Tetrahedron 67 (2011) 1609–1616

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Gold(I)-catalysed iodoalkoxylation of allenes

Amelie Heuer-Jungemann, Ross G. McLaren, Maximillian S. Hadfield, Ai-Lan Lee *

School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

ARTICLE INFO

Article history:
Received 8 October 2010
Received in revised form 13 December 2010
Accepted 6 January 2011
Available online 13 January 2011

Keywords:
Gold catalysis
Allenes
Ethers
Iodoalkoxylation

ABSTRACT

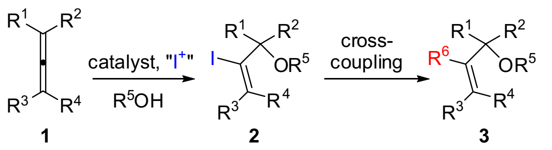
Gold(I)-catalysed intermolecular iodoalkoxylation of allenes occurs in a regioselective and stereoselective manner to produce versatile iodo-*tert*-allyllic ether products. The products can be further elaborated through cross-couplings to yield highly substituted *tert*-allylic ethers.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

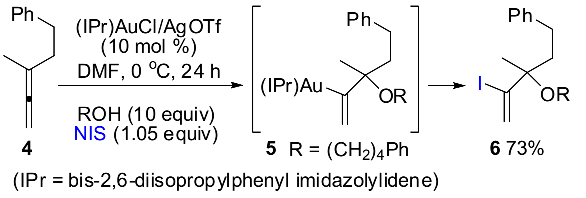
Allenes are a class of versatile compounds that have proven to be useful building blocks in organic synthesis.[1] For example, Ma and co-workers have carried out pioneering work into electrophilic additions to allenes.[2e] Extensive investigations into the stereoselective iodohydroxylation of functionalised allenes to furnish synthetically useful alcohol products[2] and intramolecular iodoalkoxylations of allenes have been successfully achieved.[3]

The *intermolecular* iodoalkoxylation of allenes, however, appears to be a very challenging transformation (**1**→**2**, Scheme 1). Nevertheless, if catalytic and regioselective intermolecular iodoalkoxylation of allenes could be achieved, this would constitute an efficient entry into iodo-*tert*-allylic ethers **2**, which could be further elaborated via cross-couplings to form functionalised *tert*-allylic ethers **3** (Scheme 1). Although ethers are ubiquitous in organic chemistry, the most widely used method for formation of ethers, the Williamson ether synthesis, is seldom useful for preparing tertiary ethers as elimination reactions tend to be favoured when tertiary alkoxides or tertiary halides are used.[4] A mild and general method for the synthesis of alkyl *tert*-allylic ethers thus still remains a challenge for synthetic chemists.[5,6]



Scheme 1. Iodoalkoxylation of allenes and further elaboration of versatile intermediates **2**.

As part of our effort to address this issue, we recently disclosed a regioselective gold(I)-catalysed hydroalkoxylation of allenes to form *tert*-allylic ethers.[7–9] As proof-of-principle, we also reported *one* preliminary result where the putative vinylgold species **5** can be trapped with *N*-iodosuccinimide (NIS) in situ to carry out an overall iodoalkoxylation of the allene **4** under mild conditions (Scheme 2).[7a,10,11] To the best of our knowledge, the only previous successful report on intermolecular iodoalkoxylation of allenes requires stoichiometric amounts of mercury(II) salts, and produces iodo-allylic ethers with tertiary/primary regioselectivities from ∼5:1 to 20:1.[12] Without mercury(II), iodo*hydroxylation* predominates, even when reactions of allenes and I_2 are carried out in the presence of excess alcohol, showing how challenging it is to form the tertiary ether moiety.[2d]



Scheme 2. Gold(I)-catalysed iodoalkoxylation of allene **4**.

The iodoalkoxylation of allenes is of particular interest because the resulting tertiary ethers can now be functionalised at the R^6 position by further cross-coupling reactions, potentially allowing for the

---

* Corresponding author. Tel.: +44 131 4518030; e-mail address: a.lee@hw.ac.uk (A.-L. Lee).

0040-4020/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2011.01.021

synthesis of highly substituted tertiarty allylic ethers **3**. In this full paper, we explore the scope and generality of this regioselective iodoalkoxylation reaction as well as further elaboration of the iodo-*tert*-allylic ether products **2**, to furnish substituted *tert*-allylic ethers **3**.

2. Results and discussion

A series of monosubstituted, disubstituted, trisubstituted and tetrasubstituted allenes were either purchased or synthesised according to literature reported procedures[14] and subjected to gold (I)-catalysed iodoalkoxylation (Table 1). 1,1-Dialkylsubstituted allenes **7** and **9** react smoothly to give **8** and **10** in 73% and 60% yields, respectively (entries 1 and 2). As with the parent hydroalkoxylation reaction,[7a] the iodoalkoxylation reaction is also sensitive to sterics; for example, while allene **4** reacts smoothly to provide **6** in 73% yield (entry 3), allene **11** suffers from poorer yields of the desired iodoalkoxylation product **12** (27% yield, entry 4). The major side-product is the iodohydroxylation product **13**. It appears that where there is steric hindrance, attack of adventitious water becomes competitive.[15]

Reaction of trisubstituted allenes **14** and **16** yielded pleasing results. Both react regioselectively *and* stereoselectively with phenethyl alcohol to provide the *Z*-alkene ethers in good yields (entries 5 and 6). The ester and silyl ether groups are also unaffected by the reaction conditions. Exocyclic allene **18** reacts less well under these conditions, providing product **19** in modest yield (42%, entry 7) and with an 85:5 ratio of **19**/hydroalkoxylation product **20**. Finally, even tetrasubstituted allene **21** reacts smoothly to provide the tetrasubstituted iodo-allylic ether **22** in 76% yield (entry 8).

The gold(I)-catalysed iodoalkoxylation is not confined to 1,1-disubstituted allenes as substrates to form iodo-*tert*-allylic ethers. Iodo-*sec*-allylic ethers are also accessible from the corresponding monosubstituted (**23**) or 1,3-disubstituted (**26**) allenes. However, the conditions have to be altered for these allene substrates: standard conditions (Scheme 2) resulted in low conversions with allenes **23** and **26**. Interestingly, when allene **23** is subjected to (IPr)AuCl[16] (10 mol %), AgOTf (10 mol %), ROH (10 equiv), NIS (1.05 equiv) at rt in DCM, a 1:1 ratio of **24**/**25** is produced in ~63% combined yield. Changing the catalyst to PPh_3AuNTf_2[17] in DCM at rt produces the desired iodo-*sec*-allyl ether **24** in 60% isolated yield and with a better

Table 1
The regioselective gold(I)-catalysed iodoalkoxylation of allenes[a]

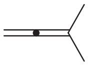
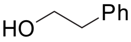
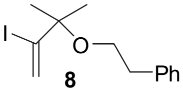
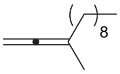
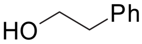
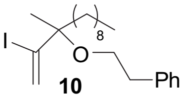
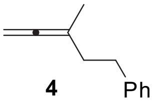
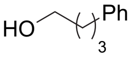
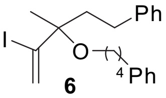
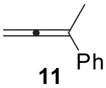
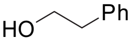
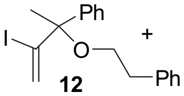
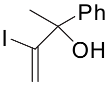
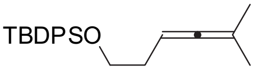
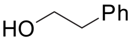
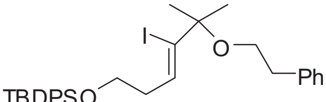
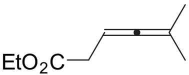
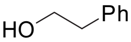
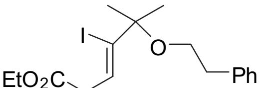
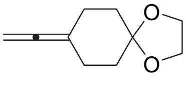
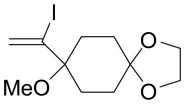
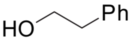
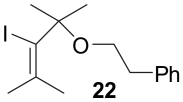
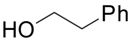
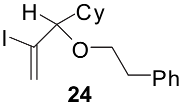
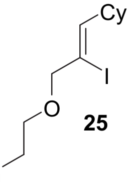
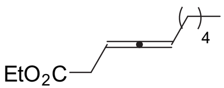
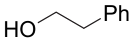
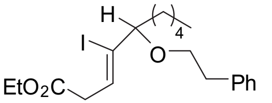
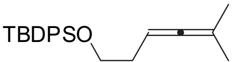
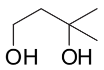
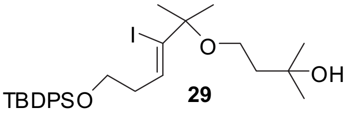
Entry	Allene	ROH	Product	Yield[b] (%)
1	 **7**		 **8**	73%
2	 **9**		 **10**	60%
3	 **4**		 **6**	73%
4	 **11**		 **12** +  **13**	27% **12** 32% **13**
5	 **14**		 **15**	68%
6	 **16**		 **17**	73%
7	 **18**	MeOH	 **19**	42%[c]
8	 **21**		 **22**	76%
9	 **23**		 **24**  **25**	(a) Using (IPr)AuCl/AgOTf:[d] 63% **24**/**25** 1:1; (b) using PPh_3AuNTf_2:[e] **24**/**25** 5:1; 60% yield of **24**

