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Iron-catalyzed oxidative synthesis of *N*-heterocycles from primary alcohols†

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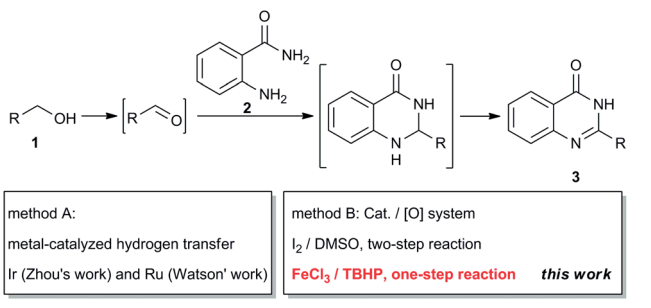
An iron-catalyzed one-pot one-step oxidative system has been successfully developed in the conversion of primary alcohols into nitrogen-containing heterocycles, such as quinazolinone, quinazoline and 3,4-dihydro-2*H*-1,2,4-benzothiadiazine 1,1-dioxide derivatives.

Quinazolinone as a building block occurs widely in natural products that exhibit a broad range of useful biological and pharmacological activities.[1] It is assigned as a privileged skeleton in drug discovery and many synthetic efforts have been made for its construction.[2] Transition metals have been extensively utilized in the syntheses of quinazolinones, for example ruthenium and platinum complexes were involved in their preparations *via* reductive *N*-heterocyclization.[3] Multicomponent reactions catalyzed by transition metals, such as gallium(III) triflate[4a] or cerium(IV) ammonium nitrate,[4b] were also described. Since 2000, Alper and co-authors have reported methods *via* tandem reactions, in which palladium-catalyzed cyclocarbonylation of 2-iodoanilines or their derivatives was the key step.[5] Later, Zhu group developed a palladium-catalyzed intramolecular C(sp^2)–H carboxamidation of *N*-arylamidines, providing a more efficient approach to quinazolinones.[6] Recently, copper or iron-catalyzed C–N couplings have made great achievements, and were applied in synthesis of quinazolinones using 2-halobenzoic acid derivatives and ammonia sources as starting materials.[7] However, stoichiometric amounts of bases were essential for the reactions, and in some cases ligands were also necessary.

As shown in Scheme 1, one of the typical synthetic methods is to utilize a condensation reaction between aldehyde and *o*-aminobenzamide **2** followed by oxidation of the aminal intermediate. For this oxidation, stoichiometric or large excess amounts of toxic oxidants, such as $KMnO_4$,[8a] MnO_2,[8b] DDQ,[8c] $CuCl_2$,[8d] were required. Some molecules that can be oxidized to aldehydes might be also used as starting materials. Very recently, Wu converted aromatic ketones into corresponding aldehydes *via* Kornblum oxidation, and used these to react with *o*-aminobenzamide for synthesis of quinazolinones.[9] Because many strategies have been devised for oxidation of alcohols to carbonyl compounds, obviously, alcohols could be substrates in this transformation. In 2011, Zhou described an oxidative cyclization of primary alcohols with *o*-aminobenzamides to quinazolinones catalyzed by iridium complex under hydrogen transfer conditions.[10a] Later, ruthenium-catalyzed hydrogen transfer was also applied (Scheme 1, method A).[10b] Thinking about high temperature and long reaction time in method A, an oxidation protocol, which involved inexpensive and less toxic catalysts with green oxidants was an alternative choice. Very recently, Wei group reported I_2-catalyzed two-step oxidative system for synthesis of quinazolinones using DMSO as a mild oxidant (Scheme 1, method B).[11] Due to the importance of quinazolinone skeleton, development of simple and environmentally benign protocols using convenient catalysts is still highly desired. Considering iron complexes as inexpensive and nontoxic catalysts were used for the oxidation of alcohols to the corresponding carbonyl compounds in the presence of peroxide,[12] we hypothesize that, in an iron-catalyzed domino sequence as shown in Scheme 1, oxidation of alcohol **1** to aldehyde followed by condensation with *o*-aminobenzamide **2** might provide quinazolinone **3** *via* the oxidation of the generated aminal intermediate. This synthetic route is a one-pot one-step oxidative system, and has an additional advantage of operational convenience.



