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Iron-catalyzed direct α-arylation of ethers with azoles†

Arkaitz Correa,*[a] Béla Fiser[b] and Enrique Gómez-Bengoa[b]

The direct α-arylation of cyclic and acyclic ethers with azoles has been achieved, which features a novel iron-catalyzed cross-dehydrogenative coupling (CDC) process. This practical oxidative method allowed the efficient C2-alkylation of a variety of (benzo)azoles constituting straightforward access to heterocycles of utmost medicinal significance and highlighting the convenient use of feedstock substrates and iron catalysts. A preliminary mechanism supported by DFT calculations is discussed as well.

Since the end of the last century sustainable development has constituted a matter of genuine concern for our society and scientific community. As a result, "green chemistry" represents one of the key factors for scientists when designing new chemical processes.[1] In this respect, the use of ethers such as tetrahydrofuran (THF) and related derivatives as important raw chemicals for the construction of more complex molecules of pharmaceutical interest has recently received a great deal of attention.[2] Indeed, direct functionalization of molecules containing $C(sp^3)$–H bonds stands out today as one of the most challenging and relevant areas in modern organic chemistry offering numerous attractive advantages such as the reduction of the reliance on existing functional groups while improving atom economy and energy efficiency.[3] The last few years have witnessed a burgeoning of cross-dehydrogenative couplings (CDCs) involving the use of catalytic amounts of first-row transition metals.[4] Based on their low-price, ready availability, and environmentally friendly character, iron salts[5] constitute potentially ideal catalysts which offer attractive advantages in this particular area of expertise. Despite the impressive achievements, the assembly of new C–C linkages based upon iron-catalyzed $C(sp^3)$–H functionalization events are still rare in the literature.[6]

[a] *Department of Organic Chemistry I, University of the Basque Country (UPV/EHU), Joxe Mari Korta R&D Center, Avda. Tolosa 72, 20018 Donostia-San Sebastión, Spain. E-mail: arkaitz.correa@ehu.es*

[b] *Department of Organic Chemistry I, University of the Basque Country (UPV/EHU), P.O. Box 1072, 20080 Donostia-San Sebastián, Spain*

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Azoles are prevalent key motifs in a myriad of biologically active compounds, agrochemicals and organic functional materials such as liquid crystals and fluorescent dyes.[7] Accordingly, C–H functionalization of azoles is an active area of research which provides simple and rapid access to a plethora of valuable functionalized heterocyclic cores. Whereas arylation, alkenylation, alkynylation and amination processes of azole derivatives have been widely explored,[8] direct alkylation still represents a challenge.[9] N-Tosyl-hydrazones[10] and carboxylic acids[11] are among the most common coupling partners to perform C2-alkylation reactions of azoles. Nevertheless, the most straightforward and convenient approach involves the use of non-functionalized ethers *via* the addition of *in situ* generated α-oxyalkyl radical species to heteroarenes generally referred to as the Minisci reaction.[12] Such processes are of prime importance within medicinal chemistry and have been accomplished using both copper[13a] and photoredox iridium catalysts[13b] and even under metal-free conditions.[13c] While these are efficient and elegant procedures, they still suffer from certain limitations such as the restricted use of (benzo)thiazoles (route a), isoquinolines and pyridines (route c) or requiring harsh reaction conditions like using 4.0 equiv. of the oxidant at high temperatures (route b). In this context, we envisioned whether the use of iron salts would facilitate the development of a complementary and advantageous strategy for the C2-alkylation of azoles with a relatively broad scope and operational simplicity. In fact, iron complexes are known to react with alkyl peroxides to generate organic radical species which can further act as powerful oxidizing agents.[14] Herein we describe a novel CDC of (benzo)azoles and ethers featuring the efficient use of a combination of FeF_2 and organic peroxides as the oxidant (Scheme 1).
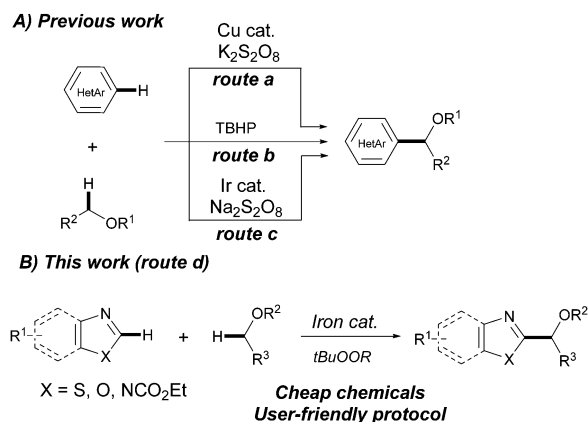
We initially selected the direct coupling of benzothiazole (**1a**) and tetrahydrofuran (THF, **2a**) as the model system to evaluate the feasibility of our approach. We anticipated that the nature of the metal source and the oxidant would have a profound impact on reactivity and accordingly the effect of such variables was systematically examined.[15] To our delight, the target CDC event took place in a remarkable 51% yield when utilizing a combination of FeF_2 and *tert*-butyl peroxybenzoate at 90 °C (Table 1, entry 6).

