Heterocycle Synthesis

DOI: 10.1002/anie.201402779

Base-Controlled Selectivity in the Synthesis of Linear and Angular Fused Quinazolinones by a Palladium-Catalyzed Carbonylation/ Nucleophilic Aromatic Substitution Sequence**

Jianbin Chen, Kishore Natte, Anke Spannenberg, Helfried Neumann, Peter Langer, Matthias Beller, and Xiao-Feng Wu**

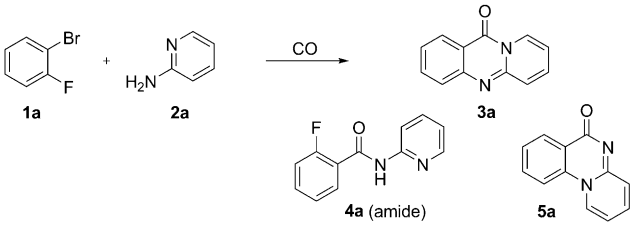
Abstract: *A new approach for the facile synthesis of fused quinazolinone scaffolds through a palladium-catalyzed carbonylative coupling followed by an intramolecular nucleophilic aromatic substitution is described. The base serves as the key modulator: Whereas DBU gives rise to the linear isomers, Et_3N promotes the preferential formation of angular products. Interestingly, a light-induced 4+4 reaction of the product was also observed.*

The presence of N heterocycles as an essential structural motif in a variety of biologically active substances has stimulated the development of new strategies and technologies for their synthesis.[1] Among the various N-heterocyclic scaffolds, quinazolinones form a privileged class of compounds. Indeed, quinazolinone derivatives possess a wide spectrum of biological and pharmacological activities, such as anti-inflammatory, antioxidant, antimicrobial, antipsychotic, and antihypertensive activity, strong analgesic activity, and many effects on the central nervous system (CNS).[2] More specifically, pyridoquinazolones exhibit strong tuberculostatic activity. Since both the linear[3] and angular[4] fused isomers have unique pharmacological and/or biological activity, synthetic methodologies which can provide these two isomers in a convenient and efficient manner are highly desired.

Although many attractive procedures have been developed for rapid access to quinazolinones,[2a,b,3,5] the related synthesis of pyridoquinazolones is still very limited. So far, known procedures require a high temperature (210 °C), multistep synthesis, or specific *ortho*-halogen-substituted benzoyl derivatives as the substrates.[6] Naturally, only the linear or the angular products can be produced.

The development of novel and improved palladium-catalyzed carbonylation reactions is an important topic in organic synthesis,[7] and many efforts have been made to apply these reactions in the synthesis of biologically active com-

Table 1: Model synthesis of pyridoquinazolones: Optimization of the reaction parameters.[a]



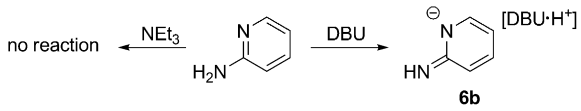
Entry	CO [bar]	Ligand	Base (equiv)	Solvent	Yield [%][b] **3a/4a/5a**
1	10	$BuPAd_2$	K_2CO_3 (2.0)	DMF	0/0/0
2	10	$BuPAd_2$	$K_3PO_4{\cdot}H_2O$ (2.0)	DMF	23/0/0
3	10	$BuPAd_2$	$K_3PO_4{\cdot}H_2O$ (2.0)	NMP	22/0/0
4	10	$BuPAd_2$	$K_3PO_4{\cdot}H_2O$ (2.0)	dioxane	1/(20)/0
5	10	$BuPAd_2$	$K_3PO_4{\cdot}H_2O$ (2.0)	toluene	1/(22)/0
6	10	$BuPAd_2$	DIPEA (2.0)	DMF	31/0/0
7	10	$BuPAd_2$	DBN (2.0)	DMF	50/0/1
8	10	$BuPAd_2$	DABCO (2.0)	DMF	30/0/4
9	10	$BuPAd_2$	DBU (2.0)	DMF	43/0/0
10	10	$BuPAd_2$	DBU (3.0)	DMF	55/0/13
11	10	$BuPAd_2$	DBU (3.0)	DMSO	54/0/7
12	10	$BuPAd_2$	DBU (3.0)	DMA	83(74)/0/6
13	10	Ph_3P	DBU (3.0)	DMA	0/0/0
14	10	DPEphos	DBU (3.0)	DMA	2/0/9
15	10	xantphos	DBU (3.0)	DMA	7/0/33
16	10	dppp	DBU (3.0)	DMA	58/0/10
17	15	$BuPAd_2$	DBU (3.0)	DMA	68/0/0
18[c]	15	$BuPAd_2$	DBU (3.0)	DMA	70/0/7
19[d]	**15**	**$BuPAd_2$**	**DBU (3.0)**	**DMA**	**90(80)/0/0**
20[d]	1	$BuPAd_2$	DBU (3.0)	DMA	70/0/9
21[e]	**15**	**$BuPAd_2$**	**Et_3N (3.0)**	**DMA**	**3/0/(60)**
22[e]	15	xantphos	Et_3N (3.0)	DMA	2/0/(56)

