Tetrahedron 65 (2009) 10334–10338

Contents lists available at ScienceDirect

Tetrahedron

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

Copper-catalysed intramolecular O–H addition to unactivated alkenes

Luis A. Adrio, Louisa Shuyi Quek, Jason G. Taylor, King Kuok (Mimi) Hii *

Department of Chemistry, Imperial College London, Exhibition Road, South Kensington, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 3 June 2009
Received in revised form 3 October 2009
Accepted 15 October 2009
Available online 20 October 2009

ABSTRACT

Intramolecular cyclisation of ω-alkenoic acids and alkenols can be achieved using a catalytic amount of $Cu(OTf)_2$ to afford lactones and cyclic ethers, offering a practical alternative to existing catalysts.

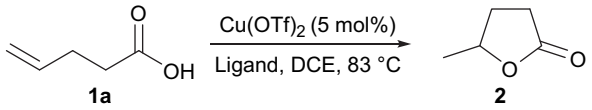
1. Introduction

Oxygen heterocycles such as lactones, furans and pyrans are prevalent in nature and exhibit a wide range of important biological activities. Consequently, their synthesis constitutes an important area of organic chemistry. One of the ways of constructing an *O*-heterocycle is by the intramolecular addition of an OH or CO_2H functionality to a C=C bond. Known as hydroalkoxylation or hydroacyalkoxylation, respectively, these atom-economical processes can be effected using strong Brønsted acids.[1] Conversely, several metal catalysts, such as $Pt(II)/PR_3$,[2a] $Sn(OTf)_4$,[2b] $Al(OTf)_3$[2c] and gold[2d] have also been reported for (either or both of) these reactions. It is interesting to note that AgOTf was known as an active catalyst,[3a] but did not preclude its use as a 'co-catalyst' with $FeCl_3$.[3b,3c]

2. Results and discussion

In our earlier work, we have reported the use of $Cu(OTf)_2$ as a catalyst in a number of intermolecular C–O and C–N bond formations, including additions of acids, phenols and alcohols to norbornene, sulfonamides to conjugate dienes and vinylarenes, and the annulation of phenols with 1,3-dienes.[4] Herein, we will report the first application of this catalyst for the intramolecular O–H additions to unactivated alkenes, leading to the formation of lactone and tetrahydrofuran rings.

Initially, reactions were conducted in air by heating at reflux a solution of 4-pentenoic acid **1a** in 1,2-dichloroethane in the presence of 5 mol % of $Cu(OTf)_2$. Cyclisation of the substrate proceeded smoothly to afford the γ-lactone **2** exclusively (Scheme 1). Subsequent investigations precluded the need for ligands, as they did not exert any beneficial effect.[5] Consequently, the scope of the reaction was established with a number of ω-alkenoic acid precursors, at 2 mol % catalyst loading (Table 1). At the end of each reaction, the paramagnetic catalyst was removed by passing the reaction mixture through a short column of silica gel, prior to ^1H NMR spectroscopic analysis. In all cases, clean 'spot-to-spot' conversions were observed, i.e., no side product was detected.



1a 2

Scheme 1. Cyclisation of 4-pentenoic acid to a γ-lactone.

Compared to the cyclisation of **1a**, the formation of the six-membered heterocycle (from **1b**) was noticeably slower (Table 1, entries 1 and 2). The introduction of a methyl group in the terminal position (**1c**) led to a mixture of γ- and δ-lactones **4** and **5**, in favour of the smaller ring (entry 3). This is notable, as it is in contrast to the regioselectivity observed previously using AgOTf, which was reported to favour the larger lactone ring by 10:1.[3a] On the other hand, the presence of the methyl substituent at the internal position (**1d**) yielded only the smaller γ-lactone **6** (entry 4). The presence of a 3-phenyl substituent led to significant reduction in the rate of reaction of **1e**, giving lactone **7** as a mixture of *syn*:*anti* isomers (entry 5); this is attributed to unfavourable 1,2-allylic strain during the cyclisation process.