Table 1 (*continued*)

Entry	Allene	ROH	Product	Yield[b] (%)
10	 **26**		 **27**	60%[f]
11	 **14**	 **28**	 **29**	49%

---

[a] All reactions were carried out with (IPr)AuCl (10 mol %), AgOTf (10 mol %), ROH (10 equiv), NIS (1.05 equiv) at 0 °C in DMF for 20–24 h unless otherwise stated. The primary isomers of the products shown were generally not detected by crude ^{1}H NMR analysis (<5%), unless otherwise stated. Crude ^{1}H NMR analysis usually indicates <5% of iodohydroxylation by-product (unless otherwise stated).

[b] Isolated yield, unless otherwise stated.

[c] The hydroalkoxylation product **22** (H replacing I in **19**) is also observed in a 85:5 ratio of **19**/**20**.

[d] Reaction carried out with (IPr)AuCl (10 mol %), AgOTf (10 mol %), ROH (10 equiv), NIS (1.05 equiv) in DCM at rt for 4 h. Leaving the reaction for 24 h gives the same 1:1 ratio of **24**/**25**.

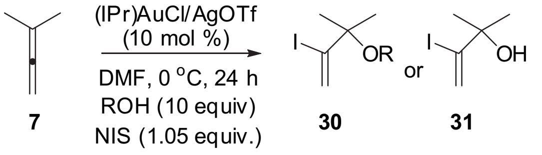
[e] Reaction carried out with PPh_3AuNTf_2 (3×5 mol %), ROH (10 equiv), NIS (1.05 equiv) in DCM at rt for 14 h.[13] ^{1}H NMR analysis of crude mixture shows approx. 5:1 of **24**/**25**.

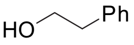
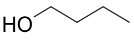
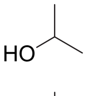
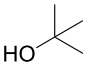
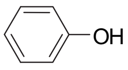
[f] Reaction carried out with PPh_3AuNTf_2 (10 mol %), ROH (10 equiv), NIS (1.05 equiv) in DCM at rt for 18 h.

selectivity of approx. 5:1 of **24**/**25** (entry 9).[18] Disubstituted allene **26** undergoes the reaction regioselectively at the alkyl substituted end to yield *sec*-iodo-allylic ether **27** in 60% yield (entry 10).

Having investigated the allene scope, we set out to investigate the scope of the alcohol nucleophiles. The equivalent gold(I)-catalysed regioselective hydroalkoxylation reaction[7a] proceeds in good yields for a variety of primary alcohols, but performs poorly for more sterically hindered alcohols (secondary and tertiary alcohols). It is thus unsurprising that the gold(I)-catalysed iodoalkoxylation also appears to work smoothly for primary alcohols (Table 2, entries 1–3) but not secondary alcohols, tertiary alcohols or phenols (Table 2, entries 4–6). The extra steric hindrance from the secondary alcohol nucleophile results in poor selectivity of iodoalkoxylation versus iodohydroxylation; products **30**/**31** are formed in a 2:3 ratio (entry 4). Increasing the steric hindrance further by using a tertiary alcohol results in the iodohydroxylation product **31** being observed as the main product (entry 5). Phenol is also not a viable nucleophile in this reaction, the main product formed with phenol is 4-iodophenol (entry 6). However, since tertiary alcohols are not reactive under these conditions, the diol **28** can be used unprotected and iodoalkoxylation occurs chemoselectively at the primary alcohol position to produce **29** (Table 1, entry 11).

Table 2
A screen of alcohols—only primary alcohols are good nucleophiles



Entry	Alcohol	Result
1		73% Yield of **30**[a]
2	MeOH	50% Yield of **30**[a,b]
3		60% Yield of **30**[a]
4		**30**/**31**, 2:3 ratio,[c] ~50% conv.[d]
5		Main product **31**, <5% **30** observed, ~50% conv.[d]
6		<5% **30** or **31**, Main product is 4-iodophenol[c]

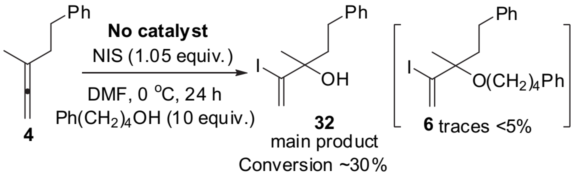
[a] Isolated yield, <5% of **31** observed by ^{1}H NMR.

[b] Moderate yield due to volatility of the product.

[c] Determined by analysis of ^{1}H NMR of the crude mixture.

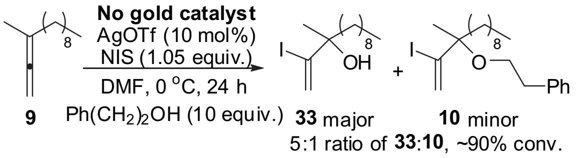
[d] Determined by analysis of ^{1}H NMR of the crude mixture with dibenzyl ether as internal standard.

In order to investigate whether the reaction is truly gold(I)-catalysed, several control reactions were carried out in the absence of the gold catalyst (Scheme 3). In the absence of both (IPr)AuCl and AgOTf, the iodohydroxylation product **32** is observed as the major product, though in only ~30% conversion (Scheme 3, cf. entry 3, Table 1). The desired iodoalkoxylation product **6** is observed in only trace amounts. It is thus clear that NIS alone cannot produce the desired product **6**.



Scheme 3. Control reaction with the absence of (IPr)AuCl and AgOTf.

Next, a control reaction was carried out with NIS and AgOTf as the reagents (Scheme 4). In the absence of (IPr)AuCl (but with AgOTf present), the conversion is ~90%, but the iodohydroxylation compound **33** is formed as the major product (**33**/**10** 5:1 ratio). It is clear from these control reactions that the gold(I) catalyst is necessary for iodoalkoxylation to occur efficiently.

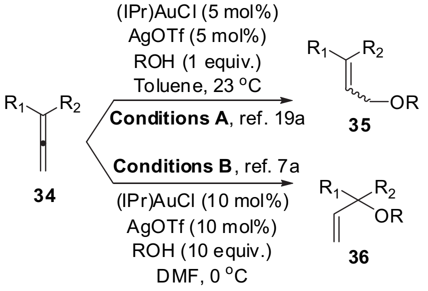


Scheme 4. Control reaction with the absence of (IPr)AuCl.

The trapping of putative intermediate **5** was also attempted with *N*-bromosuccinimide (NBS) and Selectfluor in order to form bromo-*tert*-allylic ethers and fluoro-*tert*-allylic ethers, respectively.

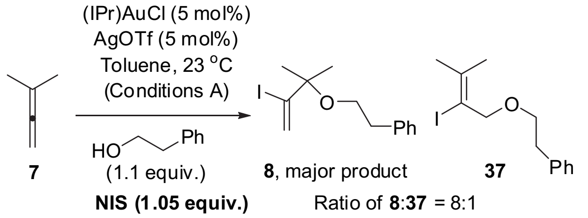
Unfortunately, under our standard gold(I)-catalysed reaction conditions (replacing NIS with NBS or Selectfluor, respectively), a complex mixture of products was observed with the NBS reaction, while the hydroalkoxylation product was observed exclusively with Selectfluor. With respect to the latter, protodeauration is clearly much faster than any trapping with Selectfluor.

In the related gold(I)-catalysed hydroalkoxylation of allenes, either primary allylic ethers **35**[19] or tertiary allylic ethers **36** can be formed regioselectively depending on the reaction conditions (Scheme 5). In the regioselective formation of primary allylic ethers, it is thought that gold(I)-catalysed isomerisation of the kinetic tertiary allylic ether product **36** to the thermodynamic primary allylic ether product **35** occurs.[7a,b,20] The change of reaction conditions (conditions B, Scheme 5) prevents the isomerisation of **36** to **35**, thus switching the regioselectivity of the reaction.

