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Gold-catalyzed hydrofunctionalization of allenes with nitrogen and oxygen nucleophiles and its mechanistic insight

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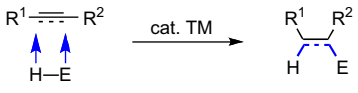
ABSTRACT

A wide range of nucleophiles, such as amines and alcohols, reacted intermolecularly with various allenes in the presence of gold catalysts to give the corresponding hydrofunctionalization products in high yields. The intermolecular hydroamination of chiral allenes with aromatic and aliphatic amines proceeded with high to good enantioface selectivities to afford the corresponding chiral allylic amines. On the other hand, in the case of the intermolecular hydroalkoxylation of chiral allenes, no chirality transfer was observed. This marked contrast on the chirality transfer indicates that the mechanisms of gold-catalysis between hydroamination and hydroalkoxylation are different.

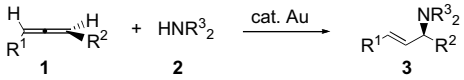
1. Introduction

The utility of gold complexes as catalysts in organic transformations has received much attention in recent years, because of their unique electronic structure, soft carbophilic nature, which can activate unsaturated C–C bonds toward nucleophilic attack, high potential for catalysis, and only partially defined information on their reactivities and mechanisms.[1] Hydrofunctionalization, that is, the formal addition of a H–E bond across an unsaturated C–C bond both in an intra- and intermolecular manner, is a direct and efficient procedure for the synthesis of various heterocycles and heteroatom-containing compounds (Scheme 1).[2]



Scheme 1.

In the addition of an electron-rich H–E bond to an electron-rich C–C unsaturated bond, a high activation barrier exists. Accordingly, such an addition does not proceed *without a catalyst*. The attack of nucleophiles under basic conditions has been studied widely, but the use of transition metal catalysts is more favorable for the addition of nucleophiles than the use of bases, primarily due to their effectiveness and milder conditions. The control of the stereochemistry and enantioselectivity through the addition process is another challenge in the transition metal catalyzed addition, especially when allenes are used as substrates.[3] Herein we report the gold-catalyzed intermolecular hydroamination and hydroalkoxylation of allenes **1**, which afford allylic amines **3** and allylic ethers **8**, respectively, in very high yields under mild conditions (Eqs. 1 and 2).



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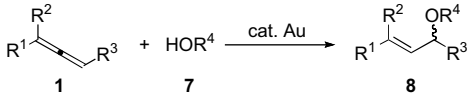

(2)

While exploring the scope and limitation of hydroamination and hydroalkoxylation, we found that enantioface selectivity and chirality transfer in hydrofunctionalization of chiral allenes depended on nucleophiles. The details on the scope of the

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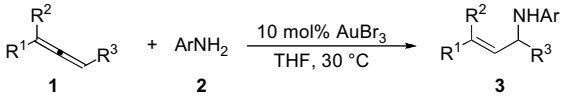
hydrofunctionalization, together with the mechanistic consideration of the gold-catalysis based on the chirality transfer experiments, are reported in this paper. The reactions described herein were handled under dry conditions using Ar atmosphere, and it was confirmed that the reactions were really catalyzed by gold complexes and not by a Brønsted acid (proton). This confirmation is very important, since it has been revealed recently that some transformations using gold complexes are not gold-catalyzed reactions but in reality proton-catalyzed reactions.[4]

2. Results and discussion

2.1. Hydroamination of allenes with aromatic amines

Hydroamination is the formal addition of an N–H bond across a C–C multiple bond.[5] The direct addition of amines to C–C multiple bonds is slightly exothermic or approximately thermoneutral process,[6] however, the reaction is hampered by a high activation barrier caused by electrostatic repulsion between the electron-rich π-bonds and the amine nitrogen bearing a lone pair.[6] Toward alkenes, [2+2] cycloaddition of N–H would be an orbital symmetry-forbidden, and unfavorable due to the high-energy gap between π(C=C) and σ(N–H).[6] The hydroamination can be mediated or catalyzed by alkali metals, transition metals, or lanthanide/actinide, which decrease the activation barrier.[5] For transition metal catalyzed intermolecular hydroamination of allenes, only few examples are known; the group IV metal catalysis,[7] palladium catalysis,[8] and recent gold catalysis.[9] We found that the intermolecular hydroamination of allenes **1** with aromatic amines **2** took place in the presence of a catalytic amount of $AuBr_3$ in THF at 30 °C to give the corresponding allylic amines **3** in good to high yields (Eq. 3).

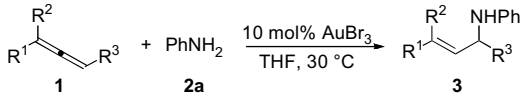


1 2 3 (3)

The scope of the hydroamination of allenes with aniline is summarized in Table 1. In the presence of 10 mol % $AuBr_3$, the reaction of *p*-tolylallene **1a** with 2 equiv of aniline **2a** in THF proceeded smoothly at 30 °C, and the corresponding allylic amine **3a** was obtained in 81% yield (entry 1). The nitrogen nucleophile was introduced on the less substituted terminal carbon of the allene regioselectively. The addition of the nitrogen nucleophile to the central carbon did not take place at all. The stereochemistry of **3a** was determined as *E*, judging from the coupling constant of olefinic protons (J=15.9 Hz). Monosubstituted aryl- and alkylallenes **1b**–**1h** proved to be good substrates for the hydroamination (entries 2–8). The sterically bulky allene **1i** gave **3i** in a lower yield (entry 9). The 1,3-disubstituted allenes **1j** and **1l** showed reactivities comparable to the monosubstituted allenes (entries 2 vs 10, and 7 vs 12), however, the 1,1-disubstituted allenes **1k** and **1m** exhibited extremely low reactivities (entries 11 and 13). Interestingly, the hydroamination proceeded very smoothly with allenes **1o**–**1q** bearing an olefin moiety tethered by an appropriate carbon chain (n=2–4) (entries 15–17).[10] However, in the case of n=1 (allylallene, **1n**), the effect of the olefin was not remarkable (entry 14). The enhancement of the reactivity may be due to the coordination of the olefin to an Au species, which would bring the allenic moiety close to Au. On the other hand, the alkyne-bearing allenes **1r** and **1s** showed low reactivities, and it was thought that the coordination of the alkyne to an Au species would be too strong to proceed the catalytic hydroamination of allenes (entries 18 and 19). A complex mixture of products was obtained from the reaction of **1r**, and the desired allylic product **3r** was detected only by GC–MS.

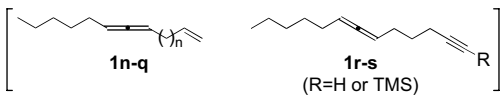
This hydroamination likely proceeds through the complexation of gold and amine, followed by the coordination of allenes. The

Table 1
Gold-catalyzed intermolecular hydroamination of allenes **1** with aniline (**2a**)[a]



1 2a 3

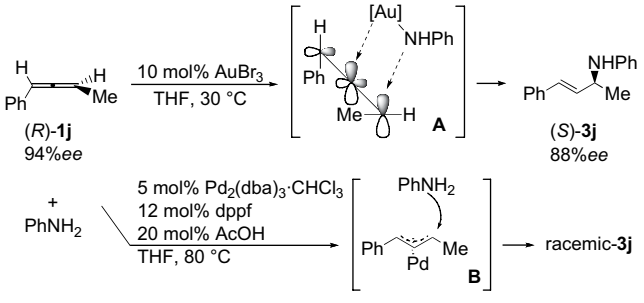
Entry	1	R^1	R^2, R^3	Time, h	3	Yield[b], %
1	**1a**	4-Me–C_6H_4	H	2	**3a**	81
2	**1b**	Ph	H	3	**3b**	78
3	**1c**	4-OMe–C_6H_4	H	2	**3c**	78
4	**1d**	4-Cl–C_6H_4	H	3	**3d**	73
5	**1e**	4-F–C_6H_4	H	6	**3e**	81
6	**1f**	Bn	H	2	**3f**	80
7	**1g**	*n*-Oct	H	1	**3g**	70
8	**1h**	Cy	H	1	**3h**	75
9[c]	**1i**	*t*-Bu	H	12	**3i**	34