Scheme 1 Synthesis of quinazolinones from primary alcohols.

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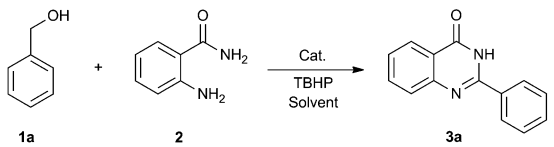
Results and discussion

To exam our hypothesis, we chose benzyl alcohol **1a** and *o*-aminobenzamide **2** as model substrates (Table 1). Initially, $FeCl_3$ (5 mol%) with TBHP (5.5 M in decane) was investigated for detecting availability of the catalytic system. Fortunately, the reaction gave the target product, 2-phenylquinazolin-4(3*H*)-one **3a** in DMSO (entry 1). Some abundant and cheap catalysts were also tested, while, the data indicated that $FeCl_3$ was the most effective one, giving the product in a moderate yield at 60 °C for 12 h (entries 1–4). Among all the solvents screened, such as DMSO, toluene, DMF, 1,4-dioxane, acetonitrile and water, DMSO was the best one (entries 1, 5–9). It should be noted that although several loadings of $FeCl_3$ were tested, 2 mol% gave a better result (entry 10), probably due to significant unknown byproduct formation with a relatively high catalyst loading. After screening the effect of reaction temperature and time (entries 11–18), the appropriate yield was achieved with the reaction conditions of **1a** and **2** at 60 °C for 7 h. Increasing or decreasing the amount of TBHP did not improve the yield significantly (entries 19 and 20). In addition, when T-HYDRO was used as an oxidant, a lower yield was obtained (entry 21). After examining the reaction profiles, we decided the conditions of entry 16 as the optimal one for our next investigations of the substrate scope.

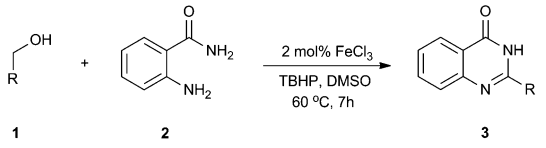
Table 1 Optimization of reaction conditions[a]



Entry	Cat. (mol%)	Solvent	Temp. (°C)	Time (h)	Yield[b] (%)
1	$FeCl_3$ (5)	DMSO	60	12	51∼
2	$CuCl_2$ (5)	DMSO	60	12	24
3	$ZnCl_2$ (5)	DMSO	60	12	26
4	$NiCl_2$ (5)	DMSO	60	12	42
5	$FeCl_3$ (5)	Toluene	60	12	40
6	$FeCl_3$ (5)	DMF	60	12	Trace
7	$FeCl_3$ (5)	1,4-Dioxane	60	12	Trace
8	$FeCl_3$ (5)	CH_3CN	60	12	46
9	$FeCl_3$ (5)	H_2O	60	12	44
10	$FeCl_3$ (2)	DMSO	60	12	93
11	$FeCl_3$ (2)	DMSO	70	12	86
12	$FeCl_3$ (2)	DMSO	50	12	90
13	$FeCl_3$ (2)	DMSO	80	12	84
14	$FeCl_3$ (2)	DMSO	40	12	86
15	$FeCl_3$ (2)	DMSO	60	10	92
16	$FeCl_3$ (2)	DMSO	60	7	93
17	$FeCl_3$ (2)	DMSO	60	5	85
18	$FeCl_3$ (2)	DMSO	60	3	75
19[c]	$FeCl_3$ (2)	DMSO	60	7	91
20[d]	$FeCl_3$ (2)	DMSO	60	7	81
21[e]	$FeCl_3$ (2)	DMSO	60	7	73

[a] *Reaction conditions*: **1a** (1.5 mmol), **2** (0.5 mmol), solvent (2 mL), 5.5 M TBHP in decane (1.5 mmol), sealed tube, under an air atmosphere. [b] Isolated yield. [c] TBHP (2 mmol). [d] TBHP (1 mmol). [e] T-HYDRO = 70% TBHP in water (1.5 mmol).

