N-Heterocyclic Carbene Catalyzed Cyclization Cascades of 3-Halopropenals and Arylnitroso Compounds to 2,3-Disubstituted Isoxazol-5(2*H*)-ones

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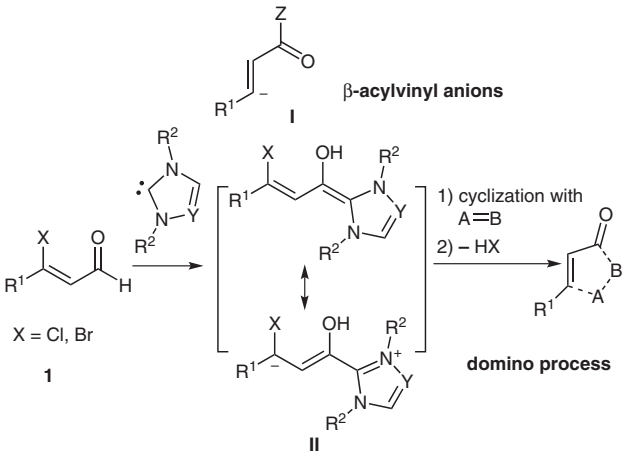
Abstract: An NHC-catalyzed annulation reaction of 3-halopropenals with nitrosobenzene derivatives, providing access to 2,3-disubstituted isoxazol-5(2*H*)-ones under mild conditions is described. This procedure represents a metal-free approach to the alternative equivalent of β-acylvinyl anions for the formation of heterocyclic compounds.

Key words: carbenes, cyclization, heterocycles, tandem reaction, umpolung

Umpolung reactivity of functional groups allows chemists the opportunity to view bond disconnections in nontraditional ways, and thus providing an unconventional access to a few target molecules selectively and efficiently.[1] In this case, β-acylvinyl anions **I** (Scheme 1), a sp^2 hybridized umpoled d^3 synthon, are versatile intermediates to give a β-bonded α,β-unsaturated functionality.[2] Traditional strategies toward **I** or their equivalents rely on the stoichiometric formation of stabilized carbanions, and are hence hampered by some limitations such as harsh reaction conditions and tedious manipulations. On the other hand, transition-metal-catalyzed processes have been developed to achieve similar conversion under mild conditions by employing vinylboronate and vinylstannane compounds as alternative precursors of **I**.[3] Although significant progress has been made by these metal-catalyzed protocols, metal-free catalytic approaches to β-acylvinyl anions or equivalents for subsequent electrophilic β-functionalization are still valuable despite remaining rarely explored.[4]

Recently, umpolung and redox reactions of aldehydes catalyzed by N-heterocyclic carbenes (NHCs) have found a wide range of applications in synthetic chemistry.[5] Remarkably, based on the generation of catalyst-bound homoenolate equivalents, NHC-catalyzed annulation of α,β-unsaturated enals has emerged as a powerful tool to access cyclic compounds.[6] However, these exciting reactions mainly limited the enal substrate to β-mono-substituted compounds like cinnamaldehyde derivatives, presumably due to the instability of related homoenolates or inherent steric hindrance.[7] We recently found that substituted 3-halopropenals **1**,[8] a sort of β,β-disubstituted enals bearing a halogen atom at β-position, can behave as an equivalent of β-acylvinyl anions upon treatment with imidazolium precatalysts and stoichiometric amounts of DBU (Scheme 1), giving rise to butenolide and pyrazolone derivatives.[9] To further demonstrate the unique reactivity of 3-halopropenals originating from the addition of nucleophilic carbene, we present herein an organocatalytic cyclization reaction of 3-halopropenals with nitroso compounds,[10,11] providing access to 2,3-disubstituted isoxazol-5(2*H*)-one derivatives.



