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Citation for final published version:


Publishers page: http://dx.doi.org/10.1126/science.aaf9621

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A general catalytic b-C–H carbonylation of aliphatic amines to b-lactams

Darren Willcox,* Ben G. N. Chappell,* Kirsten F. Hogg, Jonas Calleja, Adam P. Smalley, Matthew J. Gaunt†

Methods for the synthesis and functionalization of amines are intrinsically important to a variety of chemical applications. We present a general carbon-hydrogen bond activation process that combines readily available aliphatic amines and the feedstock gas carbon monoxide to form synthetically versatile value-added amide products. The operationally straightforward palladium-catalyzed process exploits a distinct reaction pathway, wherein a sterically hindered carboxylate ligand orchestrates an amine attack on a palladium anhydride to transform aliphatic amines into b-lactams. The reaction is successful with a wide range of secondary amines and can be used as a late-stage functionalization tactic to deliver advanced, highly functionalized amine products of utility for pharmaceutical research and other areas.

Carbon monoxide (CO) is an abundant chemical feedstock, and metal-catalyzed carbonylation reactions are integral to the laboratory- and manufacturing-scale synthesis of chemical products. Most of these processes involve CO binding to a metal to form a metal-carbonyl complex with well-established reactivity (28). Recently, our group described a sterically controlled C–H activation strategy for carbonylation of free-NH aliphatic amines (26). High-hindered amines, displaying fully substituted carbon atoms on either side of the nitrogen motif, underwent C–H carbonylation to yield b-lactams (Fig. 2A). A key factor in the success of this strategy was the sterically induced destabilization of the readily formed bis(amine)-Pd(II) complex, resulting from a clash between the two highly hindered amines, which shifts the equilibrium toward a mono(amine)-Pd(II) species required for C–H activation. The anticipated pathway for these amine-directed reactions had been based on seminal studies by Fujiiwara and colleagues (29), who outlined a mechanistic blueprint that has underpinned most subsequent directed C–H carbonylation reactions with Pd(II) catalysts: In our case, amine-directed cyclopalladation of the C–H bond formed a four-membered ring complex and was followed by coordination of CO, 1,1-migratory insertion to an acyl-Pd species, and reductive elimination to generate the carbonyl product. However, when the same re-action concept was applied to more commonly encountered, less hindered amines, the reaction failed or was low-yielding and resulted in oxidative degradation and acetylated amine products (Fig. 2A). Furthermore, we were not able to observe any trace of the corresponding four-membered-ring cyclopalladation complex, in contrast to the case for reactions with the hin-dered amine counterparts. Indeed, we calculated that a transition state for four-membered-ring cyclopalladation of these less hindered amines was too high to be a realistic pathway (30). On the basis of these observations, we reconsidered the classical mechanism for C–H carbon-ylation. CO is a strongly binding ligand, and it is perhaps surprising that it does not interact with the Pd catalyst before C–H activation. More-over, Pd(OAc)₂ (Ac, acetate group) and CO display contrasting redox properties, and their combination predictably leads to catalyst reduction, which can complicate a catalytic process. Intrigued by the apparent paradox of the redox properties of the reagents, we became inter-ested in the mechanism of CO-mediated reduc-tion of Pd(OAc)₂, outlined in Fig. 2B. Although little is known about this pathway, studies by
Moiseev and colleagues (31) provided clues that led us to propose a simplified model that we supported through computation. Two mole-cules of CO coordinate to monomeric Pd(OAc)₂ (int-I) and a calculated Pd–C–O angle of 153.7°, along with a bond distance between the carboxylate and CO of 2.06 Å, suggested an inter-action between the two ligands. An attack on one of these CO ligands by a neighboring carboxylate was energetically favorable, leading to a Pd anhydride–type species, int-II. The tran-sition state for this step (int-I to int-II) was calculated to be +11.50 kcal mol⁻¹ relative to int-I. Coordination of a further CO (int-III) could trigger an intermolecular attack of the k¹-bound acetate onto the distal carbonyl group of the anhydride, causing the release of CO₂, acetic anhydride, and Pd(0). Motivated by the potential reactivity of the putative Pd anhydride int-II, we postulated that attack by an amine on the proximal carbonyl would lead to a carbamoyl-Pd species (Fig. 2C), from which C–H activation would be possible. This unorthodox cyclopalladation pathway would lead to C–H activation two carbon atoms away from the nitrogen group—distinct from classical cyclo-palladation processes that usually result in ac-tivation three carbons from the directing motif.

