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Synthesis of Indenes by Tandem Gold(I)-Catalyzed Claisen Rearrangement/Hydroarylation Reaction of Propargyl Vinyl Ethers

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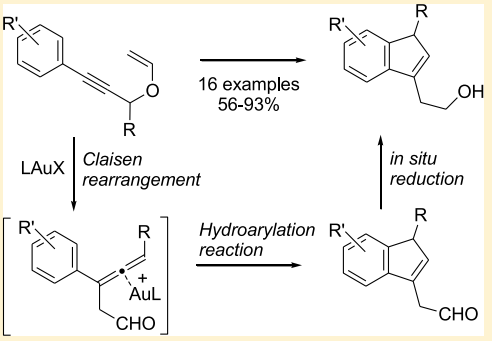
Supporting Information

ABSTRACT: The tandem gold(I)-catalyzed propargyl Claisen rearrangement/hydroarylation reaction of suitable propargyl vinyl ethers, followed by in situ reduction of the resulting carbonyl group, provides functionalized indenes in good to excellent yields. The reaction occurs at room temperature in dichloromethane in the presence of 3 mol % [IPrAuCl]/$AgBF_4$ as the best catalytic system. Instead, cyclization of the allene intermediate either does not take place or is very slow with phosphine ligands. A variety of substituents and functional groups present on the substrate are tolerated. The effect of the aryl ring substituents and the results of a density functional theory computational study suggest that the final hydroarylation is the rate-determining step of this cascade process. Further in situ chain elongation, prior final work up of the tandem process, can be carried out by Wittig olefination of the aldehyde functionality, thus incrementing the diversity of the products obtained.



INTRODUCTION

The development of efficient methods for the synthesis of indenes[1a,b] continues to attract interest from the organic chemists' community as these compounds show a variety of biological activities, including antitumor, anticonvulsant, antiallergic, anti-hypercholesterolemic, fungicidal, herbicidal, and antimicrobial activities.[2] The indene framework is also found in natural products (Figure 1),[3] and it finds application in material science[4] and in the preparation of ligands for metal complexes, for example, ligands for tailored metallocene complexes used to catalyze olefin polymerization.[5]

Metal-catalysis has been widely exploited to build this important carbocyclic structure through a variety of processes,[1a,c−j] including those based on the 1,2- or 1,3-migration and carbocyclization of propargylic esters and carbonates.[6] Given the high efficiency of Au(I) in activating triple bonds,[7] gold-catalysis has been exploited for the synthesis of indenes by the latter approach[8a,b,9] too. Other methods based on gold(I)-catalysis include for example the carbocyclization of 1-alkynyl-2-(methoxymethyl)benzene derivatives,[8c,d] the carbocyclization of 1,5- and 1,6-enynes embodying an aryl ring,[8e−g] the C_{sp^3}−H bond activation in diarylacetylene derivatives,[8h] the formal (3 + 2) cycloaddition between allenes and aryl gold(I)-carbenes,[8i] tandem transformations of 1,5-diynes embodying an aryl ring via a gold-vinylidene intermediate,[8j] and a few other multicomponent processes.[8k,l]

We have recently reported that suitably substituted propargyl vinyl ethers **1** undergo a propargyl Claisen

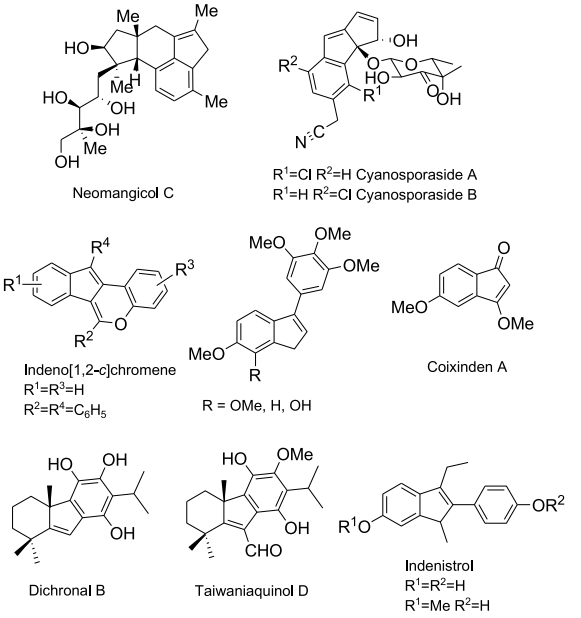


Figure 1. Examples of natural compounds embedding the indene core.

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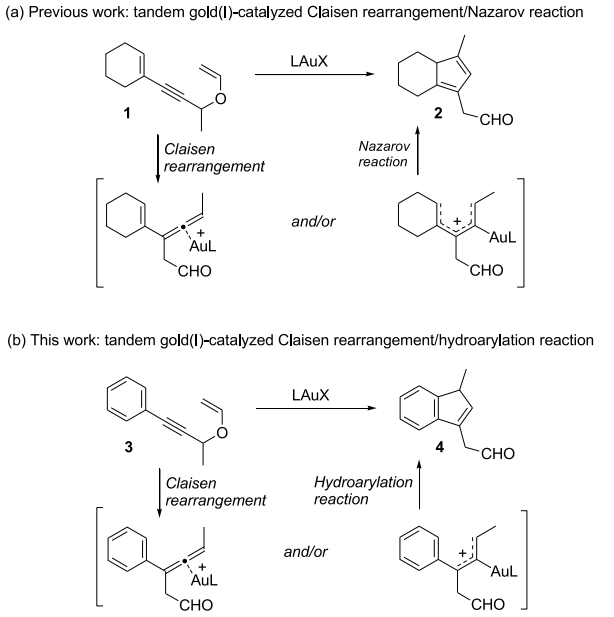
rearrangement[10] followed by a Nazarov cyclization when subjected to gold(I)-catalysis, which efficiently provided functionalized cyclopentadienes **2** fused with various N-hetero- and carbocycles [Schema 1a].[11]

In this process, the gold-catalyzed [3,3]-rearrangement generates a gold-allene complex which, once formed, immediately undergoes the 4π-electrocyclization plausibly via the corresponding pentadienyl cation to form the final product.[12] While in cyclization processes involving the initial rearrangement of propargylic esters, the final products are cyclopentenones o cyclopentadienyl alkanoates,[9] this tandem propargyl Claisen rearrangement/Nazarov reaction provides cyclopentadienes bearing, on one side chain, an aldehyde group which can be easily subjected to further in situ elaboration for incrementing the structural diversity of the products.

Given the importance of indenes, and in continuation of our study on gold-catalyzed rearrangement processes involving propargyl alcohol derivatives,[11,13] we decided to evaluate whether the same approach could be used for the construction of such important ring systems by exploiting the rearrangement of 3-aryl-substituted propargyl vinyl ethers **3** [Scheme 1b]. The

Scheme 1. Tandem Processes Involving an Au(I)-Catalyzed Propargyl Claisen Rearrangement

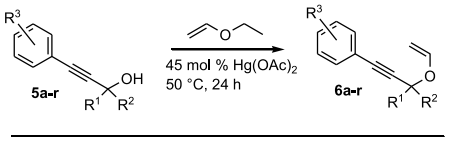


achievement of this synthetic objective through a cascade process in which the allene is generated in situ by a [3,3]-rearrangement was not guaranteed, though. The final cyclization in the tandem propargyl Claisen rearrangement/Nazarov reaction [Scheme 1a] was a fast process, but in the present case, the cyclization of the allene intermediate [Scheme 1b] involves the temporary disruption of the aromaticity of the aryl ring. Thus, the conditions (gold ligand, temperature, and counterions) required for the initial Claisen rearrangement could be unsuitable for the hydroarylation step. In this paper, we report on an experimental and computational study of the tandem gold(I)-catalyzed Claisen rearrangement/hydroarylation reaction of 3-aryl-substituted propargyl vinyl ethers and we show that, with the right choice of the catalytic system, it efficiently provides polyfunctionalized indenes. Moreover, we demonstrate that further in situ elaboration of the aldehyde functionality is possible by Wittig olefination, thus enlarging the variety of products which can be obtained by this methodology.

RESULTS AND DISCUSSION

The synthesis of the substrates (Scheme 2) for the gold-catalyzed reaction was carried out by treatment of the

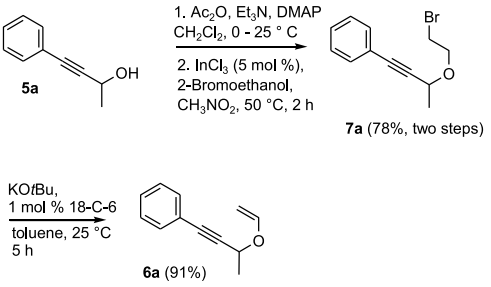
Scheme 2. Synthesis of Substrates 6a−r



6a R^1 = Me, R^2 = R^3 = H (77%)
6b R^1 = Me, R^2 = H, R^3 = *p*-Me (61%)
6c R^1 = Me, R^2 = H, R^3 = *o*-Me (62%)
6d R^1 = Me, R^2 = H, R^3 = *m*-Me (68%)
6e R^1 = Me, R^2 = H, R^3 = *p*-MeO (41%)
6f R^1 = Me, R^2 = H, R^3 = *m*-MeO (58%)
6g R^1 = Me, R^2 = H, R^3 = *p*-CH_2NHBoc (76%)
6h R^1 = Me, R^2 = H, R^3 = *p*-CH_2OBn (60%)
6i R^1 = Me, R^2 = H, R^3 = *p*-CH(-OCH_2CH_2O-) (72%)
6j R^1 = Me, R^2 = H, R^3 = *p*-Br (76%)
6k R^1 = Me, R^2 = H, R^3 = *m*-F (68%)
6l R^1 = Me, R^2 = H, R^3 = *p*-CO_2Me (79%)
6m R^1 = *n*-Pr, R^2 = R^3 = H (83%)
6n R^1 = Bn, R^2 = R^3 = H (52%)
6o R^1 = R^2 = Me, R^3 = H (74%)
6p R^1 = Me, R^2 = *i*-Bu, R^3 = H (75%)
6q R^1 = Ph, R^2 = R^3 = H (60%)
6r R^1 = *m*,*p*-$Cl_2C_6H_3$, R^2 = R^3 = H (56%)

corresponding propargylic alcohols **5** with ethyl vinyl ether in the presence of $Hg(OAc)_2$.[10d,14,15] While we used this methodology for small-scale preparations, for example, in the evaluation of the scope of the gold-catalyzed tandem process, we looked for an alternative approach to vinyl ethers **6** when these were needed in larger amount, as in the case of model substrate **6a**, in order to avoid the use of the mercury salt.[16] Out of the many approaches we experimented, the best is depicted in Scheme 3. As shown, converting **5a** into the

Scheme 3. Synthesis of Substrate 6a



corresponding acetate and then treating with $InCl_3$ in nitromethane at 50 °C in the presence of 2-bromo-1-ethanol, provided bromide **7a** in 78% yield over the two steps.[17] The next elimination step was carried out by treatment of **7a** with a strong base (*t*-BuOK in toluene) which provided model compound **6a** in 91% yield.[18]

We used substrate **6a** to find the best reaction conditions for the gold(I)-catalyzed process, and the results of the screening of various gold(I)-catalysts and gold(I)-precatalyst/silver salt combinations are reported in Table 1. The reactions were carried out by adding a solution of the substrate in dichloromethane (DCM) to a solution of the catalyst (3 mol %) generated by mixing the gold and silver salts in the same solvent at 25 °C.

