

Iron-catalyzed highly efficient aerobic oxidative synthesis of benzimidazoles direct from oximes in water

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Received: 28 October 2014 / Accepted: 21 March 2015
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Abstract This article presents a general and efficient method for aerobic oxidative synthesis of benzimidazoles from oximes catalyzed by $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ under air in water. This practical method uses air as an economic and green oxidant, water as a green solvent, and tolerates a wide range of substrates that can afford the target benzimidazoles in moderate to good yields.

Keywords Aerobic oxidation · Benzimidazoles · Oximes · Iron · Air

Introduction

Benzimidazole and its derivatives are important building blocks for the construction of pharmaceuticals, natural products, functional materials, and agrochemical compounds. They exhibit significant pharmacological and biological activities such as anticonvulsant, anticancer, antiulcer, antihypertensive, antibacterial, and antihistaminic properties [1–9]. Consequently, great effort has been made to develop efficient methods for the preparation of benzimidazoles. In general, there are two methods for the synthesis of benzimidazoles. One is the condensation of *o*-phenylenediamine with carboxylic acids or their derivatives (nitriles, imidates, orthoesters) [10–26]. The other is oxidative cyclo-dehydrogenation of aniline Schiff's bases, which are often generated in situ from the condensation of

Electronic supplementary material The online version of this article (doi:10.1007/s11164-015-2031-4) contains supplementary material, which is available to authorized users.

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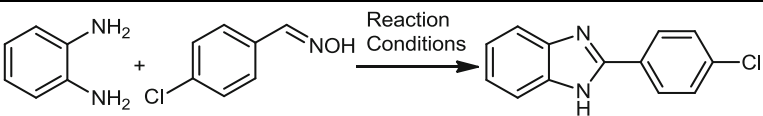
o-phenylenediamines and aldehydes [27–34]. Although the reaction was efficiently carried out by the above methods, these methods suffer from one or more disadvantages, for example, the former requires strong acidic conditions and high temperature conditions; the latter method requires stoichiometric or excess amounts of a strong oxidant, a high-cost catalyst, and odorous and unstable aldehydes, and generates environmentally hazardous/toxic by-products. Moreover, these methods are always conducted in organic solvents. Thus, it is of significant importance to develop a mild, convenient, and efficient method that can avoid the use of organic solvents for the synthesis of benzimidazoles.

Oximes have been widely used in medicine, industry, and analytical chemistry, and they are widely used as intermediates in the synthesis of commodity products, fine chemicals, medicines, and biologically active compounds [35–43]. Moreover, oximes are valuable synthetic tools, which can be either reduced to amines or oxidized to nitrile oxides [44, 45], and they can also be dehydrated to nitriles or undergo an acid-catalyzed Beckmann rearrangement to obtain amides [46–50]. However, their application in the catalytic oxidative synthesis of heterocycles is rare.

Recently, cross-coupling reactions and C-H activation reactions have been well documented for the synthesis of benzimidazoles under many reaction conditions, such as PhI/*m*CPBA and Cu(OTf)₂ [51–53]. In recent years, aerobic oxidative reactions, which are comparatively green, preferable, and practical, have attracted increasing attention because they use pure oxygen or air as the terminal oxidant in view of the concepts of green chemistry and atom economy, are much more easily disposable catalysts, and have milder reaction conditions, along with generating water as the by-product. In our previous work, we developed aerobic oxidative synthesis of benzimidazoles from aromatic alcohols and *o*-phenylenediamine was achieved by using CuCl, bpy, and TEMPO under solvent-free conditions [54]. In addition, we also developed aerobic oxidative synthesis of benzimidazoles from aromatic amines and *o*-phenylenediamine catalyzed by the Fe(NO₃)₃·9H₂O/TEMPO system under solvent-free conditions or used TBHP as an oxidant under solvent-free and catalyst-free conditions [55, 56]. Thus, based on our previous work, herein we report a general and efficient procedure for aerobic oxidative synthesis of benzimidazoles from oximes and *o*-phenylenediamine catalyzed by Fe(NO₃)₃·9H₂O using H₂O as the solvent.