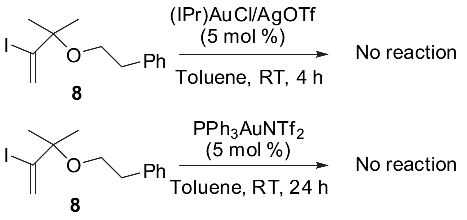


Scheme 5. Regioselectivity of the gold(I)-catalysed hydroalkoxylation of allenes is dependent on reaction conditions.

We were thus keen to ascertain whether the regioselectivity of the gold(I)-catalysed iodoalkoxylation could be similarly switched, thus enabling the synthesis of either primary or tertiary iodo-allylic ethers depending on the reaction conditions. To this end, a reaction using conditions A was carried out (Scheme 5) but with added NIS (1.05 equiv), to investigate whether primary-iodo-allylic ether **37** will be formed selectively (Scheme 6). However, analysis by crude ^{1}H NMR showed that the tertiary ether product **8** is still formed as the major product, rather than the primary ether **37** (8:1 ratio of **8**/**37**).[21] It appears that iodo-*tert*-allylic ethers such as **8** do not undergo gold(I)-catalysed isomerisation to primary-iodo-allylic ethers **37** as readily as their tertiary allylic ether counterparts **36**. Indeed, when **8** is subjected to either (IPr)AuOTf or PPh_3AuNTf_2, no isomerisation to **37** is observed (Scheme 7).

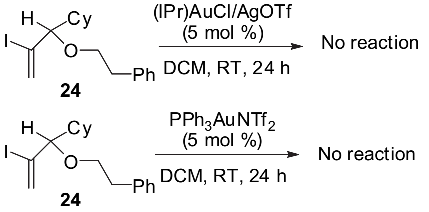


Scheme 6. Gold(I)-catalysed iodoalkoxylation using conditions A, with added NIS, still provides tertiary ether **8** as major product, rather than **37**.



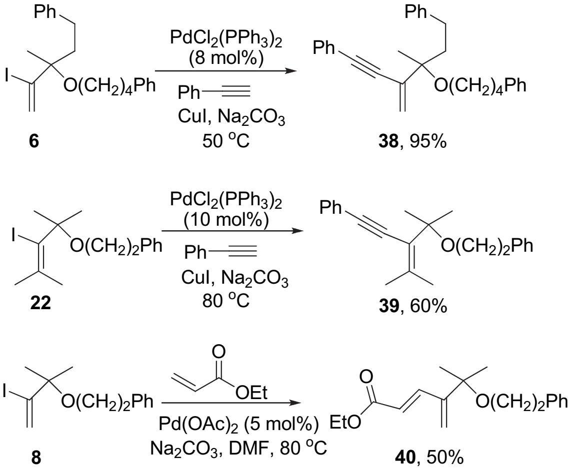
Scheme 7. Iodo-*tert*-allylic ether **8** does not isomerise under gold(I)-catalysis, unlike *tert*-allylic ethers **36**.

Although iodo-*tert*-allylic ethers such as **8** do not seem to isomerise (thus the excellent selectivity for iodo-*tert*-allylic ethers vs the primary counterpart in entries 1–7, Table 1), the selectivity for forming iodo-*sec*-allylic ether **24** (entry 9, Table 1) appears to be dependent on the catalyst employed. The NHC catalyst (IPr)AuCl/AgOTf produces a 1:1 mixture of **24** and **25**, whereas PPh_3AuNTf_2 produces the iodo-*sec*-allylic ether **24** in better selectivity (~5:1, entry 9, Table 1). However, when iodo-*sec*-allylic ether **24** is subjected to each catalyst, neither (IPr)AuCl/AgOTf nor PPh_3AuNTf_2 catalyses the isomerisation (Scheme 8). This observation suggests that for monosubstituted allenes such as **23**, any erosion in selectivity results from the initial gold(I)-catalysed iodoalkoxylation step, rather than from further isomerisation of the products.



Scheme 8. Isomerisation studies on iodo-*sec*-allylic ether **24**.

The iodoalkene is a good handle for further elaboration of the iodo-*tert*-allylic ether products (Scheme 1). For example, Sonogashira coupling[22] with phenylacetylene successfully produces **38** in 95% yield (Scheme 9). Even the tetrasubstituted iodoalkene **22** can be successfully cross-coupled to yield the fully substituted **39** in 60% yield, albeit higher catalyst loadings and temperatures are required due to the steric crowding in the iodo-*tert*-allylic ether substrates. Mizoroki-Heck coupling[23] can also be carried out in order to further functionalise the iodo-*tert*-allyl ether products. The Mizoroki–Heck coupling proceeds smoothly at 80 °C to furnish **40** in 50% yield (Scheme 9). The gold(I)-catalysed iodoalkoxylation of allenes followed by cross-coupling is thus a good way of producing *tert*-allylic ethers with various substitution patterns across the alkene moeity.



Scheme 9. Sonogashira and Heck couplings of iodoalkene products.

3. Conclusions

Gold(I)-catalysed intermolecular iodoalkoxylation of allenes occurs in a regioselective and stereoselective manner to produce versatile iodo-*tert*-alllylic ether products, which can be further elaborated through cross-couplings such as the Sonogashira and Heck reactions to yield highly substituted alkyl *tert*-allylic ethers.

The iodoalkoxylation reaction is sensitive to steric hindrance, thus the alcohol nucleophile is restricted to primary alcohols. However, a range of mono, di, tri and tetrasubstituted allene substrates readily undergo the reaction. Unlike *tert*-allylic ethers, the iodo-*tert*-allylic ethers do not undergo gold(I)-catalysed isomerisation to primary ethers and thus form the tertiary- rather than primary-iodo-allylic ethers regioselectively.

4. Experimental

4.1. General experimental section

All reactions were performed under an N_2 atmosphere. ^{1}H NMR spectra were recorded on Bruker AC200, AV 300, DPX 400 and AV 400 spectrometers at 200, 300 and 400 MHz, respectively, and referenced to residual solvent. ^{13}C NMR spectra were recorded using the same spectrometers at 50, 75 and 100 MHz, respectively. Chemical shifts (δ in parts per million) were referenced to tetramethylsilane (TMS) or to residual solvent peaks ($CDCl_3$ at δ_H 7.26). *J* values are given in hertz and s, d, dd, t, q and m abbreviations correspond to singlet, doublet, doublet of doublet, triplet, quartet and multiplet. Mass spectra were obtained at the EPSRC National Mass Spectrometry Service Centre in Swansea. Infrared spectra were obtained on Perkin–Elmer Spectrum 100 FT-IR Universal ATR Sampling Accessory, deposited neat or as a chloroform solution to a diamond/ZnSe plate. All reagents used were purchased from commercial suppliers and were used without any further purification unless otherwise stated. NIS used in the reactions was recrystallised using dioxane and CCl_4 and stored in a dessicator. DMF and DCM (CH_2Cl_2) were distilled over CaH_2 and stored over 4 Å molecular sieves. All alcohol reagents and allene substrates were dried over 4 Å molecular sieves prior to use. Tetrahydrofuran was dried by distillation from sodium/benzophenone under nitrogen. Petrol ether refers to petroleum ether (40–60%). Unless otherwise stated, all iodoalkoxylation reactions were performed at 0 °C using a jacketed reaction vessel attached to a Julabo FP40 Bohdan mini block temperature controlled recirculator with a Julabo temperature regulator. All glassware were oven dried. Flash column chromatography was carried out using Matrix silica gel 60 from Fisher Chemicals and TLC was performed using Merck silica gel 60 F_{254} precoated sheets and visualised by UV (254 nm) or stained by the use of aqueous acidic $KMnO_4$ or aqueous acidic ammonium molybdate as appropriate. 3-Methyl-buta-1,2-diene **7**, cyclohexyl allene **23** and tetramethylallene **21** were purchased from Sigma–Aldrich. All other allenes (**4**,[14a] **9**,[7a] **11**,[14b] **14**,[7a] **16**,[14c] **18**,[7a] **26**,[14c]) were prepared according to literature procedures.[14]

4.2. (2-(3-Iodo-2-methylbut-3-en-2-yloxy)ethyl)benzene (8)