Entry	1	R^1	R^2	R^3	Time, h	3	Yield[b], %
10	**1j**	Ph	H	Me	6	**3j**	68[d]
11	**1k**	Ph	Me	H	5	**3k**	9[e]
12	**1l**	*n*-Pent	H	*n*-Pent	3	**3l**	84
13	**1m**	*n*-Pent	*n*-Pent	H	18	**3m**	0
14	**1n**	*n*-Pent	H	Allyl (n=1)	3	**3n**	58[f]
15	**1o**	*n*-Pent	H	Butenyl (n=2)	1	**3o**	87[f]
16	**1p**	*n*-Pent	H	Pentenyl (n=3)	1	**3p**	96[f]
17	**1q**	*n*-Pent	H	Hexenyl (n=4)	1	**3q**	88[f]
18	**1r**	*n*-Pent	H	Pentynyl (R=H)	24	**3r**	Trace
19	**1s**	*n*-Pent	H	TMS-pentynyl	24	**3s**	40[f]

[a] To a mixture of **2a** (1.0 mmol) and catalyst (10 mol %) in THF (1 M) was added **1** (0.50 mmol) and the mixture was stirred at 30 °C.
[b] Isolated yield.
[c] Reaction was stopped after 12 h.
[d] A regioisomeric product was not detected.
[e] Combined yield of stereoisomers (*Z*/*E*=2:1, determined by ^{1}H NMR).
[f] Combined yield of the isolated regioisomers (the ratio was about 1:1, as determined by chiral HPLC).

presence of a gold-amine complex is postulated by the fact that there was an induction period for the hydroamination, and the yield was decreased when $AuBr_3$ was not exposed to the amine prior to the addition of allenes. During the investigation of hydroamination, we discovered that the chirality of allenes can be transferred on to the product, effectively. The hydroamination of (*R*)-**1j** (94% ee) with aniline produced (*S*)-**3j** in 68% yield with 88% ee. The results strongly suggest that the gold–amine complex is formed first, which approaches to the double bond of allene from less hindered side, and then the addition to the allene takes place as shown in **A**, Scheme 2. If $AuBr_3$ behaved merely as a Lewis acid, which would activate the double bond of allene and aniline attacks from the face opposite to gold coordination, (*R*)-**3j** would have been obtained. If a gold π-allyl complex was involved as a key intermediate in a similar manner to that of the palladium-catalyzed

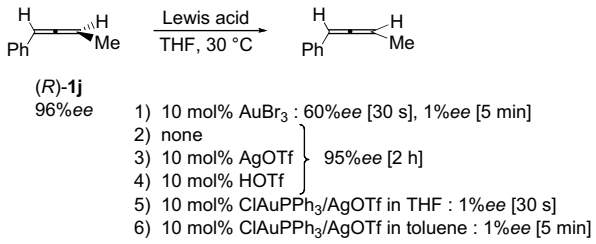


Scheme 2. Hydroamination of chiral allenes with aniline (**2a**).

hydroamination (**B**),[8] racemic **3j** should be obtained. It should be noted that all four selectivity problems of substituted allenes (positional selectivity, chemoselectivity, regioselectivity, and stereoselectivity)[3] have been solved in the formation of (*S*)-**3j**.

The chiral allene (*R*)-**1l**, which bears the same substituent on the terminal carbons of allene, was also used for the reaction with aniline, *ortho*-, *meta*-, and *para*-toluidine. The hydroamination of (*R*)-**1l** with aniline gave (*S*)-**3l** in 84% yield with 99% ee. Similarly, the use of toluidines instead of aniline afforded the corresponding chiral allylic amines in good yields with high ee values (*ortho*-toluidine; 51% yield 86% ee, *meta*-toluidine; 79% yield 96% ee, *para*-toluidine; 79% yield 99% ee).

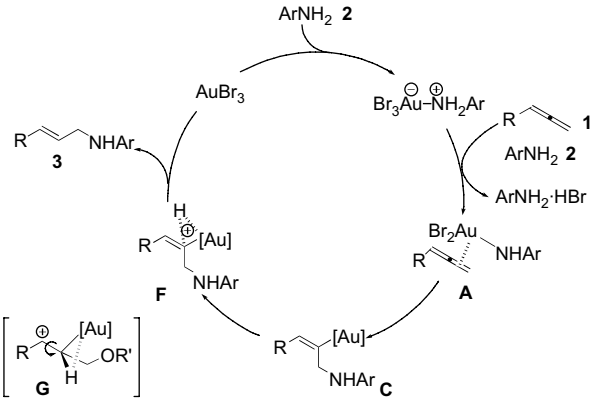
Furthermore, formation of the amine–gold complex was strongly supported from the fact that, in the absence of an amine, rapid racemization of allene (*R*)-**1j** occurred (Eq. 4, entries 1),[11] while, in the presence of an amine, highly efficient chirality transfer was accomplished. This chiral allene **1j** did not racemize in THF after 2 h in the absence of the gold catalyst (entry 2). Racemization did not take place after 2 h in the presence of either Lewis acid (AgOTf) or Brønsted acid (HOTf) (entries 3 and 4). In the presence of a reactive cationic gold, $ClAuPPh_3$/AgOTf, extremely rapid racemization took place (entries 5 and 6). Three types of intermediates are conceivable; gold–amine salt type complex [$Br_3Au\cdot NH_2Ph$], gold–amide complex [Br_2Au–NHPh], and gold–imide complex [BrAu=NPh]. The latter two intermediates can be generated effectively by the removal of a Br from $AuBr_3$. However, when AgOTf was added to a THF solution of $AuBr_3$ to promote the removal of a Br, the hydroamination of **1a** did not proceed at all. Accordingly, it seems that the gold–amide or gold–imide complexes are not involved as the intermediates in this hydroamination, but the complex [$Br_3Au\cdot NH_2Ph$] is most probably involved as an intermediate. The mechanism will be discussed later, in Scheme 4.



(4)

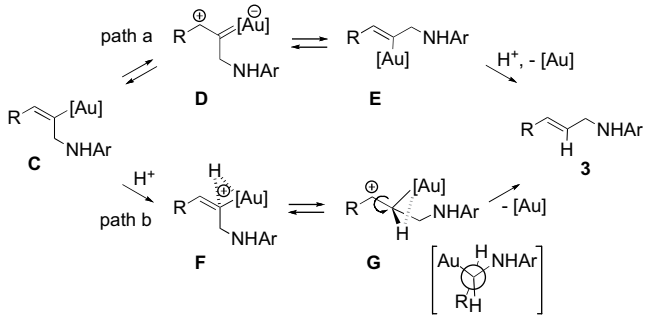
In our previous communication,[9a] we could not give a clear-cut explanation why the *E*-allylic amine **3** was produced from *E*-vinyl gold intermediate **C** in the last protonation step. In the previous communication, we postulated an equilibrium between the *E*-isomer **C** and the *Z*-isomer **E** through gold–carbene intermediate **D** (Scheme 3, path a). More recently, although we carefully monitored the reaction progress using NMR at −50 °C, we could not detect the formation of the *Z*-allylic product at all. Accordingly, we want to propose that the protonation of intermediate **C** proceeds as shown in path b. A review article on the mechanistic studies for protonolysis using platinum complexes has appeared recently.[12a] In this review, the authors noted the reaction of gold complexes and stated that a three-centered intermediate would be favorable in the protonolysis. Analogously, the formation of *E*-allylic amines most probably takes place via the three-centered intermediate **F** as shown in path b. In this pathway, the carbon attached by gold becomes sp^3 and the rotation around C–C single bond allows **G** intermediate to take *gauche* conformation. Elimination of gold occurs to form the corresponding *E*-allylic amines **3**.