Scheme 1 NHC-catalyzed cascade sequences to the equivalents of β-acylvinyl anions **I**

The study was initiated by investigating the cyclization reaction of 3-chloropropenal (**1a**) with 4-chloronitrosobenzene (**2a**) in the presence of imidazolium precatalyst **A** (10 mol%) and DBU (150 mol%) at –20 °C. To our delight, isoxazol-5(2*H*)-one **3a** was isolated in 40% yield from the reaction mixture (Table 1, entry 1). Addition of DBU by a syringe pump over three hours slightly improved the product yield (entry 2). Moreover, increasing the loading of propenal **1a** provided the product in better yield; in contrast, the reaction with excess nitrosobenzene led to a dramatic decrease in yield, along with a detectable amount of by-product (*Z*)-3-chloro-3-phenylacrylic acid (**4**) (Table 1, entries 3 and 4). A blank experiment was further carried out in the absence of azolium precatalysts, but could not result in any 3-chloroacrylic acid **4**. These results thus excluded the possibility to access **4** directly via the oxidation by nitroso compounds (Scheme 2). The structure of azolium precatalysts was found critical to the reaction outcomes; whereas imidazolium salt **B** produced **3a** in 17% yield, triazolium salts **C** or **D** could not afford

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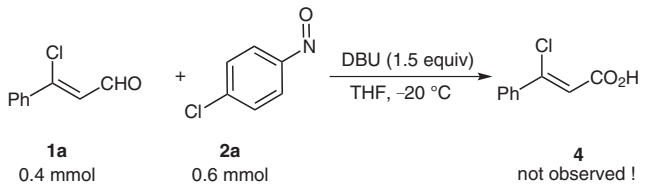
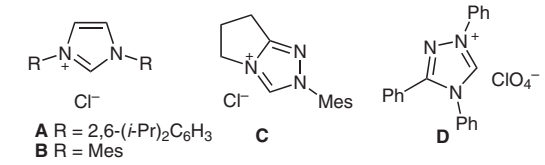
any desired product (Table 1, entries 5–7). Among the bases tested, DBU gave the best results (entries 3, 8, and 9). Finally, a survey of several solvents led to the identification of THF as the optimal solvent for the reaction (Table 1, entries 3, 10, and 11).

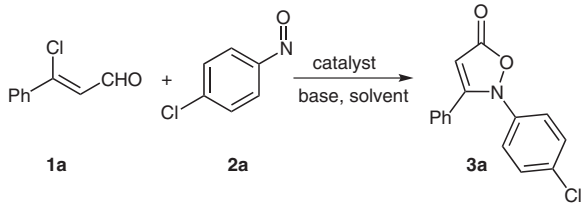


Scheme 2 Blank experiment of **1a** with **2a** in the absence of NHCs

Under the optimized reaction conditions, the NHC-catalyzed annulations of a set of 3-halopropenals with nitrosobenzene **2a** were investigated (Table 2). Bromo-substituted enals underwent the cyclization/elimination sequence as well, albeit in reduced yield (Table 2, entry 2). Electron-rich or electron-deficient aryl-substituted substrates **1c–h** all reacted readily to give the corresponding products in varying yields (Table 2, entries 3–8). Nevertheless, electron-poor substrates generally conducted conversion more clearly than their electron-rich counterparts with a higher product yield. For example, while electron-deficient substrate **1f** could furnish the targeted product in 66% yield, an electron-rich substrate of **1h** only provided the corresponding product **3g** in 20% yield (Table 2, entries 6 vs 8). Finally, thienyl-derived enals had also successfully been employed in this reaction; however, alkyl-substituted 3-halopropenal **1j** cannot undergo the cyclization reaction (Table 2, entries 9 and 10).

