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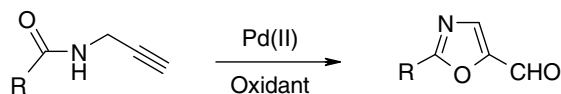
Intramolecular Pd(II)-Catalyzed Cyclization of Propargylamides: Straightforward Synthesis of 5-Oxazole-carbaldehydes

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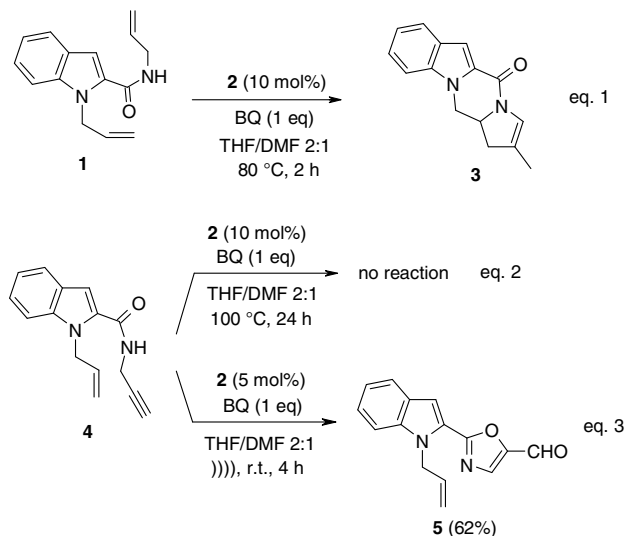


Direct synthesis of 2-substituted 5-oxazole-carbaldehydes was performed by intramolecular reaction of propargylamides through treatment with catalytic amount of Pd(II) salts in the presence of stoichiometric amount of reoxidant agent. The heterocyclization process was well tolerated by a wide range of aryl, heteroaryl and alkyl propargylamides. This protocol constitutes a valuable synthetic way to 5-oxazole-carbaldehydes, alternative to the formylation on oxazole rings, often unsatisfactory in term of regioselectivity and yields.

Intramolecular palladium-promoted cyclizations are become a milestone also in heterocyclic synthesis.¹ A widespread array of hetero(poly)cycles have been achieved by different methodologies using catalytic amount of palladium.² Among the most used reaction typologies, including the well-known Heck, Buchwald-Hartwig, and cross-coupling reactions, the Pd(II)-catalyzed oxidative reactions (*i.e.* Wacker-type reactions) play a prominent role due to the simplified requirements of the starting material.^{3,4}

Our previous contribution in this area was concerned with intramolecular cyclizations of alkenyl systems bearing a nucleophilic moiety under conditions which require Pd(II)-catalysis in the presence of stoichiometric amount of an oxidant agent.⁵ In particular, we recently found that *N*-allyl 1-allyl-2-indolecarboxamide **1** undergoes an intramolecular Pd(II)-catalyzed process to give the tetracyclic structure **3** when treated with PdCl₂(MeCN)₂ (**2**) and 1,4-benzoquinone (BQ) as reoxidant (Scheme 1, eq. 1).^{5e} This result prompted us to investigate the behavior of the related *N*-propargyl 1-allyl-2-indolecarboxamide **4** towards Pd(II)-complexes in order to

achieve reaction conditions suitable for a tandem reaction. When submitted to the conditions which successfully promoted the cyclization of **1**, compound **4** was recovered unchanged (Scheme 1, eq. 2), while it reacted only by exposition to ultrasound irradiations. However, the reaction provided a product in 62% yield, whose analytical and spectroscopic data accorded to the unexpected 5-oxazole-carbaldehyde structure **5**, arising from 5-*exo-dig* cyclization of the propargylamide moiety without involving the allylindole portion of the starting molecule (Scheme 1, eq. 3).



SCHEME 1. Pd(II)-catalyzed oxidative cyclization of 1-allyl-2-indolecarboxamides **1** and **4**.