A) Previous work

B) This work (route d)

X = S, O, NCO₂Et

Cheap chemicals
User-friendly protocol

Scheme 1 Direct α-arylation of cyclic and acyclic ethers with azoles.

Further screening of the oxidants clearly revealed that TBHP was the best choice while other common oxidants were much less effective (Table 1, entries 1–8). It is worth noting that the process was found to be compatible with the use of an aqueous solution of TBHP, albeit the product was obtained in a comparatively low yield (entry 8). Importantly, the catalytic activity was highly dependent on the counteranion and the use of other fluoride salts seemed to have a crucial effect on the reaction outcome. FeF₃ was found to be as efficient as FeF₂ (entry 12), but other iron sources (entries 9–11) as well as other fluoride metal salts (entries 13 and 14) provided lower yields.[15] Remarkably, the yield was dramatically improved upon reducing the amount of THF and adding 1,2-dichloroethane as the co-solvent. Under those conditions the amount of oxidant

Table 1 Optimization of reaction conditions for the iron-catalyzed CDC of **1a** with THF[a,b]

Entry	Metal salt	Oxidant	**3a**[b] (%)
1	FeF₂	K₂S₂O₈	0
2	FeF₂	DDQ	0
3	FeF₂	Cumene hydroperoxide	0
4	FeF₂	Dicumyl peroxide	0
5	FeF₂	*t*BuOO*t*Bu	Traces
6	FeF₂	*t*BuOOBz	51
7	FeF₂	TBHP	62
8	FeF₂	TBHP aq	41
9	FeCl₂	TBHP	Traces
10	Fe(OAc)₂	TBHP	43
11	Fe(acac)₃	TBHP	38
12	FeF₃	TBHP	61
13	CoF₂	TBHP	47
14	CuF₂	TBHP	29
15	None	TBHP	9
16	FeF₂	None	0
17	*FeF₂*	*TBHP*	*80[c,d] (62)*
18	FeF₂	TBHP	60[c,e]

[a] Reaction conditions: **1a** (0.5 mmol), **2a** (1.0 mL), metal salt (10 mol%), oxidant (2.0 equiv.) at 90 °C for 24 h under argon. [b] Yield of the isolated product after column chromatography. [c] TBHP (1.0 equiv.) using **2a** (0.5 mL) in 1,2-dichloroethane (0.5 mL). [d] Under air. [e] at 80 °C. TBHP = *tert*-butyl hydroperoxide (5.0–6.0 M in decane); TBHP aq = 70 wt% *t*BuOOH in H₂O.

could be significantly reduced to 1.0 equivalent and **3a** was obtained in 80% yield (entry 17). The performance of the process under an air atmosphere was detrimental to the reaction, although **3a** was obtained in 62% yield. The addition of other additives or variation of the temperature were found to be ineffective in improving the catalyst performance.[15–16] Additionally, several control experiments evidenced that both the iron catalyst and the peroxide were critical for success (Table 1, entries 15 and 16).

Having identified the optimal reaction conditions, we next focused on examining the preparative scope and generality of our iron-catalyzed direct arylation event. As shown for **3a–f**, moderate to good yields were obtained when differently substituted benzothiazoles were utilized. It is noteworthy that electron-deficient derivatives provided lower yields since full conversion was not achieved. Importantly, several functional groups were accommodated such as esters (**3c**), amides (**3d**), halides (**3b** and **3e**), and ethers (**3f**). Strikingly, the strongly coordinating nitrogen motif in **3d** did not interfere with the coupling, which reveals a low Lewis acidity, if any, of our catalyst system. Of particular importance is the compatibility with the presence of halides, which provides additional functionalization opportunities *via* cross-coupling techniques. Notably, the method was found applicable for the preparation of non-benzofused thiazoles (**3g–h**) and benzimidazoles (**3i**), albeit the products were obtained in moderate yields. When benzoxazole derivatives were subjected to the optimized conditions, the desired products were not detected. Gratifyingly, minor modifications on the reaction conditions such as replacing the use of TBHP by *tert*-butyl peroxybenzoate allowed for the efficient coupling of several benzoxazoles (**3j–l**).[17] In these cases, the less basic benzoate species are generated by homolytic cleavage of the oxidant and hence the corresponding coupling product can be satisfactorily obtained,[18] a significant improvement compared to the parent Cu-catalyzed process (Table 2).[13a]

Aside from THF, other related cyclic and acyclic ethers are commonly used as solvents in chemical processes and are prevalent key structures in a wide range of valuable compounds.

