Gold-catalyzed stereoselective dearomatization/metal-free aerobic oxidation: access to 3-substituted indolines/oxindoles†

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An unprecedented dearomatization of indoles with diazoesters has been developed via cationic gold(i) catalysis. The functionalization selectively occurs at the C3-position to deliver methylene indole derivatives in good yields with excellent Z-selectivity, demonstrating unusual reactivity and selectivity compared with other noble metal catalysis. Importantly, simply followed by silica gel adsorption, an unprecedented metal-free aerobic oxidation occurs for indoles bearing N-electron donating substituents, providing a novel and efficient approach towards 3-substituted indolin-2-ones with a newly formed quaternary stereocenter in excellent stereoselectivity. Notably, these processes afford direct and selective access to a variety of valuable intermediates from abundant feedstock chemicals.

Introduction

Transition-metal-catalyzed carbene transfer from diazo compounds represents a powerful tool in modern organic synthesis, allowing the rapid assembly of a range of valuable structures which cannot be easily achieved by other methodologies. Particularly, different metal-carbenes often exhibit distinct reactivity and selectivity toward the same reaction precursors, which increases molecular complexity. A good example is the reaction of diazoesters with 2,3-nonsubstituted indoles, which often leads to two principal products, namely cyclopropane derivatives (Scheme 1a) and formal C(sp2)–H insertion products (Scheme 1b). Indeed, for the addition reaction, the use of rhodium, copper, iron and palladium complexes selectively afforded C3-alkylation products. In contrast, C2-alkylation has been observed for 1H-indoles upon exposure to a ruthenium catalyst. Additionally, annulation and the N–H insertion reaction have also been reported.

On the other hand, recent literature disclosed that the reactivity and chemoselectivity of gold-carbene highly depended on the electronic and steric properties of the ancillary ligand to the gold center, as well as the choice of counterion. Variation of the gold catalysts has recently been shown to even allow the formation of gold(i) intermediates from gold(iii) precursors. In 2014, Shi and co-workers described a ligand-controlled gold-catalyzed addition of arenes to α-aryl diazoesters. They mentioned one example of indole C3-alkylation in the presence of an electron-deficient phosphite-gold catalyst, which exhibited similar chemo- and site-selectivity to rhodium and copper catalysis (Scheme 1b). However, we recently found that N-heterocyclic carbene (NHC) gold complexes displayed inverse chemoselectivity to phosphite gold catalysts even for the same substrates. Thus, we envisioned that, when exposed to different gold catalysts, the reaction of indoles with diazo compounds would probably result in distinct reaction pathways. In continuation with our interests in gold-carbene chemistry, as anticipated but not expected,

Scheme 1 Functionalization of indoles by metal-carbene transfer from diazo compounds: previous reports and our discovery.
herein we report the unprecedented stereoselective dearomation of indoles with diazoesters under cationic gold(I) catalysis (Scheme 1c). Furthermore, when N-electron-donating substituted indoles are utilized, an unprecedented metal-free aerobic oxidation occurs after the initial dearomation.

Results and discussion

At the outset, we employed N-boc indole 1a, N-benzyl indole 2a and phenyl diazoacetate 3a as model substrates to investigate the reaction (Table 1). The use of Ph3PAuCl/AgSbF6 (5 mol%) in dichloromethane at room temperature afforded C3-insertion product 5a in 70% yield (entry 1), while JohnPhosAuCl/AgSbF6 gave 16% yield of 5a (entry 2). When t-BuXPhosAuCl was used, 10% yield of 4a was obtained although 5a was still the major product (entry 3). Not surprisingly, the electron-deficient phosphite gold complex only gave 5a as a single product (entry 4). Gratifyingly, the use of IPrAuCl/AgSbF6 provided 4a in 70% yield (entry 5). We therefore started to survey other NHC gold complexes as well as to try different counterions. To our delight, the yield of 4a was improved to 79% by IPrAu(PhCN)SbF6 (entry 6), and was further increased to 81% by IPrAu(PhCN)BARF (entry 7). A screen of the solvents revealed chloroform was the best one (entries 8 to 11), providing 4a in 87% yield (entry 9), and no significant side products were detected. The structure of 4a was confirmed with NMR spectroscopy and was further identified using X-ray analysis. Notably, when N-benzyl indole 2a was subjected to this reaction, the corresponding 3-methylenindoline was not obtained and 3-substituted indolin-2-one 6a was obtained instead in 77% yield (entry 12, see ESI† for details), indicating that an aerobic oxidation occurred. Variation of the solvents did not improve the reaction (entries 13 to 15).