Table 1 Optimization of the Cyclization of **1a** and **2a**[a]

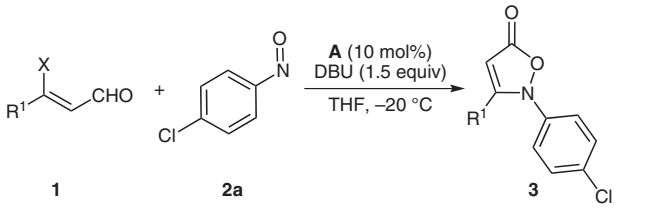




Entry	Catalyst	Base	**1a/2a** (mmol)	Solvent	Yield (%)[b]
1[c]	**A**	DBU	0.4/0.4	THF	40
2	**A**	DBU	0.4/0.4	THF	43
3	**A**	DBU	0.6/0.4	THF	58
4	**A**	DBU	0.4/0.6	THF	25[d]
5	**B**	DBU	0.6/0.4	THF	18
6	**C**	DBU	0.6/0.4	THF	–
7	**D**	DBU	0.6/0.4	THF	–
8	**A**	Cs_2CO_3	0.6/0.4	THF	34
9	**A**	DIPEA	0.6/0.4	THF	12
10	**A**	DBU	0.6/0.4	CH_2Cl_2	28
11	**A**	DBU	0.6/0.4	toluene	23

[a] Reaction conditions: 3-halopropenal **1a**, 4-chloronitrosobenzene (**2a**), and precatalyst (10 mol%) in THF (6 mL), –20 °C, N_2; DBU (150 mol%, in 2 mL of THF) was added by a syringe pump over 3 h.
[b] Yield of isolated product.
[c] DBU was added over 2 h.
[d] Along with (*Z*)-3-chloro-3-phenylacrylic acid (**4**) in 23% yield.

Table 2 Substrate Scope for the Cyclization of **1** with **2a**[a]



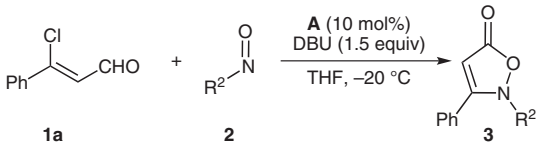
Entry	**1**, R^1	X	**3**	Yield (%)[b]
1	**1a**, Ph	Cl	**3a**	58
2	**1b**, Ph	Br	**3a**	45
3	**1c**, 4-BrC_6H_4	Cl	**3b**	33
4	**1d**, 4-FC_6H_4	Cl	**3c**	48
5	**1e**, 4-$O_2NC_6H_4$	Cl	**3d**	57
6	**1f**, 3-$O_2NC_6H_4$	Cl	**3e**	66
7	**1g**, 4-MeC_6H_4	Cl	**3f**	43
8	**1h**, 4-$MeOC_6H_4$	Cl	**3g**	20
9	**1i**, 2-thienyl	Cl	**3h**	36
10	**1j**, *n*-Pr	Cl	–	–

[a] Reaction conditions: 3-halopropenal **1** (0.6 mmol), 4-chloronitrosobenzene (**2a**; 0.4 mmol), precatalyst **A** (0.04 mmol) in THF (6 mL), –20 °C, N_2; DBU (0.6 mmol, in 2 mL of THF) was added by a syringe pump over 3 h.
[b] Yield of isolated product.

Structural variation of nitrosobenzene component was also explored (Table 3). Electron-withdrawing group at the aromatic ring were well-tolerated, although a slight decrease in yield was observed for ortho-substituted substrate (Table 3, entries 1, 2). Nevertheless, electron-rich nitrosobenzenes displayed low reactivity over this transformation. The presence of methyl group led to poor yield, and no product was derived from methoxy-substituted nitrosobenzene (Table 3, entries 5, 6).

