Unlocking the Chain-Walking Process in Gold Catalysis

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Abstract: The successful realization of gold-catalyzed chain-walking reactions, facilitated by ligand-enabled Au(I)/Au(III) redox catalysis, has been reported for the first time. This breakthrough has led to the development of gold-catalyzed annulation reaction of alkenes with iodoarenes by leveraging the interplay of chain-walking and π -activation reactivity mode. The reaction mechanism has been elucidated through comprehensive experimental and computational studies.

The chain-walking process, which refers to the movement of a metal complex along the alkyl chain through iterative migratory insertion and β -hydride elimination sequence, has emerged as a state-of-the-art technique in organic synthesis (Scheme 1a).¹ This strategy enables the utilization of alkene as a functional handle for the installation of functional groups at distant positions from the initial reaction centre. Over the past two decades, several unconventional and challenging reactions have been realized by employing this technique. For instance, Zhu,² He,³ Engle,⁴ Yuan/Zhang,⁵ and others⁶ utilized the chainwalking process for the remote C-H functionalization reactions (Scheme 1b). Advancing forward, Kochi,⁷ Yin,⁸ Lin/Yao,⁹ Wang,¹⁰ Zhou,¹¹ and Giri¹² group eloquently showcased its applicability in achieving the non-classical and challenging remote 1,n-difunctionalization of alkenes (Scheme 1c). Based on the aforementioned reactivities, recent developments extended the scope of the chainwalking process to olefin polymerization and copolymerization reactions thus emphasizing its importance in materials chemistry.¹³ Clearly, all these methodologies largely rely on the use of Pd, Ni, and Co catalysis. To expand the boundaries of this field beyond remote C-H functionalization and 1,n-difunctionalization reactions, the strategic use of chain-walking catalyzed by other transition metals should hold great promise for the discovery of new reactivity paradigms.

Over the past two decades, Au(I)/Au(III) redox catalysis has emerged as an important field of research wherein oxidative addition/reductive elimination/transmetalation steps are well developed.14 However, other fundamental processes of organometallic chemistry, such as migratory insertion and β -hydride elimination have received very little attention.¹⁵ Although there exists few reports on the viability of these fundamental elementary steps in a stoichiometric fashion,16 the chain-walking process in catalytic fashion has never been reported in gold chemistry. Recently, we demonstrated the feasibility of migratory insertion and β -hydride elimination steps in a catalytic fashion to achieve a gold-catalyzed Heck reaction.¹⁷ Later, the Xie group showcased the feasibility of the migratory insertion in gold-catalyzed iodo-alkynylation of benzynes.¹⁸ However, until now, there is no report exists on the goldcatalyzed chain-walking reactions.

Scheme 1. Transition metal-catalyzed chain-walking: general overview and present work.



Herein, we disclose the first example of a chain-walking process by utilizing ligand-enabled Au(I)/Au(III) redox catalysis. The strategic utilization of the chain-walking process led to the development of the annulation reaction of simple long-chain aliphatic alkenes with iodoarenes (Scheme 1d). In this transformation, alkenes act as four-carbon synthons and iodoarenes serve as two-carbon synthons. The key feature of this reaction involves the initial migratory insertion step to generate alkyl-Au(III) intermediate **I**, followed by a chain-walking process to form aryl alkene intermediate **II** which upon intramolecular cyclization through π -activation affords the annulation product. Such interplay between the chain-walking process and π -activation chemistry observed in the present

transformation underscores the unique reactivity profile offered by gold catalysis compared to other transition metals (Scheme 1b-c *vs* Scheme 1d).

At the outset, we chose 1-hexene 1a and 2-iodo-1methoxy-4-methylbenzene 2a as coupling partners to validate our hypothesis (Table 1). After performing preliminary screening of reaction conditions,¹⁷ we found that the reaction between 1a and 2a in the presence of MeDalPhosAuCl (10 mol%), AgOTf (1.1 equiv), and pyridine (0.7 equiv) in DCE (0.1 M) at 80 °C for 12 h of stirring delivered annulation product 3a along with the regioisomeric mixture of aryl alkenes 3a' in 60% combined yield (entry 1 in the parenthesis). With the intuition that prolonging the reaction time might promote the conversion of aryl alkene intermediates (3a') exclusively into the desired annulation product 3a, the reaction was stirred for 48 hours. Pleasingly, this led to an enhanced yield of 78% for 3a (entry 1). Further, deviation from the standard reaction conditions i.e. screening of silver salts (entries 2-4), bases (entries 5-6), and solvents (entries 7-8) had a detrimental effect on the reaction outcome.