To a stirred solution of allene **7** (22.0 mg, 0.323 mmol), DMF (0.3 mL) and 2-phenyl ethanol (0.350 mL, 2.94 mmol) at 0 °C were added (IPr)AuCl (19.0 mg, 0.031 mmol), AgOTf (8.4 mg, 0.031 mmol) and NIS (76.3 mg, 0.339 mmol). The reaction mixture was stirred for 20 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (eluent: 99:1 hexane/diethyl ether) as a clear oil (74.8 mg, 0.237 mmol, 73%). R_f=0.21 (99:1 hexane/diethyl ether). ν_{max}/cm^{-1} 1607 w, 1496 m, 1453 m (Ar C=C), 1066 s (C–O); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.35–7.12 (5H, m, Ar–*H*), 6.20 (1H, d, *J* 2.2, =C*H*), 5.96 (1H, d, *J* 2.2, =C*H*), 3.41 (2H, t, *J* 7.8, O–CH_2), 2.92 (2H, t, *J* 7.8, Ph–CH_2), 1.39 (6H, s, 2×CH_3). ^{13}C NMR (50 MHz, $CDCl_3$) δ 139.1 (C), 129.3 (CH), 128.5 (CH), 127.0 (CH_2), 126.4 (CH), 123.4 (C), 78.5 (C), 64.6 (CH_2), 37.2 (CH_2), 26.2 (CH_3). $[M+NH_4]^+$=334.0666 (calcd for $C_{13}H_{17}IO+NH_4^+$=334.0662).

4.3. (2-(2-Iodo-3-methyldodec-1-en-3-yloxy)ethyl)benzene (10)

To a stirred solution of allene **9** (51.0 mg, 0.283 mmol), DMF (0.3 mL) and 2-phenyl ethanol (0.350 mL, 2.94 mmol) at 0 °C were added (IPr)AuCl (17.5 mg, 0.028 mmol), AgOTf (8.8 mg, 0.034 mmol) and NIS (70.0 mg, 0.311 mmol). The reaction mixture was stirred for 22 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (99:1 hexane/diethyl ether) as a clear oil (73.0 mg, 0.171 mmol, 60%). R_f=0.39 (97:3 hexane/diethyl ether). ν_{max}/cm^{-1} 1606 w, 1496 m, 1454 m (Ar C=C), 1070 s (C–O); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.48–7.32 (5H, m, Ar–*H*), 6.30 (1H, d, *J* 2.2, =C*H*), 6.14 (1H, d, *J* 2.2, =C*H*), 3.54 (2H, t, *J* 7.8, OCH_2), 3.04 (2H, t, *J* 7.8, PhCH_2), 1.81–1.64 (2H, m, CH_2), 1.47–1.28 (17H, m, 7CH_2+CH_3), 1.01 (3H, t, *J* 6.6, CH_3). ^{13}C NMR (50 MHz, $CDCl_3$) δ 139.2 (C), 129.3 (CH), 128.5 (CH), 127.8 (CH_2), 126.4 (CH), 123.1 (C), 80.8 (C), 64.2 (CH_2), 39.9 (CH_2), 37.2 (CH_2), 32.1 (CH_2), 30.1 (CH_2), 29.7 (CH_2), 29.7 (CH_2), 29.5 (CH_2), 24.0 (CH_2), 22.9 (CH_2), 20.9 (CH_3), 14.4 (CH_3). $[M+NH_4]^+$=446.1913 (calcd for $C_{21}H_{33}IO+NH_4^+$=446.1914).

4.4. (4-Iodo-3-methyl-3-(4-phenylbutoxy)pent-4-enyl) benzene (6)[7a]

To a stirred solution of allene **4** (44.2 mg, 0.279 mmol) and 4-phenyl-1-butanol (0.43 mL, 2.8 mmol) in anhydrous DMF (0.28 mL) at 0 °C were added (IPr)AuCl (17.4 mg, 0.028 mmol), AgOTf (7.2 mg, 0.028 mmol) and NIS (66.2 mg, 0.294 mmol). The reaction mixture was stirred for 20 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product was isolated by flash column chromatography (eluent 98:2 *n*-pentane/diethyl ether) to yield **6** as a pale yellow oil (88.7 mg, 0.204 mmol, 73%). R_f=0.27 (98:2 *n*-pentane/diethyl ether); ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.35–7.10 (m, 10H, Ar–*H*), 6.31 (d, *J* 1.8, 1H, =C*H*), 6.07 (d, *J* 1.8, 1H, =C*H*), 3.29 (t, *J* 6.3, 2H, OCH_2), 2.60 (m, 4H, Ar–CH_2), 1.94 (m, 2H, CH_2), 1.68 (m, 4H, CH_2), 1.45 (s, 3H, CH_3). ^{13}C NMR ($CDCl_3$, 50 MHz) δ 142.8 (C), 142.3 (C), 128.7 (CH), 128.6 (CH), 128.6 (CH), 128.5 (CH), 128.0 (CH), 126.0 (CH), 125.9 (CH), 122.6 (C), 80.1 (C), 62.6 (CH_2), 41.5 (CH_2), 36.0 (CH_2), 30.5 (CH_2), 30.1 (CH_2), 28.4 (CH_2), 21.5 (CH_3). $[M+NH_4]^+$=452.1438 (calcd for $C_{22}H_{27}IO+NH_4^+$=452.1445).

4.5. (3-Iodo-2-phenethoxybut-3-en-2-yl)benzene (12) and 3-iodo-2-phenylbut-3-en-2-ol (13)

To a stirred solution of **11** (41.0 mg, 0.315 mmol), DMF (0.3 mL) and 2-phenyl ethanol (0.35 mL, 2.94 mmol) at 0 °C were added (IPr) AuCl (19.6 mg, 31.5 μmol), AgOTf (8.1 mg, 31.5 μmol) and NIS (74.5 mg, 0.331 mmol). The reaction mixture was stirred for 20 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product **12** was isolated using flash column chromatography (100% hexane) as a clear oil (32.6 mg, 0.086 mmol, 27%). R_f=0.06 (99:1 hexane/diethyl ether). ν_{max}/cm^{-1} 1603 w, 1493 m, 1447 m (Ar C=C), 1082 s (C–O); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.36–7.15 (10H, m, Ar–*H*), 6.39 (1H, d, *J* 2.1, =C*H*), 6.04 (1H, d, *J* 2.1, =C*H*), 3.59–3.39 (2H, m, OCH_2), 2.94 (2H, t, *J* 7.4, PhCH_2), 1.59 (3H, s, CH_3). ^{13}C NMR (50 MHz, $CDCl_3$) δ 144.1 (C), 139.1 (C), 129.2 (CH), 128.3 (CH), 128.0 (CH), 127.5 (CH_2), 127.2 (CH), 126.2 (CH), 125.9 (CH), 121.4 (C), 82.6 (C), 64.1 (CH_2), 36.9 (CH_2), 23.6 (CH_3). $[M+NH_4]^+$=396.0819 (calcd for $C_{18}H_{19}IO+NH_4^+$=396.0819).

3-Iodo-2-phenylbut-3-en-2-ol **13** (27.8 mg, 0.101 mmol, 32%) was also isolated as the major side-product. R_f=0.30 (4:1 *n*-pentane/diethyl ether). ν_{max}/cm^{-1} 3409 br (OH), 1613 w, 1599 w, 1492 w, 1446 w (Ar–C=C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.47–7.26 (5H, m, Ar-*H*), 6.42 (1H, d, *J* 2.4, =C*H*), 6.00 (1H, d, *J* 2.4, =C*H*), 1.79 (3H, s, CH_3). ^{13}C NMR (50 MHz, $CDCl_3$) δ 144.7 (C), 128.4 (CH), 127.7 (CH), 125.9 (CH_2), 125.4 (CH), 123.5 (C), 78.8 (C), 27.9 (CH_3). $[M]^+$=273.9852 (calcd for $C_{10}H_{11}IO$=273.9849).