From this preliminary result, we envisioned the possible development of a general method for producing 2-substituted oxazoles directly formylated in 5-position, by using propargylamides as starting material and working in the presence Pd(II)-catalysis with a reoxidant agent.

It is worthwhile to mention that the oxazole nucleus is present as key structural moiety in a wide number of natural and unnatural biologically active products,⁶ among which there are antitumor, antiviral, and antileukemia agents, as well as herpes simplex virus inhibitors, serine-threonine phosphatase inhibitors, antibacterials, antialgicids, and peripheral analgesics. Consequently, a new efficient synthesis of functionalized oxazoles may well be a valuable goal. Some protocols for the construction of the oxazole nucleus starting from propargylamides are already known in the literature⁷ and three of them are based on transition metal catalyzed cyclization (Figure 1).^{7g-i} The first represents an effective access to 2,5-disubstituted oxazoles **A** by a tandem process using propargylamides and aryl iodides in the presence of catalytic Pd(0) species.^{7g} The second concerns the synthesis of 4,4-disubstituted 4*H*-oxazol-5-ylidenacetic acid methyl esters **B** by Pd(II)-catalyzed oxidative carbonylation.^{7h} The third involves AuCl₃ as catalyst affording to 5-methyl-oxazoles **C**.⁷ⁱ Following the oxidative Pd-catalyzed process observed for compound **4**, a new methodology to furnish directly 5-oxazole-carbaldehydes would be desirable.

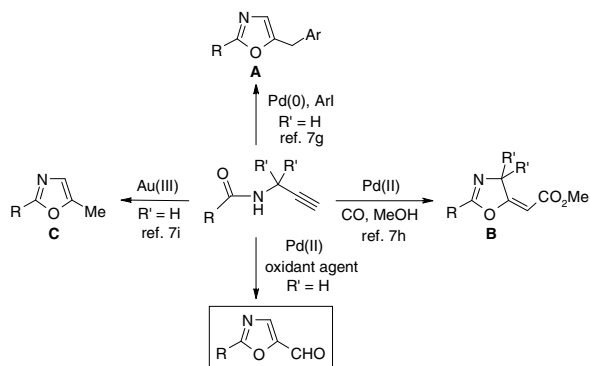
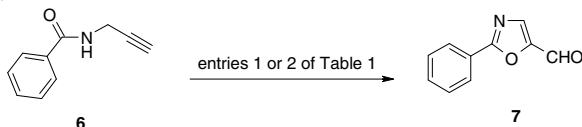


Figure 1. Behavior of propargylamides as tools for transition metal-catalyzed synthesis of oxazole derivatives.

On the basis of the above considerations, we aimed to evaluate the generality of the envisioned reaction and first we tested the behaviour of the simple *N*-propargylbenzamide **6** under the previous successful reaction conditions. The experiment was accomplished by either ultrasound activation or heating at 60 °C and in both cases afforded the 2-phenyl-oxazole-5-carbaldehyde (**7**), which was isolated in 28% and 37% yields, respectively, beside to degradation materials (Scheme 2).

SCHEME 2. Palladium-catalyzed cyclization of propargylamide **6**.



The effective cyclization of the amide **6** prompted us to perform a number of experiments in order to improve the reaction yield. As summarized in Table 1, some features were clearly evidenced. First, palladium catalyst was essential for a positive outcome of the reaction. The use of an acidic catalyst, more specifically *p*-toluenesulphonic acid (PTSA) was not able to convert the amide **6** in any solvents (entries 3-5).⁸ An attempt to carry out the reaction by exposition of microwave irradiation failed because the decomposition of amide **6** was faster than the cyclization process (entry 6). The presence of **2** in the catalyst systems proved to be highly effective for the desired cyclization product (entry 2 vs entry 7). The increase of reaction temperature (entry 10) as well as of BQ amount did not improve significantly the yields (entry 11). The reaction was inhibited working in certain solvents or in the presence of a base. The use of other oxidant systems gave rise to different results. While MnO₂ totally inhibits the conversion of **6** (entry 12), the environmentally friendly molecular oxygen showed a different behavior depending on reaction conditions. In particular, when combined with BQ or employed as sole oxidant (entries 13 and 14) it slowed the desired reaction, but produced **7** in highest yield when associated with CuCl₂ in the role of co-catalyst (entry 15). The oxidative cyclization took place also in the presence of an excess of CuCl₂ (entry 16).