Table 2 Synthesis of quinazolin-4(3*H*)-ones catalyzed by $FeCl_3$[a]



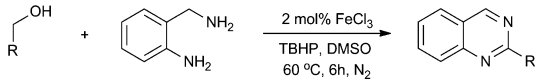
Entry	R	Product	Yield[b] (%)
1	Ph	**3a**	93
2	2-Me-C_6H_4	**3b**	57
3	4-Me-C_6H_4	**3c**	66
4	4-MeO-C_6H_4	**3d**	37
5	4-F-C_6H_4	**3e**	40
6	4-Cl-C_6H_4	**3f**	45
7	2-Br-C_6H_4	**3g**	84
8	2-I-C_6H_4	**3h**	67
9	2-furyl	**3i**	76
10	Me	**3j**	42
11	Heptyl	**3k**	60
12	1-Naphthyl	**3l**	Nd[c]

[a] *Reaction conditions*: **1** (1.5 mmol), **2** (0.5 mmol), $FeCl_3$ (2 mol%), 5.5 M TBHP in decane (1.5 mmol), DMSO (2 mL), sealed tube, under an air atmosphere, at 60 °C for 7 h. [b] Isolated yield. [c] Not detected.

With the optimized conditions in hand, various primary alcohols were investigated (Table 2). For different substituted benzyl alcohols with electron donating and withdrawing groups gave moderate to good yields. Notably, C–X (F, Cl, Br and I) bond remained intact during the reaction (entries 5–8), which provided an additional handle for further elaboration of products. Heteroaryl substrate like 2-furylmethanol was examined and the corresponding product **3i** was obtained in 76% yield (entry 9). In order to demonstrate the broad synthetic utility of this system, we investigated more challenging alkyl primary alcohols such as ethanol and octanol, fortunately, the desired products were also afforded with moderate yields (entries 10 and 11). However, 1-naphthalenemethanol produced an inseparable mixture of products (entry 12).

The success of above results encouraged us to further extend the substrate scope beyond *o*-aminobenzamide. Because of the structural similarity, we explored the possibility of using *o*-aminobenzylamine as starting material for synthesis of quinazolines which exhibit important biological properties.[13] Substituted quinazolines have been synthesized by a variety of methods,[14] one strategy is through the oxidative condensation of *o*-aminobenzylamine with aldehydes mediated by strong oxidants such as DDQ,[15a] MnO_2 (ref. 15*b*) and NaClO.[15c] Later, Cu/N-ligand/TEMPO[16a] and bi-metallic alloyed nanoclusters/dimeric catechol catalytic systems[16b] were developed as more environmentally benign methods. Very recently, an Ir-catalyzed hydrogen transfer reaction was also applied in the synthesis of substituted quinazolines starting from *o*-aminobenzylamine and aldehydes.[17] Encouraged by above results, we tested the employment of primary alcohols instead of aldehydes, the current synthetic strategy still worked well and the results were listed in Table 3. As benzyl alcohols (entries 1–7), heteroaryl

Table 3 Synthesis of quinazolines catalyzed by $FeCl_3$[a]



1 4 5

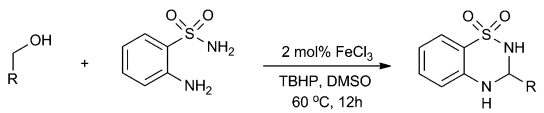
Entry	R	Product	Yield[b] (%)
1	Ph	**5a**	70
2	2-Me-C_6H_4	**5b**	60
3	4-Me-C_6H_4	**5c**	71
4	4-MeO-C_6H_4	**5d**	71
5	4-F-C_6H_4	**5e**	55
6	4-Cl-C_6H_4	**5f**	62
7	1-Naphthyl	**5g**	65
8	3-Pyridyl	**5h**	35
9	2-Furyl	**5i**	44
10	Me	**5j**	53

[a] *Reaction conditions*: **1** (1.5 mmol), **4** (0.5 mmol), $FeCl_3$ (2 mol%), 5.5 M TBHP in decane (1.5 mmol), DMSO (2 mL), sealed tube, under N_2 atmosphere, at 60 °C for 6 h. [b] Isolated yield.

primary alcohols (entries 8 and 9) and alkyl primary alcohol (entry 10) were employed, the corresponding products were obtained in moderate yields.