[a] Reaction conditions: **1a** (1 mmol), **2a** (1.0 equiv), $Pd(OAc)_2$ (2 mol%), ligand (6 mol%), solvent (2 mL), base (indicated amount), CO (indicated pressure), 120 °C, 16 h. [b] Yields were determined by GC with hexadecane as an internal standard; yields in parentheses are for the isolated product. [c] The reaction was carried out with **2a** (1.2 equiv). [d] The reaction was carried out with **2a** (1.5 equiv). [e] Reaction conditions: **1a** (0.5 mmol), **2a** (1.1 equiv), DMA (5 mL), 32 h. Ad = adamantyl, DABCO = 1,4-diazabicyclo[2.2.2]octane, DIPEA = *N*,*N*′-diisopropylethylamine, DMA = *N*,*N*-dimethylacetamide, DMF = *N*,*N*-dimethylformamide, DMSO = dimethyl sulfoxide, DPEphos = (oxybis(2,1-phenylene))bis(diphenylphosphane), dppf = 1,1′-bis(diphenylphosphanyl)ferrocene, dppp = 1,3-bis(diphenylphosphanyl)propane, NMP = 1-methyl-2-pyrrolidinone, xantphos = 4,5-bis(diphenylphosphanyl)-9,9-dimethylxanthene.

[*] J. Chen, Dr. K. Natte, Dr. A. Spannenberg, Dr. H. Neumann, Prof. Dr. P. Langer, Prof. Dr. M. Beller, Prof. Dr. X.-F. Wu
Leibniz-Institut für Katalyse an der Universität Rostock e.V.
Albert-Einstein-Strasse 29a, 18059 Rostock (Germany)
E-mail: matthias.beller@catalysis.de
xiao-feng.wu@catalysis.de

[**] We thank the State of Mecklenburg-Vorpommern, the Bundesministerium für Bildung und Forschung (BMBF), and the Deutsche Forschungsgemeinschaft for financial support. We also thank Dr. C. Fischer, S. Schareina, and Dr. W. Baumann for their excellent technical and analytical support. The useful discussion with Dr. Haijun Jiao is appreciated.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201402779.



Scheme 1. Formation of the postulated intermediate for the linear products with DBU.

pounds.[8] In general, these procedures provide efficient means to incorporate CO as a cheap C_1 source into valuable heterocyclic compounds. On the basis of our continuing research in this area, we report herein a novel approach that enables the synthesis of linear or angular fused pyridoquinazolones simply by changing the base.