The $[Ph_3PAu]^+BF_4^-$ and $[Ph_3PAu]^+TfO^-$ catalysts (entries 1 and 2) have been shown to catalyze the Claisen rearrangement of propargyl vinyl ethers.[10a] With 3 mol % of

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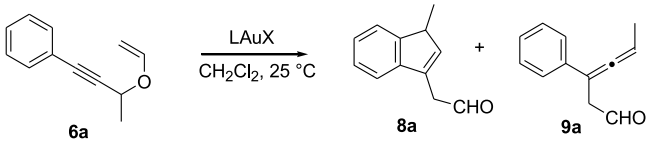
Table 1. Optimization of the Reaction Conditions[a]



entry	catalyst[b]	time (min)	product ratio[c] 6a	8a	9a
1	$[Ph_3PAuCl]/AgBF_4$	30			100
2	$[Ph_3PAuCl]/AgOTf$	30			100
3	$[Ph_3PAuCl]/AgSbF_6$	120		7	93
4	$[(p\text{-}CF_3C_6H_4)_3PAuCl]/AgOTf$	30	[d]		
5	$^tBu_3PAuNTf_2$[e]	30			100
6	$[Cy_3PAuCl]/AgOTf$	30			100
7	$[IPrAuCl]/AgSbF_6$	30		100[f]	
8	[IPrAuCl]/AgOTf	40		100[f]	
9	$[IPrAuCl]/AgBF_4$	25		100	
10	$IPrAu(CH_3CN)BF_4$[e]	60		100	
11	$IPrAuNTf_2$[e]	120		50	50
12	$[SIPrAuCl]/AgBF_4$	55		100	
13	$[ICyAuCl]/AgBF_4$	55			100
14	$[ItBuAuCl]/AgBF_4$	55			100
15	$[IMesAuCl]/AgBF_4$	55	78[g]		22
16	IPrAuCl	55			100
17	$AgBF_4$	60			100

[a]Conditions: reactions carried out on 0.2−0.3 mmol of **6a** in CH_2Cl_2 (0.05 M) at 25 °C under N_2 atmosphere. [b]Prepared by mixing the silver salt (3 mol %) and the gold chloride (3 mol %) in CH_2Cl_2 before addition of the substrate unless otherwise noted. IPr = 1,3-bis(diisopropylphenyl)imidazol-2-ylidene, SIPr = 1,3-bis(2,6-diisopropylphenyl)-4,5-dihydroimidazol-2-ylidene, IMes = 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene, ItBu = 1,3-di-*t*-butylimidazol-2-ylidene, ICy = 1,3-bis(cyclohexyl)imidazol-2-ylidene. [c]Product ratio based on integration of ^1H NMR resonances in the crude reaction mixture. [d]Complete degradation of the starting material. [e]Commercially available. [f]Some degradation of the starting material occurred. [g]Devinylation of **6a** to alcohol **5a** occurred.

these catalysts in CH_2Cl_2 substrate **6a** was quickly (less than 30 min) converted into allene **9a**.[19] However, we did not observe even traces of indene **8a** in the crude reaction mixtures by prolonging the reaction times. Only when using $AgSbF_6$ as the source of the non-coordinating anion we observed, after 2 h, the formation of a small relative amount (entry 3) of aldehyde **8a**.

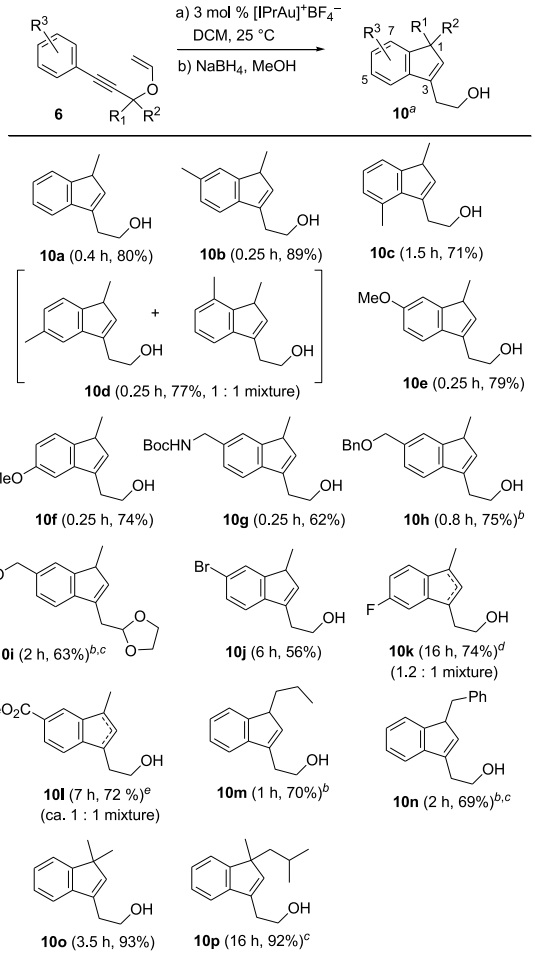
Gold salts with Ph_3P and electron-rich phosphine ligands were all competent catalysts in the tandem Claisen rearrangement/Nazarov cyclization of enynyl vinyl ethers,[11] but as it is evident from entries 1−3 and 5−6, they seem unable to promote the final hydroarylation step with substrate **6a**. Instead, with the NHC (NHC = N-heterocyclic carbene) ligand IPr and various anions (entries 7−11), we always observed the formation of indene **8a**. In particular, the best combination was the $[IPrAuCl]/AgBF_4$ catalytic system (entry 9).[20] With 3 mol % of this catalyst, we observed (by ^1H NMR) the immediate (less than 5 min) conversion of the substrate into allene **9a**, half of which already cyclized to indene **8a** (**8a**/**9a** ratio = 1:1 after 5 min). After 15 min, the ratio was 3.2:1, and in 25 min, the reaction was complete. With 1 mol % of the catalyst, the reaction was complete in 3 h. Commercial $[IPrAu(CH_3CN)]^+BF_4^-$ (entry 10) catalyzed the reaction, too, ruling out any role of the silver salt in the hydroarylation step.

On the other hand, $AgBF_4$ alone (entry 17) was able to catalyze the Claisen rearrangement, but not the cyclization, and similarly in the presence of the IPrAuCl salt alone (entry 16), only the [3,3]-rearrangement occurred.

We tested other NHC gold complexes (entries 12−15) and quite surprisingly, among these, only the SIPr ligand was effective, although the reaction was slightly slower than with IPr ligand (the **8a**/**9a** ratio was 1:1 after 15 min).[21] With ICy, ItBu, and IMes ligands, only allene **9a** was formed. Interestingly, in the Au(I)-catalyzed tandem [3,3]-rearrangement/hydroarylation of propargylic acetates to form indenes, other NHC ligands, as well as Ph_3P, were able (although not as efficiently as IPr) to promote the hydroarylation step.[8b]

Having found the best reaction conditions, these were used to evaluate the scope with 3-aryl-substituted propargyl vinyl ethers bearing various groups (R^3) on the aromatic ring and substituents (R^1, R^2) on the carbinolic position (Scheme 4). To avoid both partial degradation of aldehydes **8** and double bond migration to the exocyclic position during chromatography on silica gel (which generates α,β-unsaturated aldehydes), the reaction products were reduced in situ to the corresponding alcohols **10** by $NaBH_4$ after dilution of the DCM solution with MeOH (method A).[22] As an alternative,

Scheme 4. Scope of the Au(I)-Catalyzed Propargyl Claisen Rearrangement/Hydroarylation Reaction



[a]Numbering refers to the indene skeleton; [b]commercial $[IPrAu(CH_3CN)]BF_4$ was used; [c]6 mol % of the catalyst was used; [d]in mixture with 7-F isomer (15%); [e]reaction carried out at 40 °C.

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upon completion of the reaction, the crude aldehydes were isolated after an aqueous work-up, dissolved in MeOH, and then reduced (method B).

By using the former procedure (method A), simple indene **10a** was obtained in 80% yield after chromatography.

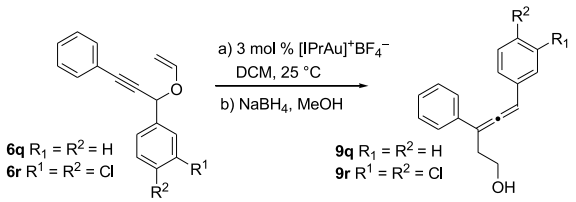
Electron-donor groups on the aromatic ring made the reaction faster and, with the exception of the *o*-methyl substituted substrate **6c**, which reacted in 1.5 h, alcohols **10b−10f** were all obtained in 15 min. *m*-Methyl- and *m*-methoxy-substituted substrates (**6d** and **6f**, respectively) of course provided a mixture of isomers deriving from ring closure at the ortho and para position. However, in the case of the *m*-methoxy-substituted compound, attack to the para position prevailed (86:14 ratio in the crude reaction mixture) and pure isomer **10f** could be isolated by chromatography in good yields.[23a] With aromatic rings bearing amino- and alkoxy-substituted methyl groups (**6g** and **6h**, respectively), the reaction proceeded smoothly, too, providing alcohols **10g** and **10h** in good yields (62 and 75% yield, respectively). In the case of **6h**, the reaction was carried out with the commercial $[IPrAu(CH_3CN)]^+BF_4^-$ and, as for the model compound **6a**, it was just slightly slower than with the $[IPrAuCl]/AgBF_4$ catalytic system. The latter, as well as the preformed catalyst, was used to carry out the reaction with the propargyl vinyl ether bearing a dioxolane moiety in the para position (**6i**). The reaction was slow (2 h for a complete conversion of the allene intermediate), and in both cases, we observed an almost complete trans-acetalization during the gold(I)-catalyzed step. Thus, compound **10i** could be obtained in 63% yield after chromatography.[24]

As expected on the basis of the above results, which suggest that the hydroarylation could be the rate-determining step of the process (see later), the hydroarylation of the allene intermediate was in fact very slow with electron-withdrawing groups on the aromatic ring (**6j−6l**). In two cases (**6k**, bearing a *m*-F group, and **6l**, bearing a *p*-CO_2Me group) either the long reaction times or the heating led to an almost equimolar mixture of isomers as a consequence of the shift of the double bond to the position 1 in the five-membered ring. Such an isomerization could be observed, to a very minor extent and regardless the presence or absence of a silver salt in the reaction mixture, also for other substrates for which, however, the adoption of method B allowed us to overcome the problem.[25] As in the case of the *m*-OMe-substituted substrate, also with *m*-F-substituted propargyl vinyl ether **6k**, the ring closure occurred predominantly (85% by ^{1}H NMR analysis of the crude reaction mixture) at the para position.[23b]

Finally, a few substrates with different substitution at the carbinolic position were evaluated, and in all cases, the reaction provided the target compounds (**10m−p**) in good to excellent yield. Benzyl-substituted indene **10n**, however, which was obtained isomerically almost pure (95%) from **6n** after 3 h in the presence of 6 mol % of the catalyst, underwent a slight double bond isomerization during the chromatography on silica gel, and it was eventually obtained as a 9:1 mixture of isomers. With the *gem*-dimethyl-substituted substrate **6o**, because of the double substitution at the propargylic moiety, the reaction was slower (3.5 h) than with the model substrate **6a** but provided the target compound **10o** in an excellent 93% yield. Similarly, the reaction of **6p** was slow (16 h), and it was carried out in the presence of 6 mol % of the catalyst, but it nevertheless provided compound **10p** in 92% yield.

The only substrates which seem unsuitable for this gold(I)-catalyzed cascade process are those bearing an aryl ring at the carbinolic position (Scheme 5). Simple phenyl-substituted

Scheme 5. Gold(I)-Catalyzed Process with Substrates 6q and 6r



propargyl vinyl ether **6q**, under various conditions, always quantitatively provided the corresponding allene **9q**. We thought the lack of reactivity could be due to the stabilization by the phenyl ring of the positively charged gold(I)-complex intermediate [Scheme 1b] making it less reactive, but the result obtained with dichloro-substituted substrate **6r** (Scheme 5) instead suggests that it is either the greater stability of the aryl-substituted allene intermediate or the steric hindrance in the ring closure step by the aryl ring being the possible reason.

A plausible mechanism for the tandem Claisen/hydroarylation reaction and the energies calculated relative to complex **II** are reported in Scheme 6. Upon coordination of the triple bond to the cationic gold(I) complex, a very fast [3,3]-rearrangement of **II** occurs and conversion of the substrate into allene **V** is immediate.[10d,26] This is experimentally observed for all types of substrates, suggesting that the Claisen rearrangement is not the rate-determining step of the process. The calculated transition state energies for the rearrangement steps (**TS1** and **TS2**) are in fact low with both IPr and Ph_3P ligands (<10−12 kcal/mol), whereas the ring closure of allene−gold(I) complex **IV**, which is in equilibrium with the free allene **V**, presents a higher barrier (17.8 kcal/mol with both ligands) and thus is the rate-determining step. When the cyclization is slow or does not take place, allene **V** can be isolated.

