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K₂CO₃-promoted aerobic oxidative cross-coupling of trialkyl phosphites with thiophenols[†]

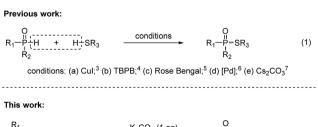
Chunxiao Wen,^a Qian Chen, ^b*^{ab} Yulin Huang,^a Xiaofeng Wang,^a Xinxing Yan,^a Jiekun Zeng,^a Yanping Huo ^b^a and Kun Zhang^{*a}

Convenient, practical and economical phosphorylation of thiols has been achieved *via* halogen- and metalfree K_2CO_3 -promoted aerobic oxidative cross-coupling of trialkyl phosphites, dimethyl phenylphosphonite, or methyl diphenylphosphinite with thiophenols using air as the oxidant at room temperature. This transformation provides a straightforward route to the construction of phosphorus–sulfur bonds with wide functional group compatibility, which affords phosphorothioates in up to 94% yield.

In recent years, the development of new methods to construct phosphorus-sulfur bonds has been of particular interest due to the wide applications of organophosphorus-sulfur compounds in biological chemistry, organic synthesis, and agrochemistry.¹ A variety of useful synthetic methods have been well documented. The traditional preparation of this class of compounds mainly relies on the use of toxic and moisture sensitive reagents or pre-functionalized substrates (e.g., R₂P(O)X, RSX and RSSR).² On the other hand, the cross-dehydrogenative coupling (CDC) between P(O)H compounds and commercially available thiols is gradually developed (Fig. 1, eqn (1)).³⁻⁷ In 2013, Kaboudin reported a copper-catalyzed coupling of H-phosphonates with thiols in the presence of Et₃N.³ In 2015, Pan reported a TBPBpromoted oxidative coupling of secondary phosphine oxides or H-phosphonates with thiols.4 In 2016, Li and Zhang reported visible-light-mediated oxidative coupling of P(O)H а compounds with thiols in the presence of a photocatalyst.⁵ Interestingly, Chen and Han recently reported an oxidant-free Pd-catalyzed dehydrogenative phosphorylation of thiols.6 Most recently, Song and Jiao reported a Cs₂CO₃-catalyzed aerobic oxidative CDC reaction of phosphonates with thiols.7 The possible mechanism showed that disulfides are reaction intermediates generated via the oxidative coupling of thiols in the presence of Cs₂CO₃ and O₂.⁷ Undoubtedly, this strategy represents more straightforward, efficient, and atom-economic to construct phosphorus-sulfur bonds. However, the CDC reactions suffered from limitations with regard to high cost and less availability of P(O)H compounds. Thus, the development of a convenient, practical and economical protocol for the synthesis of phosphorothioates is still a significant issue.

With our recent studies on the construction of carbonsulfur, phosphorus-aryl, phosphorus-fluorine, and phosphorus-oxygen bonds,8 we have been interested in studying the construction of phosphorus-sulfur bonds based on an economical approach. In comparison with P(O)H compounds, trialkyl phosphites are relatively inexpensive and readily available as phosphorus nucleophiles, which have also been widely used for the synthesis of various organophosphorus compounds.9 In consideration of searching phosphorus nucleophiles instead of P(O)H compounds, we envision that the interaction between trialkyl phosphites and thiols might produce phosphorothioates via the elimination of an alcohol. Herein, we report an alternative approach to the synthesis of phosphorothioates based on K2CO3-promoted aerobic oxidative cross-coupling of trialkyl phosphites with thiophenols using air as the oxidant at room temperature.

According to the reaction conditions of the CDC reactions between dialkyl phosphites and thiols developed by Song and Jiao,⁷ our hypothesis was tested by using a model reaction of triethyl phosphite **1a** with *p*-toluenethiol **2a** in solvents under



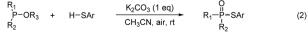


Fig. 1 Current developments in the synthesis of phosphorothioates from phosphites and thiols.