At the start of our study, the model reaction of 2-aminopyridine and 2-bromofluorobenzene was conducted in the presence of $Pd(OAc)_2$ (2 mol%) and $BuPAd_2$ (6 mol%) under typical conditions known for palladium-catalyzed carbonylation reactions (CO: 10 bar, K_2CO_3: 2.0 equiv, DMF, 120°C). Unfortunately, none of the desired product was observed (Table 1, entry 1). However, when K_3PO_4 was used as the base, the target product **3a** was formed in 23% yield (as determined by GC; Table 1, entry 2). Unfortunately, variation of the solvent led to no significant improvement. As well as inorganic bases, some organic bases were added to the reaction mixture. To our delight, 1,5-diazabicyclo(4.3.0)non-5-ene (DBN) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) gave improved product yields of up to 55% (with 3.0 equivalents of DBU). Notably, the target molecule was formed in 83% yield (as determined by GC) and isolated in 74% yield when DMA was used as the solvent under these conditions (Table 1, entries 10–12). Other phosphorus ligands were tested, and it was found that dppf gave **3a** in moderate yield (Table 1, entries 13–16). A further improvement was observed when the reaction was performed at elevated pressure (15 bar of CO) with 1.5 equivalents of **2a** and $BuPAd_2$ as the ligand: Under these conditions, **3a** was formed in 90% yield (GC) and isolated in 80% yield; Table 1, entries 17–19). This procedure even produced **3a** in reasonable yield at a CO pressure of 1 bar (Table 1, entry 20). Surprisingly, when the base DBU was simply changed to NEt_3, the selectivity was completely reversed to give **5a** as the major product in 60% yield (Table 1, entry 21). In the presence of NEt_3, xantphos showed similar efficiency to that of $BuPAd_2$ (Table 1, entry 22). Several chelating ligands [dcype (**3a**/**5a** 73:27), dppe (**3a**/**5a** 70:30), dppm (**3a**/**5a** 68:32), dppp (**3a**/**5a** 85:15), binap (**3a**/**5a** 83:17)] were

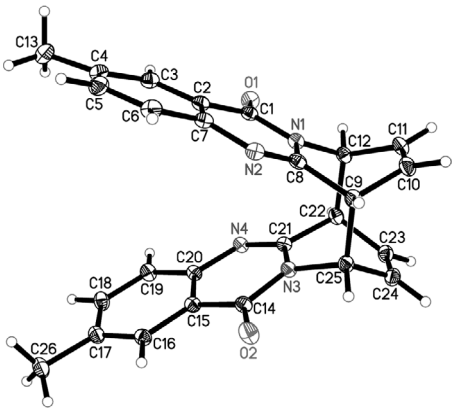
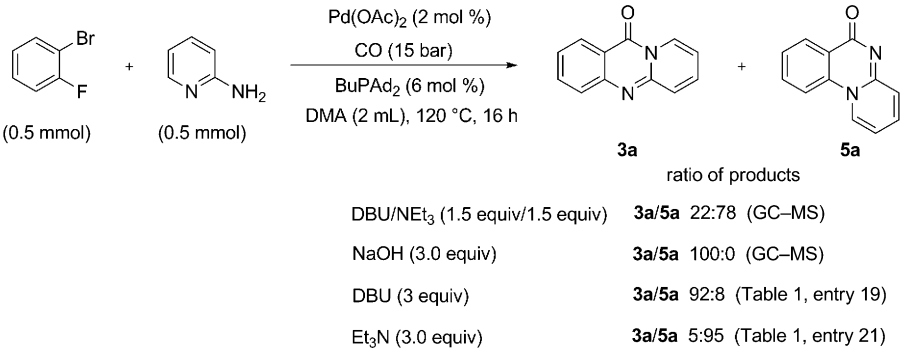
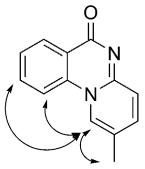