We then started to explore the substrate scope for the first dearomation (Scheme 2). The reaction of indole 1a with a variety of diazoesters was firstly examined. It was observed that methyl phenyl diazoacetate gave the corresponding product in better yield than other esters (4a to 4d). Aromatic diazoesters with different substituents were employed, providing the corresponding 3-methylenindolinones in moderate

Table 1  Optimization of the reaction conditions

| Entry | Indole | Catalyst | Solvent | 4a (5a) | 6a |
|-------|--------|----------|---------|---------|-----|
| 1     | 1a     | Ph3PAuCl/AgSbF6 | CH2Cl2 | 0 (%)    | —   |
| 2     | 1a     | JohnPhosAuCl/AgSbF6 | CH2Cl2 | 0 (%)    | —   |
| 3     | 1a     | t-BuXPhosAuCl/AgSbF6 | CH2Cl2 | 10 (%)   | —   |
| 4     | 1a     | [ArO]PAuCl/AgSbF6 | CH2Cl2 | 0 (%)    | —   |
| 5     | 1a     | IPrAuCl/AgSbF6 | CH2Cl2 | 70 (%)   | —   |
| 6     | 1a     | IPrAuPhCN/AgSbF6 | CH2Cl2 | 10 (%)   | —   |
| 7     | 1a     | IPrAuPhCN/AgSbF6 | DCE    | 81 (%)   | —   |
| 8     | 1a     | IPrAuPhCN/AgSbF6 | DCE    | 81 (%)   | —   |
| 9     | 1a     | IPrAuPhCN/AgSbF6 | CHCl3  | 87 (%)   | 3a   |
| 10    | 1a     | IPrAuPhCN/AgSbF6 | Toluene | 70 (%)  | 7a   |
| 11    | 1a     | IPrAuPhCN/AgSbF6 | THF    | 25 (%)   | 3a   |
| 12    | 1a     | IPrAuPhCN/AgSbF6 | CHCl3  | 10 (%)   | —   |
| 13    | 1a     | IPrAuPhCN/AgSbF6 | DCE    | 65 (%)   | —   |
| 14    | 1a     | IPrAuPhCN/AgSbF6 | THF    | 50 (%)   | —   |
| 15    | 1a     | IPrAuPhCN/AgSbF6 | THF    | 50 (%)   | —   |

a Reaction conditions: 1a or 2a (0.2 mmol) and 3a (0.3 mmol) in 2 mL of the solvent were added to a solution of 5 mol% gold catalyst in 2 mL of the solvent via a syringe pump under argon for 2 h. The mixture was stirred at rt for another 2 h. For 6a, silica gel (5 g) adsorption of crude products was performed and was kept in air for 12 h at rt. b Isolated yields. (ArO) = (2,4-di-tert-butylphenyl).
to excellent yields (4e to 4k). In general, electron-deficient aromatic diazoesters furnished the products (4e to 4i) in higher yields than electron-rich substrates (4j to 4k). Next, the scope of indoles was investigated. Gratifyingly, C5-, C6- and C7-substituted N-boc indoles bearing either electron-withdrawing or electron-donating groups were all tolerated, furnishing the corresponding indolines in moderate to excellent yields (4l to 4p). Furthermore, different N-substituted indoles were also examined. The protecting groups such as tosyl (Ts), benzyloxycarbonyl (Cbz), benzoyl (Bz) and acetyl (Ac) were all amenable to the reaction and the corresponding products were obtained in acceptable yields (4q to 4t). This protocol was also amenable to pyrroles. The desired dearomatization products were isolated in good yields (4u to 4x). The structure of 4x was further confirmed by single-crystal X-ray crystallography. It should be noted that all of the methylene derivatives were isolated in the single Z-configuration.

Next, we investigated the substrate scope of the tandem reaction towards the formation of 3-substituted indolin-2-ones (Scheme 3). Generally, the reaction of 2a with aromatic diazoesters either bearing electron-donating or electron-withdrawing substituents proceeded smoothly to afford the corresponding products in moderate to good yields (6a to 6h). A longer oxidation time (24 h) is needed for 6e to 6h. Afterwards, indoles bearing various substituents were examined. The use of N-methoxy and N-bromo indoles provided 6i and 6j in 81% and 74% yield, while 6-chloro and 6-methyl delivered the corresponding products in 75% and 78% yield, respectively. 7-Methoxy N-benzyl indole was also examined, and 6m was isolated in 53% yield. Finally, N-methyl and N-phenyl indoles were tested and the corresponding products (6n and 6o) were obtained in moderate yields. The structure of 6a and 6l was confirmed by X-ray analysis.