^aSchool of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou 510006, China. E-mail: qianchen@gdut.edu.cn; kzhang@ gdut.edu.cn; Fax: +86 20 3932 2235; Tel: +86 20 3932 2231

^bKey Laboratory of Functional Molecular Engineering of Guangdong Province, South China University of Technology, Guangzhou 510640, China

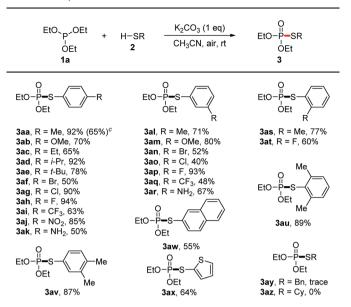
[†] Electronic supplementary information (ESI) available: General information and copies of ¹H, ¹³C, and ³¹P NMR spectra. See DOI: 10.1039/c7ra09057a

 Table 1
 Optimization of reaction conditions^{a,b}

EtO _{`P} I Ol	Et	-Me base solvent,	Etc	O D-P <mark>-</mark> STol + E OEt 3aa	O H O O Et 4a
Entry	Base (equiv.)	Solvent	Т (°С)	Yield 3aa (%)	Yield 4a (%)
1		CH ₃ CN	40	Trace	Trace
2	$Cs_2CO_3(1)$	CH ₃ CN	40	68	24
3 ^c	$Cs_2CO_3(1)$	CH ₃ CN	40	Trace	Trace
4	$Cs_2CO_3(1)$	THF	40	18	3
5	$Cs_2CO_3(1)$	Dioxane	40	28	4
6	$Cs_2CO_3(1)$	DMSO	40	Trace	Trace
7	$K_2 CO_3 (1)$	CH ₃ CN	40	98	1
8	$Na_2CO_3(1)$	CH ₃ CN	40	71	16
9	$K_3PO_4(1)$	CH ₃ CN	40	55	14
10	$Et_3N(1)$	CH ₃ CN	40	82	8
11	$K_2CO_3(1)$	CH ₃ CN	rt	97	1
12	$K_2 CO_3 (0.5)$	CH ₃ CN	rt	87	8
13	$K_2 CO_3 (0.1)$	CH ₃ CN	rt	81	12

^{*a*} Reaction conditions: **1a** (0.20 mmol), **2a** (0.46 mmol), base, solvent (1 mL), open air, 5 h. ^{*b*} Yield based on **1a** was determined by ³¹P NMR analysis of crude products using an internal standard. ^{*c*} The reaction was carried out under N_2 .

 Table 2
 Scope of thiols^{a,b}

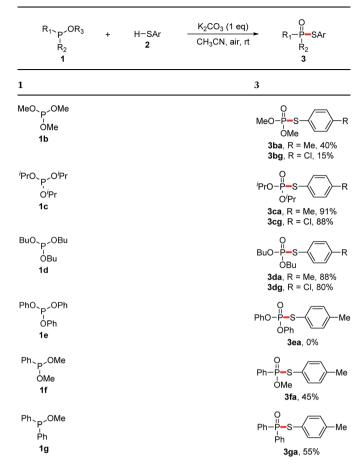


^{*a*} Reaction conditions: **1a** (0.40 mmol), **2** (0.92 mmol), and K_2CO_3 (0.40 mmol) in CH₃CN (2 mL) stirring at room temperature under air for 5–12 h. ^{*b*} Isolated yield based on **1a**. ^{*c*} The reaction was performed in a 4 mmol scale.

air atmosphere at 40 °C, and the results were shown in Table 1. Initially, the reaction of 1a with 2a in CH₃CN under air in the absence of bases gave only trace amounts of the desired coupling product 3aa (entry 1). When Cs₂CO₃ (1 equiv.) was added, the reaction proceeded smoothly to afford 3aa in 68% yield, while the oxidation product 4a was also obtained in 24% yield (entry 2). When the reaction was carried out under N₂, only trace amounts of 3aa were detected (entry 3). This result demonstrates that this reaction involved an aerobic oxidative cross-coupling. Switching the solvent from CH₃CN to THF, dioxane, or DMSO decreased the yield of 3aa (entries 4-6). We then turned to screen other bases (entries 7-10). To our delight, the use of cheaper base K_2CO_3 gave 3aa in excellent yield (98%, entry 7), while the yield of the side product 4a was significantly decreased. We then carried out the reaction at room temperature, the yield of 3aa was only slightly decreased (97%, entry 11). The catalytic efficiency of K₂CO₃ was then tested. When 0.5 or 0.1 equiv. of K₂CO₃ was introduced, 3aa was still obtained in 87% or 81% yield (entries 12 and 13). It is noteworthy that disulfide 5a, which was generated via an aerobic oxidative homocoupling of thiol 2a,10 was observed in all cases (in the presence of bases and air). Finally, we concluded that the optimized combination for the cross-coupling reaction of trialkyl phosphites with thiols was to use 1 equiv. of K₂CO₃ as the base, CH₃CN as the solvent, and the reaction was set at room temperature under air atmosphere (entry 11).