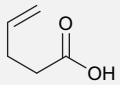
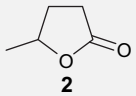
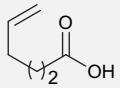
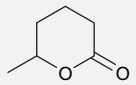
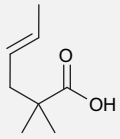
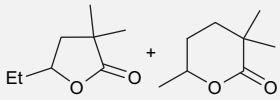
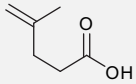
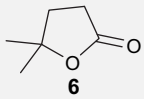
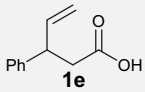
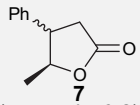
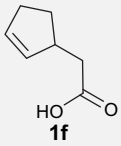
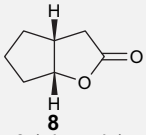
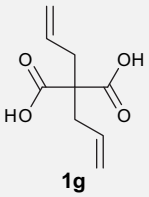
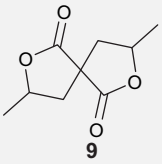
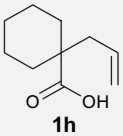
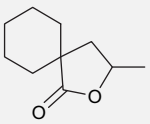
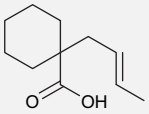
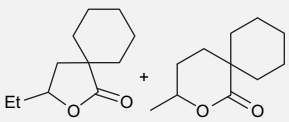
Synthesis of bicyclic rings was also attempted; this can be achieved by using the cyclopentene precursor **1f**, to give the *cis*-fused rings **8** exclusively (entry 6). Alternatively, spiro-lactones **9** and **10** can be obtained in high yields from diacids **1g** and **1h**, respectively (entries 7 and 8). Again, the introduction of a methyl substituent at the terminal alkene compromised the regioselectivity slightly (entry 9).

Many of the ω-alkenoic acid precursors were reduced to corresponding alkenols, and these were also subjected to copper

* Corresponding author. Tel.: +44 20 7594 1142; fax: +44 20 7594 5804.
E-mail address: mimi.hii@imperial.ac.uk (K. Kuok (Mimi) Hii).

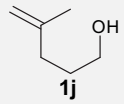
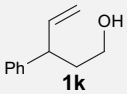
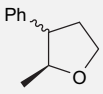
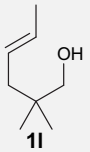
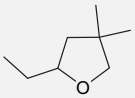
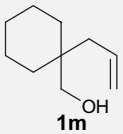
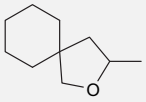
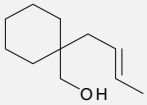
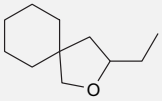
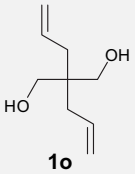
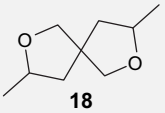
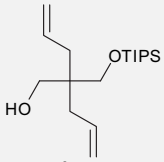
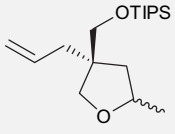
0040-4020/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2009.10.055

Table 1
Intramolecular cyclisation of γ- and δ-alkenoic acids[a]

Entry	Substrate	Product	*t*/h	Conv.[b]/%
1	 **1a**	 **2**	24	100 (88)
2	 **1b**	 **3**	36	83 (80)
3	 **1c**	 **4 : 5 (3 : 1)**	24	100 (95)
4	 **1d**	 **6**	18	100 (92)
5	 **1e**	 **7** (*syn:anti* = 3:2)	48	82 (72)[c]
6	 **1f**	 **8** 8 (*cis*- only)	24	100 (91)[c]
7	 **1g**	 **9**	22	100 (91)
8	 **1h**	 **10**	18 24[d]	100 (88) 72
9	 **1i**	 **11 : 12 (6 : 1)**	22	82 (73)

[a] Typical reaction: $Cu(OTf)_2$ (2 mol %) and 0.5 M of substrate at reflux in DCE.
[b] Conversions determined by ^1H NMR integration of crude reaction mixtures. Yields of isolated products indicated in parentheses.
[c] 5 mol % $Cu(OTf)_2$.
[d] 0.2 mol % $Cu(OTf)_2$.

Table 2
Intramolecular cyclisation of γ and δ-alkenols[a]

Entry	Substrate	Product	*t*/h	Conv.[b]/%
1	 **1j**	 **13**	21	100 (96)[c]
2	 **1k**	 **14** (*syn:anti* = 1:2.6)	26 46 75	59 (37) 88 (81) 96 (91)
3	 **1l**	 **15**	20	100 (92)
4	 **1m**	 **16**	22	80 (77)
5	 **1n**	 **17**	18 24	100 (96) 71[d]
6	 **1o**	 **18**	22	100 (89)
7	 **1p**	 **19**	18	100 (98) 100 (96)[e]