Results and discussion

We began our investigation by examining the reaction activity using 4-chlorobenzaldoxime and *o*-phenylenediamine as the model substrates (Table 1). In the absence of a catalyst, the reaction could not progress (entry 1). When 5 mol% Fe(NO₃)₃·9H₂O was added to this reaction, the desired product 2-(4-chlorophenyl)-benzimidazole was obtained with a yield of 47 % (entry 2). Screening the amounts of Fe(NO₃)₃·9H₂O showed that 10 mol% was better than others, giving the highest yield (entries 3–5). After conducting the reaction under different amounts of *o*-phenylenediamine, we found that the amount of *o*-phenylenediamine was very important for the reaction, and three equivalents was the most suitable (entries 6–9). Various metal catalysts were then screened, showing varying activities in the reaction (FeCl₃, 69 %; Fe₂(SO₄)₃,

Table 1 Optimization of reaction conditions


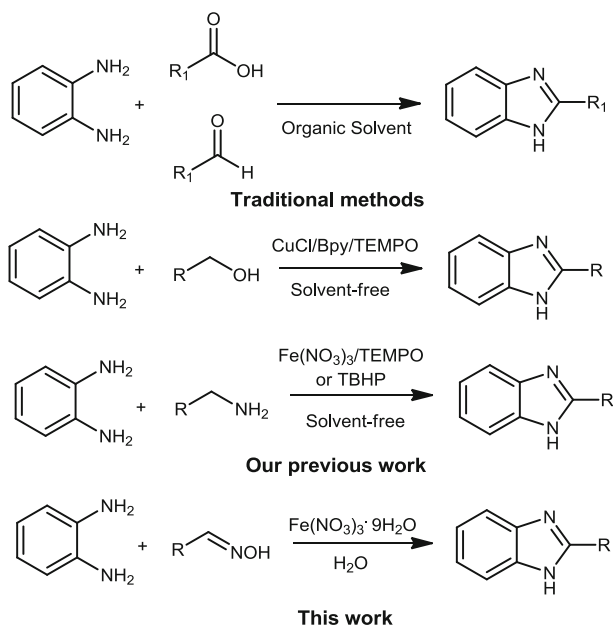
Entry	Diamine (equiv.)	Catalyst (mol%)	Solvent	T (°C)	Gas	Yield (%) ^a
1	1	–	Toluene	80	Air	Trace
2	1	Fe(NO ₃) ₃ ·9H ₂ O (5)	Toluene	80	Air	47
3	1	Fe(NO ₃) ₃ ·9H ₂ O (2.5)	Toluene	80	Air	35
4	1	Fe(NO ₃) ₃ ·9H ₂ O (10)	Toluene	80	Air	54
5	1	Fe(NO ₃) ₃ ·9H ₂ O (20)	Toluene	80	Air	54
6	2	Fe(NO ₃) ₃ ·9H ₂ O (10)	Toluene	80	Air	62
7	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	Toluene	80	Air	71
8	4	Fe(NO ₃) ₃ ·9H ₂ O (10)	Toluene	80	Air	71
9	0.5	Fe(NO ₃) ₃ ·9H ₂ O (10)	Toluene	80	Air	28
10	3	FeCl ₃ (10)	Toluene	80	Air	69
11	3	Fe ₂ (SO ₄) ₃ (10)	Toluene	80	Air	50
12	3	CuCl ₂ (10)	Toluene	80	Air	58
13	3	Cu(OAc) ₂ (10)	Toluene	80	Air	54
14	3	CuI (10)	Toluene	80	Air	39
15	3	CoCl ₂ (10)	Toluene	80	Air	35
16	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	EtOH	80	Air	78
17	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	DMSO	80	Air	68
18	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	MeCN	80	Air	73
19	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	80	Air	81
20	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	100	Air	90
21	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	60	Air	59
22	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	RT	Air	Trace
23	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	100	O ₂	90
24	3	Fe(NO ₃) ₃ ·9H ₂ O (10)	H ₂ O	100	N ₂	Trace

Reaction conditions: a mixture of diamine and *p*-chlorobenzaldehyde catalyst were mixed in 5 ml solvent, and then stirred rapidly for 24 h. The reaction progress was monitored by TLC