Reaction development and mechanistic studies

To test our hypothesis, we reacted amine 1a un-der activation three carbons from the directing motif. From the nitrogen group—lead to C

Fig. 1. A strategy for the catalytic synthesis of functionalized aliphatic amines. (A) Hypothesis: Combining well-established amine synthesis with metal-catalyzed C–H functionalization will lead to the rapid synthesis of functionalized amines. (B) Pd-catalyzed C(sp³)–H carbonylation of free-NH amines. A blue circle or R denotes a general organic group. (C) The importance of b-lactams.
methyl group and at the position adjacent to the carbonyl of the amide. However, no hydrogen-deuterium scrambling was observed in the recovered starting material d^6-1a. These observations indicate that C–H activation is reversible and takes place after an irreversible step.

Taken together, these observations suggest a catalytic cycle for this C–H carbonylation reaction (30), which we have supported with a computa-tional study of a simplified system using diisopro-pylamine 1b and pivalic acid and without the involvement of 3a or 3b (Fig. 3C). The process begins with carbonyl exchange on Pd(OAc)\(_2\): Coordination of the sterically hindered acid (RCO\(_2\)H) (R, t-butyI group) forms Pd(O\(_2\)CR\(_2\)); Coordination of the sterically hindered acid (RCO\(_2\)H) (R, t-butyI group) forms Pd(O\(_2\)CR\(_2\)); Coordination of the sterically hindered acid (RCO\(_2\)H) (R, t-butyI group) forms Pd(O\(_2\)CR\(_2\)). Next, amine coordination forms the mono(amine)-Pd(II) complex int-IV, which is in equilibrium with the off-cycle bis(amine)-Pd(II) complex (int-V); we deemed int-V, as the catalyst resting state, to be the energetic reference point. CO binding then forms int-VI, from which a viable transition state (TS1) to the Pd anhydride complex int-VII was determined. On the basis of our kinetic isotope effect and computational studies, we suggest that the attack of the amine at the internal carbonyl of int-VII (via TS2) to form carbamoyl-Pd species int-VIII is irreversible, and from this point, reversible C–H activation takes place through a concerted metalation deprotonation pathway (TS3) to form a five-membered-ring cyclopalladation intermediate int-IX (see also Fig. 2E). Last, BQ-assisted reductive elimination (via TS4) leads to β-lactam 2b after decomplexation from Pd(0); oxidation of the Pd(0) species with Cu(OAc)\(_2\) regenerates the active Pd(II) species. The amine additives 3a and 3b may stabilize the Pd(0) species before oxidation by preventing deactivating aggregation (37).

This effect may be more pronounced toward the end of the reaction, when the concentration of the amine substrate 1 is lower, and possibly explains why 3a and 3b have an effect on yield but not on the rate of reaction.

**Substrate scope with simple amines**

Having established optimal reaction conditions and validated a possible reaction mechanism, we focused our efforts on establishing the scope of the C–H carbonylation process. In setting a benchmark, we targeted a substrate scope that would encompass all structural classes of ali-phatic secondary amines with respect to substitution at the carbon atoms directly connected to the free-NH group. We previously reported a C–H activation strategy for fully substituted aliphatic secondary amines that proceeds via four-membered-ring cyclopalladation—a pathway distinct from

![Fig. 2](image-url)