[a] Typical reaction: $Cu(OTf)_2$ (2 mol %) and 0.5 M of substrate at reflux in DCE.
[b] Conversions and diastereomeric ratios determined by ^1H NMR integration of crude reaction mixtures. Yields of isolated products indicated in parentheses.
[c] 65 °C.
[d] 0.2 mol % $Cu(OTf)_2$.
[e] 10% TfOH.

catalysis (Table 2).[6] Intramolecular hydroalkoxylation reactions promptly ensued and, in many cases, quantitative conversions could be attained, furnishing cyclic ethers in high isolated yields. Compared to their corresponding CO_2H additions, OH additions are not only more facile, e.g., Table 2, entry 2 (2 mol % catalyst) vs Table 1, entry 5 (5 mol % catalyst), but are also much more regioselective (Table 2, entries 3 and 5 vs Table 1, entries 3 and 9). In one particular case, the reaction can be conducted at 65 °C without affecting turnover or yield (Table 2, entry 1), showing that milder conditions may be feasible. Catalyst loading can be further reduced in these systems—preliminary tests conducted with substrates **1h** and **1n** using 0.2 mol % of catalyst showed acceptable conversions within 24 h (Table 1, entry 8 and Table 2, entry 5, final turnover numbers unoptimised), demonstrating its efficiency favourably against other catalytic systems, which typically employ 5 mol % catalytic loading, sometimes even 10 mol %.

Triflic acid has been implicated as the true catalytic species in metal triflate-catalysed processes.[7] This was investigated in the present study by performing control reactions with numerous substrates (**1g**–**h**, **1j**, **1l**–**o**). In contrast to our previous studies,[4] the use of 10% TfOH was found to be equally effective, giving the desired products with similar yields to copper-catalysed reactions. This includes the cyclisation of the mono-TIPS protected substrate **1p**,[8] which proceeded to completion cleanly with either catalyst, to furnish tetrahydrofuran **19** in comparable yields and product distribution (Table 2, entry 7); contrary to expectations, none of the spiro structure **18** or its deprotected precursor (**1o**) can be detected in the crude reaction mixture (^1H NMR).

Thus, the catalytic activity of $Cu(OTf)_2$ is very similar to triflic acid in these intramolecular O–H addition reactions. While it is impossible to rule out the involvement of Brønsted acid-catalysis in this case, the copper catalyst may be a preferred option, due to three distinct advantages: firstly, $Cu(OTf)_2$ is a non-corrosive and non-hygroscopic solid, making it more attractive than triflic acid in terms of practicality, safety and long-term storage.[9] Secondly, over the course of our investigations, we have demonstrated its utility and superiority over the Brønsted acid in a number of inter- and intramolecular C=C heterofunctionalisation reactions,[4] i.e., it has wider applicability.[10] Last but not least, copper(II) triflate is considerably cheaper, less toxic and offers similar, if not better, turnovers at a much lower catalytic loading than other metal catalysts.[2,3]

3. Conclusions

In summary, the result from the present study showed that $Cu(OTf)_2$ can be used in the synthesis of *O*-heterocycles by facilitating the intramolecular O–H addition to unactivated C=C bonds. Compared to the other catalysts, the copper system is cheaper, more practical and effective at lower catalytic loadings. Thus broadening the scope of $Cu(OTf)_2$ as a catalyst in C=C heterofunctionalisation reactions.

4. Experimental section

4.1. General

Copper(II) trifluoromethanesulfonate was procured from Sigma–Aldrich and used as-received. Acyclic precursors were purchased from commercial sources and used without further purification, except **1c**–**e**, **1g**–**i** and **11a**–**g**, which were prepared by literature procedures (see Supplementary data).

Catalytic reactions were performed in parallel in a Radley's 12-placed reaction carousel in air. Column chromatography was performed on silica gel (Merck Kieselgel 60 F254 230–400 mesh). Thin layer chromatography (TLC) was performed on aluminium-backed plates pre-coated with silica (0.2 mm) and developed in suitable solvents.

^1H and ^{13}C NMR spectra were recorded using 400 MHz Bruker AVANCE spectrometers. The chemical shifts are expressed as parts per million (ppm) and coupling constants (*J*) are given in Hertz (Hz). Multiplicity is abbreviated to s (singlet), d (doublet), t (triplet), q (quartet) and m (multiplet). Melting points were determined using an Electrothermal Gallenhamp apparatus fitted with a calibrated thermometer with an error of ±2 °C.