4.6. *tert*-Butyl-(4-iodo-5-methyl-5-phenethyloxyhex-3-enyloxy)-diphenyl-silane (15)

To a stirred solution of **14** (108 mg, 0.308 mmol), DMF (0.3 mL) and 2-phenyl ethanol (0.35 mL, 2.9 mmol) at 0 °C were added (IPr) AuCl (19.1 mg, 30.8 μmol), AgOTf (9.5 mg, 0.037 mmol) and NIS (73.3 mg, 0.326 mmol). The reaction mixture was stirred for 20 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product **15** was isolated using flash column chromatography (eluent: 98:2 hexane/diethyl ether) as a clear oil (126 mg, 0.210 mmol, 68%). R_f=0.10 (98:2 hexane/diethyl ether). Stereochemistry of alkene was confirmed through NOE. ν_{max}/cm^{-1} 1589 w, 1496 m, 1472 m (Ar C=C), 1106 s (Si–O), 1087 s (C–O); ^1H NMR (200 MHz, $CDCl_3$) δ 7.70–7.21 (15H, m, Ar–*H*), 5.88 (1H, t, *J* 6.3, =C*H*), 3.78 (2H, t, *J* 6.3, TBDPSOC*H*$_2$), 3.41 (2H, t, *J* 7.5, OC*H*$_2$CH$_2$Ph), 2.95 (2H, t, *J* 7.5, PhC*H*$_2$), 2.52 (2H, dt, *J* 6.3, 6.3, C*H*$_2$CH), 1.45 (6H, s, 2×C*H*$_3$), 1.08 (9H, s, *t*-Bu). ^{13}C NMR (50 MHz, $CDCl_3$) δ 138.9 (C), 135.5(CH), 133.6 (C), 133.1 (CH), 129.6 (CH), 129.1 (CH), 128.2 (CH), 127.6 (CH), 126.1 (CH), 121.8 (C), 78.3 (C), 64.1 (CH_2), 62.2 (CH_2), 40.4 (CH_2), 37.0 (CH_2), 26.9 (CH_3), 26.7 (CH_3), 19.1 (C). $[M+NH_4]^+$ *m/z*=616.2095 (calcd for $C_{31}H_{39}IO_2Si+NH_4^+$=616.2102).

4.7. (*Z*)-Ethyl 4-iodo-5-methyl-5-phenethoxyhex-3-enoate (17)

To a stirred solution of allene **16** (40.0 mg, 0.259 mmol), DMF (0.3 mL) and 2-phenyl ethanol (0.35 mL, 2.94 mmol) at 0 °C were added (IPr)AuCl (18.0 mg, 30.0 μmol), AgOTf (8.0 mg, 0.031 mmol) and NIS (72.0 mg, 0.320 mmol). The reaction mixture was stirred for 22 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a plug of silica, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (eluent: 9:1 hexane/diethyl ether) as a clear oil (75.9 mg, 0.189 mmol, 73%). R_f=0.15 (9:1 hexane/diethyl ether). Stereochemistry of alkene was confirmed through NOE. ν_{max}/cm^{-1} 1734 s (C=O), 1635 w (C=C), 1604 w, 1496 m, 1453 m (Ar C=C), 1159 s (C–O), 1066 s (C–O); ^1H NMR (200 MHz) δ 7.40–7.09 (5H, m, Ar–*H*), 6.05 (1H, t, *J* 6.1, =C*H*), 4.16 (2H, q, *J* 7.1, OC*H*$_2$CH$_3$), 3.38 (2H, t, *J* 7.8, OC*H*$_2$CH$_2$Ph), 3.24 (2H, d, *J* 6.1, COC*H*$_2$CH), 2.90 (2H, t, *J* 7.8, C*H*$_2$Ph), 1.44 (6H, s, C*H*$_3$), 1.26 (3H, t, *J* 7.1, OCH$_2$C*H*$_3$). ^{13}C NMR (50 MHz, $CDCl_3$) δ 170.9 (C), 138.9 (C), 129.2 (CH), 128.7 (CH), 128.3 (CH), 126.2 (CH), 123.7 (C), 78.5 (C), 64.3 (CH_2), 61.0 (CH_2), 42.7 (CH_2), 37.0 (CH_2), 26.9 (CH_3), 14.2 (CH_3). $[M+NH_4]^+$=420.1032 (calcd for $C_{17}H_{23}IO_3+NH_4^+$=420.1030).

4.8. 8-(1-Iodo-vinyl)-8-methoxy-1,4-dioxa-spiro[4.5]decane (19)

To a stirred solution of allene **18** (50.0 mg, 0.300 mmol), DMF (0.3 mL) and methanol (0.12 mL, 2.94 mmol) at 0 °C were added (IPr)AuCl (18.0 mg, 30.0 μmol), AgOTf (8.5 mg, 0.033 mmol) and NIS (72.6 mg, 0.323 mmol). The reaction mixture was stirred for 22 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (4:1→1:2 hexane/diethyl ether) as a clear oil (39.8 mg, 0.128 mmol, 42%). The product was contaminated with approx. 15% hydroalkoxylation[7a] product **20**. R_f=0.43 (1:1 hexane/diethyl ether). ν_{max}/cm^{-1} 1639 w (C=C), 1096 s (C–O), 1071 s (C–O); ^1H NMR (200 MHz, $CDCl_3$) δ 6.28 (1H, d, *J* 2.4, =C*H*), 6.07 (1H, d, *J* 2.4, =C*H*), 3.94 (4H, m, OC*H*$_2$), 3.09 (3H, s, OC*H*$_3$), 2.06–1.56 (8H, m, C*H*$_2$). ^{13}C NMR (50 MHz, $CDCl_3$) δ 127.4 (CH_2), 122.1 (C), 108.2 (C), 76.7 (C), 64.1 (CH_2), 63.8 (CH_2), 49.6 (CH_3), 30.5 (CH_2), 29.9 (CH_2). HREI $[M]^+$=324.0216 (calcd for $C_{11}H_{17}IO_3$=324.0217).

4.9. (2-(3-Iodo-2,4-dimethylpent-3-en-2-yloxy)ethyl)benzene (22)

To a stirred solution of tetramethylallene **21** (27.0 mg, 0.281 mmol) and 2-phenyl ethanol (0.43 mL, 2.8 mmol) in anhydrous DMF (0.28 mL) at 0 °C were added (IPr)AuCl (17.4 mg, 28.0 μmol), AgOTf (7.2 mg, 28.0 μmol) and NIS (66.2 mg, 0.290 mmol). The reaction mixture was stirred for 20 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a silica plug, washed with water and brine and dried ($MgSO_4$). The product **22** was obtained by flash column chromatography (eluent 50:1 petrol ether/diethyl ether) as a pale yellow oil (73.5 mg, 0.214 mmol, 76%). R_f=0.38 (97:3 petrol ether/diethyl ether). ν_{max}/cm^{-1} 1604 w, 1495 m, 1453 m (Ar C=C), 1064 s (C–O); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.30–7.16 (m, 5H, Ar–*H*), 3.51 (t, *J* 7.6, 2H, O–C*H*$_2$), 2.84 (t, *J* 7.6, 2H, PhC*H*$_2$), 2.06 (s, 3H, C*H*$_3$), 2.03 (s, 3H, C*H*$_3$), 1.53 (s, 6H, C*H*$_3$). ^{13}C NMR ($CDCl_3$, 100 MHz) δ 140.7 (C), 139.1 (C), 129.0 (CH), 128.3 (CH), 126.1 (CH), 108.2 (C), 80.0 (C), 63.9 (CH_2), 37.0 (CH_2), 35.7 (CH_3), 30.9 (CH_3), 21.61 (CH_3). HREI $[M]^+$=344.0636 (calcd for $C_{15}H_{21}IO$=344.0632).

4.10. (2-(1-Cyclohexyl-2-iodoallyloxy)ethyl)benzene (24)

To a stirred solution of cyclohexyl allene **23** (35.0 mg, 0.287 mmol) and 2-phenyl ethanol (0.34 mL, 2.9 mmol) in DCM (0.29 mL), were added PPh_3AuNTf_2 (2:1 toluene adduct, 11.0 mg, 0.014 mmol) and NIS (68.3 mg, 0.304 mmol). The reaction mixture was stirred at rt. A further two portions of catalyst (11.0 mg×2, 0.014 mmol×2) was added after 2 h and after 4 h. The reaction mixture was then allowed to stir for 14 h at rt. The reaction mixture was then flushed through a plug of silica (diethyl ether). The product, **24**, was obtained by flash column chromatography (eluent 99:1 hexane/diethyl ether) as a colourless oil (64.0 mg, 0.173 mmol, 60%). R_f=0.23 (99:1 hexane/diethyl ether). ν_{max}/cm^{-1} 1652 w (C=C), 1612 m, 1573 m, 1512 m (Ar C=C), 1126 s (C–O); ^1H NMR (300 MHz, $CDCl_3$) δ 7.24–7.10 (5H, m, Ar–*H*), 6.17 (1H, dd, *J* 1.3, 0.8, =C*H*), 5.90 (1H, d, *J* 1.3, =C*H*), 3.62 (1H, ddd, *J* 9.3, 7.6, 6.7, OC*H*H), 3.26 (1H, ddd, *J* 9.3, 7.9, 6.9, OCH*H*), 2.88–2.79 (m, 2H, PhC*H*$_2$), 2.64 (1H, dd, *J* 8.1, 0.8, OC*H*Cy), 1.96 (1H, m, OCHC*H*(CH$_2$)$_5$), 1.73–0.60 (10H, m, 5×C*H*$_2$). ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.9 (C), 129.0 (CH), 128.2 (CH), 127.6 (CH_2), 126.1 (CH), 116.51 (C), 90.1 (CH), 69.7 (CH_2), 40.8 (CH), 36.2 (CH_2), 29.1 (CH_2), 28.56 (CH_2), 26.5 (CH_2), 25.9 (CH_2), 25.8 (CH_2). $[M+NH_4]^+$=388.1140 (calcd for $C_{17}H_{23}IO+NH_4^+$=388.1132).