Fig. 2. Toward an activation mode for C–H carbonylation of unhindered aliphatic amines. (A) Previous work: C–H carbonylation of hindered aliphatic amines via a four-membered-ring cyclopalladation pathway (left) and poor-yielding C–H carbonylation of less hindered amines (right). (B) Reduction of Pd(OAc)\(_2\) by CO. (C) Design: A sterically controlled ligand-enabled C–H activation. (D) Optimization studies. (E) C–H activation from a de novo carbamoyl-Pd complex. Computational studies were conducted using Amsterdam Density Functional software at the ZORA:BLYP-D3/TZ2P level with the COSMO solvation model (PhMe) (supplementary materials). Ph, phenyl group; Me, methyl group; Ac, acetate group; BQ, benzoquinone; Ad, adamantyl group; MesCO\(_2\)H, 2,4,6-trimethylbenzoic acid; DG, change in Gibbs free energy; TS, transition state; int, intermediate; h, hours; equiv, equivalent.
this process (26). However, the majority of amines in everyday use are represented by less substituted variants. Each class of these amine starting materials can be prepared by classical methods of C–N bond formation, thereby linking the C–H activation process to well-established preparative methods and reliable chemical feedstocks. Figure 4 shows the wide breadth of the substrate scope for this aliphatic amine C–H activation process. We began by assessing amines with five substituents around the nitrogen motif and found that these hindered secondary amines were compatible with the reaction conditions and could be efficiently converted into the corresponding b-lactams in good yields (2c to 2i). In the case of 2d, classical amine-directed five-membered-ring cyclopalladation could potentially lead to a g-lactam product; however, only the product formed via the new carbonylation pathway was observed. Amines with an unsymmetrical arrangement of four substituents around the NH motif also worked very well in the C–H activation process (2j to 2s). A variety of useful functional groups were amenable to the reaction conditions, producing the b-lactam products in good yields. The reaction with amines containing two substituents on either side of the free-NH amine motif (2a, 2b, and 2t to 2af) tolerated the incorporation of protected hydroxyl motifs (2u and 2af), carbon-yls (2w), and amine motifs (2ab, 2ad, and 2ae) into the b-lactam products, providing opportunities for downstream synthetic manipulations of these valuable products. Pyridines (2y and 2z) and thiocarbonates (2ac) were tolerated as well, with no adverse effects on regioselectivity or catalyst poisoning (38). The reaction of an N-aryl amine (to 2ag), however, was unsuccessful under these conditions, and the starting material was returned unchanged (39).

Having demonstrated that the reaction works well on heavily substituted secondary amines, we next sought to investigate the process with less hindered substrates. These types of amines would be expected to form stable bis(amine)-Pd(II) complexes (compare with int-V, Fig. 3C), and their high nucleophilicity suggested that selective attack on the putative Pd anhydride complex might be difficult to control. Additionally, each substrate contains up to four C–H bonds that can readily undergo b-hydride–elimination side reactions. Despite these potential pitfalls, we found that a range of amines with three substituents worked very well in the C–H carbonylation (2ah to 2aq) when the reaction was conducted using phenylbenzoquinone, a hindered variant of BQ that prevents deleterious oxidative amination of the quinone scaffold. A substrate with only unfunctionalized alkyl groups worked well (2ah), demonstrating that the success of the reaction is not the result of remote functionality influencing the reactivity. A variety of functional groups on the amine substituents were tolerated, including sulfones (2aj), esters (2ak), aromatic heterocycles (2al), and alkenes (2an), producing the b-lactams in high yields. Aliphatic heterocycles were also competent substrates for this reaction (2aq), thereby providing a simple method by which to functionalize readily available amine building blocks suitable for complex molecule synthesis. Our C–H carbonylation even produced unsubstituted b-lactam products from unbranched secondary amines, albeit in lower

Fig. 3. Mechanistic evaluation of the C–H carbonylation reaction. (A) Stoichiometric studies. (B) Kinetic isotope effect (KIE) studies. (C) Proposed mechanism for C–H carbonylation of aliphatic amines. In the insets, blue is nitrogen, teal is palladium, red is oxygen, and light gray is carbon. Dotted lines indicate breaking and forming bonds. Computational studies were conducted as in Fig. 2.
yields (due in part to by-products formed from N-acylation and b-hydride elimination) compared with those from the other amine types (2ar to 2as). As a whole, our scope studies demonstrate that the C–H carbonylation reaction tolerates a wide range of synthetic versatile functional groups spanning more than 40 examples, highlighting the generality of this transformation.

Application to complex molecules
Aliphatic amine motifs are present in at least 30% of small-molecule pharmaceutical agents and are heavily represented in preclinical candidates (40). Therefore, a major benefit of our aliphatic amine C–H carbonylation process is its potential amenability to mid- and late-stage functionalization applications (41). In more complex molecules, the competition between numerous Lewis basic functionalities capable of steering C–H activation could cause deactivation or selectivity issues.