The cyclization step takes place as an electrophilic aromatic substitution to form **VI**, and during this step, a partial positive charge develops on the aromatic ring (**TS3**), which explains the effect of the substituents we observed when assessing the scope of the reaction (interestingly, in the Au(I)-catalyzed tandem [3,3]-rearrangement/hydroarylation of propargylic acetates to form indenes, the reaction was very fast irrespective of the substituent present on the aryl ring, providing the products in 5 min).[8b] After proton elimination from C7a (to restore aromaticity) and protodeauration of **VII**, indene **VIII** is eventually formed. We carried out an experiment with deuterated [D]-**6a** (Scheme 7) and found out that all deuterium was incorporated in the product at position C1, meaning that, contrarily to what observed in the tandem Claisen/Nazarov reaction we have recently studied [Scheme 1a], no [1,2]-H shift from position 1 to position 2 occurs.[11] Another important difference with the tandem Claisen/Nazarov process is that we were never able to observe (and isolate) the allene intermediates in that case, as the cyclization was a fast step, especially with carbocyclic substrates.[11]

Two important points in the present cascade process are the role of the BF_4^- counterion and the effect of the IPr gold(I)-ligand, which together form the best combination (entry 9,

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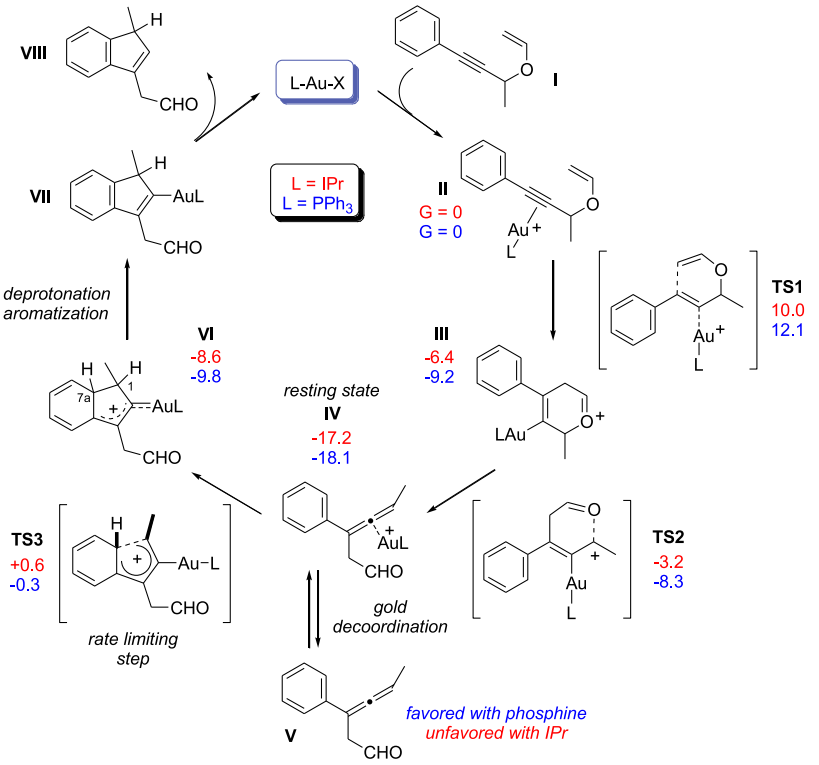
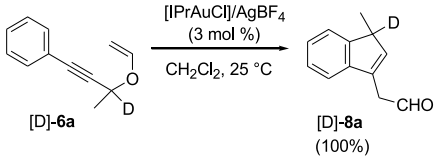
Scheme 6. Catalytic Cycle with Calculated Energies[a]



[a]Energies in kcal/mol are calculated relative to **II** (in blue for Ph_3P ligand, in red for IPr ligand). DFT calculations were carried out with the Gaussian16 set of programs and the M06 functional.

Scheme 7. Control Experiment



Scheme 8. Calculated Energies for the Dissociation of Complex IV

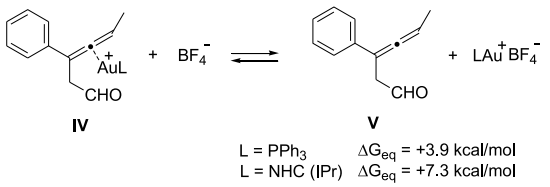
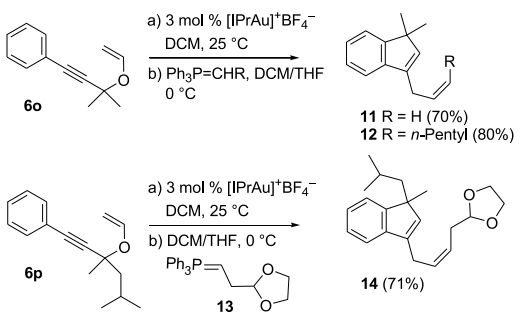


Table 1). Tetrafluoroborate is a weakly coordinating anion[27] and this could favor coordination of LAu^+ cationic complex to allene **V** to re-generate allene–gold complex **IV**. Concerning the ligands, because the calculated energies (Scheme 6) are almost the same for both IPr and Ph_3P ligands, explaining the efficiency of the NHC gold ligand compared to the phosphine ligands, with which ring closure of allene intermediate **V** does not take place or is very slow, is more difficult. It has been suggested that, in the rearrangement of a model propargyl acetate to form the corresponding allene, the latter is the resting state with a NHC ligand (IMe) and that allene coordination to gold is favored with the IMe ligand compared to a phosphine.[9d] We calculated the energies associated to the dissociation equilibrium of complex **IV** (Scheme 8) and found that the phosphine ligand is able to stabilize more efficiently the LAu^+ species, as the uphill energy is only +3.9 kcal/mol compared with +7.3 kcal/mol for the NHC carbene. Thus, the equilibrium is more shifted to the left with the latter ligand with which the formation of allene–gold(I) complex intermediate **IV** from allene **V** is more favored.

The reason why, apart from SIPr, the other NHC catalysts are unable to promote cyclization, is instead unclear at the moment.

Finally, to demonstrate that aldehyde intermediates **8** can be directly employed just after their formation for further chain elongation without prior work-up of the gold-catalyzed step, we studied the Wittig reaction of **8o** and **8p** with selected phosphorus ylides (Scheme 9). The reactions were carried out by transferring by a syringe the DCM solution containing the crude aldehyde to a tetrahydrofuran (THF) solution of the

Scheme 9. Sequential Au(I)-Catalyzed Tandem Process/ Wittig Olefination of Substrates 6o–p



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preformed ylide at 0 °C and leaving under stirring until complete consumption of **8**. With simple $Ph_3P{=}CH_2$, the reaction led to the terminal olefin **11** in 70% yield after chromatography. No isomerization of the double bonds was observed. Similarly, the reaction occurred quantitatively with a substituted ylide prepared from *n*-hexylphosphonium iodide, which provided *Z* olefin **12** in 80% yield. Finally, after rearrangement and cyclization of **6p**, the crude aldehyde **8p** was reacted with ylide **13**, prepared from the corresponding commercial phosphonium bromide, which furnished compound **14** in 71% yield.

CONCLUSIONS

In conclusion, the tandem gold(I)-catalyzed propargyl Claisen rearrangement/hydroarylation reaction of aryl-substituted propargyl vinyl ethers is an efficient way to obtain functionalized indenes. The reaction occurs at room temperature in DCM in the presence of [IPrAuCl]/$AgBF_4$ as the best catalytic system for both the propargyl Claisen rearrangement and the subsequent allene cyclization (the hydroarylation step). Instead, cyclization of the allene intermediate does not take place (or it is very slow) with phosphine ligands, which is probably due to the higher stabilization of the free cationic gold(I) in the equilibrium involving coordination/decoordination of the allene intermediate to gold(I), as suggested by density functional theory (DFT) computations. Various groups and substituents on the aryl ring and at the carbinolic position of the propargyl vinyl ether are tolerated. The effect of the substituents on the aryl ring suggests that the final hydroarylation is the rate-determining step of this cascade process with a calculated free activation energy of about 18 kcal/mol for both the NHC and phosphine ligand. Further functionalization can be achieved prior final work of the tandem process by carrying out a Wittig reaction on the aldehyde functionality, thus incrementing the diversity of the products obtained.

EXPERIMENTAL SECTION

General Information. Anhydrous solvents were prepared accordingly to the standard techniques. Commercially available reagents were used without further purification. Chromatographic separations were performed under pressure on silica gel (Merck 70−230 mesh) by using flash column techniques; R_f values refer to TLC carried out on 0.25 mm silica gel plates (F_{254}) with the same eluent as indicated for column chromatography. ^{1}H NMR (400 MHz) and ^{13}C NMR (100.4 MHz) spectra were recorded on Varian Inova and Mercury (400 MHz) spectrometers in the specified deuterated solvent at 25 °C. Solvent reference lines were set at 7.26 and 77.00 ($CDCl_3$) and 3.31 and 49.00 (CD_3OD) in ^{1}H and ^{13}C NMR spectra, respectively. Mass spectra were carried out either by direct inlet of a 10 ppm solution in CH_3OH on a LCQ Fleet Ion Trap LC/MS system (Thermo Fisher Scientific) with an electrospray ionization (ESI) interface in the positive ion mode or by EI at 70 eV or by methanol CI on a Varian GC/MS Saturn 2200 instrument equipped with a CP-sil8 Varian column. High-resolution mass spectrometry (HRMS) analyses were performed under conditions of ESI-MS through direct infusion of a 1 μM solution in MeOH in a TripleTOF 5600+ mass spectrometer (Sciex, Framingham, MA, U.S.A.), equipped with a DuoSpray interface operating with an ESI probe. Microanalyses were carried out with a CHN Thermo FlashEA 1112 Series elemental analyzer. Alcohols **5a**, **5m**, and **5q** are commercially available. Compounds [D]-**5a**,[28] **5b**,[29−32] **5c**,[29] **5d**,[29,30] **5e**,[29,30] **5f**,[31] **5j**,[29] **5k**,[29] **5l**,[31] **5n**,[30] **5o**,[33] **5p**,[32] and **6q**[10d] are known. *n*-Hexyltriphenylphosphonium iodide was prepared as reported.[34]

*[3-(2-Bromoethoxy)-but-1-ynyl]-benzene (**7a**).* A solution of (±)-4-phenyl-3-butyn-2-ol **5a** (872 μL, 6.0 mmol) in anhydrous DCM (60 mL) under nitrogen atmosphere was cooled to 0 °C (ice bath); Et_3N (2.5 mL, 18.0 mmol) and 4-dimethylaminopyridine (36 mg, 0.30 mmol) were then added, followed by dropwise addition of Ac_2O (1.5 mL, 12.0 mmol). After 10 min, the ice bath was removed and the resulting mixture was stirred at room temperature for 3 h. A satd solution of $NaHCO_3$ (60 mL) was added and the mixture was left under vigorous stirring for 5 min; after separation of the layers, the aqueous one was extracted with DCM (2 × 30 mL) and the combined organic extracts were dried over anhydrous K_2CO_3. After filtration and evaporation of the solvent, the crude acetate was purified by flash chromatography (eluent: *n*-hexane/EtOAc, 8:1; R_f = 0.41), affording the pure acetate (1.11 g, 98%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45−7.43 (m, 2H), 7.33−7.28 (m, 3H), 5.68 (q, *J* = 6.8 Hz, 1H), 2.11 (s, 3H), 1.58 (d, *J* = 6.8 Hz, 3H).