Consequently, a plausible mechanism for the hydroamination is shown in Scheme 4.

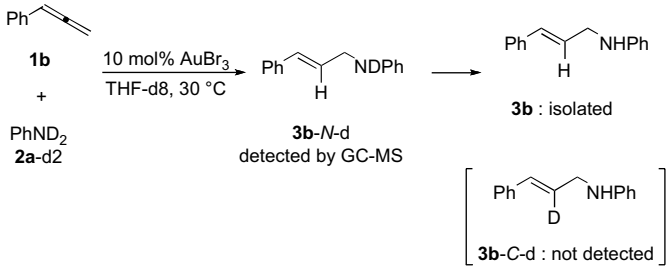


Scheme 4. A plausible mechanism.

To obtain further information on the mechanism, the hydroamination was investigated with deuterated aniline $PhND_2$ (Eq. 5). Formation of **3b**-*N*-d was detected by GC–MS analysis, but the isolated product was **3b** because facile proton-exchange took place during isolation process. When $PhND_2$ (75% D), which was prepared in our laboratory, was used, the yield of **3b** was 42%, but the yield became below 20% when commercially available highly deuterated $PhND_2$ (99% D) was used. The deuterium isotope effect was calculated as 3.17 by comparing the initial reaction rate with aniline and that with deuterated aniline in THF-d_8. The obtained deuterium isotope effects clearly suggest that the N–H(D) cleavage step exerts significant influence on the reaction speed and reaction progress. It should be noted that, while the *N*-deuterated allylic amine **3b**-*N*-d was detected by GC–MS analysis, the carbon-deuterated product **3b**-*C*-d was not detected at all. Similar observation was made by NMR analysis. It is not clear why deuteration on carbon, that is, formation of **3b**-*C*-d, did not take place.



Scheme 3. Protonation step for gold–carbon bond.



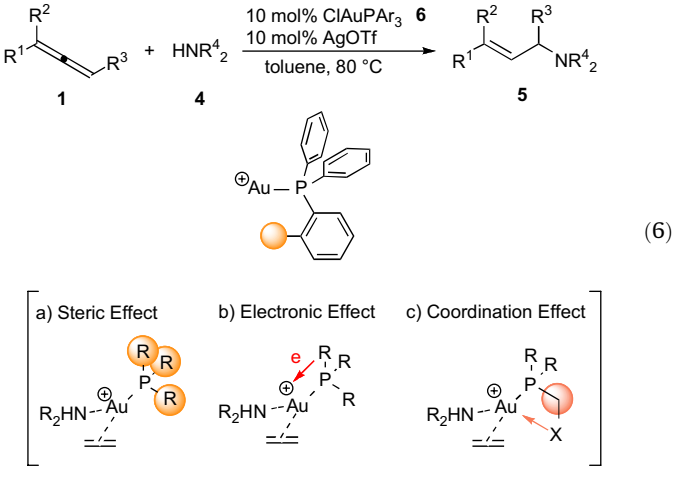
(5)

2.2. Hydroamination of allenes with aliphatic amines

The intermolecular hydroamination with aliphatic amines is rather difficult compared to that with aromatic amines, although the intramolecular version with aliphatic amines is known.[13] The $AuBr_3$ catalysis system described above did not work with the aliphatic amines at all. For the intermolecular hydroamination with aliphatic amines, the amine activation system has been studied using hard transition metals. Lanthanide,[14] actinide,[14] and early transition metals[15] have been utilized due to their high affinity to hard aliphatic amines, despite their instability, which demands highly careful handling for preparation and usage of those catalysts. The olefin activation system is also known, but in reality the olefin is not a simple aliphatic alkene but styrene.[16] In the case of our $AuBr_3$ catalysis system, the less basic and less hard aromatic amines are activated by $AuBr_3$ prior to the activation of an allene double bond, thus we thought that strong coordination of hard and basic aliphatic amines to gold center would inhibit the hydroamination. Therefore, the structural tuning of gold center in order to prevent such strong coordination had to be realized for the hydroamination with aliphatic amines.

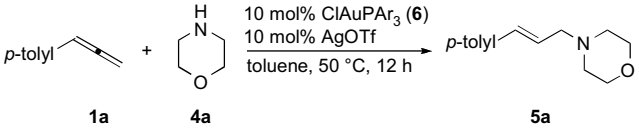
It is known that the cationic gold(I)–phosphine system, such as $ClAuPPh_3$/AgOTf, is an efficient catalyst for the addition of carbon, oxygen, and nitrogen nucleophiles to C–C unsaturated bonds.[5a,17] In the case of the hydroamination with aromatic amines, it also exhibited good catalytic activity though the efficiency was moderate. Therefore, we searched the ligands on gold suitable to the intermolecular hydroamination with aliphatic amines. After many attempts, we found that the intermolecular hydroamination of the allenes **1** with the aliphatic amines **4** took place using the cationic gold(I) catalysts with the phosphine ligand PAr_3 in toluene to give the corresponding allylic amines **5** in high to moderate yields (Eq. 6). Furthermore, we uncovered that the steric effect rather than electronic effect of PAr_3 in the catalyst system, $ClAuPAr_3$ **6**/AgOTf, was important for enhancing the yield of the corresponding product.

We planned to utilize $ClAuPAr_3$ derivatives, which are in situ converted into cationic species in the presence of AgOTf, as catalysts (Eq. 6). In order to make discussion on the reaction mechanism more straightforward and to make the steric effect of the ligands more clear-cut, only small structural change of PAr_3 is desirable. In the plan (a), the steric effect of R must exert significant influence on the reactivity, since strong interaction between basic aliphatic amines and gold is alleviated and thereby the amino-auration to a double bond is facilitated. It is also expected that the last elimination step is influenced by the steric effect. In the plan (b) and (c), the electron-donating effect or coordinative effect of X group is expected to decrease the cationic nature on gold center and thereby to diminish the amine–gold interaction facilitating the amino-auration process.



(6)

In the initial experiment, we examined the intermolecular hydroamination of *p*-tolylallene (**1a**) with morpholine (**4a**) in the presence of a catalytic amount of $ClAuPPh_3$ **6a** or $ClAuPPh_2$(*o*-anisyl) **6e**, together with AgOTf (Eq. 7). In the presence of 10 mol % of the in situ generated cationic gold(I)–phosphine catalyst, the reaction of allene **1a** and morpholine (**4a**) in toluene proceeded at 50 °C. After 12 h, the corresponding allylic amine **5a** was obtained in 17% yield using **6a**, and in 49% yield using **6e**. The X-ray diffraction of **6e** (Fig. 1) revealed that an oxygen atom faced to gold center, and O and Au atom was located within coordinative distance.



(7)

Further optimization led us to find that the reaction of allene **1a** (1.2 equiv) and morpholine (**4a**) in toluene proceeded smoothly at 80 °C in the presence of 10 mol % of the in situ generated cationic gold(I)–PPh_3 catalyst, and the corresponding allylic amine **5a** was obtained in 64% yield after 12 h (Table 2, entry 1). The reaction under this optimized condition gave **5a** in ca. 40% yield at 50 °C or at 120 °C, and in 60% yield at 100 °C. Other catalysts, such as AgOTf, CuOTf–benzene complex, $Cu(OTf)_2$, TfOH, and gold halide, did not promote the hydroamination at all.[18] In the absence of AgOTf and by merely using **6**, no reaction occurred, therefore we confirmed the efficiency of cationic gold species in this reaction.[19] The use of AgOTf among many silver salts examined gave the best result.

