Cu-catalyzed oxygenation of alkene-tethered amides with O$_2$ via unactivated C=C bond cleavage: a direct approach to cyclic imides†

Junhua Li, Jialiang Wei, Bencong Zhu, Teng Wang and Ning Jiao *ac

The transformations of unactivated alkenes through C=C bond double cleavage are always attractive but very challenging. We report herein a chemoselective approach to valuable cyclic imides by a novel Cu-catalyzed geminal amino-oxygenation of unactivated C=C bonds. O$_2$ was successfully employed as the oxidant as well as the O-source and was incorporated into alkenyl amides via C=C bond cleavage for the efficient preparation of succinimide or glutarimide derivatives. Moreover, the present strategy under simple conditions can be used in the late-stage modification of biologically active compounds and the synthesis of pharmaceuticals, which demonstrated the potential application.

5- and 6-membered cyclic imide moieties are frequently present as the key subunit in many pharmaceuticals and bioactive compounds† [Fig. 1]. For instance, 5-membered cyclic imides (succinimides) i, ii and iii are commonly used to treat petit mal epilepsy, while 6-membered cyclic imides (glutarimides) iv, v, and vi could be used as sedative-hypnotics and antineoplastic and immunomodulatory drugs. Interestingly, the pentential thalidomide vii returned to the market for the treatment of cancer under the brand name Immunoprin, since the crisis of thalidomide in the 1960s. The evolution of synthetic methods for cyclic imides is continuously driven forward by their importance in medicinal chemistry. Typical methods for the synthesis of simple imides include the ammonolysis of anhydrides at high temperature, the oxidation of lactams with strong or special oxidants, the reduction of unsaturated imides such as maleimide, and metal-catalyzed carboxylation of various precursors. However, the approach to polysubstituted cyclic imides remains challenging due to tedious transformations that are required for the preparation of anhydride precursors.

It is instructive that the difunctionalization of alkenes is such a versatile transformation for the assembly of two individual functional groups across C=C double bonds. Alkene-tethered amides, which serve as the substrates for intramolecular amidation of unactivated alkenes initiated by the photo-induced amidyl radical formation or metal-mediated amidocyclization, have emerged as the ideal precursor of $\gamma$-lactams in recent years with well-established transformations (Scheme 1[a1]).

**Fig. 1** Some pharmaceuticals with succinimide and glutarimide moieties.

---

† Electronic supplementary information (ESI) available. CCDC 1912652. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c9sc03175h
Recently, O₂ or air has been regarded as an ideal oxidant because of its inexpensive, environmentally benign and high atom economy characteristics, which attract academic and industrial attention. The oxygenations of olefins enable efficient protocols for the construction of epoxides, diols, and ketones with/without C=C double bond cleavage. Given what we discovered in our previous studies on the oxygen mediated C=C double bond cleavage, we proposed that the geminal olefin amino-oxygenation of pent-4-enamides via chemo-selective C=C double bond cleavage would be highly promising to produce succinimides in the presence of oxygen (Scheme 1b).

To date, the aerobic oxidation of enamides has only been reported in the Pd(II)-catalyzed intramolecular aza-Wacker-type cyclization. Recently, significant aminooxygenation of 4-pentenylsulfonamides was reported by Chemler and coworkers (Scheme 1(a2)), in which the C=C bond cleavage was successfully achieved in two steps. DABCO was required as a base with the formation of γ-lactam products. To the best of our knowledge, the chemo-selective cleavage of C=C double bonds in alkene-tethered amides for cyclic imide synthesis has not been accomplished yet.

Our investigation commenced with N-methoxy alkyl amide 1a. After a lot of experiments, we were surprised to find that the unactivated C=C double bond could be cleaved with the incorporation of one oxygen atom using O₂. Encouraged by the copper catalyzed olefin amino-oxygenation which delivered 2a in 47% yield (Table 1, entry 1), a variety of conditions were screened (see the ESI†). The control experiments demonstrated that the reaction could not work in the absence of the copper catalyst, or oxygen atmosphere (Table 1, entries 2 and 3). Besides, different copper catalysts, solvents, additives and ligands were also screened (Table 1, entries 5-10). The yields sharply decreased when bases or acids were used as additives. Finally, we found that with copper acetate as the catalyst and bathocuproine (Ligand II) as the ligand the unactivated C=C double bond geminal amino-oxygenation reaction in toluene proceeded well and produced the desired succinimide product 2a with excellent efficiency (83% isolated yield, Table 1, entry 10).