Table 2 Iron-catalyzed CDC of azoles **1a–l** with THF[a,b]

80% (R = H, **3a**)
54% (R = Br, **3b**)

63%[c] (R = CO₂*t*Bu, **3c**)
78%[c] (R = NHBz, **3d**)
51%[c] (R = F, **3e**)
65%[c] (R = OMe, **3f**)

53%[c] (**3g**)

55% (**3h**)

51% (**3i**)

72%[d] (R = H, **3j**)
65%[d] (R = Me, **3k**)
60%[d] (R = Cl, **3l**)

[a] Reaction conditions: **1** (0.5 mmol), FeF₂ (10 mol%), TBHP (1.0 equiv., 5.0–6.0 M in decane) in a mixture **2a**:DCE (1:1, 1.0 mL) at 90 °C for 24 h under argon. [b] Yield of the isolated product after column chromatography, average of at least two independent runs. [c] TBHP (2.0 equiv.) using **2a** (1.0 mL). [d] *t*BuOOBz (2.0 equiv.) using **2a** (1.0 mL).

Table 3 Iron-catalyzed CDC of azoles with other ethers[a,b]

82% (9:1)[c] (R = H, **3m**)
72% (R = NHBz, **3n**)
64% (R = CO₂ᵗBu **3o**)
76% (9:1)[c,d] (R = F, **3p**)

72% (85:15)[c,e] (R = H, **3q**)
63% (85:15)[c,e] (R = Me, **3r**)
62% (6:4)[c,e] (R = Cl, **3s**)

77%[e] (**3t**)

59%[d] (R = H, **3u**)
51%[d] (R = OMe, **3v**)

74% (7:3)[e] (Ar = benzothiazole, **3w:3w'**)
63% (8:2)[e] (Ar = 6-fluorobenzothiazole, **3x:3x'**)

[a] Reaction conditions: **1** (0.5 mmol), FeF₂ (10 mol%), TBHP (1.0 equiv., 5.0–6.0 M in decane) in a mixture **2a** : DCE (1 : 1, 1.0 mL) at 90 °C for 24 h under argon. [b] Yield of the isolated product after column chromatography, average of at least two independent runs. [c] Ratio of C2 *vs.* C4 isomer. [d] TBHP (2.0 equiv.) using **2** (1.0 mL). [e] ᵗBuOOBz (2.0 equiv.) using **2** (1.0 mL).

Of particular interest is 1,3-dioxolane given that its coupling would provide a masked formyl derivative through a practical and aldehyde-free synthetic protocol. Accordingly, we next explored the scope of our iron-catalyzed heteroarylation process regarding the ether coupling partner. As shown in Table 3, a wide variety of differently substituted benzothiazoles and benzoxazoles smoothly underwent the coupling with 1,3-dioxolane to afford the corresponding acetal derivatives in good yields (**3m–s**). Remarkably, 1,3-dioxolane reacted selectively at the C2 position *versus* the less reactive C4 atom providing **3n** and **3o** as single isomers. However, in most cases both isomers were detected with high regioselectivity (up to 9 : 1); whereas the products **3m** and **3p** bearing the benzothiazole core were easily separated by column chromatography, the benzoxazole derivatives **3q–s** were isolated as inseparable mixtures of both isomers (regioselectivity up to 85 : 15 determined by ¹H NMR spectroscopy). Interestingly, 1,4-dioxane could also be utilized to furnish the corresponding coupling products in moderate to good yields (**3t–v**). It is noteworthy that the acyclic ether 1,2-dimethoxyethane also underwent the target reaction at both methylene and methyl sites with good combined yields and high regioselectivities (up to 8 : 2; **3w** : **3w'** and **3x** : **3x'**). Unfortunately, other coupling partners such as dibutyl ether and ethanol or less acidic heterocycles such as 1,2,3-triazoles and indoles were found unreactive under our optimized conditions.