Using (IPr)AuCl/AgOTf conditions: To a stirred solution of cyclohexyl allene **23** (34.7 mg, 0.284 mmol) and 4-phenyl-1-butanol (0.33 mL, 2.8 mmol) in DCM (0.28 mL) were added (IPr)AuCl (17.3 mg, 0.0279 mmol), AgOTf (7.2 mg, 0.028 mmol) and NIS (65.3 mg, 0.290 mmol). The reaction mixture was stirred under N_2 atmosphere for 4 h at rt. The reaction mixture was then flushed through a plug of silica (diethyl ether). Crude ^1H NMR analysis shows ~1:1 mixture of **24**/**25**. The products were obtained by flash column chromatography (eluent 99:1 hexane/diethyl ether) as a pale yellow oil: **24** (32.0 mg, 86.5 μmol, 31%) and **25** (not pure, contaminated with ~11% **24**, 33.6 mg, 90.7 μmol, 32%). NMR data for **25**: ^1H NMR (300 MHz, $CDCl_3$) δ 7.25–7.10 (5H, m, Ar–*H*), 5.54 (1H, dt, *J* 8.7, 1.2, =C*H*), 4.04 (2H, d, *J* 1.2, OC*H*$_2$), 3.55 (2H, t, *J* 7.2, OC*H*$_2$CH$_2$), 2.84 (2H, t, *J* 7.2, PhC*H*$_2$), 2.20 (1H, m, C*H*(CH$_2$)$_5$), 1.65–0.95 (10H, m, 5×C*H*$_2$). ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.3 (CH), 138.8 (C), 129.0 (CH), 128.4 (CH), 126.3 (CH), 101.9 (C), 78.9 (CH_2), 70.6 (CH_2), 44.7 (CH), 36.3 (CH_2), 31.5 (CH_2), 25.9 (CH_2), 25.6 (CH_2).

4.11. (*Z*)-Ethyl 4-iodo-5-phenethoxydec-3-enoate (27)

To a stirred solution of allene **26** (22.0 mg, 0.112 mmol) and 2-phenyl ethanol (0.13 mL, 1.1 mmol) in DCM (0.15 mL) were added

PPh_3AuNTf_2 (2:1 toluene adduct, 8.8 mg, 0.011 mmol) and NIS (26.4 mg, 0.118 mmol). The reaction mixture was stirred for 18 h at rt. The reaction mixture was then flushed through a plug of silica (diethyl ether). The product, **27**, was obtained by flash column chromatography (eluent 9:1 hexane/diethyl ether) as a pale yellow oil (30.0 mg, 67.5 μmol, 60%). Stereochemistry of alkene was confirmed through NOE. R_f=0.28 (9:1 petrol/diethyl ether). ν_{max}/cm^{-1} 1736 s (C=O), 1653 vw (C=C), 1598, 1522, 1487 (Ar C=C), 1241 s (C–O); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.33–7.19 (5H, m, Ar–*H*), 6.19 (1H, t, *J* 6.3, =C*H*), 4.17 (2H, q, *J*=4.5, OCH_2CH_3), 3.68 (1H, ddd, *J*=9.3, 7.8, 6.5, OC*H*HCH_2Ph), 3.39 (1H, ddd, *J*=9.3, 8.0, 6.8, OC*H*HCH_2Ph), 3.29 (1H, t, *J*=6.6, OC*H*), 3.27 (2H, d, *J*=6.3, OCH_2CH=), 2.95–2.89 (2H, m, CH_2Ph), 1.65–1.51 (2H, m, CH_2), 1.32–1.24 (9H, m, CH_2×3+OCH_2CH_3), 0.89 (3H, t, *J* 6.9, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 170.5 (C), 138.9 (C), 129.7 (CH), 129.0 (CH), 128.3 (CH), 126.2 (CH), 117.9 (C), 85.6 (CH), 69.4 (CH_2), 61.0 (CH_2), 41.2 (CH_2), 36.3 (CH_2), 35.4 (CH_2), 31.6 (CH_2), 24.7 (CH_2), 22.5 (CH_2), 14.2 (CH_3), 14.0 (CH_3). $[M+NH_4]^+$=462.1488 (calcd for $C_{20}H_{29}IO_3+NH_4^+$=462.1500).

4.12. (*Z*)-4-(6-(***tert***-Butyldiphenylsilyloxy)-3-iodo-2-methyl hex-3-en-2-yloxy)-2-methylbutan-2-ol (29)

To a stirred solution of allene **14** (101 mg, 0.288 mmol), DMF (0.3 mL) and 3-methyl-1,3-butanediol **28** (0.16 mL, 1.47 mmol) at 0 °C were added (IPr)AuCl (18.0 mg, 0.030 mmol), AgOTf (8.0 mg, 0.031 mmol) and NIS (71.0 mg, 0.316 mmol). The reaction mixture was stirred for 22 h at 0 °C, after which the mixture was diluted with Et_2O, filtered through a plug of silica, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (2:1 hexane/diethyl ether) as a colourless oil (82.3 mg, 0.142 mmol, 49%). Stereochemistry of alkene was confirmed through NOE. R_f=0.38 (1:2 hexane/diethyl ether). ν_{max}/cm^{-1} 3454 br (OH), 1631 w (C=C), 1590 w, 1472 m, 1427 m (Ar C=C), 1111 s (Si–O), 1088 s (C–O); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.49 (10H, m, Ar–*H*), 5.89 (1H, t, *J* 6.4, =C*H*), 3.76 (2H, t, *J* 6.3, SiOCH_2), 3.44 (2H, t, *J* 5.9, OCH_2), 2.49 (2H, td, *J* 6.3, 6.4, CH_2CH=C), 1.75 (2H, t, *J* 5.9, OCH_2CH_2CMe$_2$OH), 1.44 (6H, s, CH_3), 1.25 (6H, s, CH_3), 1.05 (9H, s, CH_3). ^{13}C NMR (50 MHz, $CDCl_3$) δ 135.5 (CH), 133.7 (C), 133.6 (CH), 129.7 (CH), 127.7 (CH), 120.7 (C), 78.6 (C), 70.6 (C), 62.2 (CH_2), 59.9 (CH_2), 41.6 (CH_2), 40.5 (CH_2), 29.4 (CH_3), 26.9 (CH_3), 26.8 (CH_3), 19.2 (C). $[M+NH_4]^+$=598.2202 (calcd for $C_{28}H_{41}IO_3Si+NH_4^+$=598.2208).

4.13. 2-Iodo-3-methoxy-3-methylbut-1-ene (30, R=Me)[12]

To a stirred solution of allene **7** (30.0 mg, 0.441 mmol), DMF (0.4 mL) and dry methanol (0.18 mL, 4.4 mmol) at 0 °C were added (IPr)AuCl (27.3 mg, 44.0 μmol), AgOTf (11.3 mg, 44.0 μmol) and NIS (104 mg, 0.462 mmol). The reaction mixture was stirred for 17 h at 0 °C after which the mixture was diluted with Et_2O, filtered through a plug of silica, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (eluent: 98:2 *n*-pentane/diethyl ether) as a pale yellow oil (49.4 mg, 0.219 mmol, 50%). The product is slightly volatile. R_f=0.19 (98:2 *n*-pentane/diethyl ether). ν_{max}/cm^{-1} 1645 w (C=C), 1091 s (C–O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.26 (1H, d, *J* 2.2, =C*H*), 6.00 (1H, d, *J* 2.2, =C*H*), 3.14 (3H, s, OCH_3), 1.39 (6H, s, 2×CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 127.1 (CH_2), 122.7 (C), 78.3 (C), 50.7 (CH_3), 25.5 (CH_3).