Comparison of the effect of PAr_3 on the hydroamination is summarized in Table 2. When $ClAuPPh_3$ (**6a**) was used, the product was obtained in 64% yield, which was comparable to the result using $ClAuPPh_2$(*o*-anisyl) (**6e**) (entries 1 and 5). Thus, the coordinating effect of anisyl-moiety on the reactivity was not remarkable under this optimized condition. To improve the yield of **5a**, we applied $ClAuP(t\text{-}Bu)_2$(*o*-biphenyl) (**6b**),[2d,20] which Widenhoefer and Han found as a very efficient catalyst for intramolecular hydroamination. However, the yield decreased slightly, suggesting that the result of the intramolecular reaction is not necessarily applicable to the intermolecular version (entry 2). Thus, we started to search for better catalysts in the present reaction system.

The catalysts bearing an electron-donating or electron-withdrawing group at *para* position (*p*-OMe **6c** and *p*-CF_3 **6d**) show reactivity comparable to $ClAuPPh_3$ (**6a**), indicating that the influence of electronic effect upon the chemical yield is not so strong (entries 3 and 4). Next, we introduced heteroatom-containing

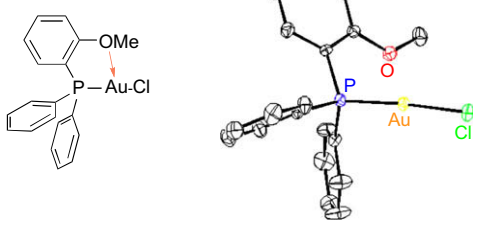
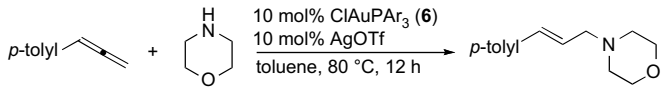
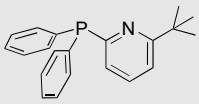


Figure 1. The structure of complex **6e**; selected bond distances (Å) and angles (°): Au–P, 2.2312(11); Au–Cl, 2.3001(12); Au–O, 3.360(3); P–Au–Cl, 175.96(3).

Table 2
Au(I)-catalyzed hydroamination of allene **1a** with morpholine (**4a**) using various Au(I) complexes **6**[a]

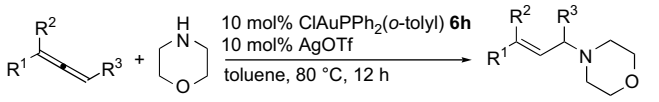


1a **4a** **5a**

Entry	PAr_3	**6**	Yield[b], %
1	PPh_3	**6a**	64
2	P(*t*-Bu)$_2$(*o*-biphenyl)	**6b**	51
3	PPh_2(*p*-anisyl)	**6c**	62
4	PPh_2(*p*-CF_3–C_6H_4)	**6d**	63
5	PPh_2(*o*-anisyl)	**6e**	63
6	PPh_2(*o*-OH–C_6H_4)	**6f**	27
7	PPh_2(*o*-pyridyl)	**6g**	30
8	PPh_2(*o*-tolyl)	**6h**	83
9	PPh(*o*-tolyl)$_2$	**6i**	79
10	P (*o*-tolyl)$_3$	**6j**	32
11		**6k**	59

[a] To a mixture of **4a** (0.5 mmol) and catalyst (10 mol %) in toluene (1 M) was added **1a** (0.60 mmol) and the mixture was stirred at 80 °C for 12 h.
[b] Isolated yield.

Table 3
Gold-catalyzed intermolecular hydroamination of allenes **1** with morpholine (**4a**)[a]



1 **4a** **5**

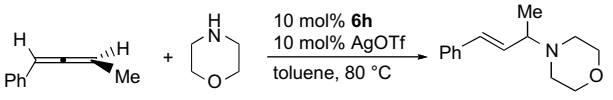
Entry	**1**	R^1	R^2	R^3	Time, h	**5**	Yield[b], %
1	**1a**	*p*-Tolyl	H	H	12	**5a**	83
2	**1b**	Ph	H	H	24	**5b**	66
3	**1c**	*p*-Anisyl	H	H	6	**5c**	95
4	**1e**	*p*-F–C_6H_4	H	H	24	**5e**	74
5	**1f**	Bn	H	H	12	**5f**	56
6	**1g**	*n*-Oct	H	H	9	**5g**	46
7	**1h**	Cy	H	H	12	**5h**	39
8	**1i**	*t*-Bu	H	H	24	**5i**	4[c]
9	**1j**	Ph	H	Me	36	**5j**/**5j′**	74/14[d]
10	**1k**	Ph	Me	H	36	**5k**	17[e]
11	**1l**	*n*-Pent	H	*n*-Pent	36	**5l**	80
12	**1m**	*n*-Pent	*n*-Pent	H	36	**5m**	0

[a] To a mixture of **4a** (0.5 mmol) and catalyst **6** and AgOTf (10 mol %) in toluene (1 M) was added **1** (0.60 mmol) and the mixture was stirred at 80 °C.
[b] Isolated yield.
[c] Reaction was finished after 24 h.
[d] Yield of regioisomer.
[e] Combined yield of stereoisomer (*E*/*Z*=1:1, determined by ^{1}H NMR).

groups at *ortho* position (*o*-OH **6f** and *o*-pyridyl **6g**[21]) with the aim to know the influence of coordination of those heteroatoms to the gold center. Compared with the effectiveness of complex **6e**, the reaction using **6f** and **6g** resulted in low yields (27% and 30%: entries 6 and 7). Judging from the dramatic decrease of the yield in the case of **6f** and **6g**, and from non-positive result using **6e**, we should consider more deeply and elaborately the coordination effect of PAr_3. Lastly, we investigated the steric effect by introducing Me group at *ortho* position. The use of the monomethylated complex **6h** and dimethylated complex **6i** enhanced the yield of **5a** up to 83% and 79%, respectively (entries 8 and 9). On the other hand, the trimethylated analogue **6j** gave the product only in 32% yield (entry 10). Comparison between **6g** and **6k**, in which a bulkier *t*-Bu group is attached next to nitrogen is interesting; the yield of hydroamination was improved from 30% for **6g** to 59% for **6k** (entry 7 vs entry 11). These results suggest that adjustment of the steric environment around gold center is a key for enhancing the yield of the intermolecular hydroamination.

The scope of the hydroamination under the optimized condition is summarized in Table 3. Aryl allenes **1a**–**1e** and **1j** were proved to be good substrates for the hydroamination (entries 1–4, and 9). In the case of electron-rich allene, such as *p*-anisyl allene **1c**, the corresponding product was obtained in 95% yield (entry 3). The aliphatic allenes **1f**–**1h** gave the corresponding products in moderate yields (entries 5–7), but the sterically bulky aliphatic allene **1i** exhibited extremely low reactivity (entry 8).[22] We also investigated the reactivities of disubstituted allenes. The 1,3-disubstituted allene **1j** showed reactivity comparable to the monosubstituted allene (entry 9) and gave a small amount of regioisomer **5j′**. In the $AuBr_3$-catalyzed hydroamination, a disubstituted allene with arylamines gave an excellent regioselectivity without producing a regioisomer. The aliphatic 1,3-disubstituted allene **1l** gave the corresponding product in high yield unlike monosubstituted allene (entry 11). The 1,1-substituted allene **1k** gave the product as an inseparable stereoisomeric mixture in low yield, and **1m** gave no product at all (entry 10 and 12). The *E*/*Z* ratio of products **5k** was about 5:4, determined by NOE experiments.

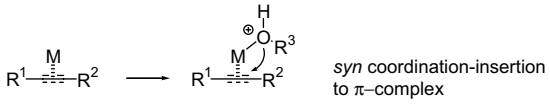
The chirality transfer was examined using the chiral allene **1j** (Eq. 8). Though the absolute configuration could not be determined, the corresponding allylic amine **5j** was obtained with 55% ee. It seems that higher reaction temperature and/or the difference of the catalytic species, Au (III) and Au (I), are a reason for obtaining a lower ee in the hydroamination of the aliphatic amine.