The acetate (941 mg, 5.0 mmol) was then dissolved in nitromethane (20 mL) under nitrogen atmosphere, and 2-bromoethanol (1.1 mL, 15.0 mmol) was added followed by anhydrous $InCl_3$ (55 mg, 0.25 mmol). The resulting mixture was heated at 50 °C (external) for 2 h. After cooling, the solvent was removed under *vacuum* and purification of the crude residue by flash chromatography (eluent: *n*-hexane/EtOAc, 20:1; R_f = 0.30), afforded pure **7a** (1.01 g, 80%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.33−7.30 (m, 3H), 4.48 (q, *J* = 6.8 Hz, 1H), 4.10 (dt, *J* = 10.8, 6.4 Hz, 1H), 3.81 (dt, *J* = 10.8, 6.4 Hz, 1H), 3.57−3.49 (m, 2H), 1.55 (d, *J* = 6.8 Hz, 3H). ^{13}C {^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 131.7, 128.4, 128.3, 122.5, 88.5, 85.4, 68.5, 66.1, 30.3, 22.1. GCMS (CI) *m*/*z* (%): 255 ([M + 1]$^+$, 3) and 253 ([M + 1]$^+$, 3), 153 (15) and 151 (17), 129 (100). Anal. Calcd for $C_{12}H_{13}BrO$: C, 56.94; H, 5.18. Found: C, 57.02; H, 5.23.

*(3-Viniloxy-but-1-ynyl)-benzene (**6a**).* To a solution of **7a** (1.0 g, 3.95 mmol) and 18-crown-6 (10 mg, 1 mol %) in anhydrous toluene (5.9 mL) under nitrogen atmosphere, solid *t*-BuOK (532 mg, 4.74 mmol) was added in one portion, and the mixture was left under vigorous stirring for 5 h. After cooling, the mixture was filtered through a short pad of silica gel (980 mg) and the pad was washed with *n*-hexane/EtOAc, 20:1 (4 mL). The solvent was then removed under *vacuum*, and purification of the crude residue by flash chromatography (eluent: *n*-hexane/EtOAc, 20:1; R_f = 0.21) afforded pure **6a** (619 mg, 91%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.32−7.28 (m, 3H), 6.50 (dd, *J* = 14.0, 6.4 Hz, 1H), 4.77 (q, *J* = 6.4 Hz, 1H), 4.48 (dd, *J* = 14.0, 1.6 Hz, 1H), 4.16 (dd, *J* = 6.4, 1.6 Hz, 1H), 1.60 (d, *J* = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 131.8, 128.5, 128.2, 122.4, 89.8, 87.9, 85.6, 65.1, 21.9. GCMS (EI) *m*/*z* (%): 172 (M$^+$, 24), 157 (100), 128 (43). Anal. Calcd for $C_{12}H_{12}O$: C, 83.69; H, 7.02. Found: C, 83.45; H, 6.82.

Compound **6a** was also prepared according to the general procedure reported below. Vinylation of alcohol **5a** (150 mg, 1.02 mmol) afforded pure **6a** (135 mg) after chromatography in 77% yield.

General Procedures for the Synthesis of the 3-Aryl-Substituted Propargyl Vinyl Ethers. In a screw-cap vial, $Hg(OAc)_2$ (0.45 mmol) was added in one portion to a solution of substrate **5** (1 mmol) in ethyl vinyl ether (2.5 mL) under nitrogen atmosphere, and the reaction mixture was heated at 50 °C (external) for 24 h. The mixture was then cooled to room temperature and a solution of satd Na_2CO_3 (5 mL) was added. The product was extracted with Et_2O (3 × 5 mL), and the combined organic extracts were dried over anhydrous K_2CO_3. After filtration and evaporation of the solvent, the crude reaction mixture was purified by flash column chromatography to give pure **6** which was stored at 4 °C as a solution in *n*-hexane until use.

*1-Methyl-4-(3-viniloxy-but-1-ynyl)-benzene (**6b**).* Vinylation of compound **5b** (150 mg, 0.95 mmol) afforded **6b**, which was purified by flash chromatography (*n*-hexane + 1% Et_3N; R_f = 0.28). Pure **6b** was obtained as a colorless oil (108 mg, 61%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33 (d, *J* = 8.0 Hz, 2H), 7.11 (d, *J* = 8.0 Hz, 2H), 6.50 (dd, *J* = 14.0, 6.8 Hz, 1H), 4.77 (q, *J* = 6.8 Hz, 1H), 4.48 (dd, *J* = 14.0, 2.0 Hz, 1H), 4.16 (dd, *J* = 6.8, 2.0 Hz, 1H), 2.35 (s, 3H), 1.60 (d, *J* = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.7, 138.6, 131.7, 129.0, 119.3, 89.7, 87.2, 85.8, 65.2, 21.9, 21.5. GCMS

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(EI) m/z (%): 186 (M^+, 5), 171 (100), 143 (9), 128 (13). Anal. Calcd for $C_{13}H_{14}O$: C, 83.83; H, 7.58. Found: C, 83.48; H, 7.63.

*1-Methyl-2-(3-viniloxy-but-1-ynyl)-benzene (**6c**).* Vinylation of compound **5c** (185 mg, 1.15 mmol) afforded **6c**, which was purified by flash chromatography (*n*-hexane; R_f = 0.30). Pure **6c** was obtained as a colorless oil (133 mg, 62%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41 (d, J = 7.6 Hz, 1H), 7.25−7.18 (m, 2H), 7.15−7.11 (m, 1H), 6.52 (dd, J = 14.0, 6.8 Hz, 1H), 4.82 (q, J = 6.8 Hz, 1H), 4.49 (dd, J = 14.0, 1.6 Hz, 1H), 4.18 (dd, J = 6.8, 1.6 Hz, 1H), 2.43 (s, 3H), 1.63 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 140.3, 132.0, 129.4, 128.5, 125.5, 122.1, 91.8, 89.7, 84.5, 65.1, 22.0, 20.7. GCMS (EI) m/z (%): 186 (M^+, 12), 171 (39), 157 (100), 129 (33). Anal. Calcd for $C_{13}H_{14}O$: C, 83.83; H, 7.58. Found: C, 84.00; H, 7.32.

*1-Methyl-3-(3-vinyloxy-but-1-ynyl)-benzene (**6d**).* Vinylation of compound **5d** (163 mg, 1.01 mmol) afforded **6d**, which was purified by flash chromatography (*n*-hexane + 1% Et_3N; R_f = 0.40). Pure **6d** was obtained as a pale yellow oil (129 mg, 68%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27−7.24 (m, 2H), 7.22−7.17 (m, 1H), 7.14−7.12 (m, 1H), 6.51 (dd, J = 14.0, 6.4 Hz, 1H), 4.77 (q, J = 6.8 Hz, 1H), 4.48 (dd, J = 14.0, 1.6 Hz, 1H), 4.17 (dd, J = 6.4, 1.6 Hz, 1H), 2.33 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 137.9, 132.3, 129.4, 128.8, 128.1, 122.2, 89.8, 87.5, 85.8, 65.1, 21.9, 21.2. GCMS (EI) m/z (%): 186 (M^+, 35), 171 (100), 143 (82), 128 (43). Anal. Calcd for $C_{13}H_{14}O$: C, 83.83; H, 7.58. Found: C, 83.47; H, 7.82.

*1-Methoxy-4-(3-vinyloxy-but-1-ynyl)-benzene (**6e**).* Vinylation of compound **5e** (193 mg, 1.1 mmol) afforded **6e**, which was purified by flash chromatography (*n*-hexane/EtOAc, 50:1 + 1% Et_3N; R_f = 0.40). Pure **6e** was obtained as a colorless oil (91 mg, 41%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39−7.35 (m, 2H), 6.85−6.81 (m, 2H), 6.50 (dd, J = 14.4, 6.8 Hz, 1H), 4.76 (q, J = 6.8 Hz, 1H), 4.47 (dd, J = 14.0, 2.0 Hz, 1H), 4.15 (dd, J = 6.8, 1.6 Hz, 1H), 3.80 (s, 3H), 1.59 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 159.7, 149.7, 133.2, 114.5, 113.9, 89.7, 86.5, 85.6, 65.3, 55.3, 22.0. GCMS (EI) m/z (%): 203 ([M + 1]$^+$, 28), 202 (M^+, 100), 188 (63), 159 (28). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 76.96; H, 7.12.

*1-Methoxy-3-(3-vinyloxy-but-1-ynyl)-benzene (**6f**).* Vinylation of compound **5f** (200 mg, 1.14 mmol) afforded **6f**, which was purified by flash chromatography (*n*-hexane + 1% Et_3N; R_f = 0.17). Pure **6f** was obtained as a pale yellow oil (134 mg, 58%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23−7.19 (m, 1H), 7.04−7.02 (m, 1H), 6.97−6.95 (m, 1H), 6.89−6.86 (m, 1H), 6.49 (dd, J = 14.0, 6.8 Hz, 1H), 4.77 (q, J = 6.8 Hz, 1H), 4.47 (dd, J = 14.0, 2.0 Hz, 1H), 4.17 (dd, J = 6.8, 2.0 Hz, 1H), 3.80 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 159.2, 149.6, 129.3, 124.3, 123.4, 116.5, 115.1, 89.8, 87.7, 85.5, 65.1, 55.3, 21.8. GCMS (EI) m/z (%): 203 ([M + 1]$^+$, 45), 202 (M^+, 100), 188 (44), 159 (25). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.55; H, 7.01.

*[4-(3-Vinyloxy-but-1-ynyl)-benzyl]-carbamic Acid tert-Butyl Ester (**6g**).* To a solution of (4-bromobenzyl)-carbamic acid *tert*-butyl ester (918 mg, 3.2 mmol) in anhydrous Et_3N (16 mL) were added $(Ph_3P)_2PdCl_2$ (5 mol %), CuI (3 mol %) and (±)-3-butyn-2-ol (1.2 equiv), under nitrogen atmosphere, and the reaction mixture was stirred at 50 °C (external) for 3 h. A second portion of (±)-3-butyn-2-ol (0.5 equiv), CuI (1.5 mol %), and $(Ph_3P)_2PdCl_2$ (2.5 mol %) was then added. Heating was continued at 50 °C for 16 h. The mixture was cooled to room temperature and water (16 mL) was added. The product was extracted with Et_2O (3 × 16 mL), and the combined organic extracts were washed once with brine (50 mL) and dried over anhydrous K_2CO_3. After filtration and evaporation of the solvent, the crude reaction mixture purified by flash column chromatography (*n*-hexane/EtOAc, 2:1 + 1% Et_3N; R_f = 0.29) afforded pure enynyl alcohol **5g** (696 mg, 79%) which was used immediately in the next step. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, J = 8.4 Hz, 2H), 7.21 (d, J = 8.0 Hz, 2H), 4.87 (br s, 1H), 4.77−4.72 (m, 1H), 4.33−4.24 (m, 2H), 2.08 (br s, 1H), 1.54 (d, J = 6.4 Hz, 3H), 1.45 (s, 9H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 155.8, 139.3, 131.8, 127.3, 121.5, 91.0, 83.7, 58.8, 44.4, 28.4, 24.4.

Vinylation of compound **5g** (343 mg, 1.25 mmol) afforded **6g**, which was purified by flash chromatography (*n*-hexane/EtOAc, 5:1 + 1% Et_3N; R_f = 0.28). Pure **6g** was obtained as a pale yellow oil (286 mg, 76%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39 (d, J = 8.4 Hz, 2H), 7.21 (d, J = 8.0 Hz, 2H), 6.48 (dd, J = 14.0, 6.8 Hz, 1H), 4.87 (br s, 1H), 4.76 (q, J = 6.8 Hz, 1H), 4.46 (dd, J = 14.0, 2.0 Hz, 1H), 4.31−4.26 (m, 2H), 4.15 (dd, J = 6.8, 2.0 Hz, 1H), 1.59 (d, J = 6.8 Hz, 3H), 1.45 (s, 9H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 155.8, 149.6, 139.5, 132.0, 127.2, 121.3, 89.8, 87.9, 85.4, 79.6, 65.1, 44.4, 28.4, 21.8. HRMS (ESI/TOF) m/z: [M + Na]$^+$ calcd for $C_{18}H_{23}NO_3Na$, 324.1570; found, 324.1569.