Having successfully achieved the synthesis of quinazolinones and quinazolines, we tried to expand the current catalytic system to the synthesis of 3,4-dihydro-2*H*-1,2,4-benzothiadiazine 1,1-dioxide derivatives. Benzothiadiazine derivatives, such as cyclothiazide and 7-chloro-3-methyl-3,4-dihydro-2*H*-1,2,4-benzothiadiazine 1,1-dioxide (IDRA-21) were the modulators of AMPA receptor desensitization.[18] Very recently, a Pd-catalyzed synthetic route was developed for the preparation of benzothiadiazine derivatives by using *o*-aminobenzene-sulfonamide and primary alcohols as starting materials.[19] Generally, these compounds were prepared from *o*-amino-benzenesulfonamide by condensation with aldehydes or ethyl hemiacetals in acidic medium.[20] As shown in Table 4, using the present system, the final products, cyclic aminals (**7**) without C=N bond formation were obtained. The result indicated the second oxidation didn't occur in current conditions. Both aryl and alkyl primary alcohols were tolerated in this transformation, and aryl primary alcohols were more reactive.

Table 4 Synthesis of 3,4-dihydro-2*H*-1,2,4-benzothiadiazine 1,1-dioxides catalyzed by $FeCl_3$[a]



1 6 7

Entry	R	Product	Yield[b] (%)
1	Ph	**7a**	75
2	2-Me-C_6H_4	**7b**	57
3	4-Me-C_6H_4	**7c**	83
4	4-MeO-C_6H_4	**7d**	58
5	4-F-C_6H_4	**7e**	39
6	4-Cl-C_6H_4	**7f**	47
7	2-Br-C_6H_4	**7g**	51
8	2-I-C_6H_4	**7h**	52
9	1-Naphthyl	**7i**	44
10	Me	**7j**	24
11	Heptyl	**7k**	29

[a] *Reaction conditions*: **1** (1.5 mmol), **6** (0.5 mmol), $FeCl_3$ (2 mol%), 5.5 M TBHP in decane (1.5 mmol), DMSO (2 mL), sealed tube, under an air atmosphere, at 60 °C for 12 h. [b] Isolated yield.

Conclusions

In summary, we have successfully developed an iron-catalyzed one-pot one-step oxidative system for the synthesis of *N*-heterocycles from the cyclization of primary alcohols **1** with *o*-aminobenzamide **2**, *o*-aminobenzylamine **4** or *o*-amino-benzenesulfonamide **6** using similar conditions. Furthermore, this environmentally friendly protocol displays good functional group compatibility and both aromatic and alkyl primary alcohols were reactive. The present results provided an economic and feasible way to prepare bioavailable skeletons, such as quinazolinones, quinazolines and benzothiadiazine derivatives.

Acknowledgements

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Notes and references

1 (*a*) S. B. Mhaske and N. P. Argade, *Tetrahedron*, 2006, **62**, 9787–9826 and references therein; (*b*) A. Witt and J. Bergman, *Curr. Org. Chem.*, 2003, **7**, 659–677 and references therein.