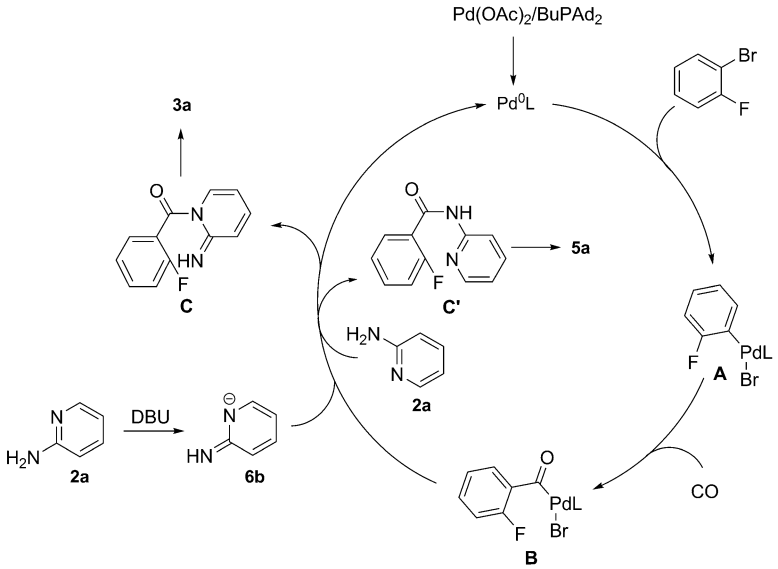
Figure 1. Molecular structure of a derivative of **3b** (cycloaddition dimer) formed during X-ray crystallography. Displacement ellipsoids correspond to 30% probability.



Scheme 2. Control experiments.



Scheme 3. Identification of the angular isomer **5e** by NOESY correlations.



Scheme 4. Proposed catalytic cycle.

tested in place of $BuPAd_2$, but no improvement was detected.

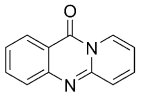
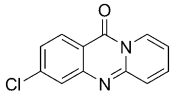
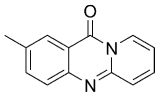
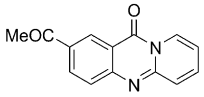
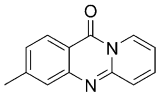
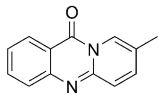
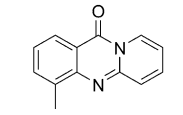
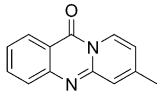
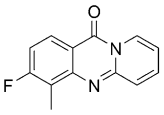
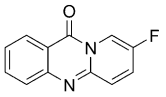
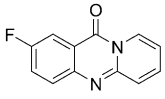
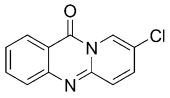
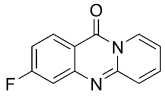
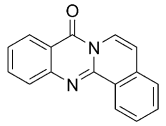
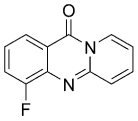
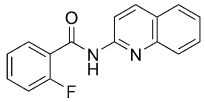
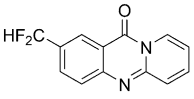
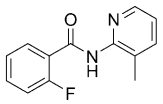
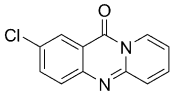
To gain some insight into this interesting selectivity switch, we conducted a set of control experiments. We suspected that the strength of the base may play a pivotal role in this process (the acidities of the conjugate acids are $pK_a = 12$ and 10.8 for DBU and NEt_3, respectively). Indeed, NMR spectroscopic experiments confirmed that DBU deprotonates 2-aminopyridine (**2a**) to a major extent to afford the 2-imino-2*H*-pyridin-1-ide, which was not observed in the presence of NEt_3 (Scheme 1). This selectivity switch was also seen in the presence of other strong bases, such as NaOH. Unfortunately, in this case **3a** was only obtained in low yield despite the excellent chemoselectivity. In the presence of DBU and NEt_3 (1:1), the procedure gave a mixture of the angular isomer **5a** and **3a** (Scheme 2).