Subsequently, a good number of pent-4-enamides were smoothly converted to succinimides in moderate to good yields (Table 2). Several N-alkoxy protecting groups were well tolerated (up to 84%, 2a-2c) while substrates bearing bulky groups showed poor conversion (2d and 2e). When a hydrogen atom (2f) or benzyl group (2g) was attached to the amide nitrogen, the reaction did not work. The reason is that the alkyl-metal intermediate formation might be favored with the assistance of alkyloxy protecting groups. N,G-Geminal substituted substrates worked well in this transformation (Table 2, 2h-2o), producing polysubstituted and spiro-succinimides in moderate to good yields. It is noteworthy that the reaction could contain one of the identical allyl groups specifically to give the allylic imide in 44% yield (2o). The mono-methyl or benzyl substituted enamides were also tolerated, and the desired products could be obtained in fair yields (2p and 2q). To our delight, the vinylcyclohexane derived enamide underwent the process smoothly to afford the corresponding imide 2s. 2-Vinylbenzamide was also compatible to give the synthetically important phthalimide 2t albeit the efficiency is a little bit low because the conjugated alkenes would undergo unwanted oxidation. Unfortunately, the alkene-tethered amide without alkylation of the backbone did not work. Notably, the glutarimide derivatives 4a-4d were also obtained in moderate yields with hex-5-enamides (Table 3).

To demonstrate the synthetic value of our strategy, several late-stage modifications of biologically active compounds were carried out under standard conditions (Scheme 2).

### Table 1 Screening of reaction conditions<br>

<table>
<thead>
<tr>
<th>entry</th>
<th>catalyst</th>
<th>ligand</th>
<th>solvent</th>
<th>additive</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cu(OAc)₂</td>
<td>1,10-phenanthroline</td>
<td>PhMe</td>
<td>–</td>
<td>47</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>1,10-phenanthroline</td>
<td>PhMe</td>
<td>–</td>
<td>nd²</td>
</tr>
<tr>
<td>3³</td>
<td>Cu(OAc)₂</td>
<td>1,10-phenanthroline</td>
<td>PhMe</td>
<td>–</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Cu(OAc)₂</td>
<td>–</td>
<td>PhCF₃</td>
<td>–</td>
<td>53 (60)</td>
</tr>
<tr>
<td>5</td>
<td>CuOAc</td>
<td>1,10-phenanthroline</td>
<td>PhMe</td>
<td>–</td>
<td>66</td>
</tr>
<tr>
<td>6</td>
<td>CuOAc</td>
<td>1,10-phenanthroline</td>
<td>PhCF₃</td>
<td>–</td>
<td>82</td>
</tr>
<tr>
<td>7</td>
<td>CuOAc</td>
<td>bathocuproine</td>
<td>PhCF₃</td>
<td>K₂CO₃</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>CuOAc</td>
<td>bathocuproine</td>
<td>PhCF₃</td>
<td>Ph₃PO</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
<td>CuOAc</td>
<td>bathocuproine</td>
<td>PMe</td>
<td>–</td>
<td>81 (83)</td>
</tr>
<tr>
<td>10</td>
<td>CuOAc</td>
<td>bathocuproine</td>
<td>PMe</td>
<td>–</td>
<td>(80)³</td>
</tr>
</tbody>
</table>

*Reaction conditions: 1a (0.2 mmol), catalyst (0.02 mmol), ligand (0.024 mmol) and additive (1.0 equiv.) were stirred in solvent (2.0 mL) at 80 °C under O₂. Determined by ¹H NMR analysis using 1,1,2,2-tetrachloroethane as the internal standard. The numbers in parentheses are isolated yields. Under an argon atmosphere. Not detected. This reaction was carried out under air.