Although the detailed mechanistic picture clearly requires further studies, several control experiments as well as DFT studies[15,19] were performed to gain some insights into the reaction mechanism. The CDC event was entirely suppressed upon addition of radical scavengers such as BHT and 1,1-diphenylethylene; interestingly, in the latter case the coupling product **4** was isolated instead, in 10% yield.[20] Besides, the addition of TEMPO results in very low conversion of the azole and just traces of the product were detected. These experimental pieces of evidence tentatively support a radical pathway. Notably, subsequent competition experiments with benzoxazole **1j** utilizing an equimolecular
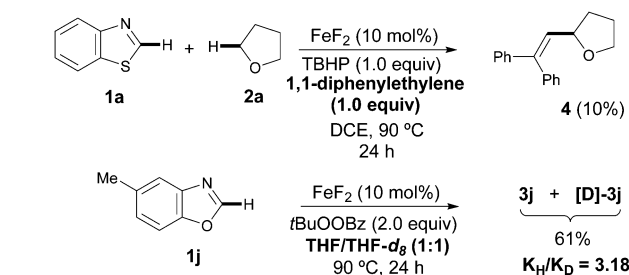
Scheme 2 Control experiments.

mixture of THF/THF-d_8 showed a significant kinetic isotopic effect (k_H/k_D = 3.18), thus suggesting that the C(sp³)–H bond cleavage with concomitant formation of an α-oxyalkyl radical is likely the rate-determining step (Scheme 2). In order to clarify the role of the iron catalyst, Sc(OTf)₃, Bi(OTf)₃ and AlCl₃ were used instead and the coupling product **3a** was obtained in much lower yields; hence it is unlikely that FeF₂ is acting as a simple Lewis acid.[15,21] Based on the above results, a plausible mechanism supported by DFT studies is outlined in Scheme 3. Initially, FeF₂ facilitates the homolytic cleavage of the starting oxidant to form the hydroxide and *tert*-butoxy radical species under heating conditions.[6b,22] Computational data confirm that the homolytic cleavage of ᵗBuOOH is a highly endergonic process, with an uphill Gibbs Free energy of 5.1 kcal mol⁻¹ and the Fe catalyst helps stabilize the arising radical species by the formation of a very stable Fe(III) complex, which lies *ca.* 80 kcal mol⁻¹ lower in energy than the starting reactants. Next, the C(sp³)–H adjacent to the oxygen atom of THF can be abstracted by *tert*-butoxy radical species to furnish **I**, with an activation energy of only 12.5 kcal mol⁻¹,[23] and further oxidized through a SET event to the corresponding oxonium cation **II** by FeF₂(OH), lying *ca.* 5 kcal mol⁻¹ lower in energy than the sum of the starting Fe(III) complex and radical species.[24] Finally, the hydroxide anion is basic enough to easily deprotonate the azole **1a**, with a low activation energy of only 2.6 kcal mol⁻¹, which eventually reacts with oxonium ion **II** through an extremely favorable process (ΔG_R = −82.1 Kcal mol⁻¹).[25] On balance then, we assume that FeF₂ plays a key redox role in assisting both the heterolytic cleavage of the oxidant and the oxidation of the carbon radical **I** to the oxonium ion **II**.

In summary, we have developed a novel catalytic approach to the direct α-heteroarylation of cyclic and acyclic ethers with azoles. This practical and environmentally friendly protocol highlights the advantageous use of iron salts and cheap feedstock substrates
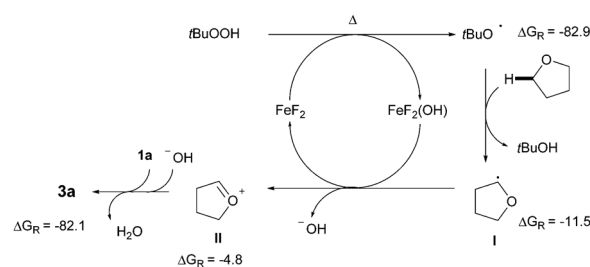
Scheme 3 Proposed mechanism.

while featuring a dual C–H bond oxidative cross-coupling. Furthermore, the method was found to be applicable to the assembly of a wide variety of functionalized heterocycles of paramount medicinal importance and represents an attractive, yet complementary, strategy for the C–H alkylation of azoles. We anticipate that our experimental and computational studies could lead to acquiring new knowledge in catalyst design, thus opening up new vistas in iron-catalyzed C–H functionalization events.

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16 All attempts to use iodide sources such as tetrabutylammonium iodide, sodium iodide or potassium iodide were unsuccessful. Besides, the addition of supporting ligands such as DMEDA, TMEDA or 1,10-phenanthroline was detrimental for the catalyst performance.
17 This distinct reactivity profile of benzothiazole *vs.* benzoxazole could be attributed to the higher acidity of the latter and its tendency to open up under basic conditions.
18 When using *t*BuOOBz as the oxidant, benzoic acid was obtained as a side-product, which was easily eliminated upon basic workup of the reaction crude prior to chromatographic purification.
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25 At this stage the intermediacy of a radical into an azole derivative and subsequent C–C bond formation through termination of such species and intermediate **I** cannot be entirely ruled out. However, it remains unlikely given the fact that the bis-heteroaryl compound resulting from the corresponding homocoupling was never detected.