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Selective aerobic oxidation of sulfides to sulfoxides catalyzed by coenzyme NAD^+ models

Hua-Jian Xu [a,b,*], Yi-Cheng Lin [a], Xin Wan [a], Chun-Yan Yang [a], Yi-Si Feng [a,b,*]

[a] School of Chemical Engineering, Hefei University of Technology, Tunxi Road 193, Hefei 230009, PR China
[b] Anhui Key Laboratory of Controllable Chemical Reaction & Material Chemical Engineering, Hefei 230009, PR China

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ABSTRACT

Coenzyme NAD^+ models can be applied in the photooxygenation of sulfides to sulfoxides as organocatalysts at room temperature. A series of sulfoxides are synthesized easily with this protocol and the possible mechanism is discussed. This procedure provides a reliable approach to the clean production of useful sulfoxides in synthetic chemistry.

1. Introduction

The coenzyme NAD^+ and its reduced form NADH play vital roles in biological oxidation-reduction processes.[1] NAD^+ models have been successfully applied to selective oxygenation of α-methylstyrene,[2] benzyl alcohol,[3] *p*-xylene,[4] 4,4′-dimethylbiphenyl,[5] tetraphenylethylene,[6] and 1,4-dihydropyridines[7] as effective catalysts. Owing to our interest in the reactions and mechanisms of coenzyme NAD^+/NADH models,[8] we envisioned that NAD^+ models might be utilized in the oxidation of sulfides with O_2. Herein we wish to report an efficient, environmentally benign protocol in which O_2 has been used as the oxidant at room temperature in the presence of NAD^+ models for the selective oxidation of sulfides.

Selective oxidation of sulfides to sulfoxides is an important transformation in organic chemistry because organic sulfoxides often perform a major function as therapeutic agents, such as antiulcer (proton pump inhibitor),[9] antibacterial, antifungal, anti-atherosclerotic,[10] antihypertensive,[11] and cardiotonic agents,[12] as well as psychotonics[13] and vasodilators.[14] In addition, sulfoxides are valuable synthons in synthetic organic chemistry for carbon–carbon bond formation[15] and mediating Diels–Alder reactions,[16] as chiral auxiliaries[17] and metal-centered catalysis.[18]

A number of methods have been developed for the transformation of sulfides to sulfoxides. Sulfoxides were obtained mainly from the oxidation of sulfides with peroxides in most synthetic protocols.[19] However, as we known, oxygen, a cheap and clean oxidant, can oxidize organic compounds with a high atom efficiency without disposal of waste.[20] Although some transformations of sulfides to sulfoxides oxidated by oxygen were reported,[21] but, the development of more efficient, general, clean and catalytic aerobic oxidation of sulfides under mild reaction conditions remains a challenging task.

2. Results and discussion

Initially, we performed a set of preliminary experiments on the oxidation of diphenyl sulfide **3** as a model substrate using 30% aqueous hydrogen peroxide and molecular oxygen irradiated with a 450 W high-pressure mercury lamp in the presence of catalytic amounts of NAD^+ models at room temperature under different solvent conditions. The results are depicted in Table 1.

In order to find the ideal catalyst, we evaluated the catalytic activity of NAD^+ models **1** and **2** on the oxidation of **3** with O_2 and H_2O_2 or O_2,[22] no obvious difference on yield was observed in the same conditions (Table 1, entries 1, 2 and 15, 16). It is well known that the synthetic procedure of **2** is more inconvenient than **1**, so **1** was selected as the catalyst in following research. Next, the reaction was carried out in MeCN (Table 1, entries 3–6) using 5 mol % of catalyst **1** and **4** from 17 to 53% yield was obtained after 48 h. Interestingly, a less amount of H_2O_2 could produce a higher.

Yield of **4**. A 72% and 19% yield of **4** was obtained, respectively, without H_2O_2 in the presence of O_2 and with H_2O_2 in the absence of O_2 (Table 1, entries 7 and 8). Solvents also played important roles in this reaction. The experimental results suggested that MeCN was the best solvent among the screened ones, such as MeOH, $CHCl_3$, and AcOH (Table 1, entries 10–12). To our delight, when the amount of MeCN was increased gradually, the yield of **4** was improved synchronously (Table 1, entries 13–15) and a 99% yield of **4** was obtained until the volume of MeCN was added to 12 mL.[23]

Only a slight decrease of yield of **4** was observed when the amount of catalyst **1** was reduced to 3 mol % (Table 1, entry 17). It is noteworthy that almost no reaction was observed under similar

* Corresponding authors. Tel.: +86 551 2904405; fax: +86 551 2901450; e-mail address: hjxu@hfut.edu.cn (H.-J. Xu).