(*R*)-**1j** 96%*ee* **4a** **5j** 55%*ee* (8)

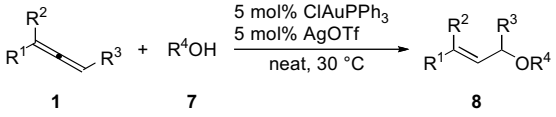
2.3. Hydroalkoxylation of allenes

Due to the difference of nucleophilicity between oxygen and nitrogen, it is of interest to know how the formal H–O bond addition across C–C multiple bonds proceeds in the presence of a gold catalyst.[23] Several mechanistic studies on the hydroalkoxylation using alcohols as nucleophiles and on the hydration using water as nucleophile were reported.[24] In the reports, the activation of C–C multiple bonds followed by oxygen coordination onto the metal center was proposed (Scheme 5).[25] In 1997, Teles and co-workers reported the hydroalkoxylation of alkynes using $MeAuPPh_3$ and $MeSO_3H$, which would act as a precursor for the in situ generated Au cationic catalyst.[26] They also proposed a similar mechanism via π-complexes as shown in Scheme 5, based on the experimental results and ab initio calculations. However, most of these additions could not be stopped at the stage of the first addition, instead the second addition took place very quickly leading to the formation of dialkyl acetals. Only one example for the addition to the cumulated double bond of allene was reported; the gold-catalyzed reaction of gaseous allene (CH_2=C=CH_2) with MeOH gave the corresponding dimethyl acetal, $(MeO)_2C(CH_3)_2$.[26a]



Scheme 5.

We found that the gold-catalyzed intermolecular hydroalkoxylation of allenes with alcohols smoothly proceeded under ambient temperature without solvent (Eq. 9).[27b] Very recently, Widenhoefer and Zhang reported independently the gold-catalyzed intermolecular hydroalkoxylation of allenes.[27a] We observed that essentially no chirality transfer took place in the hydroalkoxylation of a chiral allene, although highly efficient chirality transfer occurred in the hydroamination. This dramatic change depending on the nucleophiles suggests that the mechanism of hydroalkoxylation is different from that of hydroamination.

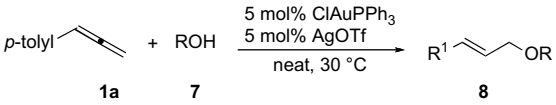


1 7 8 (9)

The scope and limitations of the hydroalkoxylation with various alcohols under the optimized conditions are summarized in Table 4. Primary, secondary, and tertiary alcohols **7a**–**7e** were proved to be good substrates for the hydroalkoxylation (entries 1–5). Benzyl alcohol **7f** and its derivative **7g** showed high reactivity to give the corresponding allylic ethers in good to high yields (entries 6 and 7). The olefinic alcohol, such as allyl alcohol **7h**, gave the corresponding product in good yield (entry 8). However, the reactivity of propargyl alcohol **7i** and phenol **7j** was too high to give an inseparable mixture of products even under diluted conditions with toluene (entries 9 and 10).[28] In the case of a diol, such as ethyleneglycol **7k**, the reaction also proceeded well to give a nearly 1:1 mixture of product **8k** and **8k′**. Monohydroalkoxylation gave **8k** and further hydroalkoxylation from **8k** (double-hydroalkoxylation) produced **8k′** (entry 11).

Aryl allenes **1a**–**1e**, **1j**, and **1k** were proved to be good substrates for the hydroalkoxylation (Table 5, entries 1–4, and 9–10), except for highly reactive *p*-anisyl allene, which gave an inseparable mixture of products (entry 3).[28] The aliphatic allenes **1f**–**1h** gave the corresponding products in moderate yields (entries 5–7), but the sterically bulky aliphatic allene **1i** gave the corresponding product in 38% yield (entry 8).[29] We also investigated the reactivities of disubstituted allenes. The 1,3-disubstituted allene **1j** showed reactivity comparable to the monosubstituted allene (entry 9) without producing a regioisomer. The aliphatic 1,3-disubstituted allene **1l** gave the corresponding product in high yield unlike monosubstituted allene (entry 11 vs entries 5–7). The 1,1-disubstituted allene **1k** gave the corresponding product as the single stereoisomer in a moderate yield (entry 10). In the hydroamination with aliphatic amines, this allene gave the corresponding allylic amine as a stereoisomeric mixture. The structure of product **9k** was determined as *E* by NOE experiments. However, the aliphatic 1,1-disubstituted allene **1m** gave the corresponding product with extremely low yield (entry 12).

Table 4
Gold-catalyzed intermolecular hydroalkoxylation of allene **1a** with alcohols **7**[a]



1a 7 8

Entry	7	R	Time, h	8	Yield[b], %
1	**7a**	*i*-Pr	2	**8a**	98
2	**7b**	Me	0.5	**8b**	98
3	**7c**	*n*-Bu	1	**8c**	98
4	**7d**	Cy	1.25	**8d**	98
5	**7e**	*t*-Bu	5	**8e**	84
6	**7f**	Bn	0.3	**8f**	69
7	**7g**	1-PhEt	1	**8g**	86
8	**7h**	Allyl	1	**8h**	71
9	**7i**	Propargyl	0.5	**8i**	Messy
10	**7j**	Ph	0.5	**8j**	Messy
11	**7k**	$-CH_2CH_2OH$	7	**8k**/**8k′**	28[c]/27[d]

[a] To a mixture of **7** (0.75 mmol) and catalyst (5 mol %) was added **1a** (0.50 mmol) and the mixture was stirred at 30 °C.
[b] Isolated yield.
[c] One alcohol moiety reacted.
[d] Both alcohol moiety reacted.

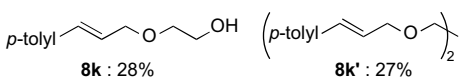
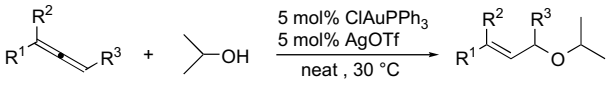


Table 5
Gold-catalyzed intermolecular hydroalkoxylation of allenes **1** with *i*-PrOH (**7a**)[a]

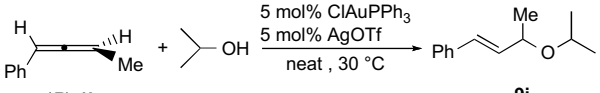


1 7a 9

Entry	1	R^1	R^2	R^3	Time, h	9	Yield[b], %
1	**1a**	*p*-Tolyl	H	H	2	**9a**	98
2	**1b**	Ph	H	H	2.5	**9b**	96
3	**1c**	*p*-Anisyl	H	H	0.1	**9c**	Messy
4	**1e**	4-F–C_6H_4	H	H	5	**9e**	99
5	**1f**	Bn	H	H	1	**9f**	57
6	**1g**	*n*-Oct	H	H	2.5	**9g**	62
7	**1h**	Cy	H	H	2	**9h**	42
8	**1i**	*t*-Bu	H	H	12	**9i**	38[c]
9	**1j**	Ph	H	Me	2	**9j**	93[d]
10	**1k**	Ph	Me	H	6	**9k**	65[d]
11	**1l**	*n*-Pent	H	*n*-Pent	2.5	**9l**	97
12	**1m**	*n*-Pent	*n*-Pent	H	6	**9m**	13

[a] To a mixture of **7a** (0.75 mmol) and catalyst (5 mol %) was added **1** (0.50 mmol) and the mixture was stirred at 30 °C.
[b] Isolated yield.
[c] Reaction was stopped after 12 h, and the yield was determined by NMR using dibromomethane as a standard.
[d] A regioisomeric product was not detected.