4.2. General procedure for copper-catalysed reactions

A Radley's reaction tube was charged with a magnetic stir bar, the requisite alkenoic acid or alcohol (1 mmol), copper(II) trifluoromethanesulfonate (0.02 mmol 2 mol%) and 1,2-dichloroethane (2 mL). The reaction tube was then placed in the carousel and heated at reflux for the required length of time. After cooling to room temperature, the solvent was removed under reduced pressure to furnish a residue, which was purified by column chromatography, to afford the corresponding lactones or cyclic ethers.

4.2.1. 5-Methyldihydrofuran-2(3H)-one, ***2***[3a]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.69–4.59 (1H, m), 2.59–2.51 (2H, m), 2.41–2.30 (1H, m), 1.89–1.77 (1H, m), 1.41 (3H, d, *J*=6.3). δ_C (101 MHz, $CDCl_3$) 177.5, 77.4, 29.6, 29.1, 21.0.

4.2.2. 6-Methyltetrahydro-2H-pyran-2-one, ***3***[3a]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.51–4.37 (1H, m), 2.64–2.53 (1H, m), 2.51–2.37 (1H, m), 1.97–1.78 (3H, m), 1.58–1.45 (1H, m), 1.37 (3H, d, *J*=6.3). δ_C (101 MHz, $CDCl_3$) 171.8, 76.9, 29.6, 29.2, 21.7, 18.5.

4.2.3. 5-Ethyl-3,3-dimethyldihydrofuran-2(3H)-one, ***4***[3a]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.39–4.29 (1H, m), 2.13 (1H, dd, *J*=12.6, 5.8), 1.82–1.67 (2H, m), 1.67–1.54 (1H, m), 1.26 (3H, s), 1.24 (3H, s), 0.98 (3H, t, *J*=7.5). δ_C (101 MHz, $CDCl_3$) 182.1, 78.3, 43.1, 40.5, 28.6, 25.1, 24.5, 9.5.

4.2.4. 3,3,6-Trimethyltetrahydro-2H-pyran-2-one, ***5***[3a]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.52–4.38 (1H, m), 1.88–1.78 (1H, m), 1.78–1.66 (3H, m), 1.37 (3H, d, *J*=6.3), 1.29 (3H, s), 1.28 (3H, s). δ_C (101 MHz, $CDCl_3$) 177.6, 78.0, 37.8, 34.5, 27.9, 27.8, 22.1.

4.2.5. 5,5-Dimethyldihydrofuran-2(3H)-one, ***6***[1b]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 2.62 (2H, t, *J*=8.2), 2.05 (2H, t, *J*=8.2), 1.41 (6H, s). δ_C (101 MHz, $CDCl_3$) 176.7, 84.6, 34.6, 29.3, 27.7.

4.2.6. Dihydro-5-methyl-4-phenyl-2(3H)-furanone, ***7***[3a]. Colourless oil. *syn-isomer*: δ_H (400 MHz, $CDCl_3$) 7.41–7.27 (3H, m), 7.14 (2H, dt, *J*=8.3, 2.5), 4.93 (1H, dq, *J*=6.4, 6.5), 3.76 (1H, dt, *J*=8.4, 6.4), 2.95 (1H, dd, *J*=17.4, 8.4), 2.82 (1H, dd, *J*=17.4, 6.0), 1.03 (3H, d, *J*=6.5). δ_C (101 MHz, $CDCl_3$) 176.7, 137.6, 128.8, 127.8, 127.6, 80.0, 44.8, 34.8, 16.7. *anti-isomer*: δ_H (400 MHz, $CDCl_3$) 7.42–7.18 (5H, m), 4.56 (1H, dq, *J*=8.6, 6.2), 3.25 (1H, dt, *J*=11.0, 8.6), 2.95 (1H, dd, *J*=17.6, 8.6), 2.83–2.76 (1H, dd, *J*=17.6, 11.0), 1.43 (3H, d, *J*=6.2). δ_C (101 MHz, $CDCl_3$) 175.5, 138.3, 129.2, 127.9, 127.2, 83.2, 49.7, 37.5, 19.2.

4.2.7. cis-Hexahydrocyclopenta[b]furan-2-one, ***8***[11]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.96 (1H, dd, *J*=8.3, 3.4), 2.74–2.89 (2H, m), 2.24 (1H, dd, *J*=8.3, 3.4), 2.06–1.94 (1H, m), 1.90–1.73 (1H, m), 1.61–1.75 (3H, m), 1.56–1.43 (1H, m). δ_C (101 MHz, $CDCl_3$) 177.8, 86.4, 37.9, 36.1, 33.6, 33.5, 23.4.