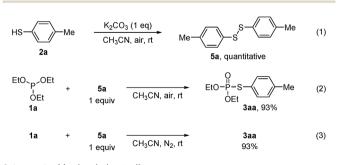
We then set out to explore the generality of the crosscoupling of trialkyl phosphites with thiols. We first applied the optimized conditions to the coupling of triethyl phosphite **1a** with a variety of thiols **2**, and the results are illustrated in Table 2. The results showed that thiophenol substrates bearing different groups such as alkyl groups, OMe, NH₂, Br, Cl, F, CF₃, and NO₂ at *para*, *ortho* or *meta* or at both positions of aromatic rings, as well as 2-naphthalenethiol and thiophene-2-thiol, were all well tolerated. The corresponding products **3aa–3ax** were isolated in moderate to high yields, indicating that the electronic and steric effects were not evident in this reaction. However, the phosphorylation of aliphatic thiols such as benzylthiol and cyclohexylthiol failed to give the desired **3ay** or **3az**. The scale-up of the reaction of **1a** with **2a** was also attempted. When we increased the scale of the reaction from 0.4 to 4 mmol, **3aa** was also isolated in good yield (65%).

We then turned to explore the generality of the crosscoupling of trialkyl phosphites and their derivatives with p-toluenethiol 2a and/or p-chlorobenzenethiol 2g under the optimized conditions, and the results were shown in Table 3. Trimethyl phosphite 1b afforded the desired 3ba and 3bg in low yields probably due to its relatively weak nucleophilicity, while triisopropyl phosphite 1c and tributyl phosphite 1d smoothly gave the desired 3ca, 3cg, 3da, and 3dg in high yields. However, triphenyl phosphite 1e failed to give the coupling product 3ea. In addition, the cross-coupling of P(m) compounds bearing one or two methoxy substituents were also attempted. Pleasingly, the protocol was found to work well when dimethyl phenylphosphonite 1f or methyl diphenylphosphinite 1g was employed as the phosphorus nucleophile. The corresponding coupling products 3fa and 3ga were isolated in 45% and 55% yields, respectively. Notably, the side products 4 and disulfides 5 were detected in most cases of Tables 2 and 3.

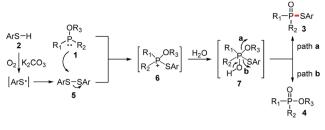


^{*a*} Reaction conditions: **1** (0.40 mmol), **2** (0.92 mmol), and K_2CO_3 (0.40 mmol) in CH₃CN (2 mL) stirring at room temperature under air for 5–12 h. ^{*b*} Isolated yield based on **1**.

The above experimental results (Table 1, entries 1 and 3) showed that both bases and air are indispensable for the crosscoupling reaction. To gain more insight into the mechanism of this reaction, a couple of control experiments were then conducted (Scheme 1). In consideration of the generation of disulfides in all cases, the reaction of thiol **2a** with K_2CO_3 under air was carried out, leading to the formation of disulfide **5a** in quantitative yield (eqn (1)), which suggests that K_2CO_3 might increase the oxidation rate of thiols with dioxygen.^{11,12} In



Scheme 1 Mechanistic studies.



Scheme 2 Proposed mechanism.

addition, the reaction of **1a** with disulfide **5a** under air or N_2 in the absence of K_2CO_3 also gave **3aa** in high yield (eqn (2) and (3)). The above results suggest that disulfide might be an intermediate in the cross-coupling reaction.