*1-Benzyloxymethyl-4-(3-vinyloxy-but-1-ynyl)-benzene (**6h**).* Alcohol **5h** was prepared as reported for **5g**, by Sonogashira coupling of 1-benzyloxymethyl-4-bromobenzene (664 mg, 2.4 mmol) and (±)-3-butyn-2-ol (1.2 equiv). Purification by flash column chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.25) afforded pure enynyl alcohol **5h** (288 mg, 45%) which was used immediately in the next step. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43−7.39 (m, 2H), 7.38−7.34 (m, 4H), 7.33−7.29 (m, 3H), 4.79−4.72 (m, 1H), 4.56 (s, 2H), 4.55 (s, 2H), 1.56 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 138.7, 138.0, 131.7, 128.4, 127.8, 127.7, 127.5, 121.8, 90.9, 83.9, 72.3, 71.6, 58.9, 24.4.

Vinylation of compound **5h** (224 mg, 0.84 mmol) afforded **6h**, which was purified by flash chromatography (*n*-hexane/EtOAc, 20:1; R_f = 0.30). Pure **6h** was obtained as a pale yellow oil (148 mg, 60%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.38−7.36 (m, 4H), 7.33−7.31 (m, 3H), 6.51 (dd, J = 14.0, 6.4 Hz, 1H), 4.78 (q, J = 6.8 Hz, 1H), 4.559 (s, 2H), 4.555 (s, 2H), 4.49 (dd, J = 14.0, 2.0 Hz, 1H), 4.18 (dd, J = 6.8, 2.0 Hz, 1H), 1.61 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 138.8, 138.0, 131.8, 128.4, 127.8, 127.7, 127.5, 121.6, 89.8, 87.9, 85.5, 72.2, 71.6, 65.1, 21.8. GCMS (EI) m/z (%): 292 (M^+, 3), 277 (100), 91 (19). Anal. Calcd for $C_{20}H_{20}O_2$: C, 82.16; H, 6.89. Found: C, 81.99; H, 7.05.

*2-[4-(3-Vinyloxy-but-1-ynyl)-phenyl]-[1,3]dioxolane (**6i**).* Alcohol **5i** was prepared as reported for **5g**, by Sonogashira coupling of 2-(4-bromophenyl)-[1,3]dioxolane (515 mg, 2.2 mmol) and (±)-3-butyn-2-ol (1.2 equiv). Purification by flash column chromatography (*n*-hexane/EtOAc, 2:1; R_f = 0.27) afforded pure enynyl alcohol **5i** (467 mg, 97%) which was used immediately in the next step. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43−7.39 (m, 4H), 5.79 (s, 1H), 4.76−4.69 (m, 1H), 4.12−3.99 (m, 4H), 2.33 (d, J = 4.8 Hz, 1H), 1.53 (d, J = 6.4 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 137.9, 131.6, 126.4, 103.2, 91.5, 83.6, 65.3, 58.7, 24.3.

Vinylation of compound **5i** (186 mg, 0.85 mmol) afforded **6i**, which was purified by flash chromatography (*n*-hexane/EtOAc, 10:1; R_f = 0.25). Pure **6i** was obtained as a pale yellow oil (150 mg, 72%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46−7.40 (m, 4H), 4.49 (dd, J = 14.0, 6.8 Hz, 1H), 5.80 (s, 1H), 4.77 (q, J = 6.8 Hz, 1H), 4.47 (dd, J = 14.0, 2.0 Hz, 1H), 4.16 (dd, J = 6.8, 2.0 Hz, 1H), 4.13−4.01 (m, 4H), 1.60 (d, J = 6.8 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 138.2, 131.8, 126.4, 123.2, 103.2, 89.8, 88.4, 85.3, 65.3, 65.1, 21.8. GCMS (CI) m/z (%): 245 ([M + 1]$^+$, 100), 73 (91). Anal. Calcd for $C_{15}H_{16}O_3$: C, 73.75; H, 6.60. Found: C, 73.50; H, 6.92.

*1-Bromo-4-(3-vinyloxy-but-1-ynyl)-benzene (**6j**).* Vinylation of compound **5j** (225 mg, 1.0 mmol) afforded **6j**, which was purified by flash chromatography (*n*-hexane + 1% Et_3N; R_f = 0.50). Pure **6j** was obtained as a pale yellow oil (191 mg, 76%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.31−7.27 (m, 2H), 6.48 (dd, J = 14.0, 6.8 Hz, 1H), 4.75 (q, J = 6.4 Hz, 1H), 4.47 (dd, J = 14.0, 2.0 Hz, 1H), 4.17 (dd, J = 6.8, 2.0 Hz, 1H), 1.59 (d, J = 6.4 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 149.6, 133.2, 131.5, 122.8, 121.3, 89.9, 89.1, 84.5, 65.0, 21.7. GCMS (EI) m/z (%): 252 (M^+, 19) and 250 (M^+, 18), 237 (100) and 235 (86), 128 (55). Anal. Calcd for $C_{12}H_{11}BrO$: C, 57.39; H, 4.42. Found: C, 57.54; H, 4.21.

*1-Fluoro-3-(3-vinyloxy-but-1-ynyl)-benzene (**6k**).* Vinylation of compound **5k** (150 mg, 0.92 mmol) afforded **6k**, which was purified by flash chromatography (*n*-hexane; R_f = 0.40). Pure **6k** was obtained as a colorless oil (119 mg, 68%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31−7.27 (m, 1H), 7.24−7.21 (m, 1H), 7.16−7.13 (m, 1H), 7.07−7.01 (m, 1H), 6.50 (dd, J = 14.0, 6.8 Hz, 1H), 4.78 (q, J = 6.4 Hz,

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1H), 4.49 (dd, J = 14.0, 2.0 Hz, 1H), 4.19 (dd, J = 6.8, 2.0 Hz, 1H), 1.61 (d, J = 6.4 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 162.3 (d, J_{CF} = 246.0 Hz), 149.6, 129.8 (d, J_{CF} = 9.0 Hz), 127.6 (d, J_{CF} = 3.0 Hz), 124.1 (d, J_{CF} = 10.0 Hz), 118.6 (d, J_{CF} = 23.1 Hz), 115.9 (d, J_{CF} = 21.1 Hz), 89.9, 88.8, 84.3 (d, J_{CF} = 4.0 Hz), 64.9, 21.7. GCMS (EI) m/z (%): 190 (M^+, 26), 189 ($[M - 1]^+$, 18), 175 (100), 146 (35), 127 (15). Anal. Calcd for $C_{12}H_{11}FO$: C, 75.77; H, 5.83. Found: C, 75.59; H, 5.87.

*4-(3-Vinyloxy-but-1-ynyl)-benzoic Acid Methyl Ester (**6l**).* Vinylation of compound **5l** (260 mg, 1.28 mmol) afforded **6l**, which was purified by flash chromatography (*n*-hexane/EtOAc, 25:1; R_f = 0.21). Pure **6l** was obtained as a pale yellow oil (232 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.99−7.95 (m, 2H), 7.50−7.47 (m, 2H), 6.48 (dd, J = 14.0, 6.4 Hz, 1H), 4.78 (d, J = 6.8 Hz, 1H), 4.47 (dd, J = 14.0, 2.0 Hz, 1H), 4.18 (dd, J = 6.4, 2.0 Hz, 1H), 3.91 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 166.4, 149.5, 131.7, 129.8, 129.4, 127.0, 90.8, 89.9, 84.8, 64.9, 52.5, 21.7. GCMS (EI) m/z (%): 230 (M^+, 3), 215 (100). Anal. Calcd for $C_{14}H_{14}O_3$: C, 73.03; H, 6.13. Found: C, 72.88; H, 6.39.

*(3-Vinyloxyhex-1-ynyl)-benzene (**6m**).* Vinylation of commercially available compound **5m** (158 μL, 0.86 mmol) afforded **6m**, which was purified by flash chromatography (*n*-hexane/EtOAc, 50:1; R_f = 0.40). Pure **6m** was obtained as a pale yellow oil (143 mg, 83%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.46−7.41 (m, 2H), 7.34−7.28 (m, 3H), 6.51 (dd, J = 14.0, 6.8 Hz, 1H), 4.64 (t, J = 6.8 Hz, 1H), 4.48 (dd, J = 14.0, 2.0 Hz, 1H), 4.15 (dd, J = 6.8, 2.0 Hz, 1H), 1.94−1.79 (m, 2H), 1.62−1.52 (m, 2H), 0.99 (t, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.9, 131.8, 128.4, 128.2, 122.5, 89.6, 87.2, 86.3, 69.1, 37.5, 18.5, 13.7. GCMS (EI) m/z (%): 200 (M^+, 6), 171 (100), 157 (20), 128 (29). Anal. Calcd for $C_{14}H_{16}O$: C, 83.96; H, 8.05. Found: C, 84.12; H, 7.98.

*(4-Phenyl-3-viniloxybut-1-ynyl)-benzene (**6n**).* Vinylation of compound **5n** (363 mg, 1.63 mmol) afforded **6n**, which was purified by flash chromatography (*n*-hexane/EtOAc, 75:1; R_f = 0.34). Pure **6n** was obtained as a colorless oil (210 mg, 52%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.42−7.39 (m, 2H), 7.35−7.26 (m, 8H), 6.51 (dd, J = 14.4, 6.8 Hz, 1H), 4.84 (t, J = 6.8 Hz, 1H), 4.51 (dd, J = 14.4, 2.0 Hz, 1H), 4.18 (dd, J = 6.8, 2.0 Hz, 1H), 3.27−3.14 (m, 2H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.6, 136.5, 131.7, 129.8, 128.5, 128.3, 128.2, 126.8, 122.3, 89.9, 87.3, 86.6, 70.0, 41.9. GCMS (CI) m/z (%): 249 ($[M + 1]^+$, 100), 205 (22). Anal. Calcd for $C_{18}H_{16}O$: C, 87.06; H, 6.49. Found: C, 86.85; H, 6.72.

*(3-Methyl-3-vinyloxybut-1-ynyl)-benzene (**6o**).* Vinylation of compound **5o** (191 mg, 1.19 mmol) afforded **6o**, which was purified by flash chromatography (*n*-hexane/EtOAc, 75:1; R_f = 0.30). Pure **6o** was obtained as a colorless oil (164 mg, 74%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.33−7.29 (m, 3H), 6.76 (dd, J = 14.0, 6.4 Hz, 1H), 4.52 (dd, J = 14.0, 1.2 Hz, 1H), 4.16 (dd, J = 6.4, 1.2 Hz, 1H), 1.62 (s, 6H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 147.4, 131.7, 128.5, 128.3, 122.4, 91.5, 90.2, 85.2, 72.6, 29.3. GCMS (EI) m/z (%): 186 (M^+, 14), 171 (100), 128 (13). Anal. Calcd for $C_{13}H_{14}O$: C, 83.83; H, 7.58. Found: C, 84.02; H, 7.43.

*(3,5-Dimethyl-3-viniloxyhex-1-ynyl)-benzene (**6p**).* Vinylation of compound **5p** (193 mg, 0.96 mmol) afforded **6p**, which was purified by flash chromatography (*n*-hexane/EtOAc, 15:1; R_f = 0.80). Pure **6p** was obtained as a colorless oil (164 mg, 75%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.45−7.42 (m, 2H), 7.34−7.30 (m, 3H), 6.78 (dd, J = 14.0, 6.4 Hz, 1H), 4.50 (dd, J = 14.0, 0.8 Hz, 1H), 4.14 (dd, J = 6.4, 0.8 Hz, 1H), 2.06−1.99 (m, 1H), 1.82−1.69 (m, 2H), 1.59 (s, 3H), 1.05 (d, J = 6.4 Hz, 3H), 1.04 (d, J = 6.4 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 147.3, 131.6, 128.4, 128.3, 122.5, 91.1, 89.8, 86.4, 75.7, 50.1, 27.9, 24.9, 24.1, 23.9. GCMS (EI) m/z (%): 228 (M^+, 8), 185 (100). Anal. Calcd for $C_{16}H_{20}O$: C, 84.16; H, 8.83. Found: C, 84.05; H, 9.02.

*(3-(Vinyloxy)prop-1-yne-1,3-diyl)dibenzene (**6q**).*[10d] Vinylation of compound **5q** (284 μL, 1.5 mmol) afforded **6q**, which was purified by flash chromatography (*n*-hexane/EtOAc, 50:1; R_f = 0.40). Pure **6q** was obtained as a pale yellow oil (189 mg, 60%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.62−7.59 (m, 2H), 7.50−7.47 (m, 2H), 7.47−7.30 (m, 6H), 6.58 (dd, J = 14.0, 6.4 Hz, 1H), 5.75 (s, 1H), 4.58 (dd, J = 14.0, 2.0 Hz, 1H), 4.23 (dd, J = 6.4, 2.0 Hz, 1H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.4, 137.7, 131.8, 128.7, 128.6, 128.3, 127.4, 122.2, 90.6, 88.3, 85.9, 71.2. GCMS (CI) m/z (%): 235 ($[M + 1]^+$, 100).