The linear and angular isomers were fully characterized by NMR spectroscopy, and their structural assignment was confirmed by X-ray crystallography (Figure 1 and Scheme 3). The regiochemical outcome of the reactions was determined by comparison of the products with previously reported compounds (**3a**, **3j**, **3m**, **3n**, **5e**), by NOESY experiments (e.g. **5e**), and by X-ray crystallography on **3b**. Interestingly, during the X-ray crystallographic measurements, the isolated product underwent a further [4+4] cycloaddition reaction induced by light or the X-ray beam (Figure 1).[9]

We propose a catalytic cycle for the palladium-catalyzed carbonylation/intramolecular nucleophilic aromatic substitution reaction in Scheme 4. The formation of the active catalyst takes place by the reduction of Pd^{II} to Pd^0 with CO or amines. The oxidative addition of 1-bromo-2-fluorobenzene to Pd^0 then leads to the corresponding organopalladium species **A**. By the coordination and insertion of CO, the key intermediate acyl palladium complex **B** is formed. In the presence of DBU, 2-imino-2*H*-pyridin-1-ide (**6b**) undergoes nucleophilic attack on the acyl palladium complex with the elimination of **C**. On the other hand, in the presence of NEt_3 as the base, the nucleophilic reaction of 2-aminopyridine with the acyl palladium complex yields compound **C′**. Finally, intramolecular nucleophilic aromatic substitution of intermediate **C** or **C′** affords the terminal linear or angular product, respectively. The active Pd^0 catalyst is regenerated with the assistance of the base.

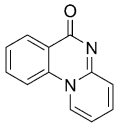
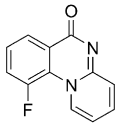
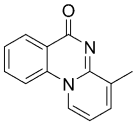
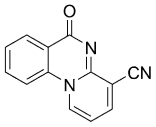
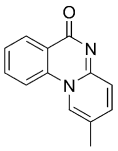
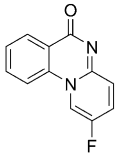
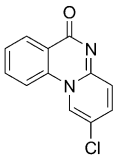
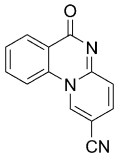
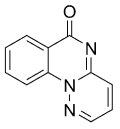
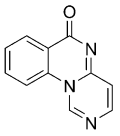
Next, we turned our attention to the scope and limitations of this methodology. The results are summarized in Table 2 for linear products and Table 3 for angular products. A variety of analogues of 1-bromo-2-fluorobenzene were tolerated in this procedure and delivered the corresponding products **3a**–**l** in moderate to good yields. Notably, 4- and 5-substituted substrates gave better yields than 3-substituted substrates (**3b**,**c** versus **3d**). This observation is in line with the results with electron-withdrawing fluoro substituents (**3f**,**g** versus **3h**). Interestingly, 2-bromo-4-(difluoromethyl)-1-fluorobenzene was successfully converted into the desired product **3i** in 60% yield. These results are of general importance owing to the current interest in fluoro-containing products.[10] Chloride substituents and acetyl groups remained intact under our conditions to provide valuable products in moderate to good yields (products **3j**–**l**). Subsequently, different kinds of 2-aminopyridines were investigated. Methyl- and fluoro-substituted products **3m**–**o** were isolated without any problem. However, halides attached to the pyridine ring also reacted.

Table 2: Synthesis of linear fused pyridoquinazolones: Scope of the reaction.[a]

Entry	Product	Entry	Product
1	 **3a** 80%	11	 **3k** 26%
2	 **3b** 78%	12	 **3l** 29%
3	 **3c** 75%	13	 **3m** 25%
4	 **3d** 39% (+25% amide)	14	 **3n** 69%
5[c]	 **3e** 64%	15	 **3o** 12% (+30% **3a**)
6	 **3f** 48%	16	 **3p** 0% (+65% **3a**)
7	 **3g** 51%	17	 **3q**, trace
8	 **3h** 37%	18	 **4r**, 17%
9	 **3i** 60%	19	 **4s**, 63%
10	 **3g** 80%		

[a] Reaction conditions: **1** (1 mmol), **2** (1.5 equiv), $Pd(OAc)_2$ (2 mol%), $BuPAd_2$ (6 mol%), DMA (2 mL), DBU (3.0 equiv), CO (15 bar), 120°C, 16 h. [b] Yield of the isolated product. [c] The reaction was carried out with **1** (0.32 mmol) and $Pd(OAc)_2$ (10 mol%). [d] Compound **3a** was also recovered in 30% yield. [e] Compound **3a** was recovered in 65% yield. [f] A trace amount of the product was detected by GC–MS.

