E (2008) Rev Med Virol 18:19
16. Caso MF, D'Alonzo D, D'Errico S, Palumbo G, Guaragna A, Ghosh RK, Ghosh SM, Chawla S (2011) Expert Opin Pharmacother 12:31

17. Wu JY, Luo ZB, Dai LX, Hou XL (2008) J Org Chem 73:9137
18. Clegg W, Harrington RW, North M, Villuendas P (2010) J Org Chem 75:6201
19. Samzadeh-Kermani A (2014) Monatsh Chem 145:611
20. Yavari I, Ghazanfarpour-Darjani M, Hossaini Z, Sabbaghan M, Hosseini N (2008) Synlett:889
21. Ghazanfarpour-Darjani M, Khodakarami A (2016) Monatsh Chem 147:829
22. Yavari I, Ghazanfarpour-Darjani M (2014) J Sulfur Chem 35:477
23. Samzadeh-Kermani A, Zamenraz S (2017) Monatsh Chem 148:1753
24. Ghazanfarpour-Darjani M, Babapour-Kooshalshahi M, Mousavi-Safavi SM, Akbari-Neyestani J, Khalaj M (2016) Synlett 27:259
25. Samzadeh-Kermani A (2016) Tetrahedron 72:5301
26. Samzadeh-Kermani A (2016) Synlett 26:643
27. Khalaj M, Ghazanfarpour-Darjani M (2016) Monatsh Chem 147:2043
28. Khalaj M, Ghazanfarpour-Darjani M (2015) RSC Adv 5:80698
29. Khalaj M, Ghazanfarpour-Darjani M, Talei Bavil Olyai MR, Faraji-Shamami S (2016) J Sulfur Chem 37:211
30. Khalaj M, Ghazanfarpour-Darjani M, Barat-Seftejani F, Nouri A (2017) Synlett 28:1445
31. Ghazanfarpour-Darjani M, Barat-Seftejani F, Khalaj M, Mousavi-Safavi SM (2017) Helv Chim Acta. doi:10.1002/hlca.201700082
32. Hojo M, Ohkuma M, Hosomi A (1992) Chem Lett 21:1073