*1,2-Dichloro-4-(3-phenyl-1-vinyloxy-prop-2-ynyl)-benzene (**6r**).* Phenylacetylene (439 μL, 4.0 mmol) was added dropwise to a solution of *n*-BuLi (1.6 M in hexanes, 2.75 mL, 4.4 mmol) in anhydrous THF (9 mL) cooled at −78 °C (internal), keeping the temperature below −70 °C. After 30 min, a solution of 3,4-dichlorobenzaldehyde (840 mg, 4.8 mmol) in anhydrous THF (1.5 mL) was slowly added and, after further 5 min, the cooling bath was removed, and the reaction mixture was stirred at room temperature until complete consumption of the starting material (2.5 h). A satd solution of NH_4Cl (6 mL) was added under vigorous stirring, followed by water (5 mL). The phases were separated and the aqueous one was extracted by Et_2O (3 × 10 mL). The combined organic extracts were dried over anhydrous Na_2SO_4. After filtration and evaporation of the solvent, crude **5r** was isolated and purified by flash chromatography (eluent: *n*-hexane/EtOAc, 10:1; R_f = 0.20), affording pure enynyl alcohol **5r** (1.02 g, 93%) which was used immediately in the next step. ^1H NMR (400 MHz, $CDCl_3$): δ 7.71 (d, J = 2.0 Hz, 1H), 7.49−7.45 (m, 4H), 7.37−7.32 (m, 3H), 5.65 (d, J = 4.8 Hz, 1H), 2.41 (d, J = 5.2 Hz, 1H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 140.7, 132.7, 132.4, 131.8, 130.6, 128.9, 128.7, 128.4, 126.0, 121.9, 87.6, 87.3, 63.8.

Vinylation of compound **5r** (278 mg, 1.0 mmol) afforded **6r**, which was purified by flash chromatography (*n*-hexane/EtOAc, 75:1; R_f = 0.25). Pure **6r** was obtained as a yellow oil (169 mg, 56%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.69 (d, J = 2.0 Hz, 1H), 7.50−7.47 (m, 3H), 7.44−7.42 (m, 1H), 7.37−7.33 (m, 3H), 6.55 (dd, J = 14.0, 6.4 Hz, 1H), 5.69 (s, 1H), 4.58 (dd, J = 14.0, 2.0 Hz, 1H), 4.27 (dd, J = 6.4, 2.0 Hz, 1H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.1, 137.9, 132.80, 132.78, 131.9, 130.6, 129.3, 129.0, 128.4, 126.6, 121.7, 91.3, 89.0, 84.6, 69.8. GCMS (CI) m/z (%): 305 ($[M + 1]^+$, 70) and 303 ($[M + 1]^+$, 100), 304 (20). Anal. Calcd for $C_{17}H_{12}Cl_2O$: C, 67.35; H, 3.99. Found: C, 67.55; H, 4.01.

*(3-Viniloxy-but-1-ynyl)-benzene ([D]-**6a**).* Vinylation of compound [D]-**5a** (300 mg, 2.04 mmol) afforded [D]-**6a**, which was purified by flash chromatography (*n*-hexane/EtOAc, 50:1; R_f = 0.30). Pure [D]-**6a** was obtained as a colorless oil (223 mg, 63%). ^1H NMR (400 MHz, $CDCl_3$): δ 7.48−7.42 (m, 2H), 7.34−7.28 (m, 3H), 6.51 (dd, J = 14.4, 6.4 Hz, 1H), 4.49 (dd, J = 14.4, 2.0 Hz, 1H), 4.18 (dd, J = 6.8, 2.0 Hz, 1H), 1.61 (s, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.6, 131.7, 128.5, 128.2, 122.3, 89.7, 87.8, 85.6, 64.7 (t, J_{CD} = 22.8 Hz), 21.7. GCMS (CI) m/z (%): 174 ($[M + 1]^+$, 28), 146 (100).

General Procedure for the Gold(I)-Catalyzed Propargyl Claisen Rearrangement/Hydroarylation Reaction Followed by in Situ Reduction. The solution of **6** in *n*-hexane was concentrated and dried under vacuum just prior use.

Gold(I) complex $[IPrAu]^+BF_4^-$ was prepared by adding an equimolar amount of $AgBF_4$ (as a 0.3 M solution in toluene) to a 0.003 M solution of IPrAuCl in DCM and leaving the mixture under stirring for 1 min at 25 °C before adding the substrate.

Method A. To a solution of gold(I) complex $[IPrAu]^+BF_4^-$ (3 mol %) in DCM (3 mL; 0.003 M) stirred at 25 °C under nitrogen atmosphere was added a solution of propargyl vinyl ether **6** (0.3 mmol) in DCM (3 mL; final concentration 0.05 M), and the reaction mixture was stirred at 25 °C. After complete consumption of **6** (TLC monitoring), the mixture was diluted with MeOH (12 mL) and $NaBH_4$ (0.3 mmol) was immediately added. After 10 min, the reduction was completed. The solvent was then evaporated, water was added to the residue (15 mL), and the product was extracted with DCM (3 × 15 mL). The combined organic extracts were dried over anhydrous K_2CO_3. After filtration and evaporation of the solvent, the oily residue was purified by flash chromatography to give the corresponding indene **10**.

Method B. To a solution of gold(I) complex $[IPrAu]^+BF_4^-$ (3 mol %) in DCM (3 mL; 0.003 M) stirred at 25 °C under nitrogen atmosphere was added a solution of propargyl vinyl ether **6** (0.3

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mmol) in DCM (3 mL; final concentration 0.05 M), and the reaction mixture was stirred at 25 °C. After complete consumption of **6** (TLC monitoring), water (6 mL) was added and, after separation of the layers, the aqueous one was extracted with DCM (3 × 6 mL) and the combined organic extracts were dried over anhydrous Na_2SO_4. After filtration and evaporation of the solvent, the oily residue was dissolved in MeOH (12 mL) and $NaBH_4$ (0.3 mmol) was added. After 10 min, the reduction was completed. The solvent was then evaporated, water was added to the residue (15 mL), and the product was extracted with DCM (3 × 15 mL). The combined organic extracts were dried over anhydrous K_2CO_3. After filtration and evaporation of the solvent, the oily residue was purified by flash chromatography to give the corresponding indene **10**.

*2-(3-Methyl-3H-inden-1-yl)-ethanol (**10a**).* Compound **10a** was prepared following Method A, starting from **6a** (252 mg, 1.48 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 25 min. Purification by flash chromatography (*n*-hexane/EtOAc, 12:1; R_f = 0.16) afforded pure **10a** (204 mg, 80%) as a pale yellow oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.44−7.41 (m, 1H), 7.35−7.22 (m, 3H), 6.27 (m, 1H), 3.96−3.91 (m, 2H), 3.48 (qd, J = 7.6, 2.0 Hz, 1H), 2.86−2.81 (m, 2H), 1.32 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 149.9, 144.0, 138.8, 137.2, 126.3, 125.0, 122.7, 119.0, 61.0, 43.9, 31.0, 16.3. GCMS (EI) m/z (%): 156 ($[M - 18]^+$, 62), 141 (100), 115 (35). Anal. Calcd for $C_{12}H_{14}O$: C, 82.72; H, 8.10. Found: C, 82.53; H, 8.22.

*2-(3,5-Dimethyl-3H-inden-1-yl)-ethanol (**10b**).* Compound **10b** was prepared following Method A, starting from **6b** (88 mg, 0.48 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 15 min. Purification by flash chromatography (*n*-hexane/EtOAc, 5:1; R_f = 0.37) afforded pure **10b** (80 mg, 89%) as a pale yellow oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.24 (s, 1H), 7.22 (d, J = 7.6 Hz, 1H), 7.11 (d, J = 7.6 Hz, 1H), 6.21−6.18 (m, 1H), 3.94−3.89 (m, 2H), 3.43 (q, J = 7.2 Hz, 1H), 2.83−2.79 (m, 2H), 2.41 (s, 3H), 1.30 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 150.2, 141.4, 138.6, 136.3, 134.8, 127.0, 123.7, 118.7, 61.0, 43.7, 31.1, 21.5, 16.4. GCMS (EI) m/z (%): 170 ($[M - 18]^+$, 100), 155 (83), 128 (12). Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.73; H, 8.65.

*2-(3,7-Dimethyl-3H-inden-1-yl)ethanol (**10c**).* Compound **10c** was prepared following Method A, starting from **6c** (72 mg, 0.39 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 1.5 h. Purification by flash chromatography (*n*-hexane/Et_2O, 3:1 + 1% Et_3N; R_f = 0.20) afforded pure **10c** (52 mg, 71%) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.26−7.24 (m, 1H), 7.13−7.09 (m, 1H), 7.03−7.01 (m, 1H), 6.21 (m, 1H), 3.97−3.92 (m, 2H), 3.41−3.36 (m, 1H), 3.03−2.99 (m, 2H), 2.57 (s, 3H), 1.56 (t, J = 6.0 Hz, 1H), 1.28 (d, J = 7.6 Hz, 1H). $^{13}C\{^1H\}$ NMR (100.4 MHz, CD_3OD): δ 152.0, 142.9, 141.7, 137.8, 131.6, 130.2, 125.9, 121.6, 62.5, 44.3, 34.8, 20.3, 17.1. GCMS (EI) m/z (%): 188 (M^+, 10), 170 ($[M - 18]^+$, 9), 157 (70), 144 (100), 115 (26). Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.78; H, 8.71.

*2-(3,6-Dimethyl-3H-inden-1-yl)ethanol (**10d**).* Compound **10d** was prepared following Method A, starting from **10d** (91 mg, 0.49 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 15 min. Purification by flash chromatography (*n*-hexane/EtOAc, 5:1; R_f = 0.20) afforded **10d** (71 mg, 77%) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) (1:1 mixture of 3,6- and 3,4-dimethyl-substituted products): δ 7.31 (d, J = 7.6 Hz, 1H), 7.24−7.15 (m, 3H), 7.07−7.05 (m, 1H), 7.03−7.02 (m, 1H), 6.26−6.23 (m, 1 H both compounds), 3.97−3.88 (m, 2 H both compounds), 3.46−3.50 (m, 1H), 3.47−3.41 (m, 1H), 2.84−2.79 (m, 2 H both compounds), 2.45 (s, 3H), 2.42 (s, 3H), 1.32 (d, J = 7.2 Hz, 3H), 1.29 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$) (1:1 mixture of 3,6- and 3,4-dimethyl-substituted products): δ 147.6, 147.0, 144.2, 144.0, 138.7, 138.4, 137.61, 137.59, 135.9, 133.1, 126.9, 126.7, 125.8, 122.5, 119.7, 116.7, 61.05, 61.03, 43.49, 43.48, 31.03, 30.99, 21.5, 18.8, 16.4, 15.0. GCMS (EI) m/z (%): 170 ($[M - 18]^+$, 87), 155 (100). Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.88; H, 8.67.

*2-(5-Methoxy-3-methyl-3H-inden-1-yl)-ethanol (**10e**).* Compound **10e** was prepared following Method A, starting from **10e** (85 mg, 0.42 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 15 min. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.35) afforded pure **10e** (68 mg, 79%) as a pale yellow oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.21 (d, J = 8.4 Hz, 1H), 7.00 (d, J = 2.4 Hz, 1H), 6.83 (dd, J = 8.4, 2.4 Hz, 1H), 6.14−6.12 (m, 1H), 3.91 (t, J = 6.4 Hz, 2H), 3.84 (s, 3H), 3.45−3.39 (m, 1H), 2.81−2.77 (m, 2H), 1.29 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 158.3, 151.8, 138.4, 137.1, 135.1, 119.3, 111.5, 109.6, 61.0, 55.6, 43.8, 31.1, 16.6. GCMS (EI) m/z (%): 186 ($[M - 18]^+$, 100), 171 (48). Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90. Found: C, 76.26; H, 7.99.