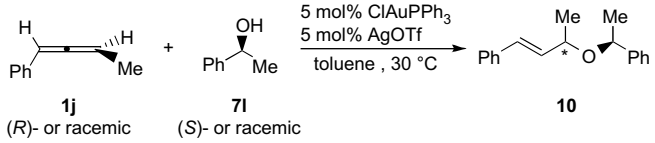
The chirality transfer was also examined using the chiral allene **1j** (Eq. 10). Surprisingly, the chirality of allene was not transferred onto the product at all. The experiment was also examined in toluene (under diluted conditions), however, only a racemic product was obtained. No chirality transfer suggests that the mechanism of the hydroalkoxylation is different from that of hydroamination. Widenhoefer and Zhang reported moderate chirality transfer took place under their reaction conditions; they used allenes bearing an ester group as substrates, which may be a reason that chirality transfer took place to some extent.[27a] In the hydroamination, a highly nucleophilic amine reacts first with a gold complex then the resulting amine–gold complex reacts with allenes. In the case of hydroalkoxylation, alcohols are in general less nucleophilic than amines and thus a gold complex may react with the allene (*R*)-**1j** prior to the reaction with alcohols, leading to the formation of a gold–allene complex followed by racemization of the allene.



(*R*)-**1j** 96%*ee* **7a** **9j** 0%*ee* (10)

Next, we examined kinetic resolution using a chiral substrate with an excess amount of racemic reaction partner (Table 6). The reaction was carried out under diluted condition in toluene at 30 °C, which is much milder than the neat condition. In the control experiment, a diastereoisomeric mixture of the corresponding product **10** was obtained in a ratio of 2.9:1 (entry 1). When the chiral allene (*R*)-**1j** was treated with the racemic alcohol **7l** (3 equiv), the same ratio of **10** (2.9:1) as the control experiment was

Table 6
Gold-catalyzed intermolecular hydroalkoxylation of allenes **1j** with alcohol **7l**



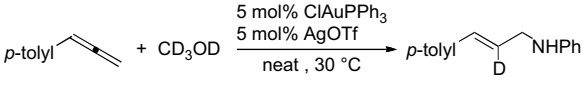
1j (*R*)- or racemic **7l** (*S*)- or racemic **10**

Entry	1j	7l	Time	10[e]
1[a]	Racemic	Racemic (1.5 equiv)	45 min	2.9:1
2[b]	Chiral (96% ee)	Racemic (3 equiv)	1.5 h	2.9 (1% ee):1 (4% ee)
3[c]	Racemic (3 equiv)	Chiral	1 h	3.5 (95% ee):1 (>99% ee)
4[d]	Racemic (3 equiv)	Chiral	1 h	4.0 (95% ee):1 (>99% ee)

[a] To a mixture of **7l** (0.75 mmol) and catalyst (5 mol %) was added **1** (0.50 mmol) and the mixture was stirred at 30 °C.
[b] To a mixture of **1j** (0.50 mmol) and catalyst (5 mol %) in toluene (2.0 mL) was added **7l** (1.5 mmol) and the mixture was stirred at 30 °C.
[c] To a mixture of **7l** (0.50 mmol) and catalyst (5 mol %) in toluene (2.0 mL) was added **1j** (1.5 mmol) and the mixture was stirred at 30 °C.
[d] To a mixture of **7l** (0.50 mmol) and catalyst (5 mol %) in toluene (2.0 mL) was added **1j** (1.5 mmol) and the mixture was stirred at 0 °C.
[e] Diastereomer ratio (determined by chiral HPLC).

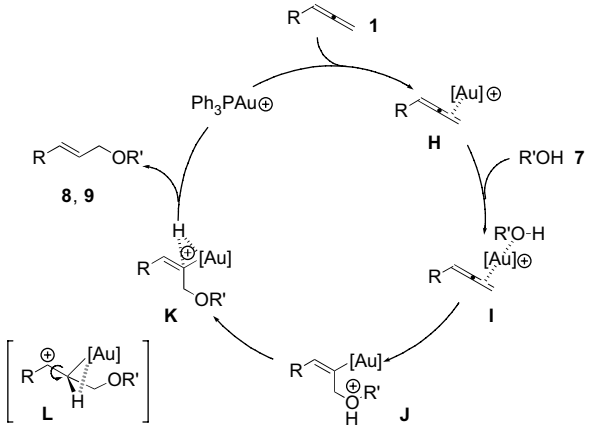
obtained (entry 2). This result, that is, no chirality transfer, suggested that the addition of alcohol might occur after the racemization of the allene by gold catalyst. When the chiral alcohol (*S*)-**7l** was used with the racemic allene **1j** (3 equiv), the ratio increased to 3.5:1 at 30 °C, and up to 4:1 at 0 °C (entries 3 and 4). Unfortunately, the rate of this reaction dramatically dropped at −20 °C. The reaction reached completion after 2 days and the diastereomeric ratio was not improved.

To obtain further information on the reaction mechanism, the hydroalkoxylation with deuterated methanol CD_3OD **7b**-d_4 was investigated (Eq. 11). While the hydroamination using $PhND_2$ did not give the corresponding carbon-deuterated allylic product, the hydroalkoxylation gave the corresponding carbon-deuterated allylic ether **8b**-*C*-d with 70% D. It is not clear why such a marked contrast took place between the hydroamination and hydroalkoxylation. However, it seems that the basic condition using aniline made the protonation step rather slow compared to the neutral conditions used with alcohols.



1a **7b**-d4 **8b**-*C*-d isolated (70%-D) (11)

A plausible mechanism, though speculative, is shown in Scheme 6. The cationic gold species was generated in situ from $ClAuPPh_3$ by halogen precipitation as silver salt. The catalytic cycle is initiated most probably by coordination of the allene to gold to afford intermediate **H**; both no chirality transfer and racemization of chiral allenes in the absence of nucleophiles support this hypothesis. The addition of an alcohol on allene takes place through inter-sphere pathway, which readily generates **I** and then forms the vinyl–gold intermediate **J**. The type of intermediate **I** was proposed in the study of gas-phase reaction and theoretical study.[26,30] Alternatively, one may point out the intervention of an allylic cation intermediate. However, the addition of alcohols occurred only at the less substituted carbon terminus of the allene; if an allylic cation is involved as an intermediate, the carbocation at the substituted carbon terminus is more stable than that at the less substituted carbon center and therefore the regioisomeric allylic ether should be obtained as the major product. One may also point out a possibility that π-allyl gold species can be generated from **H**. However, as far as we know, this type of complex is not known in spite of long history of research on gold complexes; only two examples of η^1-allyl gold (not π-allyl gold) were known.[31] Therefore, we believe that the allenyl gold type complexes **H** and **I** are involved. Finally, protonolysis on carbon–metal bond through intermediate **K** occurs to produce allylic ether together with Ph_3PAu^+. Intermediate **K** is proposed in a manner similar as the Section 2.1.[12] The formation of *E*-allylic ether **8** or **9** is explainable through the intermediate **L**, which enables the C–C single bond to rotate as shown by an arrow during the gold elimination process.



Scheme 6. Proposed mechanism.

3. Conclusion

We have found that the *intermolecular* hydro-heterofunctionalization of allenes is catalyzed highly efficiently by gold complexes. The addition of aromatic amines and alcohols proceeded smoothly at ambient temperature using commercially available gold complexes. The addition of aliphatic amines was also succeeded, though a higher temperature with the use of the cationic gold(I) complexes was required. To achieve the efficient conversion with aliphatic amines, the use of PAr_3 ligand having appropriate bulkiness was needed. It should be noted that the axial chirality of allenes is transferred to the products with high ees during the hydroamination, however, it is not transferred at all during the hydroalkoxylation. This result of chirality transfer and further studies provided valuable information on the mechanism of intermolecular hydrofunctionalization with gold catalysis.