Table 3: Synthesis of angular fused pyridoquinazolones: Scope of the reaction.[a]

Entry	Product		Yield [%][b]
1		**5a**	60 (32 h)
2[c]		**5b**	71 (19 h)
3		**5c**	72 (32 h)
4		**5d**	64 (32 h)
5		**5e**	67 (32 h)
6		**5f**	40 (19 h)[d]
7		**5g**	41 (19 h)[e]
8[f]		**5h**	56 (32 h)
9[g]		**5i**	78 (20 h)
10[h]		**5j**	63 (28 h)

[a] Reaction conditions: **1** (0.5 mmol), **2** (1.1 equiv), $Pd(OAc)_2$ (2 mol%), $BuPAd_2$ (6 mol%), DMA (5 mL), Et_3N (3.0 equiv), CO (15 bar), 120°C. [b] Yield of the isolated product; the yield of all other isomers was less than 5%. [c] The reaction was carried out with **1** (1 mmol). [d] Conversion: 78%. The corresponding amide was also obtained in 22% yield. [e] Conversion: 70%. The corresponding amide was also obtained in 12% yield. [f] The reaction was carried out with the ligand xantphos (6 mol%). Conversion: 85%. [g] Reaction conditions: **1** (0.2 mmol), $Pd(OAc)_2$ (5 mol%), $BuPAd_2$ (25 mol%), DMA (2 mL). [h] Reaction conditions: **1** (0.2 mmol), $Pd(OAc)_2$ (5 mol%), $BuPAd_2$ (10 mol%), DMA (2 mL).

Hence, the dehalogenated products corresponding to **3o** and **3p** were isolated, and **3q** was detected by GC–MS. Unfortunately, in the case of more sterically hindered substrates, only the corresponding amides were isolated (products **4r**,**s**).

In the case of the angular products (Table 3), steric and electronic modification of the substrates did not influence the outcome of the reactions. *Ortho*-methyl- and cyano-substituted 2-aminopyridines delivered the corresponding products **5c** and **5d** in 72 and 64% yield. A methyl group at the *para* position as a representative example of an electron-donating group was tolerated well (product **5e**). Substrates with electron-deficient *p*-cyano, *p*-fluoro, and *p*-chloro substituents were also converted into the corresponding angular isomers **5f–h** in moderate yields. The uncyclized amides corresponding to **5f**,**g** were also isolated. Notably, besides aminopyridines, even aminopyrimidine and aminopyridazine could be applied as substrates under our conditions and gave the desired products in good yields (products **5i**,**j**).

In summary, an efficient novel palladium-catalyzed carbonylation/intramolecular nucleophilic aromatic substitution reaction to give pyridoquinazolones has been developed. The selective formation of both linear and angular fused isomers in moderate to good yields could simply be controlled by the choice of base (NEt_3 or DBU). Whereas in the presence of DBU the linear products were obtained, NEt_3 gave the angular derivatives. This novel methodology is complementary to previously reported synthetic procedures and enables straightforward access to this biologically interesting class of compounds.