Table 1. Optimization studies.[a],[b]



^[a]Reaction time 12 h. ^[b]Product **3a** along with the regioisomeric mixture of aryl alkenes **3a'**.

Having identified the optimal condition, we examined the scope of alkenes 1 by using 2-iodo-1-methoxy-4methylbenzene 2a as a model substrate (Scheme 2). To our delight, a wide range of alkenes 1a-1p reacted smoothly to afford the desired cyclized products 3a-3p in up to 87% yield. For instance, alkenes 1b-1f reacted smoothly under the standard reaction conditions to afford the corresponding products 3b-3f in 51-71% yield. Besides, the alkene tethered with phenoxide groups reacted with 2a to afford the desired product 3g and 3h in 51% and 55% yield, respectively. Furthermore, the alkene tethered with sulfone, dimethyl malonates, phthalimide, indole, and protected aniline also reacted smoothly with 2a to deliver the products 3i-3m in 44-59% yield. Notably, a single *cis*-diastereomer of product 3n was obtained in 74% yield when 1-vinyl-cyclohexane was used as an alkene source. Additionally, 4-substituted-1vinyl-cyclohexane derivatives (10-1p) also reacted efficiently to deliver the desired products **30-3p** in 60-87% yield as a single diastereomer. Next, we turned our attention to the scope of aryl iodides 2 (Scheme 2). Gratifyingly, a series of aryl iodides (2b-2p) having different substituents at ortho, meta, and para positions reacted smoothly to deliver the products 4b-4p in up to 96% yield as a single cisdiastereomer. For instance, iodobenzene (2b) reacted smoothly under standard reaction conditions to deliver the desired product 4b in 60% yield. Besides, para-substituted aryl iodides (2c-2h) reacted efficiently to afford the products 4c-4h in 56-96% yield. Further, mesyl-protected para-iodo-N-methylaniline 2i also reacted nicely to deliver the product 4i in 65% yield. Moreover, the products 4j and 4k were obtained in 87% and 58% yield when orthoiodoanisole (2j) and meta-iodoanisole (2k) were used as substrates. Additionally, para-iodoanisole bearing halo (Br, Cl) or electron-donating substituents also reacted smoothly under the standard reaction conditions, furnishing the corresponding products 41-40 in 47-87% yield with excellent chemoselectivity for the C(sp²)-I bond over other $C(sp^2)$ -X bonds (X = Br, Cl.; see entries 4l, 4m, 4o).

Interestingly, when the simple alkenes were replaced with appropriately substituted aryl alkenes 1q-1r, we observed the formation of 1,3-diarylation products 5a-5e and 1,3-hydroarylation products 6a-6b instead of regular annulation products (Scheme 3). This suggests that the allylic Heck products generated in the reaction could be directly intercepted by the tethered aryl ring to afford the observed products (*cf.* **III**).

A few mechanistic investigations were carried out to gain a deeper understanding of the reaction mechanism (Scheme 4). To begin, time-dependent experiments were performed to understand the plausible intermediates for the formation of products 3 or 4. In particular, when alkene 1a was treated with 2f under the standard reaction conditions, the allylic Heck product 7 was obtained in 80% yield in just 2 h;¹⁷ however, prolonged reaction time (14 h) resulted in the formation of 4p in 30% yield (Scheme 4a). Similarly, when alkenes 1n and 1p were reacted with aryl iodides 2, the chain-walking products 8a-8d were formed in 51-65% yield in 2-12 h;19 while, further extending the reaction time to 36-48 h resulted in the formation of cyclized products 4f, 4l, and 4o in 72%, 87%, and 47% yields, respectively (Scheme 4b). These control experiments (Schemes 4a and 4b) suggest that the allylic Heck product 7 and the chainwalking product 8 serve as intermediates in the formation of products 3 or 4. Next, when the deuterated alkene 10-D was treated with 2f in the presence of MeDalPhosAuCl (1 equiv) and AgOTf (2 equiv), the product 8e-D was obtained in 54% yield (Scheme 4c). The migration of deuterium from the C1 (80% D) to C2 (64% D) position in product 8e-D suggests that the chain-walking process is operative. Further, the alkene **1s-D** provided deuterium scrambling product 6c-D in 44% yield (Scheme 4c). The scrambling of deuterium (0.15 D at C3 and 0.30 D at C2) and loss of D at C1 (1.35 H) in the product clearly suggests that the chainwalking process is operational. Furthermore, the formation of 1,n-hydroarylated products 6a-6c (Scheme 3b) and incorporation of deuterium at the C3 position (0.15 D) in product 6c-D (Scheme 4c) indicates that the chain-walking process follows a dissociative pathway. Additionally, the cis ring fusion in compounds 3 and 4 (Scheme 2) implies the π activation mechanism.