4. Experimental section

4.1. General information

^1H and ^{13}C NMR spectra were recorded on JEOL JNM-LA300 (300 MHz), JMTC-400/54/SS (400 MHz), JNM α-500 (500 MHz), and ECA-600 (600 MHz) spectrometer. ^1H NMR spectra are reported as follows: chemical shift in parts per million (δ) relative to the chemical shift of $CHCl_3$ at 7.24 ppm, integration, multiplicities (s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet, and br=broadened), and coupling constants (hertz). ^{13}C NMR spectra reported in parts per million (δ) relative to the central line of triplet for $CDCl_3$ at 77.0 ppm. ^{31}P NMR spectra reported in parts per million (δ) relative to the chemical shift of H_3PO_4 at 0 ppm. IR spectra were recorded on JASCO FT/IR-460*plus* and JASCO FT/IR-4100 spectrometer, absorptions are reported in cm^{-1}. High resolution mass spectra were obtained on Bruker APEXIII FT-ICR-MS, JEOL JMS-DX 303, and JEOL JMS-DX 500. Chiral HPLC analysis was performed on Hitachi D-7000 HPLC system (equipped with a L-7100 pump, L-7400 UV–vis detector, and D-7000 system manager detector) and

on JASCO LC-NetII/ADC HPLC system (equipped with a PU-2089*plus* gradient pump, AS-2055 sampler, CO-2060plus column thermostat, UV-2075*plus* UV/VIS detector, CD-2095*plus* chiral detector, and ChromNAV system manager detector) using Daicel Chiralcell OD-H column (0.46 cm×25 cm). Optical rotations were measured on JASCO DIP-1000 digital polarimeter.

4.2. Materials

Anhydrous tetrahydrofuran (Kanto), anhydrous toluene (Wako), $AuBr_3$ (Aldrich), $ClAuPPh_3$ (Strem), AgOTf (Wako) were purchased and used as received. All metal complexes were used only in Ar box. Amines (Wako, Aldrich, TCI) were treated by CaH and distilled before use. Aniline-*N*,*N*-d_2 (CDN isotopes) was purchased as an ample and used as received in Ar box. Alcohols (Wako or Aldrich) were purchased then dried by activated molecular sieves before use. All the allenes were prepared according to the literature procedure and distilled to use.[32] All $ClAuPPh_3$ derivatives were prepared according to the literature procedure and recrystallized to use.[33] All other compounds used were commercially available.

4.3. General procedure for hydroamination of allenes with aromatic amines

To a suspension of $AuBr_3$ (21.8 mg, 0.05 mmol) in THF (0.5 mL) was added aniline (93 mg, 1.0 mmol) and the mixture was stirred at 30 °C under Ar atmosphere for about 5 min. To the reaction mixture was added *p*-tolylallene **1a** (65.4 mg, 0.50 mmol). After the reaction was completed (2 h), the reaction mixture was filtered through short silica gel pad with ether as an eluent and concentrated. The product was purified by column chromatography (silica gel, hexane/ethyl acetate=10:1 to 5:1) to give **3a** in 81% yield (91.3 mg).

4.4. General procedure for hydroamination of allenes with aliphatic amines

To a suspension of $ClAuPPh_2$(*o*-tolyl) (**6h**, 25.4 mg, 0.05 mmol) and AgOTf (12.8 mg, 0.05 mmol) in toluene (0.5 mL) was added morpholine (**4a**, 43.7 mg, 0.502 mmol). To the reaction mixture was added *p*-tolylallene (**1a**, 79.3 mg, 0.6 mmol) and the resulting mixture was stirred at 80 °C under an Ar atmosphere. The reaction mixture was colorless and heterogeneous at the beginning, but it turned yellow to brown as the reaction progressed. After the reaction was completed (12 h), the reaction mixture was filtered through short basic silica gel pad with EtOAc as an eluent and the resulting filtered solution was concentrated. The product was purified quickly by short column chromatography (basic silica gel, hexane/EtOAc=100:1 to 10:1) to give **5a** in 83% yield (90.8 mg).

4.5. General procedure for hydroalkoxylation of allenes

To a suspension of $ClAuPPh_3$ (12.4 mg, 0.025 mmol) and AgOTf (6.4 mg, 0.0025 mmol) in *i*-PrOH (**7a**, 57 μL, 0.75 mmol; neat condition) was added *p*-tolylallene (**1a**, 93 mg, 1.0 mmol) and the mixture was stirred at 30 °C under Ar atmosphere. After the reaction was completed (2 h), the reaction mixture was filtered through short silica gel pad with ether as an eluent and concentrated. The product was purified by column chromatography (silica gel, pentane) to give **8a** in 98% yield (93.4 mg).

4.6. Gold mediated racemization experiment of chiral allene

To a suspension of $AuBr_3$ (21.8 mg, 0.05 mmol) in THF (0.5 mL) was added *p*-tolylallene **1a** (65.4 mg, 0.50 mmol) at 30 °C under Ar atmosphere. A portion of the reaction mixture (10 μL) was taken and quenched by filtering through short silica gel pad with hexane as an eluent. A portion of the reaction mixture was taken after 30 s, 1 min, 5 min, and 15 min. The resulting solution was analyzed by chiral HPLC. The experiment in toluene, or with $Ph_3PAuOTf$ also investigated.

4.7. Monitoring the progress of hydroamination with aniline

To a suspension of $AuBr_3$ (21.8 mg, 0.05 mmol) in THF (0.5 mL) was added aniline (93 mg, 1.0 mmol) and the mixture was stirred at 30 °C under Ar atmosphere for about 5 min. To the reaction mixture were added dibromomethane (35 μL, 0.50 mmol) and *p*-tolylallene **1a** (65.4 mg, 0.50 mmol). A portion of the reaction mixture (10 μL) was taken every 10 min until the reaction time reaches to 1 h, and every 15 min after 1 h until 2 h, and quenched by filtering through short silica gel pad with $CDCl_3$ as an eluent. The resulting solution was analyzed by ^{1}H NMR.

4.8. Monitoring the progress of hydroamination with aniline at a low temperature

To a suspension of $AuBr_3$ (2.2 mg, 0.005 mmol) in THF-d_8 (0.5 mL) was added aniline (9 mg, 0.1 mmol) and the mixture was stirred at 30 °C under Ar atmosphere for about 5 min. To the reaction mixture was added *p*-tolylallene **1a** (6.5 mg, 0.050 mmol) and the mixture was placed at a low temperature (in NMR tube cooled at −50 °C). The reaction progress was monitored for 1 day.

4.9. General procedure for the hydroamination with deuterated aniline-*N*,*N*-d_2

In an Ar box, to a suspension of $AuBr_3$ (21.8 mg, 0.05 mmol) in THF-d_8 (0.5 mL) was added aniline-*N*,*N*-d_2 (93 mg, 1.0 mmol) and the mixture was stirred at 30 °C under Ar atmosphere for about 5 min. To the reaction mixture was added *p*-tolylallene **1a** (65.4 mg, 0.50 mmol). After 2 h, D_2O was added to the reaction mixture in an Ar box. Then it was analyzed by GC–MS and NMR to know whether the nitrogen deuterated product was formed or not and to clarify whether the carbon-deuterated product is formed or not.

4.10. General procedure for the hydroalkoxylation with deuterated methanol-d_4

In an Ar box, to a suspension of $ClAuPPh_3$ (12.4 mg, 0.025 mmol) and AgOTf (6.4 mg, 0.0025 mmol) in CD_3OD (**7b**-d_4, 57 μL, 0.75 mmol; neat condition) was added *p*-tolylallene (**1a**, 93 mg, 1.0 mmol) and the mixture was stirred at 30 °C. After 30 min, D_2O was added to the reaction mixture in an Ar box, and the product was purified by column chromatography. Then it was analyzed by NMR.

4.11. Analytical data

*4.11.1. (E)-N-(3-(4-Methoxyphenyl)allyl)aniline (**3c**)*

Pale yellow solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.79 (3H, br s), 3.90 (2H, dd, *J*=6.0, 1.3 Hz), 6.18 (1H, dt, *J*=15.8, 6.0 Hz), 6.55 (1H, d, *J*=15.8 Hz), 6.66 (2H, d, *J*=7.7 Hz), 6.71 (1H, t, *J*=7.3 Hz), 6.83 (2H, dd, *J*=8.5, 2.1 Hz), 7.15–7.21 (2H, m), 7.29 (2H, dd, *J*=8.5, 2.1 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 46.3, 55.3, 113.0, 114.0, 117.6, 124.7, 127.5, 129.2, 129.6, 131.1, 148.1, 159.2; IR (neat, ATR) 3390, 2836, 1598, 1499, 1310, 1241, 1175, 1029, 968, 842 cm^{-1}. HRMS (EI) calcd for $C_{16}H_{17}NO$ (M+Na) 262.1202, found 262.1201.