A plausible mechanism for the NHC-catalyzed cyclization/elimination reaction is depicted in Scheme 3. Thus, 3-chloropropenal **1** is first attacked by the in situ generat-

Table 3 NHC-Catalyzed Reactions of **1a** and **2**[a]

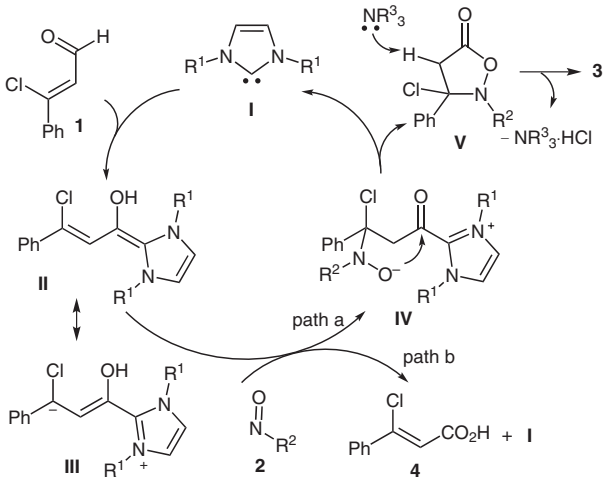


Entry	2	R^2	3	Yield (%)[b]
1	**2a**	4-ClC_6H_4	**3a**	58
2	**2b**	2-ClC_6H_4	**3i**	52
3	**2c**	Ph	**3j**	46
4	**2d**	4-$MeO_2CC_6H_4$	**3k**	48
5	**2e**	4-MeC_6H_4	**3l**	30
6	**2f**	4-$MeOC_6H_4$	–	–

[a] Reaction conditions: 3-halopropenal **1a** (0.6 mmol), nitroso compound **2** (0.4 mmol), and precatalyst **A** (0.04 mmol) in THF (6 mL), –20 °C, N_2; DBU (0.6 mmol, in 2 mL of THF) was added by a syringe pump over 3 h.
[b] Yield of isolated product.

ed imidazolium carbene **I** to afford β-chloro-conjugated Breslow intermediate **II** or homoenolate **III**. Subsequent reactions of the resulting homoenolate equivalent with nitrosobenzenes proceed by two pathways. By path a, this resulting catalyst-bound intermediate in turn attacks the nitrosobenzene **2** at the nitrogen atom, followed by intramolecular acylation and β-elimination sequence to furnish product **3** with the regeneration of the carbene catalyst. On the other hand, when an excess amount of nitrosobenzene was used, the homoenolate equivalent is probably oxidized by nitroso compounds and thus collapses to form 3-chloroacrylic acid **4** (path b). However, presently the mechanical details for this oxidation are not completely clear.

In conclusion, we have disclosed an NHC-catalyzed annulation cascade of 3-halopropenals and nitrosobenzene, providing access to 2,3-disubstituted isoxazol-5(2*H*)-ones. This procedure represents a metal-free approach to the alternative equivalent of β-acylvinyl anions for the synthesis of heterocyclic compounds. Further studies for the application of the methodology in organic synthesis are still underway.



Scheme 3 Plausible mechanism of the NHC-catalyzed annulations

All melting points were measured with a SGW X-4 apparatus and are uncorrected. NMR spectra were recorded on AM400 (Bruker) instruments in $CDCl_3$ with TMS as the internal standard at 25 °C. High-resolution mass spectral (HRMS) analyses were measured on an APEX (Bruker) mass III spectrometer using ESI (electrospray ionisation) techniques. IR spectra were recorded with a Nicolet 470 FT-IR spectrophotometer. Thin-layer chromatography (TLC) was performed on silica gel plates (60F-254) using UV-light (254 and 365 nm) detection. Flash chromatography was conducted on silica gel (300–400 mesh). In experiments requiring anhydrous solvents and reagents, THF and toluene were distilled from sodium, while CH_2Cl_2, DBU and DIPEA were distilled from CaH_2. All reactions were carried out under a nitrogen atmosphere. Nitroso compounds **2** were prepared according to the known methods.[12]