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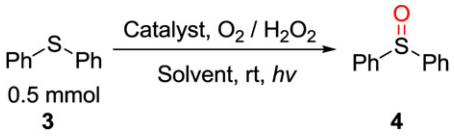
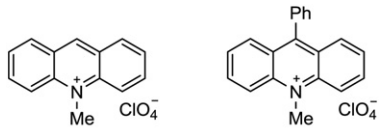
Table 1
Optimization of reaction conditions for oxidation of **3**



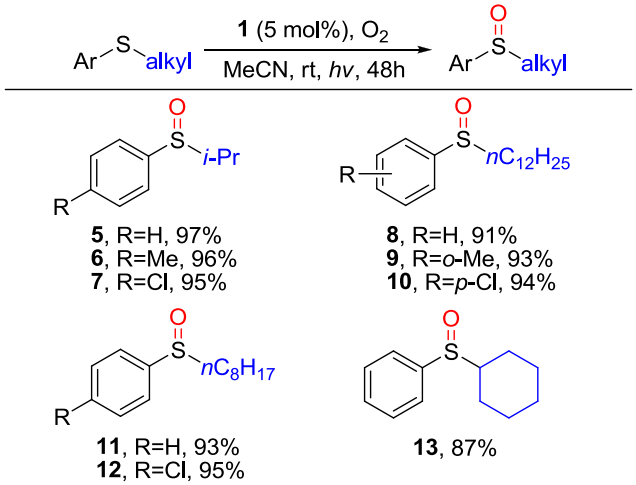
Entry	Catalyst (mol %)	H_2O_2 (equiv)	Solvent (mL)	Time (h)	Yield[a] (%)
1	**1** (5)	1	MeCN (5)	24	20
2	**2** (5)	1	MeCN (5)	24	18
3	**1** (5)	1	MeCN (5)	48	45
4	**1** (5)	2	MeCN (5)	48	17
5	**1** (5)	0.5	MeCN (5)	48	51
6	**1** (5)	0.25	MeCN (5)	48	53
7	**1** (5)	—	MeCN (5)	48	72
8[b]	**1** (5)	1	MeCN (5)	48	19
9[b]	**1** (5)	—	MeCN (5)	48	—
10	**1** (5)	—	MeOH (5)	48	61
11	**1** (5)	—	$CHCl_3$ (5)	48	48
12	**1** (5)	—	AcOH(5)	48	65
13	**1** (5)	—	MeCN (8)	48	86
14	**1** (5)	—	MeCN (10)	48	94
15	**1** (5)	—	MeCN (12)	48	**99**
16	**2** (5)	—	MeCN (12)	48	95
17	**1** (3)	—	MeCN (12)	48	90
18	—	—	MeCN (12)	48	—

Bold value '99' is the highest yield.
[a] GC yield.
[b] Without addition of O_2.



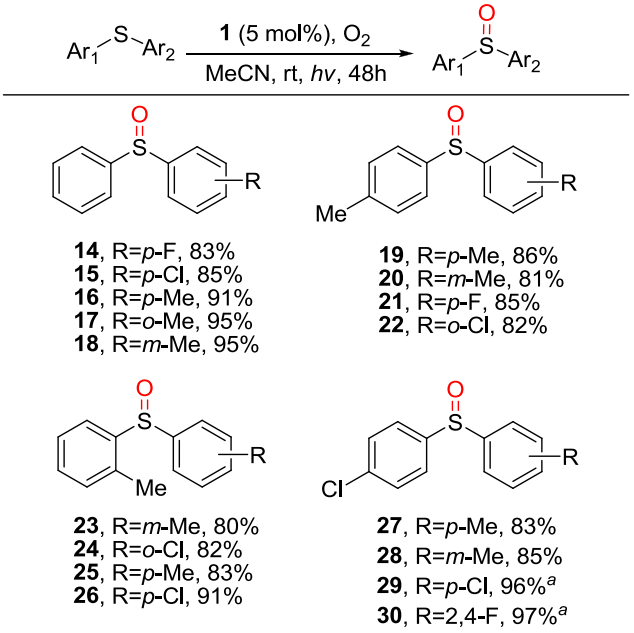
reaction conditions in the absence of O_2 or **1** in two control experiments (Table 1, entries 9 and 18). Therefore, the optimized conditions employed 5 mol % **1** in MeCN at room temperature with O_2 under irradiation of a 450 W high-pressure mercury lamp.

To examine the reliability of this protocol, some of the alkyl phenyl sulfides were screened under optimized reaction conditions (Scheme 1). Excellent yields of corresponding products **5**–**13** were obtained as the previous documented methods. So, this protocol can be applied in the preparation of sulfoxides. It is always difficult for selective oxygenation from diaryl sulfides to diarylsulfoxides in documented methods. We wonder whether the selective oxygenation can be achieved under our developed protocol. A series of

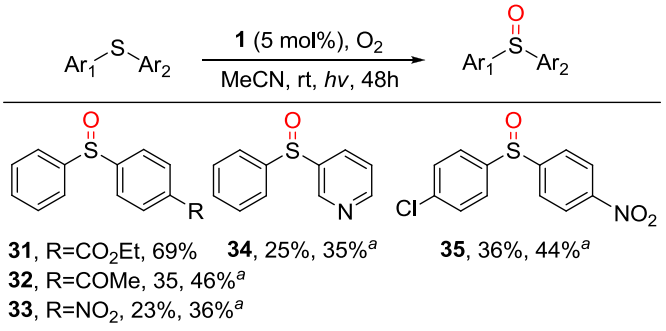


Scheme 1. The oxygenation of alkyl phenyl sulfides.