^a Isolated yield






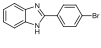


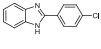





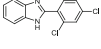


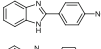


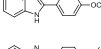


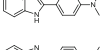


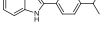


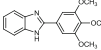





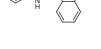











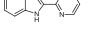


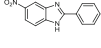








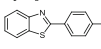


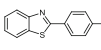
50 %; CuCl₂, 58 %; Cu(OAc)₂, 54 %; CuI, 39 %; CoCl₂, 35 %), but often in lower yields (entries 10–15). Solvent screening showed that H₂O seemed a little better than others (entries 7, 16–19), and as an environmental consideration, we chose H₂O as solvent. Further optimization by screening the reaction temperature, the results showed that 100 °C was optimal for this reaction (entries 19–22). Finally, we tested the influence of the gas, and we found that the reaction could not progress under N₂ atmosphere (entry 24), and O₂ is significant for the reaction. Further, when using O₂ in the reaction, the yield was equal to using air (entries 20, 23). As an economic consideration, we chose air as the oxidant (Scheme 1).

With the optimized reaction conditions in hand, the iron-catalyzed method was then applied to various oximes and *o*-phenylenediamine derivatives to test the scope and generality, as shown in Table 2. A variety of oximes reacted with *o*-phenylenediamine smoothly to give the corresponding benzimidazoles in good to excellent yields, regardless of whether oximes were in electron-donating or electron-withdrawing groups on the benzene ring. Clearly, the electronic effects of substituents on the benzene ring affected the reaction to some extent. For instance, electron-donating substituents favored the transformation (entries 7, 9–10). Meanwhile, electron-withdrawing substituents rejected the transformation (entry 6). The sterical hindrance of the substituted oximes also influenced the reaction. For example, the more sterically hindered ortho-chlorobenzaldoxime which reacted with *o*-phenylenediamine furnished the target product in lower yield than para-chlorobenzaldoxime (entries 2, 4). When 1-naphthaldehyde oxime and cinnamaldehyde oxime were subjected to the standard conditions, good yields could be successfully obtained (entries 11–12). Moreover, we also conducted heterocyclic oximes under the employed reaction conditions. To our surprise, heterocyclic oximes show high reactivity to give the corresponding benzimidazoles in good yields (entries 13–15). In addition, 4-chloro-*o*-phenylenediamine and 4-nitro-*o*-phenylenediamine were also employed in the reaction, and to our delight, it resulted in good yields (entries 16–17). Having successfully achieved the synthesis of benzimidazoles, this catalytic system was expanded to catalyze the synthesis of benzoxazoles and benzothiazoles using *o*-aminophenol and *o*-aminothiophenol,



Scheme 1 Aerobic oxidative synthesis of benzimidazoles directly oximes and *o*-phenylenediamine catalyzed by $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ using H_2O as the solvent

Table 2 Synthesis of 2-substituted benzimidazoles from oximes and diamines

$ \begin{array}{c} \text{R}_1\text{-C}_6\text{H}_3\text{(NH}_2\text{)}_2\text{-X} + \text{R}_2\text{-CH=NOH} \\ \text{X=NH, O, S} \end{array} \xrightarrow[\text{H}_2\text{O}]{10 \text{ mol\% Fe(NO}_3)_3 \cdot 9\text{H}_2\text{O}} \text{R}_1\text{-C}_6\text{H}_3\text{(NH)}_2\text{-X-R}_2 $					
Entry	X	Diamine	Amine	Product	Yield (%) ^a
1	H				90
2	H				82
3	H				90
4	H				66
5	H				81
6	H				71
7	H				88
8	H				72
9	H				90
10	H				86
11	H				82
12	H				85
13	H				75
14	H				79
15	H				72
16	H				85
17	H				83
18	O				Trace
19	S				76
20	S				82
21	S				65

Reaction conditions: 3 mmol diamine, 1 mmol oxime, and 0.1 mmol $\text{Fe(NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were mixed in 5 ml H_2O , and then stirred rapidly at 100 °C for 24 h. The reaction progress was monitored by TLC