Scheme 2. Scope of the gold-catalyzed annulation reaction of alkenes with iodoarenes^{[a],[b]}

^[a]Reaction conditions: 0.6 mmol 1, 0.2 mmol 2, 0.02 mmol MeDalPhosAuCl, 0.22 mmol AgOTf, 0.14 mmol pyridine, DCE (0.1 M), 80 °C. ^[b]Isolated yields.

Scheme 3. Gold-catalyzed 1,3-diarylation and 1,3-hydroarylation of alkenes.



^[a]Yield calculated with respect to alkene.

To support the proposed mechanism,¹⁹ DFT computations were performed with the Gaussian 16 set of program using 1-vinyl-cyclohexane and 4-iodoanisole as model substrates (Figure 1).¹⁹ The study revealed that insertion of the alkene into the Au–Ar bond requires 14.8 kcal/mol free energy of activation (**TSAB**) and is exergonic by 7.1 kcal/mol. As discussed in our previous study,¹⁷ the

resulting complex **B** shows a κ^1 -C coordination between gold and the ipso aryl carbon, making the benzylic hydrogen inaccessible for a *cis* β -H elimination. Lengthening of the *ipso*C–Au distance followed by β -H elimination resulted in the formation of the alkene complex **D** (-18.5 kcal/mol) through TSBD (-3.4 kcal/mol). Next, the insertion of the alkene moiety into the Au-H bond can provide the agostic complex E (-16.5 kcal/mol) through TS_{DE} (-13.0 kcal/mol). Lengthening of the Au-H distance revealed TSEF (-8.6 kcal/mol), leading to the non-agostic complex F (-14.2 kcal/mol). Flipping of the chair via TSFG (-11.3 kcal/mol) proved necessary to reach the agostic complex G (-15.9 kcal/mol). The endocyclic alkene complex H (-17.8 kcal/mol) could be connected to G after β -H elimination through TS_{GH} (-13.9 kcal/mol). Back-flipping of the pseudo-chair via TSHI (-12.1 kcal/mol) provided the more stable conformer I (-18.2 kcal/mol). Complex I is less stable than **D** by 0.3 kcal/mol, but once the gold hydride moiety is removed and the free alkenes optimized, the endocyclic one is more stable by 1.6 kcal/mol.¹⁹ It is also worthy of note that the dissociation of ${\bf I}$ into the gold hydride ${\bf J}$ and the experimentally-observed alkene 8a is exergonic by 2.2 kcal/mol (-20.4 kcal/mol). This is consistent with the fact that the formation of products 8 (Scheme 4b) is independent from that of the hydroarylation products (dissociative



pathway). Hydroarylation was modeled from **K** (-16.3 kcal/mol), which is simple conformer of **I** preorganized for

the *anti*-nucleophilic attack of the anisole fragment on the endocyclic alkene. A free energy of 23.7 kcal/mol must be overcome to reach $\mathbf{TS}_{\mathbf{KL}}$ (25.9 kcal/mol from **D**). The Wheland intermediate **L** (5.8 kcal/mol) is, of course, obtained in a markedly endergonic fashion. Its deprotonation by pyridine would lead to **M** (-24.6 kcal/mol). Its reductive elimination through $\mathbf{TS}_{\mathbf{MN}}$ (-21.8 kcal/mol) requires only 2.8 kcal/mol of free energy of activation. The experimentally observed *cis* product **N** (-57.6 kcal/mol) is finally obtained in a strongly exergonic manner. Various other modes of approach, as well as another Lewis acid ((P,N)Au(I)⁺), were tested, but these options proved more energetically demanding or ineffective.¹⁹

In conclusion, we have reported the first successful demonstration of the gold-catalyzed chain-walking under ligand-enabled Au(I)/Au(III) catalysis. Through the strategic utilization of chain walking, we have successfully developed gold-catalyzed annulation reaction of alkenes with iodoarenes. This methodology provided direct access to synthetically challenging tetrahydronaphthalene and octahydrophenanthrene derivatives with high diastereoselectivity. Given the realization of "chainwalking" in gold catalysis, along with the distinctive reactivities observed in contrast to other transition metals, we foresee significant opportunities emerging within the realm of organometallic catalysis.

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Figure 1. M11L/SDD+f(Au):6-311+G(d,p) free energy profile (ΔG_{298} , kcal/mol; some hydrogen atoms have been omitted for clarity; selected distances in Å).

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