2-(4-Chlorophenyl)-3-phenylisoxazol-5(2*H*)-one (3a); Typical Procedure

A solution of (*Z*)-3-chloro-3-phenylacrylaldehyde (**1a**; 99.6 mg, 0.6 mmol), 4-chloronitrosobenzene (**2a**; 56.6 mg, 0.4 mmol) and precatalyst **A** (17 mg, 0.04 mmol) in THF (6 mL) was cooled to –20 °C under N_2 atmosphere. A solution of DBU (91.2 mg, 0.6 mmol) in THF (2 mL) was added by a syringe pump over 3 h, and then the mixture was stirred for 1 h at –20 °C. After the complete consumption of **2a** (detected by TLC), the reaction was quenched with H_2O (10 mL) and warmed to r.t. The product was extracted with Et_2O (3 × 10 mL); the combined organic layers were washed with brine (15 mL), dried ($MgSO_4$), filtered, and concentrated in vacuum. The residue was purified by column chromatography on silica gel with 4:1 hexane–EtOAc as an eluent to afford **3a** (63.2 mg, 58%) as a yellow solid; mp 79–81 °C.

IR (KBr): 3062, 1736, 1608, 1562, 1488, 1386, 879, 758 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.48–7.37 (m, 5 H), 7.29 (d, *J* = 8.4 Hz, 2 H), 7.13 (d, *J* = 8.8 Hz, 2 H), 5.69 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.9, 165.2, 137.8, 135.0, 131.6, 129.7, 129.2, 127.9, 127.2, 127.0, 92.5.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{11}ClNO_2$ $[M + H]^+$: 272.0473; found: 272.0477.

3-(4-Bromophenyl)-2-(4-chlorophenyl)isoxazol-5(2*H*)-one (3b)

Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3b** (46.1 mg, 33%) as a white solid; mp 138–140 °C.

IR (KBr): 3105, 1744, 1609, 1487, 1408, 891, 789, 487 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.54 (d, *J* = 8.4 Hz, 2 H), 7.32 (d, *J* = 9.2 Hz, 2 H), 7.28 (d, *J* = 8.4 Hz, 2 H), 7.13 (d, *J* = 8.4 Hz, 2 H), 5.69 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.6, 164.1, 137.6, 135.3, 132.5, 129.9, 129.3, 127.1, 126.3, 126.0, 92.9.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{10}BrClNO_2$ $[M + H]^+$: 349.9578; found: 349.9580.

2-(4-Chlorophenyl)-3-(4-fluorophenyl)isoxazol-5(2*H*)-one (3c)

Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3c** (55.5 mg, 48%) as a white solid; mp 92–94 °C.

IR (KBr): 3128, 1746, 1613, 1504, 1487, 1236, 892, 844 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.42 (dd, *J* = 5.6, 8.4 Hz, 2 H), 7.32 (d, *J* = 8.0 Hz, 2 H), 7.14–7.07 (m, 4 H), 5.67 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.7, 164.3 ($J_{C,F}$ = 253 Hz), 164.3, 137.7, 135.2, 130.1 ($J_{C,F}$ = 8.9 Hz), 129.8, 127.2, 123.3 ($J_{C,F}$ = 3.6 Hz), 116.5 ($J_{C,F}$ = 22 Hz), 92.6.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{10}ClFNO_2$ [M + H]$^+$: 290.0379; found: 290.0383.

2-(4-Chlorophenyl)-3-(4-nitrophenyl)isoxazol-5(2*H*)-one (3d)
Prepared according to general procedure with 3:1 hexane–EtOAc as an eluent to afford **3d** (72.1 mg, 57%) as a yellow solid; mp 180–182 °C.

IR (KBr): 3147, 1725, 1557, 1528, 1491, 1349, 1090, 853 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.26 (d, *J* = 8.4 Hz, 2 H), 7.63 (d, *J* = 8.8 Hz, 2 H), 7.34 (d, *J* = 8.4 Hz, 2 H), 7.15 (d, *J* = 8.0 Hz, 2 H), 5.84 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.1, 162.8, 149.3, 137.0, 135.9, 133.0, 130.1, 129.0, 127.3, 124.4, 94.7.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{10}ClN_2O_4$ [M + H]$^+$: 317.0324; found: 317.0326.