^a Isolated yield

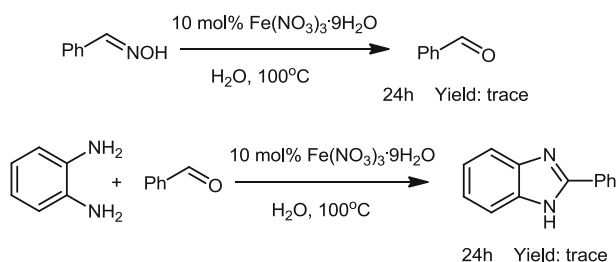
respectively, with benzaldoxime as the starting materials. We found that trace only was obtained of 2-phenyl-benzoxazole (entry 18), but 2-phenyl-benzothiazole resulted in a yield of 76 % (entry 19). Furthermore, 4-chlorobenzaldoxime and 4-nitrobenzaldoxime were used to react with *o*-aminothiophenol, and benzothiazoles were also converted in high yields (entries 20–21).

Preliminary mechanistic studies of the reaction were also conducted. Originally, we speculated that the possible reaction pathway could be divided into two steps, including the oximes oxidated to aldehydes, and the generated aldehydes reacted with *o*-phenylenediamine to form benzimidazoles under the catalytic system. Thus, we conducted the two kinds of reaction in this catalytic system. Unfortunately, the oximes could not be oxidated to aldehydes, and aldehydes could not react with *o*-phenylenediamine in the catalytic system, as shown in Scheme 2.

Subsequently, we speculated that *o*-phenylenediamine with oximes took place to form imine, and the imine further reacted with another amine group of *o*-phenylenediamine to form benzimidazoline, benzimidazole could obtained after oxidation of benzimidazoline. First, we turn our attention to the reaction of aniline and benzaldoxime to synthesize the cross imines as shown in Table 3. When aniline and benzaldoxime was treated with $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ under air atmosphere at 100 °C for 24 h, the desired imine was isolated in 88 % yield (entry 1). In addition, we found that almost no desired product occurred in absence of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ or under N_2 atmosphere (entries 2, 3). Therefore, this reaction was an aerobic oxidative step which catalyzed by $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, O_2 in the air as the oxidant.

By these encouraging results, we focused on the cyclo-dehydrogenation of 2-phenylbenzimidazoline (2-phenylbenzimidazoline is unstable in air; therefore, 2-phenylbenzimidazoline is formed in situ from an equimolar amount of *o*-phenylenediamine and benzaldehyde in a mixed solution, $\text{EtOH}:\text{H}_2\text{O} = 1:1$, at room temperature after 2 h). Preliminary studies of the reaction were conducted, the result is shown in Table 4. After optimizing the reaction condition, the yield of the desired product 2-phenyl-1H-benzimidazole reached 85 % only when $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ added to the reaction under air atmosphere (entry 1). In the absence of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, the yield decreased substantially (entry 2). Moreover, the reaction could not react under N_2 atmosphere (entry 3). Therefore, $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and O_2 were essential for the reaction.

Based on these results, a plausible reaction pathway for the formation of benzimidazole is shown in Scheme 3. First, the aerobic oxidative synthesis of



Scheme 2 The oxidation of oxime and the reaction of *o*-phenylenediamine and aldehyde

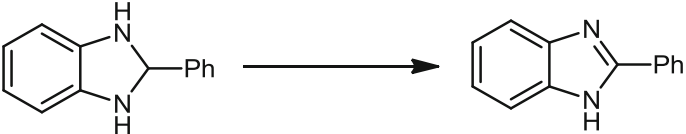
Table 3 $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ catalyzed aerobic oxidation of benzylamine and aniline to imine under air

$\text{Ph}-\text{NH}_2 + \text{Ph}-\text{CH}=\text{NOH} \longrightarrow \text{Ph}-\text{CH}=\text{N}-\text{Ph}$			
Entry	Catalyst	Gas	Yield ^a (%)
1	$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	Air	88
2	—	Air	Trace
3	$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	N_2	Trace

Reaction conditions: 3 mmol aniline, 1 mmol benzaldoxime, 0.1 mmol $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were mixed in 5 ml H_2O , and then stirred rapidly at 100 °C for 24 h at corresponding conditions. The reaction progress was monitored by TLC

