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Cu-catalyzed C(sp^2)–N-bond coupling of boronic acids and cyclic imides†

Linn Neerbye Berntsen, Thomas Nordbø Solvi, Kristian Sørnes, David S. Wragg and Alexander H. Sandtorv *

A general Cu-catalyzed strategy for coupling cyclic imides and alkenylboronic acids by forming C(sp^2)–N-bonds is reported. The method enables the practical and mild preparation of (*E*)-enimides. A large range of cyclic imides are allowed, and di- and tri-substituted alkenylboronic acids can be used. Full retention was observed in the configuration of the alkene double bond in the coupled products. The method is also applicable for preparing *N*-arylimides, using arylboronic acids as coupling partners. The usefulness of this strategy is exemplified by the convenient derivatization of the chemotherapy medication 5-flurouracil, the nucleoside uridine and the anti-epileptic drug phenytoin.

Enimides (Fig. 1) are functional groups found in *N*-sulfonylurea isosteres,[1] biologically active structures,[2,3] functional materials,[4] and natural products such as the parazoanthines A–E.[5] They are also building blocks in synthesis of complex structures,[6] polycyclic architecture,[7] and β-2-amino acid derivatives.[8]

The growing interest in the enimide moiety has catalyzed a recent spurt of attention for methodology appropriate for its construction (Fig. 2).[9] In reactions where the enimidic C(sp^2)–N-bond is formed, only a few strategies are known. The main access point is the Ru-catalyzed hydroimidation strategy, wherein imides and alkynes are condensed (Fig. 2, strategy 1).[10] Drawbacks include the use of an expensive Ru-catalysts, and the structural limitations imposed. A second approach involves the Cu-mediated coupling of imides and vinylic halides (Fig. 2, strategy 2).[11] This strategy is only applicable to phthalimide, and therefore specialized. Other examples are substrate specific.[12,13]

The Chan–Lam[14] inspired Cu-catalyzed process using alkenylic boron coupling partners, is an attractive route to enimides for several reasons: (i) the availability of alkenylboronic reagents[15] provide synthetic flexibility, (ii) the use of an inexpensive Cu-catalyst is attractive, and (iii) a potentially larger structural diversity of enimides is conceivable, compared to Ru-methods currently used. Thus far, only highly substrate dependent examples are known,[16] but a general method has not been reported before now.

Our endeavors were initiated as shown in Table 1. Due to our ongoing interest[17] in the pharmaceutically relevant hydantoin framework,[18] hydantoin **1a** was used as a model substrate, with styrylboronic acid **2a** as reagent. The optimal conditions (entry #1) involved the use of excess reagent **2a** (3.0 equiv.) with copper(II)triflate and pyridine in ethanol at 25 °C. Less expensive Cu-salts may also be effective (#2 and 3). The process was also effective using 2.0 equiv. of the reagent (entry #4), so less reagent can be employed if a slight reduction in yield is acceptable. Our investigations uncovered that the process was inefficient in aprotic solvents such as DMF and toluene (entries #6 and 7), and that the use of base/ligand was of paramount importance. Surprisingly, triethylamine (entry #8) performed poorly compared to pyridine. Strong, non-nucleophilic bases (entries #9 and 11) were also ineffective. The complete optimization study can be found in the ESI.†

We next investigated the scope and limitations of the method, Scheme 1. Complete retention of the configuration

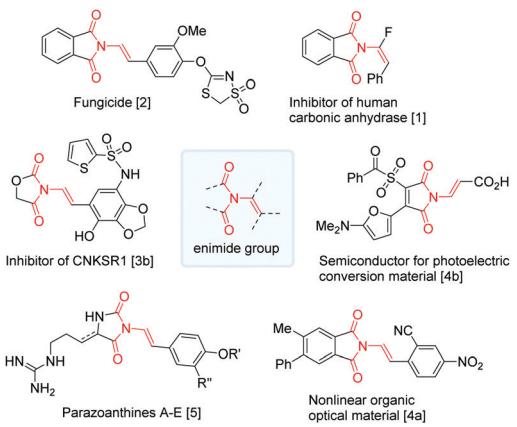

Fig. 1 Some examples of cyclic enimides.