According to the literatures and our observations, together with the generation of side products 4, a plausible reaction mechanism is outlined in Scheme 2. Initially, thiyl radical is generated from a single electron oxidation of thiol 2 in the presence of dioxygen, followed by the loss of the proton with the assistance of K_2CO_3 . Thiyl radical could undergo homocoupling to produce disulfide 5.^{7,11-13} Then the nucleophilic attack of P(m) compound 1 on disulfide 5 affords phosphonium cation 6, which reacts with water to form the unstable intermediate 7. Subsequent alcohol elimination of 7 gives the desired phosphorothioate 3 (path a), whereas the thiophenol elimination affords the oxidation product 4 (path b).

Conclusions

In conclusion, we have developed the K_2CO_3 -promoted aerobic oxidative cross-coupling of trialkyl phosphites, dimethyl phenylphosphonite, or methyl diphenylphosphinite with thiophenols, which provides a convenient, practical and economical protocol for the synthesis of phosphorothioates with wide functional group compatibility. We envision that the reaction mode outlined here will have potential applications in organic synthesis. Further studies on the transformations of thiols with electrophiles are ongoing and will be reported in due course.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Science and Technology Planning Project of Guangdong Province (No. 2015A020211026 and 2017A010103044), 100 Young Talents Programme of Guangdong University of Technology (220413506), and the Open Fund of the Key Laboratory of Functional Molecular Engineering of Guangdong Province (2016kf07, South China University of Technology). 1 (a) N. N. Melnikov, Chemistry of Pesticides, Springer-Verlag, New York, 1971; (b) L. D. Quin, A Guide to Organophosphorus Chemistry, Wiley Interscience, New York, 2000; (c) P. J. Murphy, Organophosphorus Reagents, Oxford University Press, Oxford, UK, 2004; (d) N.-S. Li, J. K. Frederiksen and J. A. Piccirilli, Acc. Chem. Res., 2011, 44, 1257; (e) J. F. Milligan and O. C. Uhlenbeck, Biochemistry, 1989, 28, 2849; (f) S. H. Vollmer, M. B. Walner, K. V. Tarbell and R. F. Colman, J. Biol. Chem., 1994, 269, 8082; (g) S. Cogoi, V. Rapozzi, F. Quadrifoglio and L. Xodo, Biochemistry, 2001, 40, 1135; (h) G. G. Durgam, T. Virag, M. D. Walker, R. Tsukahara, S. Yasuda, K. Liliom, L. A. van Meeteren, W. H. Moolenaar, N. Wilke, W. Siess, G. Tigyi and D. D. Miller, J. Med. Chem., 2005, 48, 4919; (i) P. Carta, N. Puljic, C. Robert, A.-L. Dhimane, L. Fensterbank, E. Lacôte and M. Malacria, Org. Lett., 2007, 9, 1061; (j) M. Piekutowska and Z. Pakulski, Carbohydr. Res., 2008, 343, 785; (k)V. K. Pandey, A. Dwivedi, O. P. Pandey and S. K. Sengupta, J. Agric. Food Chem., 2008, 56, 10779; (l) T. Ruman, K. Długopolska, A. Jurkiewicz, D. Rut, T. Fraczyk, J. Cieśla, A. Leś, Z. Szewczuk and W. Rode, Bioorg. Chem., 2010, 38, 74; (m) A. M. Lauer, F. Mahmud and J. Wu, J. Am. Chem. Soc., 2011, 133, 9119; (n) A. M. Lauer and J. Wu, Org. Lett., 2012, 14, 5138; (o) M. W. Loranger, S. A. Beaton, K. L. Lines and D. L. Jakeman, Carbohydr. Res., 2013, 379, 43; (p) T. S. Kumar, T. Yang, S. Mishra, C. Cronin, S. Chakraborty, J.-B. Shen, B. T. Liang and K. A. Jacobson, J. Med. Chem., 2013, 56, 902; (q) Y. Qiu, J. C. Worch, D. N. Chirdon, A. Kaur, A. B. Maurer, S. Amsterdam, C. R. Collins, T. Pintauer, D. Yaron, S. Bernhard and K. J. T. Noonan, Chem.-Eur. J., 2014, 20, 7746.

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