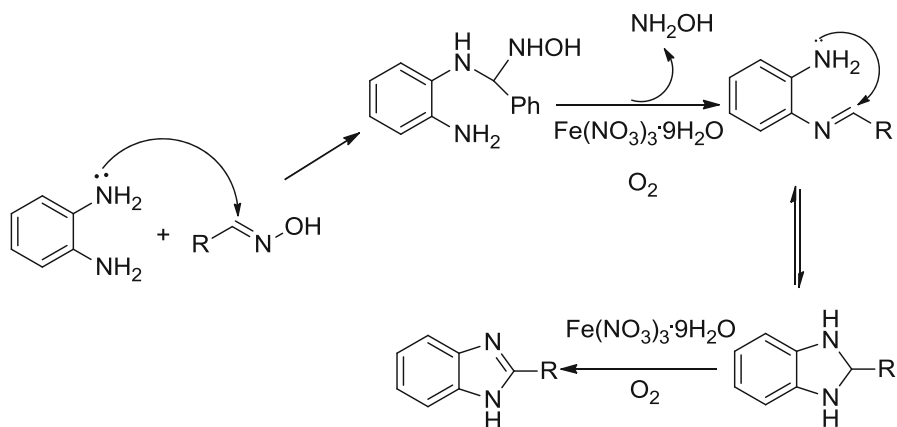
^a Isolated yield

Table 4 The cyclo-dehydrogenation of benzimidazoline to benzimidazole

			
Entry	Catalyst	Gas	Yield ^a (%)
1	$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	Air	85
2	—	Air	29
3	$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	N_2	Trace

Reaction conditions: to a solution of 1 mmol *o*-phenylenediamine and 1 mmol benzaldehyde, 2.5 ml ethanol, 2.5 ml H_2O , the solution was stirred at room temperature for 2 h. 0.1 mmol $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ was then added and stirred rapidly at 100 °C for 24 h at corresponding conditions. The reaction progress was monitored by TLC

^a Isolated yield

**Scheme 3** A plausible reaction pathway for the formation of benzimidazole by oxime and *o*-phenylenediamine

benzimidazoline proceed via the coupling of *o*-phenylenediamine with oxime to form imine, and then the imine further reacted with another amine group of *o*-phenylenediamine to form benzimidazoline. Finally, in the cyclo-dehydrogenation of benzimidazoline step, benzimidazoline was oxidated to form benzimidazole catalyzed by $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ under air atmosphere.

Experimental section

All starting materials were purchased from commercial sources and used without further treatment. Melting points were determined on a Thomas Hoover capillary apparatus and were uncorrected. All known compounds were identified by an appropriate technique, such as ^1H NMR, and compared with previously reported data. ^1H NMR (500 MHz) was recorded on a Bruker 500 spectrometer with tetramethylsilane (TMS) as an internal standard. Mass spectra were recorded on an Agilent Technologies 6110 quadrupole LC/MS equipped with an electrospray ionization (ESI) probe operating in positive ion mode. Analytical thin layer chromatography (TLC) was performed on precoated silica gel 60 F254 plates. Yields refer to the isolated yields of the products after purification by silica-gel column chromatography (300 mesh). The spectra were in supporting information.

Typical procedure for oxidative synthesis of benzimidazoles

A mixture of 1 mmol oximes and 3 mmol diamines, 0.1 mmol $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, H_2O (5 ml) were prepared in a 10-ml three-necked flask, and then stirred at 100 °C for 24 h, and the reaction progress was monitored by TLC. After completion of the reaction, the reaction mixture was cooled to room temperature, the solution was directly evaporated to dryness and the residue was purified by chromatography using hexane/ethyl acetate (7:3) as eluent.