2 For selected examples, see: (*a*) D. A. Horton, G. T. Bourne and M. L. Smythe, *Chem. Rev.*, 2003, **103**, 893–930; (*b*) D. J. Connolly, D. Cusack, T. P. O'Sullivan and P. J. Guiry, *Tetrahedron*, 2005, **61**, 10153–10202; (*c*) A. Kamal, K. S. Reddy, B. R. Prasad, A. H. Babu and A. V. Ramana, *Tetrahedron Lett.*, 2004, **45**, 6517–6521; (*d*) J. F. Liu, P. Ye, B. L. Zhang, G. Bi, K. Sargent, L. B. Yu, D. Yohannes and C. M. Baldino, *J. Org. Chem.*, 2005, **70**, 6339–6345; (*e*) J. F. Liu, P. Ye, K. Sprague, K. Sargent, D. Yohannes, C. M. Baldino, C. J. Wilson and S. C. Ng, *Org. Lett.*, 2005, **7**, 3363–3366; (*f*) A. H. Romero, J. Salazar and S. E. Lopez, *Synthesis*, 2013, **45**, 2043–2050; (*g*) H. Hikawa, Y. Ino, H. Suzuki and Y. Yokoyama, *J. Org. Chem.*, 2012, **77**, 7046–7051; (*h*) H. Wang, X. Cao, F. Xiao, S. Liu and G.-J. Deng, *Org. Lett.*, 2013, **15**, 4900–4903.

3 M. Akazome, T. Kondo and Y. Watanabe, *J. Org. Chem.*, 1993, **58**, 310–312.

4 (*a*) J. Chen, D. Wu, F. He, M. Liu, H. Wu, J. Ding and W. Su, *Tetrahedron Lett.*, 2008, **49**, 3814–3818; (*b*) D. Rocchi, J. Francisco Gonzalez and J. Carlos Menendez, *Green Chem.*, 2013, **15**, 511–517.

5 (*a*) C. Larksarp and H. Alper, *J. Org. Chem.*, 2000, **65**, 2773–2777; (*b*) Z. Zheng and H. Alper, *Org. Lett.*, 2008, **10**, 829–832; (*c*) F. Zeng and H. Alper, *Org. Lett.*, 2010, **12**, 1188–1191; (*d*) F. Zeng and H. Alper, *Org. Lett.*, 2010, **12**, 3642–3644.

6 B. Ma, Y. Wang, J. Peng and Q. Zhu, *J. Org. Chem.*, 2011, **76**, 6362–6366.

7 (*a*) H. Xu and H. Fu, *Chem. – Eur. J.*, 2012, **18**, 1180–1186; (*b*) X. Liu, H. Fu, Y. Jiang and Y. Zhao, *Angew. Chem., Int. Ed.*, 2009, **48**, 348–351; (*c*) J. Zhou, L. Fu, M. Lv, J. Liu, D. Pei and K. Ding, *Synthesis*, 2008, 3974–3980; (*d*) D. K. Sreenivas, N. Ramkumar and R. Nagarajan, *Org. Biomol. Chem.*, 2012, **10**, 3417–3423; (*e*) W. Xu, Y. Jin, H. Liu, Y. Jiang and H. Fu, *Org. Lett.*, 2011, **13**, 1274–1277; (*f*) W. Xu and H. Fu, *J. Org. Chem.*, 2011, **76**, 3846–3852; (*g*) X. Zhang, D. Ye, H. Sun, D. Guo, J. Wang, H. Huang, X. Zhang, H. Jiang and H. Liu, *Green Chem.*, 2009, **11**, 1881–1888; (*h*) X. Huang, H. Yang, H. Fu, R. Qiao and Y. Zhao, *Synthesis*, 2009, 2679–2688.

8 (*a*) T. Hisano, M. Ichikawa, A. Nakagawa and M. Tsuji, *Chem. Pharm. Bull.*, 1975, **23**, 1910–1916; (*b*) C. Balakumar, P. Lamba, D. P. Kishore, B. L. Narayana, K. V. Rao, K. Rajwinder, A. R. Rao, B. Shireesha and B. Narsaiah, *Eur. J. Med. Chem.*, 2010, **45**, 4904–4913; (*c*) Y. Mitobe, S. Ito, T. Mizutani, T. Nagase, N. Sato and S. Tokita, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 4075–4078; (*d*) R. J. Abdel-Jalil, W. Voelter and M. Saeed, *Tetrahedron Lett.*, 2004, **45**, 3475–3476.

9 Y.-P. Zhu, Z. Fei, M.-C. Liu, F.-C. Jia and A.-X. Wu, *Org. Lett.*, 2013, **15**, 378–381.

10 (*a*) J. Zhou and J. Fang, *J. Org. Chem.*, 2011, **76**, 7730–7736; (*b*) A. J. A. Watson, A. C. Maxwell and J. M. J. Williams, *Org. Biomol. Chem.*, 2012, **10**, 240–243.