Fig. 4. The scope of the aliphatic amine C–H carbonylation. Yields of isolated products are shown. All compounds are racemic. Piv, pivaloyl group; Et, ethyl group; Phth, phthalimido group; Cbz, carbobenzyloxy group.
To test this, we prepared an amine (1at) with three possible sites of C–H activation and found that C–H carbonylation was directed by the aliphatic amine motif (to form 2at) without any trace of the competitive pyridine-directed C–H activation product (Fig. 5A). To further the potential for late-stage functionalization, we subjected a selection of pharmaceutical derivatives and biologically active molecules to our C–H carbonylation protocol (Fig. 5B). Salbutamol and propranolol are β₂-adrenergic receptor agonists and are representative of a huge range of marketed pharmaceutical agents with a distinctive secondary amino alcohol. Simple derivatives of these molecules (6a and 6b) effectively underwent C–H carbonylation to form β-lactams (7a and 7b) in synthetically useful yields. A derivative of the acute heart failure drug dobutamine (6c) reacted smoothly to afford β-lactam in 72% yield (7c). Fenfluramine (6d), part of an anti-obesity treatment, was successfully carbonylated to yield a separable mixture of regioisomeric β-lactams (7d, 2.5:1), highlighting a moderate selectivity for the branched methyl group. Last, C–H carbonylation on the aza-sterol 6e, an inhibitor of the hedgehog-activating transmembrane protein Smoothened (42), formed the β-lactam 7e in useful yield, providing access to valuable analogs of this molecule that would be difficult to obtain by other means. A successful late-stage functionalization program would require the delivery of multiple analogs to get the maximum benefit from the strategy; β-lactams support a rich array of chemistry that can transform the amide function into pharmaceutically relevant motifs (43).

Removal of the hydroxyl-protecting group from β-lactam 7b yielded alcohol 8, reductive ring opening afforded β-amino alcohol 9, and esterification yielded β-amino ester 10 (Fig. 5C). Under certain reductive conditions, the β-lactam could be transformed into azetidine 11, an important structural feature that is common in many drug development programs (Fig. 5C), underlining the diversity of structural motifs readily available from this aliphatic C–H activation tactic.

**Outlook**

We expect this general C–H carbonylation process for aliphatic secondary amines to find broad application among practitioners of synthetic and pharmaceutical chemistry. In addition to the utility of this protocol, we anticipate that the distinct reactivity of free-NH aliphatic amines in combination with Pd catalysts will inspire further advances in a range of C–H activation processes. Moreover, this C–H carbonylation pathway is conceptually distinct from classical cyclopalladation-related approaches and may lead to opportunities for C–H activation reactions in other classes of functionalized aliphatic and aromatic molecules.

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**Fig. 5. Application to complex substrates.** (A) Regioselective C–H activation in the presence of competing directing groups. (B) Late-stage C–H functionalization on biologically active molecules. (C) Derivatizations of the β-lactam framework. TIPS, triisopropylsilyl; WHO, World Health Organization; Smo, Smoothened (protein); TBAF, tetrabutylammonium fluoride; THF, tetrahydrofuran; dr, diastereoisomeric ratio; rr, regioisomeric ratio; rt, room temperature.
REFERENCES AND NOTES

29. We considered a number of alternative pathways as part of our assessment of possible catalytic cycles. See the supplementary materials for details of these calculations.

ACKNOWLEDGMENTS

We gratefully acknowledge funding from the European Research Council and the UK Engineering and Physical Sciences Research Council (EPSRC) (to D.W., K.F.H., A.P.S., and M.J.G.), the Herchel Smith Trust (to B.G.N.C.), the Marie-Curie Foundation (to J.C.), and the Royal Society (Wolfson Merit Award to M.J.G.). Mass spectrometry data were acquired at the EPSRC UK National Mass Spectrometry Facility at Swansea University. Computational work was performed with the Darwin Supercomputer of the University of Cambridge High Performance Computing Service (http://www.hpc.cam.ac.uk/); provided by Dell, using Strategic Research Infrastructure Funding from the Higher Education Funding Council for England. The supplementary materials contain 1H and 13C NMR spectra and computational details. Crystallographic data are available free of charge from the Cambridge Crystallographic Data Centre under reference numbers CCDC-1508626 to CCDC-1508631.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/354/6314/851/suppl/D1C1

Materials and Methods

Figs. S1 to S3

NMR Spectra

References (44–55)