substituted diphenyl sulfides were determined and all results were summarized in Scheme 2 and Scheme 3. As shown in Scheme 2, good to excellent yield (80–97%) of corresponding sulfoxides (14–30) were obtained when the substituents of phenyl ring are methyl, fluoro, and chloro groups. Importantly, the reaction does not appear to be significantly affected by steric effectsof *ortho*-position substituent in the present procedure (**17**, **22**–**26**, **30**). However, the corresponding sulfoxides yields were decreased dramatically passing from 4-methyl to 4-CO_2Et, –COMe, $-NO_2$ (Scheme 3, **31**–**35**). Clearly, the reactivity of the sulfide is strongly reduced when the electron-withdrawing group (EWG) is directly bonded to the phenyl ring. Low yields of **32**–**35** were gained except that the moderate yield of **31** was observed. Low yields (35–46%) were still obtained even though amount of **1** is added to 10 mol % and MeCN is added to 20 mL.



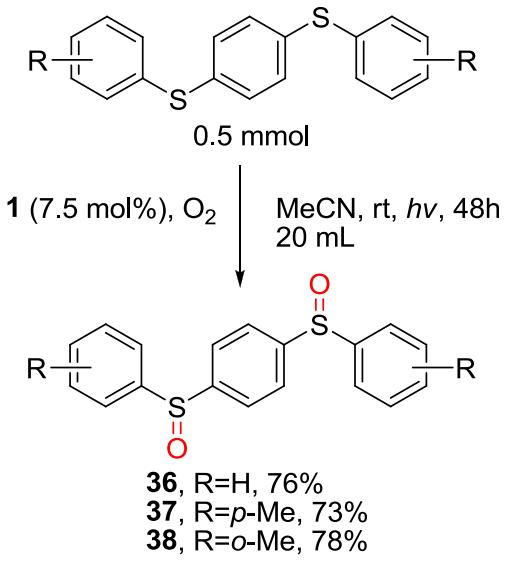
Scheme 2. The oxygenation of diaryl sulfides with methyl or halogen substituents. [a]Reaction time is reduced to 12 h.



Scheme 3. The oxygenation of diaryl sulfides with EWGs. [a]Amount of **1** is added to 10 mol %, MeCN is added to 20 mL.

We next examined the catalytic efficiency of NAD^+/O_2 system in the oxidation of aryl disulfides. When the catalyst (7.5 mol %) was employed, a selective oxygenation was also readily achieved upon the control of equivalents of MeCN (20 mL). The corresponding disulfoxides were produced in good yields (73–78%) with excellent selectivity (Scheme 4).

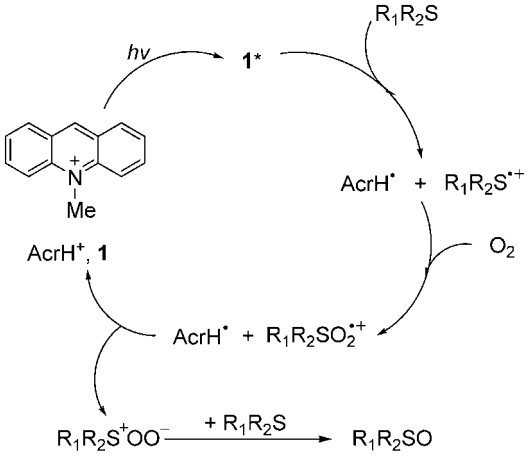
It should be noted that sulfides can be oxygenated to the corresponding sulfoxides almost without over-oxidation products in our protocol compared with other documented reaction systems.



Scheme 4. The oxygenation of aryl disulfides.

Unfortunately, some substituted diphenyl sulfides with EDG as hydroxyl and amino couldn't go well by virtue of this protocol, because they are all strong radical inhibitors, which affect dramatically the reactivity.[23]

On the basis of these observations and by reference to the literatures,[24] a plausible mechanism could be drawn for the **1**-catalyzed photooxygenation of sulfides as shown in Scheme 5. $R_1R_2S^{+\bullet}$ is produced by an electron transfer from lone pair electron of sulfur atom of R_1R_2S to **1***, and it reacts with O_2 to yield $R_1R_2SO_2^{+\bullet}$ followed by an electron transfer to result in the regeneration of **1** and the formation of $R_1R_2S^+OO^-$, which reacts with additional R_1R_2S to yield R_1R_2SO.[25] Since the initial electron transfer is rate-determining, electronic spin density of the sulfur atom will be the most important factor for photooxidation of diaryl sulfides with O_2. Thus Me-substituted (EDG) diphenyl sulfides gave excellent yields, while NO_2-substituted (EWG) diphenyl sulfides could hardly be oxygenated.



Scheme 5. The proposed mechanism for oxidation of sulfides to the corresponding sulfoxides with O_2 catalyzed by **1**.

3. Conclusion

In conclusion, the present procedure demonstrates that sulfides can be oxidized by O_2 under mild conditions with the catalysis of NAD^+ models. Moderate to excellent yields were obtained. Thus we have developed a metal-free and simple protocol, which is a highly selective, efficient, and green process for the selective oxygenation of sulfides into corresponding sulfoxides using an organocatalyst. It provides a reliable approach for the clean production of sulfoxides in synthetic chemistry.