References

1. W.A. Denny, G.W. Rewcastle, B.C. Bauley, J. Med. Chem. **33**, 814 (1990)
2. T. Güngör, A. Fouquet, J.-M. Eulon, D. Provost, M. Cazes, A. Cloarec, J. Med. Chem. **35**, 4455 (1992)
3. E. Seyhan, N. Sultan, A. Nilgun, N. Noyanalpan, Arzneim.-Forsch. **47**, 410 (1997)
4. L. Hu, M.L. Kully, D.W. Boykin, N. Abood, Bioorg. Med. Chem. Lett. **19**, 3374 (2009)
5. R. Schiffmann, A. Neugebauer, C.D. Klein, J. Med. Chem. **49**, 511 (2006)
6. R.P. Verma, Bioorg. Med. Chem. **13**, 1059 (2005)
7. K.-J. Soderlind, B. Gorodetsky, A.K. Singh, N. Bachur, G.G. Miller, J.W. Loun, Anti-Cancer Drug Des. **14**, 19 (1999)
8. D.A. Horton, G.T. Bourne, M.L. Smythe, Chem. Rev. **103**, 893 (2003)
9. T. Roth, M.L. Morningstar, P.L. Boyer, S.H. Hughes, R.W. Buckheit Jr, C.J. Michejda, J. Med. Chem. **40**, 4199 (1997)
10. Y. Wang, K. Sarris, D.R. Sauer, S.W. Djuric, Tetrahedron Lett. **47**, 4823 (2006)
11. W. Huang, R.M. Scarborough, Tetrahedron Lett. **40**, 2665 (1999)
12. Y.-C. Chi, C.-M. Sun, Synlett **5**, 591 (2000)
13. D. Kumar, M.R. Jacob, M.B. Reynolds, S.M. Kerwin, Bioorg. Med. Chem. **10**, 3997 (2002)