11 W. Ge, X. Zhu and Y. Wei, *RSC Adv.*, 2013, **3**, 10817–10822.

12 For selected examples, see: (*a*) S. E. Martin and A. Garrone, *Tetrahedron Lett.*, 2003, **44**, 549–552; (*b*) A. Al-Hunaiti, T. Niemi, A. Sibaouih, P. Pihko, M. Leskela and T. Repo, *Chem. Commun.*, 2010, **46**, 9250–9252; (*c*) F. Shi, M. K. Tse, M.-M. Pohl, A. Brueckner, S. Zhang and M. Beller, *Angew. Chem., Int. Ed.*, 2007, **46**, 8866–8868; (*d*) F. Shi, M. K. Tse, Z. Li and M. Beller, *Chem. – Eur. J.*, 2008, **14**, 8793–8797; (*e*) B. Join, K. Moeller, C. annenberg, K. Ziebart, K. Schroeder, D. Goerdes, K. Thurow, A. SpJunge and M. Beller, *Adv. Synth. Catal.*, 2011, **353**, 3023–3030; (*f*) N. Panda and A. K. Jena, *J. Org. Chem.*, 2012, **77**, 9401–9406.

13 (*a*) H. A. Burris, *Oncologist*, 2004, **9**, 10–15; (*b*) B. A. Foster, H. A. Coffey, M. J. Morin and F. Rastinejad, *Science*, 1999, **286**, 2507–2510; (*c*) C. Girard, S. Liu, F. Cadepond, D. Adams, C. Lacroix, M. Verleye, J. M. Gillardin, E. E. Baulieu, M. Schumacher and G. Schweizer-Groyer, *Proc. Natl. Acad. Sci. U. S. A.*, 2008, **105**, 20505–20510; (*d*) S. J. Hays, B. W. Caprathe, J. L. Gilmore, N. Amin, M. R. Emmerling, W. Michael, R. Nadimpalli, R. Nath, K. J. Raser, D. Stafford, D. Watson, K. Wang and J. C. Jaen, *J. Med. Chem.*, 1998, **41**, 1060–1067; (*e*) A. Luth and W. Lowe, *Eur. J. Med. Chem.*, 2008, **43**, 1478–1488; (*f*) R. Gundla, R. Kazemi, R. Sanam, R. Muttineni, J. Sarma, R. Dayam and N. Neamati, *J. Med. Chem.*, 2008, **51**, 3367–3377; (*g*) J. F. M. da Silva, M. Walters, S. Al-Damluji and C. R. Ganellin, *Bioorg. Med. Chem.*, 2008, **16**, 7254–7263; (*h*) L. A. Doyle and D. D. Ross, *Oncogene*, 2003, **22**, 7340–7358.

14 For recent examples, see: (*a*) X. Su, C. Chen, Y. Wang, J. Chen, Z. Lou and M. Li, *Chem. Commun.*, 2013, **49**, 6752–6754; (*b*) J. Zhang, C. Yu, S. Wang, C. Wan and Z. Wang, *Chem. Commun.*, 2010, **46**, 5244–5246; (*c*) B. Han, C. Wang, R.-F. Han, W. Yu, X.-Y. Duan, R. Fang and X.-L. Yang, *Chem. Commun.*, 2011, **47**, 7818–7820; (*d*) S. K. Panja, N. Dwivedi and S. Saha, *Tetrahedron Lett.*, 2012, **53**, 6167–6172; (*e*) Y. Yan, Y. Zhang, C. Feng, Z. Zha and Z. Wang, *Angew. Chem., Int. Ed.*, 2012, **51**, 8077–8081; (*f*) R. Sarma and D. Prajapati, *Green Chem.*, 2011, **13**, 718–722; (*g*) Y. Yan and Z. Wang, *Chem. Commun.*, 2011, **47**, 9513–9515; (*h*) C. Huang, Y. Fu, H. Fu, Y. Jiang and Y. Zhao, *Chem. Commun.*, 2008, 6333–6335; (*i*) Y. Lv, Y. Li, T. Xiong, W. Pu, H. Zhang, K. Sun, Q. Liu and Q. Zhang, *Chem. Commun.*, 2013, **49**, 6439–6441; (*j*) Z.-H. Zhang, X.-N. Zhang, L.-P. Mo, Y.-X. Li and F.-P. Ma, *Green Chem.*, 2012, **14**, 1502–1506; (*k*) M. A. McGowan, C. Z. McAvoy and S. L. Buchwald, *Org. Lett.*, 2012, **14**, 3800–3803; (*l*) P. Sang, Y. Xie, J. Zou and Y. Zhang, *Org. Lett.*, 2012, **14**, 3894–3897; (*m*) Y. Wang, H. Wang, J. Peng and Q. Zhu, *Org. Lett.*, 2011, **13**, 4604–4607; (*n*) J. Zhang, D. Zhu, C. Yu, C. Wan and Z. Wang, *Org. Lett.*, 2010, **12**, 2841–2843.