*2-(6-Methoxy-3-methyl-3H-inden-1-yl)-ethanol (**10f**).* Compound **10f** was prepared following Method A, starting from **6f** (86 mg, 0.42 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 15 min. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.10) afforded pure **10f** (64 mg, 74%) as a pale yellow oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.29 (d, J = 8.0 Hz, 1H), 6.87 (d, J = 1.6 Hz, 1H), 6.77 (dd, J = 8.0, 1.6 Hz, 1H), 6.29−6.27 (m, 1H), 3.92 (q, J = 6.4 Hz, 2H), 3.84 (s, 3H), 3.45−3.39 (m, 1H), 2.82−2.77 (m, 2H), 1.49 (t, J = 5.6 Hz, 1H), 1.28 (d, J = 7.6 Hz, 3.H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 159.0, 145.5, 142.1, 138.7, 138.6, 123.1, 110.4, 105.1, 61.0, 55.6, 43.2, 31.0, 16.5. GCMS (EI) m/z (%): 186 ($[M - 18]^+$, 94), 171 (100). Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.90. Found: C, 76.55; H, 8.01.

*[1-(2-Hydroxyethyl)-3-methyl-3H-inden-ylmethyl]-carbamic Acid tert-Butyl Ester (**10g**).* Compound **10g** was prepared following Method A, starting from **6g** (60 mg, 0.20 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 15 min. Purification by flash chromatography (*n*-hexane/EtOAc, 2:1; R_f = 0.25) afforded pure **10g** (38 mg, 62%) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.33 (s, 1H), 7.27−7.26 (m, 1H), 7.21−7.18 (m, 1H), 6.26−6.24 (m, 1H), 4.84 (br s, 1H), 4.39−4.29 (m, 2H), 3.91 (q, J = 6.4 Hz, 2H), 3.47−3.41 (m, 1H), 2.83−2.79 (m, 2H), 1.54 (t, J = 5.6 Hz, 1H), 1.47 (s, 9H), 1.29 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 155.9, 150.4, 143.4, 138.6, 137.4, 135.8, 125.8, 122.2, 119.0, 61.0, 44.9, 43.8, 31.0, 28.4, 16.3. HRMS (ESI/TOF) m/z: $[M + Na]^+$ calcd for $C_{18}H_{25}NO_3Na$, 326.1727; found, 326.1740.

*2-(5-Benzyloxymethyl-3-methyl-3H-inden-1-yl)-ethanol (**10h**).* Compound **10h** was prepared following Method A, starting from **6h** (72 mg, 0.25 mmol) and using commercially available $[IPrAu(CH_3CN)]^+BF_4^-$ as the catalyst. The reaction was complete in 50 min. Purification by flash chromatography (*n*-hexane/Et_2O + 1% Et_3N, 3:1; R_f = 0.12) afforded pure **10h** (55 mg, 75%) as a colorless oil. ^1H NMR (400 MHz, CD_3OD): δ 7.40−7.24 (m, 10H), 6.25−6.23 (m, 1H), 4.58 (s, 2H), 4.54 (s, 2H), 3.84 (t, J = 7.2 Hz, 2H), 3.45−3.39 (m, 1H), 1.27 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, CD_3OD): δ 151.5, 145.4, 140.3, 139.6, 137.9, 136.0, 129.4, 129.0, 128.7, 127.5, 123.7, 119.7, 73.6, 73.0, 61.7, 44.9, 31.9, 16.7. HRMS (ESI/TOF) m/z: $[M + Na]^+$ calcd for $C_{20}H_{22}O_2Na$, 317.1512; found, 317.1529.

*(1-[1,3]Dioxolan-2-ylmethyl-3-methyl-3H-inden-5-yl)-methanol (**10i**).* Compound **10i** was prepared following Method B, starting from **6i** (105 mg, 0.43 mmol) and using commercially available $[IPrAu(CH_3CN)]^+BF_4^-$ as the catalyst (6 mol %). The reaction was complete in 2 h. Purification by flash chromatography (*n*-hexane/Et_2O, 2:1 + 1% Et_3N; R_f = 0.28) afforded pure **10i** (67 mg, 63%) as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.42−7.26 (m, 3H), 6.34−6.33 (m, 1H), 5.18 (t, J = 4.8 Hz, 1H), 4.74−4.72 (m, 2H), 4.01−3.99 (m, 2H), 3.90−3.88 (m, 2H), 3.50−3.44 (m, 1H), 2.91−2.88 (m, 2H), 1.31 (d, J = 7.6 Hz, 3H). $^{13}C\{^1H\}$ NMR (100.4 MHz, $CDCl_3$): δ 150.1, 144.2, 138.4, 137.6, 136.8, 125.4, 121.7, 119.3, 103.5, 65.0, 43.9, 32.9, 29.7, 16.1. GCMS (CI) m/z (%): 246 (M^+, 34), 230 (100), 73 (52). HRMS (ESI/TOF) m/z: $[M + Na]^+$ calcd for $C_{15}H_{18}O_3Na$, 269.1148; found, 269.1132.

*2-(5-Bromo-3-methyl-3H-inden-1-yl)-ethanol (**10j**).* Compound **10j** was prepared following Method A, starting from **6j** (62 mg, 0.25 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 6 h. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.32) afforded pure **10j** (35 mg, 56%) as a white

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foam. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 (d, J = 1.6 Hz, 1H), 7.41 (dd, J = 8.0, 1.6 Hz, 1H), 7.17 (d, J = 8.0 Hz, 1H), 6.25−6.23 (m, 1H), 3.92 (t, J = 6.4 Hz, 2H), 3.48−3.42 (m, 1H), 2.81−2.76 (m, 2H), 1.29 (d, J = 7.6 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 152.0, 143.0, 138.4, 137.4, 129.3, 126.2, 120.3, 119.3, 61.0, 43.9, 30.9, 16.1. GCMS (EI) m/z (%): 254 (M^+, 5) and 252 (M^+, 5), 161 (66), 133 (100), 105 (92). Anal. Calcd for $C_{12}H_{13}BrO$: C, 56.94; H, 5.18. Found: C, 56.45; H, 5.52.

*2-(6-Fluoro-3-methyl-3H-inden-1-yl)-ethanol (**10k**).* Compound **10k** was prepared following Method A, starting from **6k** (98 mg, 0.52 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 16 h. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.20) afforded **10k** (74 mg, 74%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) (1.2:1 mixture of 3*H*-isomer and 1*H*-isomer): δ 7.32−7.29 (m, 1H), 7.20−7.18 (m, 1H), 7.13−7.10 (m, 1H), 7.02−6.97 (m, 2H), 6.93−6.87 (m, 1H), 6.33 (s, 1H, 3*H*-isomer), 6.20 (s, 1H, 1*H*-isomer), 3.94−3.89 (m, 2H, 3*H*-isomer), 3.73−3.68 (m, 2H, 1*H*-isomer), 3.55−3.51 (m, 1H, 1*H*-isomer), 3.46−3.40 (m, 1H, 1*H*-isomer), 2.82−2.75 (m, 2H), 2.19−2.11 (m, 1H + 3 H 3*H*-isomer), 1.79−1.73 (m, 1H), 1.28 (d, J = 7.6 Hz, 3 H 3*H*-isomer). ^{13}C {^{1}H} NMR (100.4 MHz, $CDCl_3$) (1.2:1 mixture of 3*H*-isomer and 1*H*-isomer): δ 163.2 (d, J_{CF} = 80.3 Hz), 160.8 (d, J_{CF} = 80.3 Hz), 150.1 (d, J_{CF} = 8.0 Hz), 146.0 (d, J_{CF} = 9.0 Hz), 145.1 (d, J_{CF} = 2.0 Hz), 141.3 (d, J_{CF} = 2.0 Hz), 139.2, 138.4 (d, J_{CF} = 3.0 Hz), 133.0 (d, J_{CF} = 4.0 Hz), 123.3 (d, J_{CF} = 9.0 Hz), 119.6 (d, J_{CF} = 9.0 Hz), 115.0 (d, J_{CF} = 3.0 Hz), 113.1 (d, J_{CF} = 22.1 Hz), 111.5 (d, J_{CF} = 23.1 Hz), 110.5 (d, J_{CF} = 23.1 Hz), 106.2 (d, J_{CF} = 23.1 Hz), 61.3, 60.9, 45.9 (d, J_{CF} = 3.0 Hz), 43.3, 34.4, 30.8, 16.3, 13.0. GCMS (EI) m/z (%): 192 (M^+, 26), 161 (100), 148 (63). Anal. Calcd for $C_{12}H_{13}FO$: C, 74.98; H, 6.82. Found: C, 74.89; H, 7.02.

*1-(2-Hydroxyethyl)-3-methyl-3H-indene-5-carboxylic Acid Methyl Ester (**10l**).* Compound **10l** was prepared following Method A but heating at 40 °C (external), starting from **6l** (58 mg, 0.25 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 7 h. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.18) afforded **10l** (42 mg, 72%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) (1:1 mixture of 3*H*-isomer and 1*H*-isomer): δ 8.06 (s, 1H), 8.01−7.98 (m, 1H), 7.94 (s, 1H), 7.93−7.91 (m, 1H), 7.45 (d, J = 7.6 Hz, 1H), 7.35 (d, J = 8.0 Hz, 1H), 6.44−6.42 (m, 1H), 6.30−6.29 (m, 1H), 3.95−3.90 (m, 2H, 1*H*-isomer), 3.93 (s, 3H), 3.92 (s, 3H), 3.71 (t, J = 6.4 Hz, 2H, 3*H*-isomer), 3.62−3.57 (m, 1H, 1*H*-isomer), 3.53−3.47 (m, 1H, 3*H*-isomer), 2.85−2.80 (m, 2H, 3*H*-isomer), 2.22−2.14 (m, 1H, 1*H*-isomer), 2.17 (t, J = 1.6 Hz, 3H, 1*H*-isomer), 1.81−1.74 (m, 1H, 1*H*-isomer), 1.32 (d, J = 7.6 Hz, 3H, 3*H*-isomer). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$) (1:1 mixture of 3*H*-isomer and 1*H*-isomer): δ 167.7, 167.6, 153.2, 149.7, 148.8, 145.8, 140.7, 138.9, 138.8, 134.3, 128.7, 128.5, 126.7, 126.6, 123.7, 122.5, 120.1, 118.7, 61.3, 61.0, 52.02, 51.98, 46.1, 44.0, 34.2, 30.8, 15.9, 12.9. GCMS (EI) m/z (%): 233 ($[M + 1]^+$, 13), 215 (35), 202 (56), 189 (100). Anal. Calcd for $C_{14}H_{16}O_3$: C, 72.39; H, 6.94. Found: C, 72.31; H, 7.09.

*2-(3-Propyl-3H-inden-1-yl)-ethanol (**10m**).* Compound **10m** was prepared following Method A, starting from **6m** (80 mg, 0.40 mmol) and using commercially available $[IPrAu(CH_3CN)]^+BF_4^-$ as the catalyst. The reaction was complete in 1 h. Purification by flash chromatography (*n*-hexane/Et_2O, 8:1 + 1% Et_3N; R_f = 0.26) afforded pure **10m** (57 mg, 70%) as a colorless oil. ^{1}H NMR (400 MHz, CD_3OD): δ 7.37 (d, J = 7.2 Hz, 1H), 7.30 (d, J = 7.2 Hz, 1H), 7.22 (t, J = 7.2 Hz, 1H), 7.15 (t, J = 7.2 Hz, 1H), 6.29 (s, 1H), 3.84 (t, J = 7.2 Hz, 2H), 3.42−3.34 (m, 1H), 2.76 (t, J = 7.2 Hz, 2H), 1.91−1.80 (m, 1H), 1.47−1.33 (m, 3H), 0.94 (t, J = 7.2 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, CD_3OD): δ 147.9, 144.0, 139.1, 133.4, 125.2, 123.8, 121.8, 117.8, 59.8, 48.2, 33.2, 30.0, 19.8, 12.7. GCMS (EI) m/z (%): 202 (M^+, 38), 171 (50), 158 (98), 129 (100). Anal. Calcd for $C_{14}H_{18}O$: C, 83.12; H, 8.97. Found: C, 83.01; H, 9.15.