The role of CuCl₂ is only of reoxidant agent and the absence of palladium inhibits the process.

Table 1 Optimization of the palladium catalyzed cyclization of propargylamide **6**.

Entry	Catalyst	Oxidant	Solvent ^a	T (°C)	Yields of 7
1	2 ^b	BQ ^d	THF/DMF 5:3	r.t. ^g	28
2	2 ^b	BQ ^d	THF/DMF 5:3	60	37
3	PTSA ^c	BQ ^d	THF ^c	r.t.	–
4	PTSA ^c	BQ ^d	CH ₂ Cl ₂	r.t.	–
5	PTSA ^c	BQ ^d	THF/DMF 5:3	r.t. ^g	–
6	2 ^b	BQ ^d	DMF	–	11
7	Pd(OAc) ₂ ^c	BQ ^d	THF/DMF 5:3	60	15
8	Pd(OAc) ₂ ^c	BQ ^d	DMF	100	18
9	2 ^b	BQ ^d	THF/DMF 5:3	r.t.	10
10	2 ^b	BQ ^d	THF/DMF 5:3	100	23
11	2 ^c	BQ ^c	THF/DMF 5:3	100	26
12	2 ^c	MnO ₂ ^f	THF/DMF 5:3	100	–
13	2 ^b	BQ ₂ ^d O ₂	THF/DMF 5:3 ⁱ	60	29
14	2 ^c	O ₂	THF/DMF 5:3	100	17
15	2 ^b	CuCl ₂ ^c O ₂	DMF ^j	100	46
16	2 ^b	CuCl ₂ ^c	DMF	100	41
17	–	CuCl ₂ ^c O ₂	DMF ^j	100	–

^a If not differently stated, the reaction time was 3 h. ^b 5 mol%. ^c 10 mol%. ^d 1 equiv. ^e 3 equiv. ^f 2 equiv. ^g Reactions were carried out under ultrasound irradiation. ^h Reactions were carried out under microwave irradiation. ⁱ 90 min. ^j 2 h.

Having established the optimal reaction conditions, we screened a series of propargylamides to generate different 2-substituted oxazole-5-carbaldehydes. The cyclization of substrates **8a-j** took place in higher yields working in conditions of entries 2 or 15 of Table 1. The better results are collected in Table 2. The access to the oxazole compounds **9** was accomplished on propargylamides of aromatic, heteroaromatic, and aliphatic carboxylic acids as well as of natural α -aminoacids. The crucial feature of this approach lies in its ability to access to 5-oxazole-carbaldehydes bearing an electron-rich heterocycles in position 2 (entries e-h). In fact, direct formylation of oxazoles substituted in position 2 with a pyrrolyl, furyl or thienyl ring provides for a competitive functionalization involving both the heterocyclic rings.

Despite several investigations in different reaction conditions, we have not in our hands a clear-cut evidence for determining the Pd mechanistic role. Although highly speculative, we propose the outcome of oxidative heterocyclization depicted in Scheme 3. The complexation of the amide **6** with Pd(II) salts takes place on the C-C triple bond (intermediate **10**) making it susceptible of nucleophilic attack. The role of nucleophile is covered by the oxygen atom of the amide group, which gives rise to 5-*exo-dig* cyclization to produce the oxazole skeleton by formation of the σ -alkenylpalladium complex **11**. The intervention of water provided, through its enol form, the 4,5-dihydro-oxazole-5-carbaldehyde **12**, neither isolated nor detected in the reaction mixture (NMR). At this level the oxidizing system intervenes with a double role, namely *i*) to re-oxidize the Pd(0) species, formed at the end of the catalytic cycle, to the active Pd(II) and *ii*) to promote the dehydrogenation of **12** giving **7**.⁹