15 (*a*) J. J. Vandeneynde, J. Godin, A. Mayence, A. Maquestiau and E. Anders, *Synthesis*, 1993, 867–869; (*b*) Y. Y. Peng, Y. Y. Zeng, G. Y. S. Qiu, L. S. Cai and V. W. Pike, *J. Heterocycl. Chem.*, 2010, **47**, 1240–1245; (*c*) C. U. Maheswari, G. S. Kumar, M. Venkateshwar, R. A. Kumar, M. L. Kantam and K. R. Reddy, *Adv. Synth. Catal.*, 2010, **352**, 341–346.

16 (*a*) B. Han, X. L. Yang, C. Wang, Y. W. Bai, T. C. Pan, X. Chen and W. Yu, *J. Org. Chem.*, 2012, **77**, 1136–1142; (*b*) H. Yuan, W.-J. Yoo, H. Miyamura and S. Kobayashi, *Adv. Synth. Catal.*, 2012, **354**, 2899–2904.

17 J. Fang, J. Zhou and Z. Fang, *RSC Adv.*, 2013, **3**, 334–336.

18 (*a*) F. Impagnatiello, A. Oberto, P. Longone, E. Costa and A. Guidotti, *Proc. Natl. Acad. Sci. U. S. A.*, 1997, **94**, 7053–7058; (*b*) D. M. Thompson, A. Guidotti, M. Dibella and E. Costa, *Proc. Natl. Acad. Sci. U. S. A.*, 1995, **92**, 7667–7671; (*c*) N. Nagarajan, C. Quast, A. R. Boxall, M. Shahid and C. Rosenmund, *Neuropharmacology*, 2001, **41**, 650–663; (*d*) I. Zivkovic, D. M. Thompson, M. Bertolino, D. Uzunov, M. Dibella, E. Costa and A. Guidotti, *J. Pharmacol. Exp. Ther.*, 1995, **272**, 300–309.

19 H. Hikawa, N. Matsuda, H. Suzuki, Y. Yokoyama and I. Azumaya, *Adv. Synth. Catal.*, 2013, **355**, 2308–2320.

20 (*a*) P. de Tullio, S. Boverie, B. Becker, M. H. Antoine, Q. A. Nguyen, P. Francotte, S. Counerotte, S. Sebille, B. Pirotte and P. Lebrun, *J. Med. Chem.*, 2005, **48**, 4990–5000; (*b*) S. Boverie, M. H. Antoine, F. Somers, B. Becker, S. Sebille, R. Ouedraogo, S. Counerotte, B. Pirotte, P. Lebrun and P. de Tullio, *J. Med. Chem.*, 2005, **48**, 3492–3503; (*c*) D. Braghiroli, G. Puia, G. Cannazza, A. Tait, C. Parenti, G. Losi and M. Baraldi, *J. Med. Chem.*, 2002, **45**, 2355–2357; (*d*) J. M. Loynes, H. F. Ridley and R. G. Spickett, *J. Med. Chem.*, 1965, **8**, 691–694.