*4.11.2. (E)-N-(3-(4-Fluorophenyl)allyl)aniline (**3e**)*

Colorless solid; mp 69 °C (hexane/EtOAc); ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.73–4.13 (1H, br s), 3.92 (2H, d, *J*=5.6 Hz), 6.23 (1H, dt,

J=16.0, 5.6 Hz), 6.57 (1H, d, *J*=16.0 Hz), 6.65 (1H, s), 6.66–6.68(1H, m), 6.73 (1H, t, *J*=7.3 Hz), 6.94–7.02 (2H, m), 7.15–7.21 (2H, m), 7.31 (2H, dd, *J*=7.7, 5.6 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 46.2, 113.1, 115.5 [d, *J* (^{13}C–^{19}F)=21.7 Hz], 117.8, 126.8 [d, *J* (^{13}C–^{19}F)=2.8 Hz], 127.8 [d, *J* (^{13}C–^{19}F)=7.6 Hz], 129.3, 130.4, 133.0 [d, *J* (^{13}C–^{19}F)=1.9 Hz], 147.9, 162.3 [d, *J* (^{13}C–^{19}F)=246.6 Hz]; IR (neat) 3413, 3050, 2834, 1601, 1503, 1224, 1157, 966, 844 cm^{-1}. HRMS (ESI) calcd for $C_{15}H_{14}FN$ (M+H) 228.1183, found 228.1182.

4.11.3. (*E*)-(3-(4-Methoxyphenyl)allyl)morpholine (**5c**)

Pale yellow oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.48 (4H, br s), 3.11 (2H, d, *J*=6.8 Hz), 3.72 (4H, dd, *J*=4.7, 4.7 Hz), 3.79 (3H, s), 6.09 (1H, dt, *J*=15.8, 6.8 Hz), 6.45 (1H, d, *J*=15.8 Hz), 6.81–6.85 (2H, m), 7.27–7.31 (2H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 53.7, 55.3, 61.6, 67.0, 114.0, 123.7, 127.5, 129.6, 132.8, 159.2; IR (neat) 1605, 1509, 1242, 1173, 1113, 1027, 972, 870, 813 cm^{-1}. HRMS (ESI) calcd for $C_{14}H_{19}NO_2$ (M+H) 234.1489, found 234.1490.

4.11.4. (*E*)-(3-(4-Fluorophenyl)allyl)morpholine (**5e**)

Pale yellow oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.48 (4H, br s), 3.12 (2H, dd, *J*=6.8, 1.1 Hz), 3.72 (4H, dd, *J*=4.7, 4.7 Hz), 6.15 (1H, dt, *J*=15.8, 6.8 Hz), 6.47 (1H, d, *J*=15.8 Hz), 6.95–7.01 (2H, m), 7.28–7.34 (2H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 53.7, 61.4, 67.0, 115.5 [d, *J* (^{13}C–^{19}F)=21.7 Hz], 125.8, 127.8 [d, *J* (^{13}C–^{19}F)=8.5 Hz], 132.2, 133.0 [d, *J* (^{13}C–^{19}F)=3.8 Hz], 162.3 [d, *J* (^{13}C–^{19}F)=246.6 Hz]; IR (neat) 1601, 1508, 1454, 1225, 1115, 1006, 968, 870, 846, 818 cm^{-1}. HRMS (ESI) calcd for $C_{13}H_{16}FNO$ (M+H) 222.1289, found 222.1289.

4.11.5. (*E*)-*N*-(Tridec-7-en-6-yl)morpholine (**5l**)

Pale yellow oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.81–0.89 (6H, m), 1.13–1.40 (14H, m), 1.95–2.06 (2H, m), 2.35–2.46 (2H, m), 2.47–2.56 (2H, m), 2.59 (1H, td, *J*=9.0, 4.3 Hz), 3.62–3.72 (4H, m), 5.21 (1H, ddt, *J*=15.4, 9.0, 1.3 Hz), 5.45 (1H, dt, *J*=15.4, 6.8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.0, 22.5, 22.6, 26.0, 29.1, 31.4, 31.8, 32.4, 50.4, 67.3, 68.2, 129.1, 134.4; IR (neat): 2954, 2925, 2853, 1453, 1119, 974 cm^{-1}. HRMS (ESI) calcd for $C_{17}H_{33}NO$ (M+H) 268.2635, found: 268.2634.

4.11.6. $ClAuPPh_2$(6-tert-Bu-2-pyridyl) (**6k**)

Colorless crystal; mp 151 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 1.25 (9H, s), 7.37–7.50 (7H, m), 7.66–7.73 (5H, m), 7.89 (1H, dd, *J*=7.8, 7.8 Hz); ^{13}C NMR (149.4 MHz, $CDCl_3$) δ 29.9, 38.0, 120.9, 128.2, 128.7 [d, *J* (^{13}C–^{31}P)=12.2 Hz], 129.0 [d, *J* (^{13}C–^{31}P)=18.6 Hz], 131.7 [d, *J* (^{13}C–^{31}P)=2.2 Hz], 134.6 [d, *J* (^{13}C–^{31}P)=13.6 Hz], 136.7, 151.9 [d, *J* (^{13}C–^{31}P)=86.0 Hz], 170.9 [d, *J* (^{13}C–^{31}P)=14.3 Hz; ^{31}P NMR (121.5 MHz, $CDCl_3$) δ 31.5; IR (neat, ATR): 2957, 1578, 1474, 1435, 1173, 1140, 1102, 985, 812 cm^{-1}. Anal. Calcd for $C_{21}H_{22}AuClP$ (2×complex+1×toluene): C, 49.22; H, 4.38; N, 2.34; Cl, 5.93. Found: C, 49.02; H, 4.54; N, 2.34; Cl, 6.02. HRMS (ESI) calcd for $C_{21}H_{22}AuClP$ (M+Na) 574.0736, found 574.0734.

4.11.7. (*E*)-(1-(4-Phenylbut-3-en-2-yloxy)ethyl)benzene (**10**-major)

Colorless oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.29 (3H, d, *J*=6.6 Hz), 1.42 (3H, d, *J*=6.6 Hz), 3.85 (1H, dq, *J*=7.8, 6.6 Hz), 4.57 (1H, q, *J*=6.6 Hz), 6.12 (1H, dd, *J*=15.8, 7.8 Hz), 6.38 (1H, d, *J*=15.8 Hz), 7.20–7.42 (10H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.2, 24.8, 73.3, 74.3, 126.2, 126.4, 127.3, 127.6, 128.4, 128.6, 131.2, 131.8, 136.7, 144.3.

4.11.8. (*E*)-(1-(4-Phenylbut-3-en-2-yloxy)ethyl)benzene (**10**-minor)

Colorless oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.30 (3H, d, *J*=6.4 Hz), 1.41 (3H, d, *J*=6.4 Hz), 4.06 (1H, dq, *J*=6.8, 6.4 Hz), 4.57 (1H, q, *J*=6.4 Hz), 6.04 (1H, dd, *J*=15.8, 6.8 Hz), 6.40 (1H, d, *J*=15.8 Hz), 7.13–7.37 (10H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.9, 23.6, 73.5, 74.7, 126.2, 126.4, 127.2, 127.4, 128.3, 128.4, 129.9, 132.5, 136.9, 144.6.

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29. The progress of this reaction could not be monitored by TLC or GC–MS, because of low boiling points of the starting allene and product. Thus, the reaction was stopped after 24 h. Isolation of the product was also very difficult for the same reason as above, and therefore the NMR yield was calculated using dibromomethane as an internal standard.
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