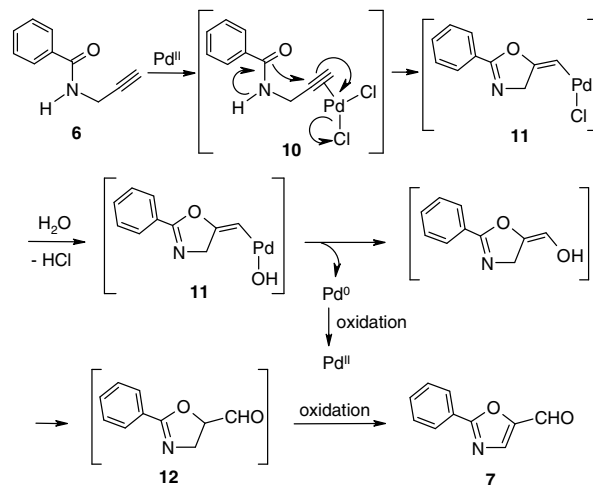
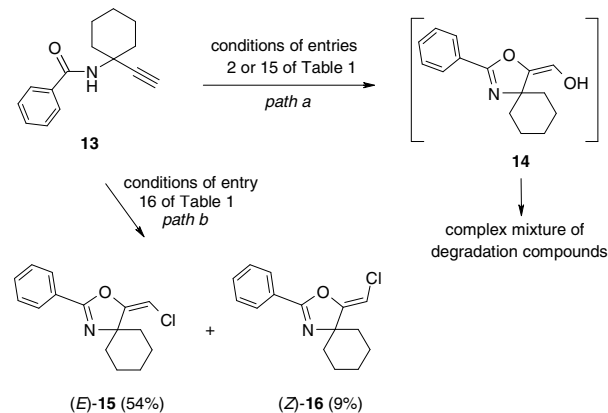
Table 2 Cyclization yields of the propargylamides **8a-j** into the 5-oxazole-carbaldehydes **9a-j**

Entry	R	Condition	Yield of 9
A		entry 15	48
B		entry 2	41
C		entry 2	54
D		entry 15	61
E		entry 15	39
F		entry 15	37
G		entry 15	48
H		entry 15	37
I		entry 15	42
J		entry 15	39

In search for evidence to support the proposed mechanism, we applied our protocol to the α,α -disubstituted propargylamide **13** foreseeing the impossibility of the 4,5-dihydro-oxazole-5-carbaldehyde intermediate to undergo the dehydrogenation step. Accordingly, the amide **13** was submitted to the conditions of entries 2 and 15 (Scheme 4, path a). In both conditions, the $^1\text{H-NMR}$ spectrum of the crude mixture revealed only signals arising from degradation of the starting material, plausibly because the lack of hydrogen in 4-position of the 4,5-dihydro-oxazole precluded the oxidative aromatization of the putative intermediate **14**. On the other hand, the treatment of the amide **13** with **2** (10 mol %) and CuCl_2 (3 equiv) in DMF gave a mixture (63 % yield) of the compounds **15** and **16** (*E/Z* 6:1 ratio) (Scheme 4, path b).¹⁰ This finding indicates that the presence of chloride ions as potential nucleophiles warrants the formation of the stable vinyl chlorides **15** and **16** instead of **14**.

In conclusion, the direct and effective protocol to 2-substituted 5-oxazole-carbaldehydes described in this paper represents a valuable alternative to the formylation on oxazole rings, often unsatisfactory in term of regioselectivity and yields. Moreover, the protocol can be carried out by using aryl, heteroaryl, and alkyl propargylamides, with tolerance of various functional groups and sensitive heterocycles such as *N*-unsubstituted pyrrole and furan. This protocol increases the

versatility of the propargylamides as tools in Pd-catalyzed reactions for the direct synthesis of oxazoles and increases the availability of different functionalized oxazoles accessible by transition metal catalysis.