*2-(3-Benzyl-3H-inden-1-yl)-ethanol (**10n**).* Compound **10n** was prepared following Method B, starting from **6n** (87 mg, 0.35 mmol) and using commercially available $[IPrAu(CH_3CN)]^+BF_4^-$ as the catalyst (6 mol %). The reaction was complete in 2 h. Purification by flash chromatography (*n*-hexane/Et_2O, 4:1 + 1% Et_3N; R_f = 0.17) afforded pure **10n** (60 mg, 69%) as a colorless oil. ^{1}H NMR (400 MHz, CD_3OD): δ 7.30−7.10 (m, 9H), 6.17 (s, 1H), 3.77 (t, J = 7.2 Hz, 2H), 3.68−3.64 (m, 1H), 3.06 (dd, J = 13.2, 6.8 Hz, 1H), 2.74−2.68 (m, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, CD_3OD): δ 147.0, 144.1, 139.7, 139.3, 133.1, 128.2, 127.1, 125.5, 125.1, 123.7, 122.3, 117.9, 59.7, 49.8, 37.2, 29.9. HRMS (ESI/TOF) m/z: $[M + H]^+$ calcd for $C_{18}H_{18}O$, 251.1430; found, 251.1419.

*2-(3,3-Dimethyl-3H-inden-1-yl)-ethanol (**10o**).* Compound **10o** was prepared following Method A, starting from **6o** (86 mg, 0.53 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst. The reaction was complete in 3.5 h. Purification by flash chromatography (*n*-hexane/Et_2O, 2:1; R_f = 0.12) afforded pure **10o** (93 mg, 93%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35−7.32 (m, 1H), 7.29−7.20 (m, 3H), 6.16 (m, 1H), 3.95−3.89 (m, 2H), 2.81−2.77 (m, 2H), 1.61 (t, J = 5.6 Hz, 1H), 1.32 (s, 6H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 154.1, 143.2, 142.8, 136.3, 126.3, 125.3, 121.2, 119.2, 61.0, 48.4, 30.8, 24.7. GCMS (CI) m/z (%): 189 ($[M + 1]^+$, 100), 172 (70), 146 (87). Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.67; H, 8.72.

*2-(3-Isobutyl-3-methyl-3H-inden-1-yl)-ethanol (**10p**).* Compound **10p** was prepared following Method A, starting from **6p** (105 mg, 0.46 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst (6 mol %). The reaction was complete in 16 h. Purification by flash chromatography (*n*-hexane/EtOAc, 4:1; R_f = 0.30) afforded pure **10p** (97 mg, 92%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30−7.18 (m, 4H), 6.17 (s, 1H), 3.92 (m, 2H), 2.81 (t, J = 6.4 Hz, 2H), 1.82−1.70 (m, 2H), 1.27 (s, 3H), 1.22−1.15 (m, 1H), 0.81 (d, J = 6.8 Hz, 3H), 0.55 (d, J = 6.4 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 153.2, 143.5, 141.8, 136.8, 126.2, 125.1, 121.5, 119.0, 61.1, 52.3, 47.5, 30.9, 25.6, 25.3, 25.0, 24.3. GCMS (EI) m/z (%): 230 (M^+, 4), 174 (25), 143 (100), 130 (34). Anal. Calcd for $C_{16}H_{22}O$: C, 83.43; H, 9.63. Found: C, 83.26; H, 9.71.

*(3-Methyl-3H-inden-1-yl)-acetaldehyde ([D]-**8a**).* Aldehyde [D]-**8a** was prepared following Method B (first step only), starting from [D]-**7a** (38 mg, 0.12 mmol) and using $[IPrAu]^+BF_4^-$ as the catalyst (3 mol %). The reaction was complete in 35 min. After filtration and evaporation of the solvent, the ^{1}H NMR analysis of the crude mixture showed the presence of aldehydes [D]-**8a** (77%) and **8a** (23%). [D]-**8a**. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.76 (t, J = 1.6 Hz, 1H), 7.64 (d, J = 8.0 Hz, 2H), 7.28 (d, J = 8.0 Hz, 2H), 4.22−4.16 (m, 1H), 3.72 (dt, J = 16.8, 1.2 Hz, 1H), 3.41 (dt, J = 16.8, 1.2 Hz, 1H), 3.04−2.96 (m, 1H), 2.43 (s, 3H), 2.09−2.00 (m, 2H), 1.86 (s, 3H), 1.53−1.46 (m, 1H), 1.28−1.16 (m, 1H), 1.00−0.88 (m, 1H) ppm.

*3-Allyl-1,1-dimethyl-1H-indene (**11**).* The solution of **6o** in *n*-hexane was concentrated and dried under *vacuum* just prior use. A solution of gold(I) complex $[IPrAu]^+BF_4^-$ (3 mol %) was prepared by adding $AgBF_4$ (0.3 M solution in toluene, 62 μL, 0.019 mmol) to a solution of IPrAuCl (12 mg, 0.019 mmol) in DCM (6.3 mL) at 25 °C under nitrogen atmosphere and, after 1 min, a solution of propargyl vinyl ether **6o** (100 mg, 0.62 mmol) in DCM (6.3 mL) was added. The resulting reaction mixture was stirred at 25 °C for 3.5 h.

A solution of commercially available methyltriphenylphosphonium bromide (450 mg, 1.26 mmol) in anhydrous THF (24 mL) was cooled to 0 °C and a 1.0 M solution of *t*-BuOK in THF (1.36 mL, 1.36 mmol) was then added dropwise. After 30 min, the crude reaction mixture containing aldehyde **8o** was slowly added, and the resulting mixture was stirred at 0 °C. After complete consumption of **8o** (TLC monitoring; 30 min), the mixture was quenched by the addition of brine (50 mL) and the product was extracted by Et_2O (2 × 30 mL) and DCM (30 mL), and the combined organic extracts were dried over anhydrous Na_2SO_4. After filtration and evaporation of the solvent, the oily residue was purified by flash chromatography (*n*-hexane + 1% Et_3N; R_f = 0.43) affording pure **11** (80 mg, 70%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34−7.31 (m, 1H), 7.28−7.19 (m, 3H), 6.09−5.99 (m, 2H), 5.21−5.16 (m, 1H), 5.14−5.11 (m, 1H), 3.28−3.24 (m, 2H), 1.32 (s, 6H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 154.1, 143.1, 142.2, 138.0, 135.6, 126.2, 125.0, 121.0, 119.4, 116.2, 48.1, 32.0, 24.7. GCMS (CI) m/z (%): 185 ($[M + 1]^+$, 100). Anal. Calcd for $C_{14}H_{16}$: C, 91.25; H, 8.75. Found: C, 90.93; H, 9.03.

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*1,1-Dimethyl-3-oct-2-enyl-1H-indene (**12**).* Compound **12** was prepared as reported for **11**, starting from **6o** (112 mg, 0.69 mmol) and *n*-hexylphosphonium iodide[34] (656 mg, 1.38 mmol). The Wittig reaction was complete in 45 min. Purification by flash chromatography (*n*-hexane; R_f = 0.50) afforded pure **12** (140 mg, 80%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32−7.18 (m, 4H), 6.04 (s, 1H), 5.66−5.52 (m, 2H), 3.23 (d, J = 6.4 Hz, 2H), 2.17−2.12 (m, 2H), 1.44−1.37 (m, 2H), 1.34−1.27 (m, 4H), 1.30 (s, 6H), 0.92−0.88 (m, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 154.2, 143.3, 141.5, 138.8, 131.6, 126.2, 126.1, 125.0, 121.0, 119.2, 48.0, 31.6, 29.3, 27.3, 25.6, 24.7. GCMS (EI) m/z (%): 254 (M^+, 24), 197 (37), 143 (100). Anal. Calcd for $C_{19}H_{26}$: C, 89.70; H, 10.30. Found: C, 89.61; H, 10.60.

*2-[4-(3-Isobutyl-3-methyl-3H-inden-1-yl)-but-2-enyl]-[1,3]-dioxolane (**14**).* Compound **14** was prepared as reported for **11**, starting from **6p** (82 mg, 0.36 mmol) and commercially available 2-(1,3-dioxolan-2-yl)-ethyltriphenylphosphonium bromide (320 mg, 0.72 mmol). The Wittig reaction was complete in 30 min. Purification by flash chromatography (*n*-hexane/EtOAc, 20:1; R_f = 0.20) afforded pure **14** (80 mg, 71%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27−7.15 (m, 4H), 6.05 (t, J = 2.0 Hz, 1.6H), 5.85−5.78 (m, 1H), 5.67−5.60 (m, 1H), 4.95 (t, J = 4.8 Hz, 1H), 4.03−3.96 (m, 2H), 3.92−3.86 (m, 2H), 3.27 (d, J = 7.2 Hz, 2H), 2.57−2.54 (m, 2H), 1.78−1.68 (m, 2H), 1.24 (s, 3H), 1.20−1.14 (m, 1H), 0.78 (d, J = 6.4 Hz, 3H), 0.54 (d, J = 6.4 Hz, 3H). ^{13}C{^{1}H} NMR (100.4 MHz, $CDCl_3$): δ 153.3, 143.9, 140.3, 138.8, 129.6, 126.1, 124.8, 124.2, 121.3, 119.1, 103.9, 65.0, 51.9, 47.6, 32.3, 25.9, 25.5, 25.3, 25.0, 24.4. HRMS (ESI/TOF) m/z: $[M + Na]^+$ calcd for $C_{21}H_{28}O_2Na$, 335.1982; found, 335.1972.

Computational Methods. All structures were initially optimized using DFT with B3LYP[35] and the 6-31G(d,p) basis set and SDD[36] for Au as implemented in Gaussian 16.[37] Final energies were calculated at the M06[38]/def2tzvpp[39] level of theory, in a solvent model (IEFPCM, solvent = DCM).[40] The stationary points were characterized by frequency calculations in order to verify that they have the right number of imaginary frequencies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.9b00646.

Copies of ^{1}H and ^{13}C NMR spectra of all new compounds and Cartesian coordinates and energies of the structures included in the manuscript (PDF)

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Notes

The authors declare no competing financial interest.

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(23) (a) The structure of isomer **10f** was assigned on the basis of the chemical shift and coupling constants of aromatic protons. The two protons ortho to the methoxy group (at positions 4 and 6) are shielded and resonate below 7.00 ppm. The 4-H is a doublet at 6.87 ppm with a very small ^{4}J with the proton at position 6 (0.6 Hz) and the latter is a doublet of doublets at 6.77 ppm with a larger vicinal coupling constant (8 Hz) with 7-H which resonates as a doublet at 7.29 ppm. (b) The ratio between the 5-F and 7-F isomers was 85:15 in the crude reaction mixture. The structure of major isomer **10k** was assigned (for both double bond isomers) on the basis of the chemical shift and coupling constants of aromatic protons. The two protons *ortho* to the F atom at C4 and C6 resonates as dd ($^{3}J_{HF}$ = 8.8 Hz and $^{4}J_{HH}$ = 2.4 Hz) and ddd ($^{4}J_{HH}$ = 2.4 Hz, $^{3}J_{HH}$ = 8.4 Hz, $^{3}J_{HF}$ = 8.7 Hz,), respectively. The proton at C7 resonates instead as a dd ($^{4}J_{HF}$ = 5.2 Hz and $^{3}J_{HH}$ = 8.4 Hz).
(24) The structure of compound **10i** was assigned by analysis of ^{1}H, ^{13}C and bidimensional NMR spectra (gCOSY and gHSQC) (see Supporting Information). Diagnostic ^{1}H NMR signals (in $CDCl_3$) are the triplet at 5.19 ppm for the proton of the dioxolane moiety which couples with the side chain CH_2 group at C3, which in turn is a doublet at 2.90 ppm The benzylic protons at C6 is a doublet at 4.73 ppm for the coupling with the proton of the hydroxyl group.
(25) In some cases we observed a slow isomerization in $CDCl_3$ (for example when recording ^{13}C NMR spectra overnight) and in such cases we used CD_3OD as the solvent for the characterization.
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