2-(4-Chlorophenyl)-3-(3-nitrophenyl)isoxazol-5(2*H*)-one (3e)
Prepared according to general procedure with 3:1 hexane–EtOAc as an eluent to afford **3e** (83.4 mg, 66%) as a yellow solid; mp 156–157 °C.

IR (KBr): 3105, 1726, 1609, 1592, 1506, 1349, 1260, 890 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 8.31 (s, 2 H), 7.75 (d, *J* = 8.0 Hz, 1 H), 7.63 (t, *J* = 8.4 Hz, 1 H), 7.35 (d, *J* = 8.0 Hz, 2 H), 7.18 (d, *J* = 8.4 Hz, 2 H), 5.85 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.2, 163.1, 148.4, 137.1, 136.0, 133.5, 130.5, 130.1, 128.8, 127.5, 126.0, 122.8, 94.4.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{10}ClN_2O_4$ [M + H]$^+$: 317.0324; found: 317.0327.

2-(4-Chlorophenyl)-3-*p*-tolylisoxazol-5(2*H*)-one (3f)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3f** (49.0 mg, 43%) as a yellow solid; mp 99–100 °C.

IR (KBr): 3117, 1738, 1618, 1561, 1483, 1368, 1146, 887 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.29 (d, *J* = 8.0 Hz, 4 H), 7.18 (d, *J* = 8.4 Hz, 2 H), 7.13 (d, *J* = 8.4 Hz, 2 H), 5.64 (s, 1 H), 2.36 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 170.0, 165.4, 142.2, 138.0, 134.9, 129.8, 129.7, 127.8, 127.0, 124.3, 92.0, 21.4.

HRMS (ESI): *m*/*z* calcd for $C_{16}H_{13}ClNO_2$ [M + H]$^+$: 286.0629; found: 286.0633.

2-(4-Chlorophenyl)-3-(4-methoxyphenyl)isoxazol-5(2*H*)-one (3g)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3g** (24.1 mg, 20%) as a white solid; mp 109–111 °C.

IR (KBr): 3105, 1726, 1609, 1506, 1490, 1260, 1090, 890 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.34 (d, *J* = 8.8 Hz, 2 H), 7.31 (d, *J* = 8.4 Hz, 2 H), 7.14 (d, *J* = 9.2 Hz, 2 H), 6.88 (d, *J* = 8.8 Hz, 2 H), 5.61 (s, 1 H), 3.82 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 170.1, 165.3, 162.1, 138.3, 134.9, 129.7, 129.6, 127.2, 119.3, 114.5, 91.4, 55.4.

HRMS (ESI): *m*/*z* calcd for $C_{16}H_{13}ClNO_3$ [M + H]$^+$: 302.0578; found: 302.0581.

2-(4-Chlorophenyl)-3-(thiophen-2-yl)isoxazol-5(2*H*)-one (3h)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3h** (39.9 mg, 36%) as a yellow solid; mp 68–70 °C.

IR (KBr): 3114, 1725, 1581, 1562, 1486, 1327, 1093, 906 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.50 (d, *J* = 5.2 Hz, 1 H), 7.39 (d, *J* = 8.8 Hz, 2 H), 7.28 (d, *J* = 8.4 Hz, 2 H), 7.18 (d, *J* = 3.6 Hz, 1 H), 7.04 (t, *J* = 4.0 Hz, 1 H), 5.70 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.9, 159.7, 138.2, 136.2, 130.7, 130.5, 129.9, 128.4, 128.2, 127.9, 91.6.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_9ClNO_2S$ [M + H]$^+$: 278.0037; found: 278.0041.

2-(2-Chlorophenyl)-3-phenylisoxazol-5(2*H*)-one (3i)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3i** (56.4 mg, 52%) as a yellow solid; mp 110–112 °C.