4. Experimental

4.1. General remarks

Diphenyl sulfide is obtained from Tokyo Chemical Industry Co., Ltd. Sulfides,[26] catalyst **1** and **2**[5] were prepared by literature procedures. Other reagents and solvents were pure analytical grade materials purchased from commercial sources and were purified according to the standard procedure before use. The ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ on a 300 MHz instrument with TMS as internal standard. High-resolution mass spectra (HRMS) were determined on a Micromass GCT-MS mass spectrometer. TLC was carried out with 0.2 mm thick silica gel plates (GF_{254}). The columns were hand packed with silica gel 60 (200–300).

4.2. General reaction procedure

A stirred solution of the sulfide (0.5 mmol) and the catalyst **1** (5 mol %) in acetonitrile (12 mL) was added to a 25 mL round-bottom Pyrex flask sealed with a rubber septum was irradiated with a 450 W high-pressure mercury lamp under an argon atmosphere at room temperature. The irradiated solution was monitored by TLC. After completion of the reaction, the resulted solution was concentrated under reduced pressure and the residue followed by column chromatography on silica gel using petroleum ether and ethyl acetate (5:1) as eluent afforded the corresponding sulfoxide.

4.2.1. Compound ***4***[27]. ^1H NMR (300 MHz, $CDCl_3$): δ 7.66–7.63 (m, 5H), 7.46–7.44 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.70, 131.11, 129.38, 124.83 ppm.

4.2.2. Compound ***5***[28]. ^1H NMR (300 MHz, $CDCl_3$): δ 7.59–7.57 (m, 2H), 7.51–7.50 (m, 3H), 2.84 (m, 1H), 1.23 (d, J=6.8 Hz, 3H), 1.14 (d, J=6.7 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 141.94, 131.03, 128.94, 125.08, 54.66, 15.95, 13.99 ppm.

4.2.3. Compound ***6***[29]. ^1H NMR (300 MHz, $CDCl_3$): δ 7.48 (d, J=8.2 Hz, 2H), 7.30 (d, J=4.6 Hz, 2H), 2.82–2.78 (m, 1H), 2.41 (s, 3H), 1.20–1.13 (m, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 141.44, 138.53, 129.62, 125.08, 54.56, 21.43, 15.77, 14.12 ppm.

4.2.4. Compound ***7***. ^1H NMR (300 MHz, $CDCl_3$): δ 7.54–7.46 (m, 4H), 2.80 (m, 1H), 1.22 (d, J=6.9 Hz, 3H), 1.12 (d, J=6.8 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 140.51, 137.29, 129.29, 126.49, 54.78, 15.86, 13.89 ppm. HRMS calcd $C_9H_{11}ClOS$: 202.0219. Found: 202.0211.

4.2.5. Compound ***8***. ^1H NMR (300 MHz, $CDCl_3$): δ 7.64–7.61 (m, 2H), 7.55–7.48 (m, 3H), 2.78 (m, 2H), 1.72–1.24 (m, 20H), 0.87 (t, J=6.7 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 144.18, 130.96, 129.25, 124.12, 57.45, 29.66, 29.57, 29.40, 29.23, 28.75, 22.75, 22.25, 14.18 ppm. HRMS calcd $C_{18}H_{30}OS$: 294.2017. Found: 294.2011.

4.2.6. Compound ***9***. ^1H NMR (300 MHz, $CDCl_3$): δ 7.90 (d, J=7.1 Hz, 1H), 7.45–7.34 (m, 2H), 7.20 (d, J=7.3 Hz, 1H), 2.72–2.66 (m, 2H), 2.37 (s, 3H), 1.83–1.25 (m, 20H), 0.88 (t, J=6.7 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.69, 134.43, 130.68, 127.25, 123.98, 55.82, 31.98, 29.80–28.93, 28.79, 22.66, 18.29, 14.18 ppm. HRMS calcd $C_{19}H_{32}OS$: 308.2174. Found: 308.2178.

4.2.7. Compound ***10***. ^1H NMR (300 MHz, $CDCl_3$): δ 7.58–7.48 (m, 4H), 2.77 (t, J=7.7 Hz, 2H), 1.74–1.25 (m, 20H), 0.88 (t, J=6.7 Hz,

3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.66, 137.27, 129.61, 125.65, 57.48, 34.08, 32.00, 29.49, 28.75, 24.94, 22.78, 22.14, 14.20 ppm. HRMS calcd $C_{18}H_{29}ClOS$: 328.1628. Found: 328.1620.

4.2.8. Compound ***11***[30]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.64–7.54 (m, 2H), 7.53–7.49 (m, 3H), 2.81–2.75 (m, 2H), 1.74–1.24 (m, 12H), 0.85 (t, *J*=5.2 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.16, 137.27, 129.61, 125.65, 57.48, 29.69, 29.42, 28.75, 22.78, 22.14, 14.20 ppm.

4.2.9. Compound ***12***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.57–7.48 (m, 4H), 2.76 (t, *J*=7.6 Hz, 2H), 1.85–1.50 (m, 2H), 1.48–1.08 (m, 10H), 0.86 (t, *J*=6.4 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.89, 137.22, 129.60, 125.61, 57.62, 31.79, 29.14, 28.75, 22.68, 22.14, 14.14 ppm. HRMS calcd $C_{14}H_{21}ClOS$: 272.1002. Found: 272.1008.