4.14. 3-Butoxy-2-iodo-3-methylbut-1-ene (30, R=*n*-Bu)

To a stirred solution of allene **7** (39.6 mg, 0.581 mmol), DMF (0.6 mL) and dry *n*-BuOH (0.53 mL, 5.8 mmol) at 0 °C were added (IPr)AuCl (36.0 mg, 58.0 μmol), AgOTf (14.9 mg, 58.0 μmol) and NIS (139 mg, 0.618 mmol). The reaction mixture was stirred for 20 h at 0 °C after which the mixture was diluted with Et_2O, filtered through a plug of silica, washed with water and brine and dried ($MgSO_4$). The product was isolated using flash column chromatography (eluent: 98:2 *n*-pentane/diethyl ether) as a pale yellow oil (93.0 mg, 0.347 mmol, 60%). R_f=0.53 (98:2 *n*-pentane/diethyl ether). ν_{max}/cm^{-1} 1608 w (C=C), 1072 s (C–O); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.23 (1H, d, *J* 2.1, =C*H*), 5.96 (1H, d, *J* 2.1, =C*H*), 3.21 (2H, t, *J* 6.8, OCH_2), 1.69–1.30 (4H, m, CH_2CH_2), 1.38 (6H, s, 2×CH_3), 0.91 (3H, t, *J* 6.8, CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 126.4 (CH_2), 123.6 (C), 77.8 (C), 62.7 (CH_2), 32.4 (CH_2), 26.0 (CH_3), 19.5 (CH_2), 14.0 (CH_3). $[M+NH_4]^+$=286.0671 (calcd for $C_9H_{17}IO+NH_4^+$=286.0662).

^{1}H NMR for side-product 3-iodo-2-methylbut-3-en-2-ol (**31**):[12] ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.32 (1H, d, *J* 2.3, =C*H*), 5.81 (1H, d, *J* 2.3, =C*H*), 1.48 (6H, s, 2×CH_3).

4.15. (4-Methyl-3-methylene-4-(4-phenylbutoxy)hex-1-yne-1,6-diyl)dibenzene (38)[7a]

(4-Iodo-3-methyl-3-(4-phenylbutoxy)pent-4-enyl)benzene, **6**, (18.0 mg, 41.4 μmol) was dissolved in anhydrous MeCN (1 mL) and stirred at rt. $PdCl_2(PPh_3)_2$ (2.4 mg, 3.4 μmol), CuI (1.3 mg, 6.7 μmol), potassium carbonate (14.5 mg, 0.11 mmol) and phenylacetylene (12 μL, 0.11 mmol) were added and the resulting mixture was heated to 50 °C for 20 h under N_2 atmosphere. The reaction mixture was then washed (diethyl ether) through a plug of silica and the product, **38**, was obtained by flash column chromatography (eluent 98:2 *n*-pentane/diethyl ether) as a yellow viscous oil (16.2 mg, 39.7 μmol, 95%). R_f=0.20 (99:1 *n*-pentane/diethyl ether); ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.42–7.07 (15H, m, Ar–*H*), 5.67 (1H, d, *J* 1.8, =C*H*), 5.60 (1H, d, *J* 1.8, =C*H*), 3.39 (2H, t, *J* 6.3, OCH_2), 2.62 (4H, m, Ar–CH_2), 2.03 (2H, m, CH_2), 1.68 (4H, m, CH_2), 1.45 (3H, s, CH_3). ^{13}C NMR ($CDCl_3$, 50 MHz) δ 142.9 (C), 142.8 (C), 136.2 (C), 131.8 (CH), 128.7 (CH), 128.6 (CH), 128.5 (CH), 128.5 (CH), 128.5 (CH), 128.4 (CH), 125.8 (CH), 125.8 (CH), 123.5 (C), 122.1 (CH_2), 90.4 (C), 88.8 (C), 78.7 (C), 62.2 (CH_2), 41.0 (CH_2), 36.1 (CH_2), 30.4 (CH_2), 30.2 (CH_2), 28.5 (CH_2), 23.0 (CH_3). $[M+NH_4]^+$=426.2793 (calcd for $C_{30}H_{32}O+NH_4$=426.2791).

4.16. (2-(2,4-Dimethyl-3-(phenylethynyl)pent-3-en-2-yloxy) ethyl)benzene (39)

(2-(3-Iodo-2,4-dimethylpent-3-en-2-yloxy)ethyl)benzene **22** (19.0 mg, 55.2 μmol) was dissolved in anhydrous MeCN (1 mL) and stirred at rt. $PdCl_2(PPh_3)_2$ (4.1 mg, 5.8 μmol), CuI (2.3 mg, 10.2 μmol), potassium carbonate (20.0 mg, 0.145 mmol) and phenylacetylene (16 μL, 0.145 mmol) were added and the reaction mixture heated to 80 °C for 20 h under N_2 atmosphere. The reaction mixture was then washed (diethyl ether) through a plug of silica and the product, **39**, was obtained by flash column chromatography (eluent 98:2 hexane/diethyl ether) as a pale yellow oil (10.5 mg, 33.0 μmol, 60%). R_f=0.11 (98:2 hexane/diethyl ether). ν_{max}/cm^{-1} 2194 w (C≡C), 1595 w, 1489 m, 1442 m (Ar C=C), 1069 s (C–O); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.50–7.20 (10H, m, Ar–*H*), 3.51 (2H, t, *J* 7.5, OCH_2), 2.87 (2H, t, *J* 7.5, PhCH_2), 2.09 (3H, s, CH_3), 2.03 (3H, s, CH_3), 1.52 (6H, s, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 145.3 (C), 139.3 (C), 130.9 (CH), 129.0 (CH), 128.4 (CH), 128.2 (CH), 127.5 (CH), 126.1 (CH), 124.3 (C), 120.9 (C), 93.8 (C), 90.3 (C), 77.2 (C), 63.9 (CH_2), 37.1 (CH_2), 28.3 (CH_3), 25.8 (CH_3), 21.0 (CH_3). $[M+H]^+$=319.2060 (calcd for $C_{23}H_{27}O$=319.2056).

4.17. (*E*)-ethyl 5-methyl-4-methylene-5-phenethoxyhex-2-enoate (40)

To a solution of 2-(2-iodo-1,1-dimethyl-allyloxy)-ethyl]-benzene **8** (18.0 mg, 56.9 μmol) and ethyl acrylate (0.024 mL, 0.23 mmol) were added $Pd(OAc)_2$ (0.6 mg, 2.8 μmol), nBu_4NCl (15.6 mg, 56.1 μmol) and sodium carbonate (14.8 mg, 0.140 mmol). The resulting mixture was heated under a N_2 atmosphere at 80 °C for 18 h. The mixture was cooled to rt, diluted with ether and washed with water. The aqueous layer was extracted with ether (×3), washed with brine and dried ($MgSO_4$). The product **40** was isolated using flash column chromatography as a pale yellow oil (8.0 mg, 0.028 mmol, 50%). R_f=0.26 (9:1 hexane/diethyl ether). ν_{max}/cm^{-1} 1713 s (C=O), 1630 m (C=C), 1590 w, 1496 m, 1454 m (Ar C=C), 1275, 1179, 1067 s (C–O); ^1H NMR (300 MHz, $CDCl_3$) δ 7.34 (1H, d, *J* 16.0, COCH=C*H*), 7.30–7.16 (5H, m, Ar–*H*), 6.35 (1H, d, *J* 16.0, COCH=CH), 5.50 (1H, s, =C*H*), 5.26 (1H, s, =C*H*), 4.23 (2H, q, *J* 7.1, OCH_2CH_3), 3.38 (2H, *J* 7.6, OCH_2CH_2Ph), 2.81 (2H, t, *J* 7.6, $PhCH_2$), 1.37 (6H, s, 2×CH_3), 1.32 (3H, t, *J* 7.1, OCH_2CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.1 (C), 149.1 (C), 143.6 (CH), 139.0 (C), 129.0 (CH), 128.3 (CH), 126.1 (CH), 120.6 (CH), 118.9 (CH_2), 77.2 (C), 64.1 (CH_2), 60.4 (CH_2), 37.0 (CH_2), 26.4 (CH_3), 14.3 (CH_3). $[M+NH_4]^+$=306.2072 (calcd for $C_{18}H_{24}O_3+NH_4^+$=306.2064).