### Table 2 Substrate scope for the synthesis of succinimides<br>

*Reaction conditions: see entry 10, Table 1. Isolated yields. Reaction for 48 hours.
Naproxen, approved by the USA Food and Drug Administration (FDA) as an anti-inflammatory, antipyretic and analgesic agent, could deliver succinimide 6 in 78% yield via analogue 5 under standard conditions (Scheme 2). The structure of 6 was confirmed by X-ray single crystal structural analysis. Additionally, the derivatives of best-selling drugs ibuprofen and flurbiprofen could also undergo the present transformation to afford the desired product 8 in 60% yield and 10 in 75% yield respectively. These results provide efficient approaches to drug analogues for future medicinal chemistry studies.

Furthermore, our strategy can be applied to the synthesis of two pharmaceutical compounds ethosuximide 1 and methsuximide 2 (Fig. 1). As shown in Scheme 3, the amidocyclization of 11 gave N-benzyloxy succinimide 12 in 69% yield under standard conditions, followed by the removal of the N-benzyloxy group by hydrogenation and treatment with 2-bromoacetophenone and triethylamine to furnish20 the ethosuximide in high yield (13, 83%), which possesses antiepileptic effects. This method avoids the use of highly toxic hydrocyanic acid in industrial production. Similarly, the methsuximide 17 could also be obtained from succinimide 15 in good overall yield.

In order to probe the mechanism, some control experiments were designed and investigated (Scheme 4). Firstly, the reaction was conducted in the presence of TEMPO as a radical scavenger, and the difunctionalization product 18 could be obtained in 87% yield, with the formation of 2a in only 10% yield (Scheme 4a). This result indicates that an alkyl radical intermediate was produced after the intramolecular amido-cyclization process. Then, to investigate the intermediacy of an aldehyde in the C=C bond cleavage, 2-pyrrolidinone 19 was employed under standard conditions. The formation of 2r with some unconsumed raw materials compared with the results in Table 2 indicates that an aldehyde might be involved in this transformation (Scheme 4b).

In addition, the isotopic labeling studies under 18O2 delivered the labeled succinimide [18O]2a in 80% yield (67% 18O) due to the exchange with H2O (see the ESI†), which supports our expectation. We also studied the reaction kinetic profile, which showed the initial increase and later consumption of the aldehyde intermediate along with the formation of succinimide (Fig. 2). This result was in accordance with our aforementioned observation. Tentative studies on trapping intermediates were also carried out by EPR (see the ESI†).

Based on previously reported21,2,2 and our own mechanistic studies, a plausible mechanism is shown in Scheme 5. We proposed that copper(II) is oxidized to copper(I) by O2 in the initial step. Then, copper(I)-catalyzed alkene cis-amidocyclization affords an unstable organocopper(I) intermediate B. Primary radical C, which could be trapped by TEMPO (Scheme 4a), is subsequently generated by the C-Cu homolysis of the intermediate B.22 The mechanism is not completely clear yet. Alternatively, the lack of detection of the amidyl radical by EPR analysis (see the ESI†) could not fully disprove its presence under the reaction conditions. The primary radical C may also be generated by the addition of the amidyl radical to the double bond. Then, the radical species C is trapped by molecular oxygen and produces the superoxide radical D. Then, the intramolecular 1,3-hydrogen migration occurs to form the intermediate E, followed by the O-O homolysis to give the aldehyde F and hydroxyl radical which is unstable and easily reduced in situ to give the hydroxide anion. The intermediate aldehyde F could be directly transformed into copper(I) enolate G which undergoes formal [2 + 2] cycloaddition with another molecule of oxygen to give the 1,2-dioxetane J via radical species...
Acknowledgements

Financial support from the National Basic Research Program of China (973 Program) (No. 2015CB856600), the National Natural Science Foundation of China (21632001, 21772002, and 81821004), the Drug Innovation Major Project (2018ZX09711-001), and the Open Research Fund of Shanghai Key Laboratory of Green Chemistry and Chemical Processes is greatly appreciated. We thank Xinyi Zhao of our group for reproducing the results of 2n and 4b.

Notes and references