14. B. Gong, F. Hong, C. Kohm, L. Bonham, P. Klein, *Bioorg. Med. Chem. Lett.* **14**, 1455 (2004)
15. S.-T. Huang, I.-J. Hsei, C. Chen, *Bioorg. Med. Chem.* **14**, 6106 (2006)
16. D.W. Dunwell, D. Evans, C.E. Smith, W.R.N. Williamson, *J. Med. Chem.* **18**, 692 (1975)
17. I.B. Dzvinchuk, A.V. Vypirailenko, M.O. Lozinskii, *Russ. J. Org. Chem.* **34**, 685 (1998)
18. E. Barni, P.J. Savarino, *J. Heterocycl. Chem.* **16**, 1583 (1979)
19. J.B. Hendrickson, M.S. Hussoin, *J. Org. Chem.* **52**, 4137 (1987)
20. T. Gungor, A. Fouquet, J.-M. Teulon, D. Provost, M. Cazes, A. Cloarec, *J. Med. Chem.* **35**, 4455 (1992)
21. A.W. White, R. Almasy, A.H. Calvert, N.J. Curtin, R.J. Griffin, Z. Hostomsky, K. Maegley, D.R. Newell, S. Srinivasan, B.T. Golding, *J. Med. Chem.* **43**, 4084 (2000)
22. B. Biasotti, S. Dallavalle, L. Merlini, C. Farina, S. Gagliardi, C. Parini, P. Belfiore, *Bioorg. Med. Chem.* **11**, 2247 (2003)
23. K. Bougrin, A. Loupy, M. Soufiaoui, *Tetrahedron* **54**, 8055 (1998)
24. A. Ben-Alloum, S. Bakkas, M. Soufiaoui, *Tetrahedron Lett.* **39**, 4481 (1998)
25. G.V. Reddy, V.V.V.N.S.R. Rao, B. Narsaiah, P.S. Rao, *Synth. Commun.* **32**, 2467 (2002)
26. Z. Mao, Z. Wang, J. Li, X. Song, Y. Luo, *Synth. Commun.* **40**, 1963 (2010)
27. F.F. Stephens, J.D. Bower, *J. Chem. Soc.* **3**, 2971 (1949)
28. R.L. Lombardy, F.A. Tanious, K. Ramachandran, R.R. Tidwell, W.D. Wilson, *J. Med. Chem.* **39**, 1452 (1996)
29. K. Bahrami, M.M. Khodaei, A. Nejati, *Green Chem.* **12**, 1237 (2010)
30. J.J. Vanden Eynde, F. Delfosse, P. Lor, Y. Van Haverbeke, *Tetrahedron* **51**, 5813 (1995)
31. K.J. Lee, K.D. Janda, *Can. J. Chem.* **79**, 1556 (2001)
32. I. Bhatnagar, M.V. George, *Tetrahedron* **24**, 1293 (1968)
33. P.L. Beaulieu, B. Hache, E. von Moos, *Synthesis* **11**, 1683 (2003)
34. K. Bahrami, M.M. Khodaei, I. Kavianinia, *Synthesis* **4**, 547 (2007)
35. G.M. Robertson, in *Comprehensive Functional Group Transformation*, vol. 3, ed. by A.R. Katritzky, O. Meth-Cohn, C.W. Rees (Elsevier, Oxford, 1995), p. 425
36. H. Iwamura, *J. Med. Chem.* **23**, 308–312 (1980)
37. Y. Takahashi, Y. Miyashita, Y. Tanaka, H. Abe, S. Sasaki, *J. Med. Chem.* **25**, 1245–1248 (1982)
38. P.A. Eyer, F. Worek, in *Chemical Warfare Agents Toxicology and Treatment*, ed. by T.C. Marrs, R.L. Maynard, F.R. Sidell (Wiley, New York, 2007), pp. 305–329
39. A. Atria, M. Michael, *Pharmazie* **37**, 551–553 (1982)
40. A. Nakayama, H. Iwamura, A. Niwa, Y. Nakagawa, T. Fujita, *J. Agric. Food Chem.* **33**, 1034–1041 (1985)
41. J.P. Ley, H.J. Bertram, *Eur. J. Lipid Sci. Technol.* **104**, 319–323 (2002)
42. M. Kato, S. Nishino, M. Ohno, S. Fukuyama, Y. Kita, Y. Hirasawa, Y. Nakanishi, H. Takasugi, K. Sakane, *Bioorg. Med. Chem. Lett.* **6**, 33–38 (1996)
43. R.W. Hartmann, M. Hector, S. Haidar, P.B. Ehmer, W. Reichert, J. Jose, *J. Med. Chem.* **43**, 4266–4277 (2000)
44. B.A. Mendelsohn, S. Lee, S. Kim, F. Teyssier, V.S. Aulakh, M.A. Ciufolini, *Org. Lett.* **11**, 1539–1542 (2009)
45. N.A. Owston, A.J. Parker, J.M.J. Williams, *Org. Lett.* **9**, 3599–3601 (2007)
46. T. Shono, Y. Matsumura, K. Tsubata, T. Kamada, K. Kishi, *J. Org. Chem.* **54**, 2249–2251 (1989)
47. S.H. Yang, S. Chang, *Org. Lett.* **3**, 4209–4211 (2001)
48. K. Yamaguchi, H. Fujiwara, Y. Ogasawara, M. Kotani, N. Mizuno, *Angew. Chem. Int. Ed.* **46**, 3922–3925 (2007)
49. N.A. Owston, A.J. Parker, J.M.J. Williams, *Org. Lett.* **9**, 3599–3601 (2007)
50. H. Fujiwara, Y. Ogasawara, K. Yamaguchi, N. Mizuno, *Angew. Chem. Int. Ed.* **46**, 5202–5205 (2007)
51. P. Saha, M.A. Ali, P. Ghosh, T. Punniyamurthy, *Org. Biomol. Chem.* **8**, 5692–5699 (2010)
52. M.M. Guru, M.A. Ali, T. Punniyamurthy, *J. Org. Chem.* **76**, 5295–5308 (2011)
53. S.K. Alla, R.K. Kumar, P. Sadhu, T. Punniyamurthy, *Org. Lett.* **15**, 1334–1337 (2013)
54. J. Yu, J. Xu, M. Lu, *Appl. Organometal. Chem.* **27**, 606–610 (2013)
55. J. Yu, Y. Xia, M. Lu, *Synth. Commun.* **44**, 3019–3026 (2014). doi:[10.1080/00397911.2014.914221](https://doi.org/10.1080/00397911.2014.914221)
56. J. Yu, M. Lu, *Synth. Commun.* **44**, 2520–2528 (2014). doi:[10.1080/00397911.2014.908310](https://doi.org/10.1080/00397911.2014.908310)