Received: February 25, 2014
Revised: April 22, 2014
Published online: May 30, 2014

Keywords: carbonylation · domino reactions · nucleophilic aromatic substitution · palladium catalysts · quinazolinones

[1] a) L. F. Tietze, G. Brasche, K. Gericke, *Domino Reactions in Organic Synthesis*, Wiley-VCH, Weinheim, **2006**; b) L. F. Tietze, *Chem. Rev.* **1996**, *96*, 115–136; c) L. F. Tietze, A. Modi, *Med. Res. Rev.* **2000**, *20*, 304–322; d) D. M. D'Souza, T. J. J. Müller, *Chem. Soc. Rev.* **2007**, *36*, 1095–1108; e) B. Willy, T. J. J. Müller, *Curr. Org. Chem.* **2009**, *13*, 1777–1790; f) A. V. Rotaru, I. D. Druta, T. Oeser, T. J. J. Müller, *Helv. Chim. Acta* **2005**, *88*, 1798–1812; g) J. E. Rixson, T. Chaloner, C. H. Heath, L. F. Tietze, S. G. Stewart, *Eur. J. Org. Chem.* **2012**, 544–558; h) D. L. Priebbenow, S. G. Stewart, F. M. Pfeffer, *Tetrahedron Lett.* **2012**, *53*, 1468–1471; i) D. L. Priebbenow, S. G. Stewart, F. M. Pfeffer, *Org. Biomol. Chem.* **2011**, *9*, 1508–1515; j) E. Merkul, T. Oeser, T. J. J. Müller, *Chem. Eur. J.* **2009**, *15*, 5006–5011.

[2] a) K. Nepali, S. Sharma, R. Ojha, K. L. Dhar, *Med. Chem. Res.* **2013**, *22*, 1–15; b) A. Chawla, C. Batra, *Int. Res. J. Pharm.* **2013**, *4*, 49–58; c) D. Arora, H. Kumar, D. Malhotra, M. Malhotra, *Pharmacologyonline* **2011**, *3*, 659–668; d) N. Malecki, P. Carato, B. Rigo, J.-F. Goossens, R. Houssin, C. Bailly, J.-P. Hénichart, *Bioorg. Med. Chem.* **2004**, *12*, 641–647; e) N. J. Liverton, D. J. Armstrong, D. A. Claremon, D. C. Remy, J. J. Baldwin, R. J. Lynch, G. Zhang, R. J. Gould, *Bioorg. Med. Chem. Lett.* **1998**, *8*, 483–486; f) S. E. de Laszlo, C. S. Quagliato, W. J. Greenlee, A. A. Patchett, R. S. L. Chang, V. J. Lotti, T. B. Chen, S. A.

Scheck, K. A. Faust, S. S. Kivlighn, T. S. Schorn, G. J. Zingaro, P. K. S. Siegl, *J. Med. Chem.* **1993**, *36*, 3207 – 3210; g) J. Bartroli, E. Turmo, M. Algueró, E. Boncompte, M. L. Vericat, L. Conte, J. Ramis, M. Merlos, J. García-Rafanell, J. Forn, *J. Med. Chem.* **1998**, *41*, 1869 – 1882; h) M. A. Khalil, R. Soliman, A. M. Farghaly, A. A. Bekhit, *Arch. Pharm.* **1994**, *327*, 27 – 30.

[3] C. F. Schwender, B. R. Sunday, D. J. Herzig, *J. Med. Chem.* **1979**, *22*, 114 – 116.

[4] a) É. V. Nosova, G. N. Liponova, M. A. Kravchenko, A. A. Laeva, V. N. Charushin, *Pharm. Chem. J.* **2008**, *42*, 169 – 174; b) J. R. Sheu, W. C. Hung, C. H. Wu, Y. M. Lee, M. H. Yen, *Br. J. Haematol.* **2000**, *110*, 110 – 115; c) S.-N. Wu, Y.-K. Lo, H. Chen, H.-F. Li, H.-T. Chiang, *Neuropharmacology* **2001**, *41*, 834 – 843.

[5] a) J. D. Hepworth, C. D. Gabbut, B. M. Heron, *Comprehensive Heterocyclic Chemistry*, 2nd ed., Pergamon, Oxford, **1996**; b) L. He, H. Li, J. Chen, X. F. Wu, *RSC Adv.* **2014**, *4*, 12065 – 12077; c) D. J. Connolly, D. Cusack, T. P. O'Sullivan, P. J. Guiry, *Tetrahedron* **2005**, *61*, 10153 – 10202; d) W. Zhang, J. P. Mayer, S. E. Hall, J. A. Weigel, *J. Comb. Chem.* **2001**, *3*, 255 – 256; e) A. Gopalsamy, H. Yang, *J. Comb. Chem.* **2000**, *2*, 378 – 381.