SCHEME 3. Mechanism proposed for conversion of the amide **6** on the 5-oxazole-carbaldehyde **7**.**SCHEME 4.** Outcome of Pd(II)-catalyzed cyclization of α,α -disubstituted propargylamide **13**.

Experimental Section

General procedure for the preparation of 2-substituted 5-oxazole-carbaldehydes. **Entry 2:** A solution of **6** or **8a-j** (1.0 mmol), **2** (0.05 mmol), BQ (1.0 mmol) in 8 mL of DMF/THF 3:5 was heated at 60 °C for 3 h. After washing with brine, the solution was extracted with Et_2O (2 x 20 mL). The organic layer was dried over Na_2SO_4 and taken to dryness under reduced pressure. The crude mixture was chromatographed on a silica gel column giving **7** or **9a-j**. **Entry 15:** A solution of CuCl_2 (0.1 mmol) and **2** (0.05 mmol) in DMF (20 mL) was stirred at room temperature for 30 minutes. A solution of **6** or **8a-j** (1.0 mmol) in 15 mL of DMF was added, and then the resulting mixture was warmed at 100

°C for 2 h under oxygen atmosphere. The solution was treated with brine and extracted with Et₂O (2 x 40 ml). The organic layer was dried over Na₂SO₄ and taken to dryness under reduced pressure. The crude mixture was chromatographed on a silica gel column giving **7** or **9a-j**.

2-(4-Methoxy-phenyl)-oxazole-5-carbaldehyde (9a) – Yield: 48%. M.p. 140-142 °C (diisopropyl ether). IR (nujol): 1680 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ: 3.90 (3H, s), 7.01 (2H, d, *J* = 8.8 Hz), 7.93 (1H, s), 8.13 (2H, d, *J* = 8.8 Hz), 9.79 (1H, s); ¹³C-NMR (100 MHz, CDCl₃) δ: 56.0 (q), 114.8 (d), 114.9 (d), 118.8 (s), 130.1 (d), 130.5 (d), 140.1 (d), 149.7 (s), 163.4 (s), 166.2 (s), 175.4 (d). MS: *m/z* 203 (M⁺). Anal. calcd for C₁₁H₉NO₃: C, 65.02; H, 4.46; N, 6.89. Found C, 64.88; H, 4.29; N, 7.16.

2-(2-Phenylethyl)-oxazole-5-carbaldehyde (9d) – Yield: 61%. Oil; IR (nujol): 1683 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ: 3.15-3.23 (4H, m), 7.21-7.33 (5H, m), 7.78 (1H, s), 9.74 (1H, s); ¹³C-NMR (100 MHz, CDCl₃) δ: 30.1 (t), 33.0 (t), 126.8 (d), 128.6 (d), 129.1 (d), 138.3 (d), 139.9 (s), 150.3 (s), 169.3 (s), 176.7 (d). MS: *m/z* 201 (M⁺). Anal. calcd for C₁₂H₁₁NO₂: C, 71.63; H, 5.51; N, 6.96. Found C, 71.48; H, 5.79; N, 7.08.

2-(2-Furyl)-oxazole-5-carbaldehyde (9h) – Yield: 37%. M.p. 138-140 °C (diisopropyl ether). IR (nujol): 1682 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ: 6.62-6.63 (1H, m), 7.31 (1H, d, *J* = 3.5 Hz), 7.68 (1H, s br), 7.94 (1H, s), 9.81 (1H, s); ¹³C-NMR (100 MHz, CDCl₃) δ: 113.0 (d), 116.1 (d), 139.2 (d), 142.0 (s), 146.9 (d), 149.4 (s), 157.9 (s), 176.4 (d). MS: *m/z* 163 (M⁺). Anal. calcd for C₈H₅NO₃: C, 58.90; H, 3.09; N, 8.59. Found C, 59.01; H, 2.81; N, 8.35.

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Supporting Information Available: Experimental procedures, characterization data, as well as ¹H and ¹³C NMR spectra for all products. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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