Department of Chemistry, University of Oslo, Oslo N-0315, Norway.
E-mail: a.h.sandtorv@kjemi.uio.no

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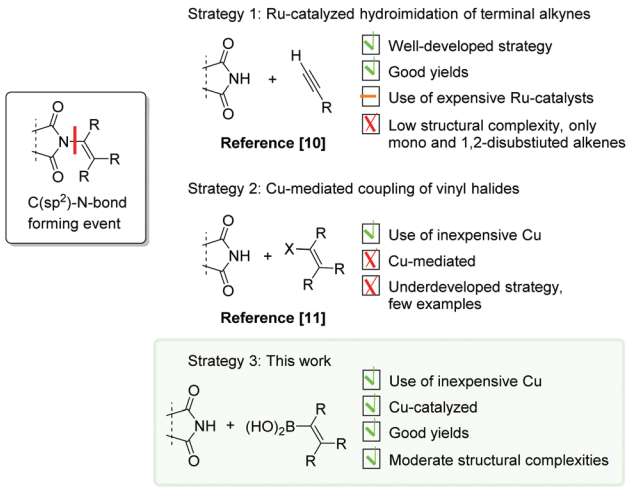
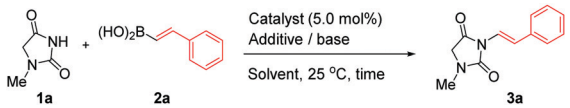


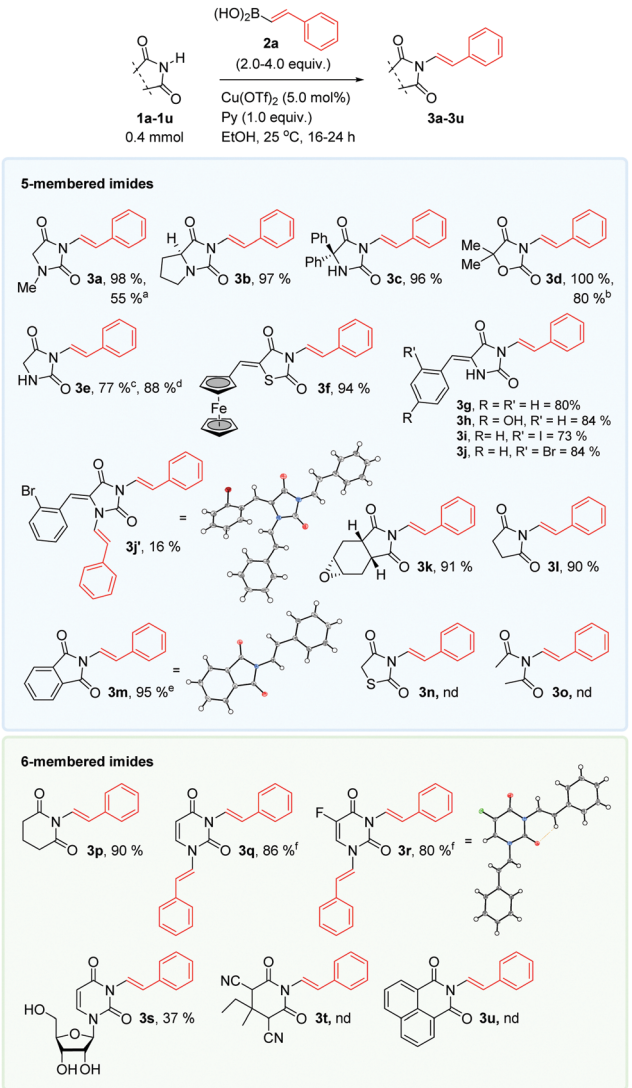
Fig. 2 Prior developments in the area of C(sp^2)–N-bond formation.

Table 1 Reaction optimization



#	Catalyst	2a (equiv.)	Additive/base (equiv.)	Solvent	Time (h)	Yield[a] (%)
1	$Cu(OTf)_2$	3.0	Py (1.0)	EtOH	9/15	98/97[b]
2	$Cu(NO_3)_2$[c]	3.0	Py (1.0)	EtOH	24	96
3	CuCl	3.0	Py (1.0)	EtOH	24	95
4	$Cu(OTf)_2$	2.0	Py (1.0)	EtOH	24	94
5[d]	$Cu(OTf)_2$	1.0	Py (1.0)	EtOH	24	71
6	$Cu(OTf)_2$	3.0	Py (1.0)	DMF	24	26
7	$Cu(OTf)_2$	3.0	Py (1.0)	PhMe	24	0
8	$Cu(OTf)_2$	3.0	Et_3N (1.0)	EtOH	24	8
9	$Cu(OTf)_2$	3.0	*t*-BuOK (1.0)	EtOH	18	22
10	—	3.0	*t*-BuOK (2.0)	EtOH	24	0
11	$Cu(OTf)_2$	3.0	LiHMDS (1.0)	EtOH	18	3

Conditions: *N*-Methylhydantoin **1a** (0.20 mmol, 1.0 equiv.), boronic acid **2a** (as specified), catalyst (0.010 mmol, 0.050 equiv.), additive/base (as specified) in solvent (as specified, 1 mL). [a] ^{1}H NMR yield using mesitylene as internal standard. [b] Isolated yield. [c] The (hemi)pentahydrate salt was used. [d] Reaction performed at 40 °C.