4.2.10. Compound ***13***[31]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.60–7.50 (m, 2H), 7.49 (m, 3H), 2.61–2.52 (m, 1H), 1.85–1.12 (m, 10H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 141.86, 130.96, 128.94, 125.03, 63.16, 26.31, 25.98–25.09, 24.02 ppm.

4.2.11. Compound ***14***[32]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.66–7.60 (m, 4H), 7.47–7.44 (m, 3H), 7.17–7.11 (m, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 166.07, 162.73, 145.51, 141.36, 131.32, 129.52, 127.32, 124.75, 116.91, 116.61 ppm.

4.2.12. Compound ***15***[28]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.64–7.56 (m, 5H), 7.48–7.41 (m, 4H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.36, 144.31, 137.32, 131.41, 129.60, 126.16, 124.76, 120.07 ppm.

4.2.13. Compound ***16***[28]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.65–7.33 (m, 6H), 7.31–7.24 (m, 3H), 2.36 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.85, 142.51, 141.77, 131.00, 130.14, 129.37, 125.11, 124.81, 21.50 ppm.

4.2.14. Compound ***17***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.96–7.93 (m, 1H), 7.58–7.45 (m, 2H), 7.43–7.30 (m, 5H), 7.17 (d, *J*=7.1 Hz, 1H), 2.36 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 144.76, 143.11, 135.92, 131.17, 129.44, 127.28, 126.04, 124.89, 18.72 ppm. HRMS calcd $C_{13}H_{12}OS$: 216.0609. Found: 216.0617.

4.2.15. Compound ***18***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.66–7.63 (m, 2H), 7.48–7.40 (m, 5H), 7.33 (t, *J*=7.6 Hz, 1H), 7.23 (d, *J*=7.5 Hz, 1H), 2.37 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.72, 145.43, 139.59, 131.97, 131.00, 129.24, 124.90, 122.02, 21.43 ppm. HRMS calcd $C_{13}H_{12}OS$: 216.0609. Found: 216.0615.

4.2.16. Compound ***19***[29]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.51 (d, *J*=8.1 Hz, 4H), 7.37–6.96 (m, 4H), 2.36 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.86, 141.47, 130.02, 124.94, 21.42 ppm.

4.2.17. Compound ***20***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.54–7.46 (m, 2H), 7.39 (d, *J*=7.7 Hz, 1H), 7.32 (t, *J*=7.5 Hz, 1H), 7.26–7.21 (m, 4H), 2.37 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.72, 142.69, 141.61, 139.56, 131.83, 130.08, 129.13, 125.03, 121.99, 21.46 ppm. HRMS calcd $C_{14}H_{14}OS$: 230.0765. Found: 230.0775.

4.2.18. Compound ***21***[33]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.65–7.60 (m, 2H), 7.51 (d, *J*=8.2 Hz, 2H), 7.27 (d, *J*=6.0 Hz, 2H), 7.14 (t, *J*=8.6 Hz, 2H), 2.38 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 165.85, 162.52, 142.33, 141.68, 130.11, 127.07, 124.82, 116.69, 116.39, 21.36 ppm.

4.2.19. Compound ***22***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.07 (dd, *J*=7.8, 1.6 Hz, 1H), 7.61 (d, *J*=8.2 Hz, 2H), 7.51 (td, *J*=7.6, 1.4 Hz, 1H), 7.36 (m, 2H), 7.29–7.15 (m, 2H), 2.36 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.38, 142.18, 141.15, 134.51, 131.93, 129.97, 126.14, 125.59, 21.49 ppm. HRMS calcd $C_{13}H_{11}ClOS$: 250.0219. Found: 250.0211.

4.2.20. Compound ***23***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.94 (d, *J*=6.2 Hz, 1H), 7.43–7.16 (m, 7H), 2.36 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 144.42, 143.04, 139.55, 135.80, 131.99, 130.96, 129.10, 127.14, 126.17, 124.75, 123.06, 21.42, 18.64 ppm. HRMS calcd $C_{14}H_{14}OS$: 230.0765. Found: 230.0771.

4.2.21. Compound ***24***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.98 (dd, *J*=7.8, 1.6 Hz, 1H), 7.59–7.47 (m, 2H), 7.46–7.33 (m, 3H), 7.32–7.17 (m, 2H), 2.62 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 142.29, 137.83, 132.10, 131.56, 130.95, 129.97, 127.88, 127.32, 126.49, 18.80 ppm. HRMS calcd $C_{13}H_{11}ClOS$: 250.0219. Found: 250.0227.

4.2.22. Compound ***25***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.96 (d, *J*=7.5 Hz, 1H), 7.55–7.30 (m, 2H), 7.24 (d, *J*=8.1 Hz, 2H), 7.16 (d, *J*=7.3 Hz, 1H), 2.36 (s, 3H), 2.32 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.18, 141.64, 135.66, 130.93, 130.06, 127.12, 126.19, 124.59, 21.45, 18.61 ppm. HRMS calcd $C_{14}H_{14}OS$: 230.0765. Found: 230.0760.