[6] a) B. A. Granger, K. Kaneda, S. F. Martin, *Org. Lett.* **2011**, *13*, 4542 – 4545; b) E. V. Nosova, A. A. Laeva, T. V. Trashakhova, A. V. Golovchenko, G. N. Lipunova, P. A. Slepukhin, V. N. Charushin, *Russ. J. Org. Chem.* **2009**, *45*, 904 – 912; c) S. H. Lee, J.-K. Son, B. S. Jeong, T.-C. Jeong, H. W. Chang, E.-S. Lee, Y. Jahng, *Molecules* **2008**, *13*, 272 – 300; d) É. V. Nosova, G. N. Lipunova, V. N. Charushin, *Russ. Chem. Bull. Int. Ed.* **2004**, *53*, 1137 – 1152; e) G. Timári, G. Hajós, A. Messmer, *J. Heterocycl. Chem.* **1990**, *27*, 2005 – 2009; f) H. Xu, H. Fu, *Chem. Eur. J.* **2012**, *18*, 1180 – 1186; g) A. Maity, S. Mondal, R. Paira, A. Hazra, S. Naskar, K. B. Sahu, P. Saha, S. Banerjee, N. B. Mondal, *Tetrahedron Lett.* **2011**, *52*, 3033 – 3037; h) R. F. Pellón, A. Martín, M. L. Docampo, M. Mesa, *Synth. Commun.* **2006**, *36*, 1715 – 1719; i) R. Pellón, M. L. Docampo, Z. Kunakbaeva, V. Gomez, H. Velez-Castro, *Synth. Commun.* **2006**, *36*, 481 – 485; j) M. J. Fray, J. P. Mathias, C. L. Nichols, Y. M. Po-Ba, H. Snow, *Tetrahedron Lett.* **2006**, *47*, 6365 – 6368; k) M. J. Deetz, J. P. Malerich, A. M. Beatty, B. D. Smith, *Tetrahedron Lett.* **2001**, *42*, 1851 – 1854; l) J. Sun, Q. Tan, W. Yang, B. Liu, B. Xu, *Adv. Synth. Catal.* **2014**, *356*, 388 – 394; m) L. Chen, H. Fu, R. Qiao, *Synlett* **2011**, 1930 – 1936.

[7] a) X. F. Wu, H. Neumann, M. Beller, *ChemSusChem* **2013**, *6*, 229 – 241; b) X. F. Wu, H. Neumann, M. Beller, *Chem. Soc. Rev.* **2011**, *40*, 4986 – 5009; c) Q. Liu, H. Zhang, A. Lei, *Angew. Chem.* **2011**, *123*, 10978 – 10989; *Angew. Chem. Int. Ed.* **2011**, *50*, 10788 – 10799; d) A. Brennführer, H. Neumann, M. Beller, *Angew. Chem.* **2009**, *121*, 4176 – 4196; *Angew. Chem. Int. Ed.* **2009**, *48*, 4114 – 4133; e) C. F. J. Barnard, *Organometallics* **2008**, *27*, 5402 – 5422.

[8] a) X. F. Wu, H. Neumann, M. Beller, *Chem. Rev.* **2013**, *113*, 1 – 35; b) D. M. D'Souza, T. J. J. Müller, *Chem. Soc. Rev.* **2007**, *36*, 1095 – 1108.

[9] S. Arumugam, V. V. Popik, *J. Am. Chem. Soc.* **2011**, *133*, 5573 – 5579.

[10] X. F. Wu, H. Neumann, M. Beller, *Chem. Asian J.* **2012**, *7*, 1744 – 1754.