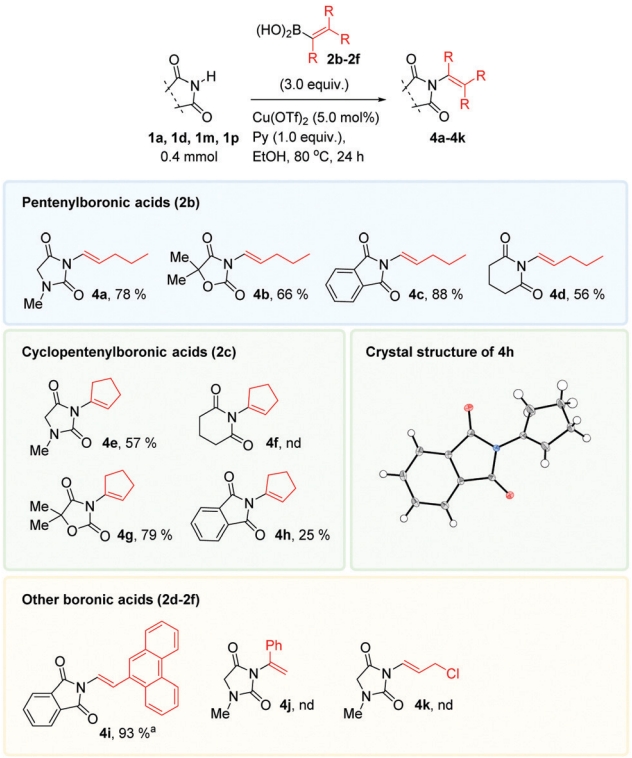


Scheme 1 Imide scope of the reaction. Conditions: imide **1a–1u** (0.40 mmol, 1.0 equiv.), boronic acid **2a** (1.2 mmol, 3.0 equiv.), $Cu(OTf)_2$ (0.020 mmol, 0.050 equiv.), pyridine (0.40 mmol, 1.0 equiv.) and EtOH (2 mL). [a] (*E*)-Styryl-9-BBN was used as coupling partner. [b] CuCl (5.0 mol%) was used as catalyst. [c] 2.0 equiv. boronic acid **2a** was used. [d] Reaction performed at 1.5 mmol scale. [e] Reaction performed at 0.40 and 1.0 mmol scale. [f] 4.0 equiv. boronic acid **2a** was used.

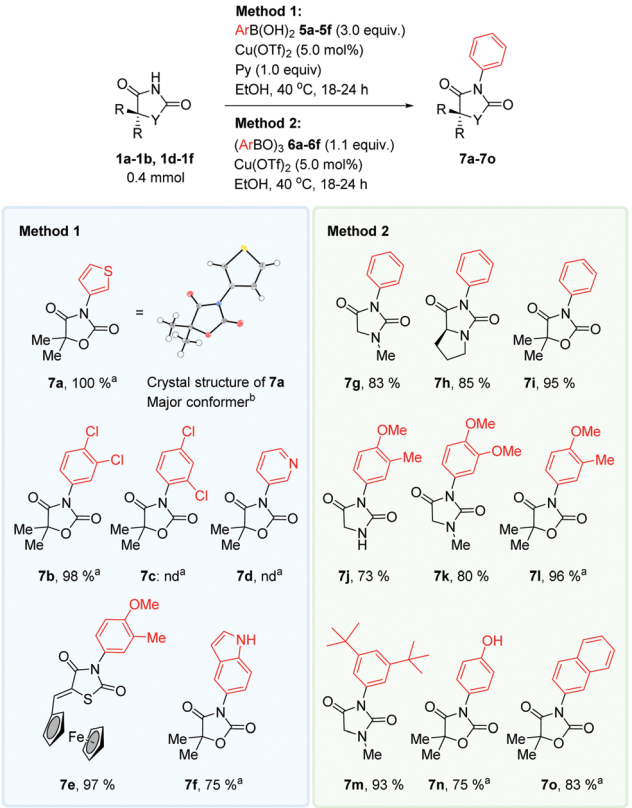
of the alkene double bond was observed in all cases. The anti-epileptic drug phenytoin **1c** was conveniently derivatized in excellent yield. Hydantoin **1e** was also smoothly alkenylated. The aldol adduct **1h** was smoothly *N*-3-alkenylated and not *O*-alkenylated, in excellent yield. We typically observed *N*-1, *N*-3-bisalkenylated hydantoins as byproducts in these reactions, such as the disubstituted hydantoin **3j′**. Phtalimide **3m** and glutarimide **3p** were obtained in excellent yields. Uracils are privileged structures in drug discovery.[19] Uracil **1q**, the chemotherapy medication 5-fluorouracil **1r** and the nucleoside uridine **1s** were bis-alkenylated to **3q**, **3r** and **3s**, respectively. These results show that the method can conjugate drugs and nucleosides and provide uracils cumbersome to access.[20] Lastly, 2,4-thiazolidinedione **1n** was unreactive, but the ferrocenyl derivative **3f** was obtained in excellent yield.