4.2.23. Compound ***26***[34]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.90 (dd, *J*=7.1, 1.9 Hz, 1H), 7.54 (dd, *J*=6.7, 1.9 Hz, 2H), 7.49–7.33 (m, 4H), 7.19 (d, *J*=6.6 Hz, 1H), 2.36 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.27, 142.69, 137.26, 135.75, 131.20, 129.55, 127.21, 124.67, 18.54 ppm.

4.2.24. Compound ***27***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.58–7.50 (m, 4H), 7.47–7.38 (m, 2H), 7.33–7.21 (m, 2H), 2.37 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 144.58, 142.19, 137.17, 130.26, 129.61, 126.11, 125.02, 21.48 ppm. HRMS calcd $C_{13}H_{11}ClOS$: 250.0219. Found: 250.0211.

4.2.25. Compound ***28***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.58 (d, *J*=6.2 Hz, 2H), 7.45–7.39 (m, 4H), 7.37–7.32 (m, 1H), 7.25 (d, *J*=6.2 Hz, 1H), 2.38 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.15, 144.39, 139.82, 137.21, 132.27, 129.61, 129.32, 126.14, 124.96, 121.98, 21.45 ppm. HRMS calcd $C_{13}H_{11}ClOS$: 250.0219. Found: 250.0223.

4.2.26. Compound ***29***[28]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.58–7.55 (m, 4H), 7.47–7.42 (m, 4H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.98, 137.73, 129.87, 126.14 ppm.

4.2.27. Compound ***30***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.87 (m, 1H), 7.73–7.59 (m, 2H), 7.55–7.38 (m, 2H), 7.16–6.99 (m, 1H), 6.86–6.79 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ166.81, 160.40, 157.08, 143.17, 137.89, 129.83, 126.82, 126.11, 113.05, 105.23, 104.88, 104.56 ppm. HRMS calcd $C_{12}H_7ClF_2OS$: 271.9874. Found: 271.9862.

4.2.28. Compound ***31***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.13–8.10 (m, 2H), 7.73–7.64 (m, 4H), 7.48–7.45 (m, 3H), 4.38 (q, *J*=7.1 Hz, 2H), 1.38 (t, *J*=7.1 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 165.62, 150.59, 145.27, 132.96, 131.62, 130.53, 129.66, 125.01, 124.49, 61.55, 14.37. HRMS calcd $C_{15}H_{14}O_3S$: 274.0664. Found: 274.0654.

4.2.29. Compound ***32***[24]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.02 (d, *J*=8.4 Hz, 2H), 7.74–7.60 (m, 4H), 7.56–7.40 (m, 3H), 2.60 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 197.10, 150.81, 145.18, 139.04, 131.68, 129.69, 129.23, 124.87, 26.84 ppm.

4.2.30. Compound ***33***[35]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.31 (d, *J*=9.0 Hz, 2H), 7.83 (d, *J*=9.0 Hz, 2H), 7.69–7.66 (m, 2H), 7.51–7.49 (m, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 153.11, 144.57, 132.12, 129.92, 125.40, 125.00, 124.54 ppm.

4.2.31. Compound ***34***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.55 (d, *J*=4.1 Hz, 1H), 8.05 (d, *J*=7.9 Hz, 1H), 7.90–7.79 (m, 3H), 7.46–7.44

(m, 3H), 7.32–7.28 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 165.92, 149.86, 144.18, 138.22, 131.23, 129.25, 124.88, 118.53 ppm. HRMS calcd $C_{11}H_9NOS$: 203.0405. Found: 203.0419.

4.2.32. Compound ***35***[28]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.32 (d, J=8.8 Hz, 2H), 7.82 (d, J=8.8 Hz, 2H), 7.72–7.57 (m, 2H), 7.48 (d, J=8.5 Hz, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 152.68, 149.59, 138.53, 130.25, 126.33, 125.38, 124.71 ppm.

4.2.33. Compound ***36***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.64–7.60 (m, 2H), 7.51–7.33 (m, 10H), 7.24 (t, J=5.7 Hz, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.42, 143.07, 142.10, 133.40, 131.05, 129.61, 129.32, 128.71, 125.48, 124.63 ppm. HRMS calcd $C_{18}H_{14}O_2S_2$: 326.0435. Found: 326.0423.

4.2.34. Compound ***37***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.51–7.43 (m, 4H), 7.35 (d, J=8.1 Hz, 2H), 7.26–7.16 (m, 6H), 2.37 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 143.00, 142.72, 142.31, 141.65, 139.18, 134.20, 130.51, 130.06, 127.96, 125.39, 124.87, 21.36 ppm. HRMS calcd $C_{20}H_{18}O_2S_2$: 354.0748. Found: 354.0742.

4.2.35. Compound ***38***. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50–7.45 (m, 3H), 7.40–7.29 (m, 2H), 7.25–7.21 (m, 6H), 7.18–7.14 (m, 1H), 2.37 (s, **3**H), 2.32 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 145.24, 143.00, 142.28, 139.54, 134.07, 131.91, 130.57, 129.46, 129.12, 128.67, 125.47, 124.84, 121.85, 21.31 ppm. HRMS calcd $C_{20}H_{18}O_2S_2$: 354.0748. Found: 354.0732.