Deuterium labeling and control experiments were conducted to understand the reaction mechanism (Scheme 4). First, 4a cannot be converted to 5a under standard reaction conditions (Scheme 4a), which ruled out the possibility of preferential formation of 5 followed by isomerization and vice versa. Next, the reaction of D-1a with 3a yielded D-4a. The high deuterium incorporation at the 2-position might indicate that a 1,2-hydrogen shift is likely involved in the reaction (Scheme 4b). Since there is significant loss of deuterium, we suspected that the reaction may be interfered with by adventitious water present in the reaction mixture. Thus, a control reaction with 3 equivalents of D2O was run. Indeed, significant deuterium incorporation into the product was observed (Scheme 4c), suggesting that there is D/H exchange with the adventitious proton source during the reaction’s progress. A study on the kinetic isotope effect (KIE) using intermolecular competition between 1a and D-1a indicated a KIE value of 3.35 (Scheme 4d), which is consistent with the 1,2-hydrogen shift being the rate-determining step. Furthermore, compound 7 was separately prepared and subjected to standard reaction conditions. Unfortunately, no reaction was observed. The chemical incompetence of 7 rules out its possible role as an intermediate in this process (Scheme 4e).

Next, mechanistic studies for the aerobic oxidation were carried out (Scheme 5). First, the reaction of D-2a with 3a gave D-6a in 73% yield with a low ratio of deuterium labeling (Scheme 5a). Moreover, the 18O-labeled product 6a' was
obtained in 78% yield under an $^{18}$O$_2$ atmosphere, indicating that the oxygen atom in 6 came from the air (Scheme 5b). Using TBHP (tert-butyl hydroperoxide) instead of air as an oxidant, the reaction was messy although 6a could still be detected by GC/MS (Scheme 5c). To determine the role of the silica gel, p-toluene sulfonic acid was added and the C-3 alkylation product 8 was obtained in high yield (Scheme 5d). Moreover, by replacing the silica gel with anhydrous MgSO$_4$, 6a was isolated in 68% yield upon exposure to air for 12 h (Scheme 5d). Therefore, the acidic property of the silica gel may not be critically important for this transformation. Its role is presumably to facilitate the aerobic oxidation by increasing the contact surface of the olefin intermediate with oxygen. Just recently, López and co-workers reported the gold-catalyzed formal insertion of aryl diazoesters into ferrocene to generate functionalized metallocenes.$^{18}$ Clearly, this gold-catalyzed dearomatization is quite different from these known processes.$^{19,20}$ Although the exact reaction mechanism is not clear at this moment, plausible ones have been proposed (Scheme 6). In view of the unique formation of Z-olefins, the carboxylate group may assist the olefin selectivity. Partially analogous to Fox’s description of rhodium-catalyzed C-3 alkylation of indoles with diazoesters$^{14}$ and density functional theory (DFT) calculations reported by Xie et al.,$^{17}$ the reaction of 3a with the cationic gold catalyst first generates gold carbene species IA or IB, which is followed by nucleophilic attack with indole to produce ylide III via transition state II. Then this ylide intermediate would undergo a 1,2-hydrogen shift to give the final dearomatization intermediate IV, together with catalyst regeneration. The assistance of the ester carbonyl group explains the Z-configuration of the observed product. Next, silica gel-assisted aerobic oxidation occurs. The reaction of IV with molecular oxygen generates intermediate V via the Schenck ene reaction.$^{21}$ Owing to the high oxidation ability of the
peroxide motif and the electron-rich nature of the indole ring, subsequent internal epoxidation can rapidly take place via either $\text{VI}$ or $\text{VII}$. Finally, semi-pinacol rearrangement of $\text{VI}^2$ or rearrangement of the amino epoxide motif in $\text{VII}^3$ leads to the observed amide. Considering the high reactivity of peroxide V, the epoxidation step occurs on the same face of the indole plane once it is formed (C–C bond rotation is thus discouraged). In this scenario, the stereochemistry integrity determines the high diastereoselectivity observed in the final product.

Conclusions

In summary, we have developed an unprecedented gold-catalyzed stereoselective dearmatization of indoles with diazoesters, providing 3-methylenindolines in good to excellent yields with unique Z-configuration. Moreover, when N-donating substituent indoles were subjected to the reaction, a tandem reaction sequence occurred including the initial dearmatization and a sequential metal-free aerobic oxidation to produce 3-substituted indol-2-ones. As a result, molecular oxygen has been successfully inlaid into the final structure. Notably, the use of the cationic gold(i) catalyst IPrAu(PhCN)BAR$_F$ is crucial to the whole process.

Conflicts of interest

There are no conflicts to declare.

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