The method is applicable to cyclic imides, and not linear imides, as imide **1o** failed to react under our conditions. As suggested by Wasielewski *et al.*[21] the carbonyl groups can adopt a parallel, coplanar conformation[22] and may chelate to Cu(II)-ions. The chelation is likely detrimental for the coupling reaction.

A selection of alkenylboronic acids **2b–2f** were next investigated with some imides, Scheme 2. The performance of the coupling reaction varied. The 1-pentenyl reagent **2b** transferred in good to moderate yields, depending on the imide substrate. The cyclopentenyl coupling partner **2c** was challenging, likely imposing a high steric demand in relevant Cu-species in the catalytic cycle. The coupled product **4g** was obtained in good yield, but the six membered product **4f** was not detected.



Scheme 2 Alkenylboronic acid scope. Conditions: imide **1a**, **1d**, **1m** or **1p** (0.40 mmol, 1.0 equiv.), boronic acid **2b–2f** (1.2 mmol, 3.0 equiv.), $Cu(OTf)_2$ (0.020 mmol, 0.050 equiv.), pyridine (0.40 mmol, 1.0 equiv.) and EtOH (2 mL). [a] Reaction performed at 0.18 mmol scale at 25 °C.



Scheme 3 Scope of *N*-arylation. Method 1: hydantoin **1a**, **b** or **1d–1f** (0.40 mmol, 1.0 equiv.), boronic acid **5a–5f** (1.2 mmol, 3.0 equiv.), $Cu(OTf)_2$ (0.020 mmol, 0.050 equiv.), pyridine (0.020 mmol, 1.0 equiv.) in EtOH (2 mL). Method 2: hydantoin **1a**, **b** or **1d–1f** (0.40 mmol, 1.0 equiv.), boroxine **6a–6f** (0.44 mmol, 1.1 equiv.), $Cu(OTf)_2$ (0.020 mmol, 0.050 equiv.). [a] Reaction performed on 0.14 mmol scale. [b] Only the major conformer of the thiophene-ring is shown.

The 1,1,2-trisubstituted alkenes obtained, are not currently accessible employing the Ru-catalyzed methods mentioned in the introduction.

Our earlier work[17] spurred an interest in employing arylboronic acids for *N*-arylation. Although the Cu-catalyzed or -mediated arylation of imides has been documented earlier,[23] the use of such conditions is sparingly described[24] using the pharmaceutically relevant hydantoin, 2,4-oxazolidinedione and related frameworks as substrates.

The method was high yielding and tolerable to diverse aryl groups, Scheme 3. The reaction performance varied if the arylboronic acid (method 1), or the corresponding anhydride (triarylboroxine, method 2) was employed. It is not possible to draw a conclusion as to which method operates best with which substrate. The pyridine likely has several key functions, such as being a Cu-ligand, acting as a base, and stabilizing boroxines *in situ*.[25]

The method smoothly transferred electron-rich aryl groups to form products such as **7j**, **7k**, **7l**, **7m** and **7n** in mostly excellent yields. Electron-rich heterocyclic fragments were also efficiently coupled. The thiophenyl product **7a** was obtained in excellent yield, and the indolyl product **7f** was obtained in good yield. The pyridinyl product **7d** was not obtained. The electron-poor 3,4-dichlorophenyl group coupled to afford product **7b** in excellent yield, whereas the 2,4-dichlorophenyl group did not couple. We attribute this to the steric hinderance of the chlorine atom in the 2-position of the aryl group. Electronically neutral phenyl and naphthyl groups coupled in good yields.

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Conflicts of interest

There are no conflicts to declare.

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