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Supplementary data

Supplementary data associated with this article can be found in online version at doi:10.1016/j.tet.2010.09.076.

References and notes

1. (a) Westheimer, F. H. In *Pyridine Nucleotide Coenzyme*; Dolphin, D., Poulson, R., Avramovic, O., Eds.; Wiley-Interscience: New York, NY, 1988; (b) Strout, D. M.; Meyers, A. I. *Chem. Rev.* **1982**, *82*, 223; (c) Murakami, Y.; Kikuchi, J.-I.; Hisaeda, Y.; Hayashida, O. *Chem. Rev.* **1996**, *96*, 721; (d) Zhu, X. Q.; Yang, Y.; Zhang, M.; Cheng, J. P. *J. Am. Chem. Soc.* **2003**, *125*, 15298; (e) Zhu, X. Q.; Zhang, M.; Liu, Q. Y.; Wang, X. X.; Zhang, J. Y.; Cheng, J. P. *Angew. Chem.* **2006**, *118*, 40581; *Angew. Chem., Int. Ed.* **2006**, *45*, 3954.
2. Suga, K.; Ohkubo, K.; Fukuzumi, S. *J. Phys. Chem. A* **2003**, *107*, 4339.
3. (a) Ohkubo, K.; Suga, K.; Fukuzumi, S. *Chem. Commun.* **2006**, 2018; (b) Xu, H. J.; Xu, X. L.; Fu, Y.; Feng, Y. S. *Chin. Chem. Lett.* **2007**, *18*, 1471.
4. (a) Ohkubo, K.; Fukuzumi, S. *Org. Lett.* **2000**, *2*, 3647; (b) Ohkubo, K.; Mizushima, K.; Iwata, R.; Souma, K.; Suzuki, N.; Fukuzumi, S. *Chem. Commun.* **2010**, 601.
5. Suga, K.; Ohkubo, K.; Fukuzumi, S. *J. Phys. Chem. A* **2005**, *109*, 4339.
6. Ohkubo, K.; Nanjo, T.; Fukuzumi, S. *Org. Lett.* **2005**, *7*, 4265.
7. Fang, X.; Liu, Y. C.; Li, C. *J. Org. Chem.* **2007**, *72*, 8608.
8. (a) Xu, H. J.; Dai, D. M.; Liu, Y. C.; Li, J.; Luo, S. W.; Wu, Y. D. *Tetrahedron Lett.* **2005**, *46*, 5739; (b) Xu, H. J.; Liu, Y. C.; Fu, Y.; Wu, Y. D. *Org. Lett.* **2006**, *8*, 3449; (c) Xu, H. J.; Liu, Y. C.; Fu, Y. *Chin. J. Chem.* **2007**, *25*, 95; (d) Xu, H. J.; Liu, Y. C.; Fu, Y. *Chin. J. Chem.* **2008**, *26*, 599; (e) Xu, H. J.; Xu, X. L.; Feng, Y. S. *Chin. J. Org. Chem.* **2009**, *29*, 289; (f) Fang, X. Q.; Xu, H. J.; Jiang, H.; Liu, Y. C.; Fu, Y.; Wu, Y. D. *Tetrahedron Lett.* **2009**, *50*, 312.
9. Lai, K. C.; Lam, S. K.; Chu, K. M.; Wong, B. C.; Hui, W. M.; Hu, W. H.; Lau, G. K.; Wong, W. M.; Yuen, M. F.; Chan, A. O.; Lai, C. L.; Wong, J. N. *N. Engl. J. Med.* **2002**, *346*, 2033.
10. Sovova, M.; Sova, P. *Ceska Slov. Farm.* **2003**, *52*, 82.
11. Kotelanski, B.; Grozmann, R. J.; Cohn, J. N. *Clin. Pharmacol. Ther.* **1973**, *14*, 427.
12. Schmied, R.; Wang, G. X.; Korth, M. *Circ. Res.* **1991**, *68*, 597.
13. Nieves, A. V.; Lang, A. E. *Clin. Neuropharmacol.* **2002**, *25*, 111.
14. Padmanabhan, S.; Lavin, R. C.; Durant, G. J. *Tetrahedron* **2000**, *11*, 3455.
15. (a) Carreno, M. *Chem. Rev.* **1995**, *95*, 1717; (b) Colobert, F.; Tito, A.; Khiar, N.; Denni, D.; Medina, M. A.; Martin-Lomas, M.; Ruano, J. L. G.; Solladié, G. *J. Org. Chem.* **1998**, *63*, 8918; (c) Carreno, M. C.; Ribagorda, M.; Posner, G. H. *Angew. Chem.* **2002**, *114*, 2877; *Angew. Chem., Int. Ed.* **2002**, *41*, 2753.
16. Khiar, N.; Fernández, I.; Alcudia, F. *Tetrahedron Lett.* **1993**, *34*, 123.
17. Fernández, I.; Khiar, N. *Chem. Rev.* **2003**, *103*, 3651.
18. (a) Hiroi, K.; Suzuki, Y.; Abe, I.; Kawagishi, R. *Tetrahedron* **2000**, *56*, 4701; (b) Hiroi, K.; Watanabe, K.; Abe, I.; Koseki, M. *Tetrahedron Lett.* **2001**, *42*, 7617; (c) Priego, J.; Mancheño, O. G.; Cabrera, S.; Carretero, J. C. *J. Org. Chem.* **2002**, *67*, 1346.