Acknowledgements

We would like to thank the Nuffield Foundation for a Nuffield Undergraduate Research Bursary (A.H.-J), ScotChem (M.S.H), EPSRC and The Royal Society for funding and the EPSRC Mass Spectrometry services at Swansea for analytical support. We thank Ursula S.D. Paul for the synthesis of allene **26**.

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2011.01.021.

References and notes

1. For some recent reviews, see: (a) Ma, S. *Chem. Rev.* **2005**, *105*, 2829; (b) Ma, S. *Aldrichimica Acta* **2007**, *40*, 91; (c) Hoffman-Roder, A.; Krause, N. *Angew. Chem., Int. Ed.* **2004**, *43*, 1196; (d) Krause, N.; Hashmi, A. S. K. *Modern Allene Chemistry*; Wiley-VCH: Weinheim, Germany, 2004.
2. For representative examples, see: (a) Ma, S.; Xie, H. *Tetrahedron* **2005**, *61*, 251; (b) Guo, H.; Qian, R.; Guo, Y.; Ma, S. *J. Org. Chem.* **2008**, *73*, 7934; (c) Gu, Z.; Deng, Y.; Shu, W.; Ma, S. *Adv. Synth. Catal.* **2007**, *349*, 1653; (d) Fu, C.-L.; Chen, G.-F.; Deng, Y.-Q.; Huang, X.; Ma, S. *Chin. J. Chem.* **2004**, *22*, 990; Review: (e) Ma, S. *Acc. Chem. Res.* **2009**, *42*, 1679.
3. For example, see: Lü, B.; Jiang, X.; Fu, C.; Ma, S. *J. Org. Chem.* **2009**, *74*, 438.
4. (a) Assabumrungrat, S.; Kiatkittipong, W.; Sevitoon, N.; Praserthdam, P.; Goto, S. *Int. J. Chem. Kinet.* **2002**, *34*, 292; (b) Shi, B.; Davis, B. H. *J. Catal.* **1995**, *157*, 359.
5. For example, see: (a) Evans, P. A.; Leahy, D. K. *J. Am. Chem. Soc.* **2002**, *124*, 7882; (b) Trost, B. M.; McEachern, E. J.; Toste, F. D. *J. Am. Chem. Soc.* **1998**, *120*, 12702; (c) Shintou, T.; Mukaiyama, T. *J. Am. Chem. Soc.* **2004**, *126*, 7359.
6. For examples of recent advances in ether synthesis (but not specifically *tert*-allylic ethers), see: (a) Mitchell, T. A.; Bode, J. W. *J. Am. Chem. Soc.* **2009**, *131*, 18057; (b) Shintou, T.; Mukaiyama, T. *J. Am. Chem. Soc.* **2004**, *126*, 7359; (c) Corma, A.; Renz, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 298 and references cited therein.
7. (a) Hadfield, M. S.; Lee, A.-L. *Org. Lett.* **2010**, *12*, 484; See also: (b) Bauer, J. T.; Hadfield, M. S.; Glen, P. E.; Lee, A.-L. *Org. Biomol. Chem.* **2010**, *8*, 4090; (c) Bauer, J. T.; Hadfield, M. S.; Lee, A.-L. *Chem. Commun.* **2008**, 6405; (d) Kilpin, K. J.; Paul, U. S. D.; Lee, A.-L.; Crowley, J. D. *Chem. Commun.* **2011**, 328.
8. For a review on gold-catalysed reaction of alcohols, see: Muzart, J. *Tetrahedron* **2008**, *64*, 5815.
9. For selected recent reviews on gold-catalysis, see: (a) Li, Z.; Brouwer, C.; He, C. *Chem. Rev.* **2008**, *108*, 3239; (b) Bongers, N.; Krause, N. *Angew. Chem., Int. Ed.* **2008**, *47*, 2178; (c) Gorin, D. J.; Toste, F. D. *Nature* **2007**, *446*, 395; (d) Fürstner, A.; Davies, P. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3410; (e) Jiménez-Núnez, E.; Echavarren, A. M. *Chem. Commun.* **2007**, 333; (f) Hashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180; (g) Shen, H. C. *Tetrahedron* **2008**, *64*, 3885; (h) Shen, H. C. *Tetrahedron* **2008**, *64*, 7847; (i) Marion, N.; Nolan, S. P. *Chem. Soc. Rev.* **2008**, *37*, 1776.
10. For examples of capture of vinylgold intermediates with iodine, see: (a) Schuler, M.; Silva, F.; Bobbio, C.; Tessier, A.; Gouverneur, V. *Angew. Chem., Int. Ed.* **2008**, *47*, 7927; (b) Kirsch, S. F.; Binder, J. T.; Crone, B.; Duschek, A.; Haug, T. T.; Liébert, C.; Menz, H. *Angew. Chem., Int. Ed.* **2007**, *46*, 2310; (c) Buzas, A.; Gagosz, F. *Synlett* **2006**, 2727; (d) Buzas, A.; Gagosz, F. *Org. Lett.* **2006**, *8*, 515; (e) Yu, M.; Zhang, L. *Org. Lett.* **2007**, *9*, 2147; (f) Alcaide, B.; Almendros, P.; del Campo, T. M. *Angew. Chem., Int. Ed.* **2007**, *46*, 6684; (g) Liu, L.-P.; Hammond, J. B. *Chem. Asian J.* **2009**, *4*, 1230.
11. For an example of gold-catalysed intramolecular iodoalkoxylation of allenes, see: Gockel, B.; Krause, N. *Eur. J. Org. Chem.* **2010**, 311.
12. Georgoulis, C.; Smada, W.; Valery, J. M. *Synthesis* **1981**, 572.
13. When the reaction was carried out with either 5 mol % or 15 mol % catalyst added in one portion at the beginning, conversions were ∼70%. A reaction time of 4 h versus 24 h seems to make no difference to the conversion. Therefore, the catalyst was added in three portions as described in order to force the reaction to completion.
14. For example, see: (a) Takaya, J.; Iwasawa, N. *J. Am. Chem. Soc.* **2008**, *130*, 15254; (b) Ngai, M. Y.; Skucas, E.; Krische, M. *Org. Lett.* **2008**, *10*, 2705; (c) Xu, D.; Lu, Z.; Li, Z.; Ma, S. *Tetrahedron* **2004**, *60*, 11879 Commercially available allenes were purchased from Sigma–Aldrich.
15. Reaction with added 3 Å MS to remove any adventitious water during the reaction results in poor conversions.
16. Commercially available from Sigma–Aldrich. For a review on applications of NHC–Au complexes, see: Marion, N.; Nolan, S. P. *Chem. Soc. Rev.* **2008**, *37*, 1776.
17. Commercially available from Sigma–Aldrich. For development of PPh_3AuNTf_2 see: Mézailles, N.; Richard, L.; Gagosz, F. *Org. Lett.* **2005**, *7*, 4133.
18. For a review on ligand effects in homogenous gold catalysis, see: Gorin, D. J.; Sherry, B. D.; Toste, F. D. *Chem. Rev.* **2008**, *108*, 3351.
19. (a) Zhang, Z.; Widenhoefer, R. *Org. Lett.* **2008**, *10*, 2079; See also: (b) Nishina, N.; Yamamoto, Y. *Tetrahedron* **2009**, *65*, 1799; (c) Nishina, N.; Yamamoto, Y. *Tetrahedron Lett.* **2008**, *49*, 4908; (d) Cui, D.-M.; Yu, K. R.; Zhang, C. *Synlett* **2009**, 1103; (e) Cui, D.-M.; Zheng, Z.-L.; Zhang, C. *J. Org. Chem.* **2009**, *74*, 1426.
20. Paton, R. S.; Maseras, F. *Org. Lett.* **2009**, *11*, 2237.
21. cf. Under our standard conditions (Table 1), the primary isomers of the products shown were not detected by crude ^1H NMR analysis (<5%), unless otherwise stated. In addition, small amounts of the corresponding hydroalkoxylation products (primary and tertiary allylic ethers, ∼12%) were also observed as by-products using conditions shown in Scheme 6.
22. Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467.
23. (a) Mizoroki, T.; Mori, K.; Ozaki, A. *Bull. Chem. Soc. Jpn.* **1971**, *44*, 581; (b) Heck, R. F.; Nolley, J. P., Jr. *J. Org. Chem.* **1974**, *96*, 1133.