IR (KBr): 3061, 1747, 1731, 1610, 1568, 1489, 1089, 840 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.47–7.33 (m, 7 H), 7.25–7.19 (m, 2 H), 5.71 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 170.4, 166.8, 136.4, 134.5, 131.7, 131.4, 131.0, 130.3, 129.0, 127.8, 127.8, 127.1, 91.8.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{11}ClNO_2$ [M + H]$^+$: 272.0473; found: 272.0476.

2,3-Diphenylisoxazol-5(2*H*)-one (3j)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3j** (43.6 mg, 46%) as a yellow solid; mp 65–66 °C.

IR (KBr): 3075, 1732, 1611, 1564, 1494, 1392, 1137, 909 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.46–7.32 (m, 8 H), 7.21–7.19 (m, 2 H), 5.66 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 170.2, 165.0, 139.1, 131.4, 129.5, 129.1, 129.0, 128.0, 127.4, 125.9, 91.8.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{12}NO_2$ [M + H]$^+$: 238.0863; found: 238.0864.

Methyl 4-(5-Oxo-3-phenylisoxazol-2(5*H*)-yl)benzoate (3k)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3k** (56.7 mg, 48%) as a yellow solid; mp 113–115 °C.

IR (KBr): 3132, 2951, 1737, 1714, 1603, 1282, 1115, 892 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.98 (d, *J* = 8.0 Hz, 2 H), 7.52–7.47 (m, 1 H), 7.43–7.42 (m, 4 H), 7.20 (d, *J* = 9.2 Hz, 2 H), 5.65 (s, 1 H), 3.90 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 169.4, 165.8, 163.8, 142.2, 131.6, 130.8, 129.5, 129.3, 127.9, 127.3, 123.8, 92.4, 52.4.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{14}NO_4$ [M + H]$^+$: 296.0917; found: 296.0919.

3-Phenyl-2-*p*-tolylisoxazol-5(2*H*)-one (3l)
Prepared according to general procedure with 4:1 hexane–EtOAc as an eluent to afford **3l** (30.1 mg, 30%) as a yellow solid; mp 72–74 °C.

IR (KBr): 3103, 1723, 1613, 1570, 1507, 1373, 1148, 891 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 7.42–7.36 (m, 5 H), 7.10 (dd, *J* = 8.4, 15.6 Hz, 4 H), 5.63 (s, 1 H), 2.32 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$/TMS): δ = 170.4, 165.2, 139.6, 136.7, 131.2, 130.1, 128.9, 128.0, 127.5, 126.0, 91.5, 21.1.

HRMS (ESI): *m/z* calcd for $C_{16}H_{14}NO_2$ $[M + H]^+$: 252.1019; found: 252.1022.

(*Z*)-3-Chloro-3-phenylacrylic Acid (4)

A solution of (*E*)-3-chloro-3-phenylacrylaldehyde (**1a**; 66.6 mg, 0.4 mmol), 4-chloronitrosobenzene (**2a**; 84.6 mg, 0.6 mmol), and pre-catalyst **A** (15.6 mg, 0.04 mmol) in THF (6 mL) was cooled to –20 °C under N_2 atmosphere. A solution of DBU (91.2 mg, 0.6 mmol) in THF (2 mL) was added by a syringe pump over 3 h, and the mixture was stirred for additional 2 h at –20 °C. H_2O (10 mL) was added and the resulting mixture was extracted with Et_2O (3 × 10 mL). The combined organic layers were washed with brine (15 mL), dried ($MgSO_4$), filtered, and concentrated in vacuum. The residue was purified by column chromatography on silica gel (with hexane–EtOAc from 4:1 to 3:1 as an eluent) to give **3a** (27.3 mg, 25%) and **4** (16.7 mg, 23%).

^{1}H NMR (400 MHz, $CDCl_3$/TMS): δ = 10.08 (br, 1 H), 7.71 (d, *J* = 6.8 Hz, 2 H), 7.47–7.41 (m, 3 H), 6.61 (s, 1 H).

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

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