19. Representative examples for oxidation of sulfides to sulfoxides with peroxides, see: (a) Adam, W.; Rodriguez, A. *J. Am. Chem. Soc.* **1980**, *102*, 404; (b) Murahashi, S.; Oda, T.; Masui, Y. *J. Am. Chem. Soc.* **1989**, *111*, 5002; (c) Gelalcha, F. G.; Schulze, B. *J. Org. Chem.* **2002**, *67*, 8400; (d) Baciocchi, E.; Gerini, M. F.; Lapi, A. *J. Org. Chem.* **2004**, *69*, 3586; (e) Firouzabadi, H.; Iranpoor, N.; Jafari, A. A.; Riazymontazer, E. *Adv. Synth. Catal.* **2006**, *348*, 434; (f) Koo, D. H.; Kim, M.; Chang, S. *Org. Lett.* **2005**, *7*, 5015; (g) Kerber, W. D.; Ramdhanie, B.; Goldberg, D. P. *Angew. Chem.* **2007**, *119*, 3792; *Angew. Chem., Int. Ed.* **2007**, *46*, 3718; (h) Bordoloi, A.; Vinu, A.; Halligudi, S. B. *Chem. Commun.* **2007**, 4806; (i) Russoa, A.; Lattanzia, A. *Adv. Synth. Catal.* **2009**, *351*, 521.
20. Kerber, W. D.; Ramdhanie, B.; Goldberg, D. P. *Angew. Chem.* **2007**, *119*, 3792; *Angew. Chem., Int. Ed.* **2007**, *46*, 3718.
21. Representative examples for oxidation of sulfides to sulfoxides with O_2, see: (a) Correa, P. E.; Riley, D. P. *J. Org. Chem.* **1985**, *50*, 1787; (b) Tsuboi, T.; Takaguchi, Y.; Tsuboi, S. *Chem. Commun.* **2008**, 76; (c) Baciocchi, E.; Giacco, T. D.; Elisei, F.; Gerini, M. F.; Guerra, M.; Lapi, A.; Liberali, P. *J. Am. Chem. Soc.* **2003**, *125*, 16444; (d) Bonesi, S. M.; Manet, I.; Freccero, M.; Fagnoni, M.; Albini, A. *Chem.—Eur. J.* **2006**, *12*, 4844; (e) Imada, Y.; Iida, H.; Ono, S.; Masui, Y.; Murahashi, S. I. *Chem.—Asian. J.* **2006**, *1-2*, 136.
22. $AcrH_2$, a reduced form of $AcrH^+$, often is used as a model of coenzyme NADH. So, $AcrH^+$ is defined as a model of coenzyme NAD^+ in this article.
23. Huang, R. L.; Goh, S. H.; Ong, S. H. *The Chemistry of Free Radicals*; Edward Arnold: London, 1974.
24. (a) Clennan, E. L.; Zhang, H. W. *J. Am. Chem. Soc.* **1995**, *117*, 4218; (b) Ohkubo, K.; Nanjo, T.; Fukuzumi, S. *Bull. Chem. Soc. Jpn.* **2006**, *79*, 1489.
25. Nahm, K.; Foote, C. S. *J. Am. Chem. Soc.* **1989**, *111*, 1909.
26. (a) Xu, H. J.; Zhao, X. Y.; Fu, Y.; Feng, Y. S. *Synlett* **2008**, 3063; (b) Xu, H. J.; Zhao, X. Y.; Deng, J.; Fu, Y.; Feng, Y. S. *Tetrahedron Lett.* **2009**, *50*, 434; (c) Feng, Y. S.; Li, Y. Y.; Tang, L.; Wu, W.; Xu, H. J. *Tetrahedron Lett.* **2010**, *51*, 2489.
27. Casarini, D.; Lunazzi, L.; Mazzanti, A. *Angew. Chem.* **2001**, *113*, 2604; *Angew. Chem., Int. Ed.* **2001**, *40*, 2536.
28. Chandrasekaran, R.; Perumal, S.; Wilson, D. A. *Magn. Reson. Chem.* **1989**, *27*, 360.
29. Maitro, G.; Vogel, S.; Prestat, G.; Madec, D.; Poli, G. *Org. Lett.* **2006**, *8*, 5951.
30. Bellesia, F.; Ghelfi, F.; Pagnoni, U. M.; Pinetti, A. *Synth. Commun.* **1993**, *23*, 1759.
31. Johnson, C. R.; Kirchhoff, R. A.; Reischer, R. J.; Katekar, G. F. *J. Am. Chem. Soc.* **1973**, *95*, 4287.
32. Kaplan, L. J.; Martin, J. C. *J. Am. Chem. Soc.* **1973**, *95*, 793.
33. Laali, K. K.; Nagvekar, D. S. *J. Org. Chem.* **1991**, *56*, 1867.
34. Xia, M.; Chen, Z. C. *Synth. Commun.* **1997**, *27*, 1315.
35. Colonna, S.; Banfi, S.; Annunziata, R.; Casella, L. *J. Org. Chem.* **1986**, *51*, 891.