4.2.8. 3, 8-Dimethyl-2,7-dioxaspiro[4.4]nonane-1,6-dione, ***9***[12]. White solid. Obtained as an inseperable mixture of diastereomers. Mp 105–107 °C (lit.[13] 105–106 °C). Isomer 1: δ_H (400 MHz, $CDCl_3$) 5.09–4.93 (2H, m), 2.86–2.77 (2H, m), 1.90 (2H, ddd, *J*=13.2, 9.6, 3.8), 1.49 (3H, d, *J*=6.3), 1.48 (3H, d, *J*=6.3). Isomer 2: δ_H (400 MHz, $CDCl_3$) 4.80–4.60 (2H, m), 2.66–2.25 (4H, m), 1.53 (6H, d, *J*=6.2). δ_C (101 MHz, $CDCl_3$) 173.8, 173.5, 76.0, 75.9, 75.5, 75.0, 53.9, 41.6, 40.7, 40.4, 39.6, 21.1, 20.9, 20.6.

4.2.9. 3-Methyl-2-oxaspiro[4.5]decan-1-one, ***10***[14]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.54 (1H, tq, *J*=9.5, 6.2), 2.40 (1H, dd, *J*=12.9, 6.2), 1.90–1.17 (14H, m). δ_C (101 MHz, $CDCl_3$) 181.68, 73.70, 45.43, 41.22, 34.38, 31.53, 25.33, 22.21, 22.15, 21.45.

4.2.10. 3-Ethyl-2-oxaspiro[4.5]decan-1-one, ***11***[15]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.32 (1H, ddd, *J*=12.9, 9.7, 6.2), 2.38 (1H, dd, *J*=12.9, 6.2), 1.90–1.16 (13H, m), 0.99 (3H, t, *J* 7.4). δ_C (101 MHz, $CDCl_3$) 181.7, 78.7, 45.0, 39.0, 34.3, 31.6, 28.9, 25.3, 22.2, 22.1, 9.6.

4.2.11. 3-Methyl-2-oxaspiro[5.5]undecan-1-one, ***12***. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.47–4.36 (1H, m), 2.10–1.94 (2H, m), 1.90–1.67 (2H, m), 1.71–1.54 (7H, m), 1.35 (3H, d, *J*=6.3), 1.35–1.48 (3H, m). δ_C (101 MHz, $CDCl_3$) 183.9, 76.9, 41.4, 35.7, 33.6, 28.8, 27.6, 25.5, 22.1, 20.9, 20.8.

4.2.12. 2,2-Dimethyltetrahydrofuran, ***13***[2b]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 3.87–3.80 (2H, m), 1.99–1.88 (2H, m), 1.73–1.65 (2H, m), 1.23 (6H, s). δ_C (101 MHz, $CDCl_3$) 80.2, 66.1, 38.2, 27.8, 26.1.

4.2.13. 2-Methyl-3-phenyltetrahydrofuran, ***14***[3a]. Colourless oil. As a mixture of 1:2.6 of *syn*/*anti* isomers. δ_H (400 MHz, $CDCl_3$) major isomer: 7.44–7.05 (5H, m), 4.09–3.98 (2H, m), 3.94–3.80 (1H, m),

2.81 (1H, q, J=8.8), 2.36–2.44 (1H, m), 2.25–2.06 (1H, m), 1.23 (3H, d, J=6.0). minor isomer: 7.44–7.05 (5H, m), 4.24–4.11 (2H, m), 3.94–3.80 (1H, m), 3.40–3.27 (1H, m), 2.36–2.44 (1H, m), 2.25–2.06 (1H, m), 0.85 (3H, d, J=6.4). δ_C (101 MHz, $CDCl_3$): *syn*: 141.8, 128.4, 128.2, 126.3, 78.2, 67.0, 48.4, 32.9, 16.9; *anti*: 141.5, 128.6, 127.6, 126.7, 82.2, 67.4, 53.0, 35.4, 19.0.

4.2.14. 2-Ethyl-4,4-dimethyltetrahydrofuran, ***15***[16]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 3.95–3.86 (1H, m), 3.50 (1H, d, J=8.1), 3.43 (1H, d, J=8.1), 1.76 (1H, dd, J=12.2, 6.5), 1.69–1.56 (1H, m), 1.53–1.41 (1H, m), 1.31 (1H, dd, J=12.2, 9.0), 1.10 (6H, s), 0.92 (3H, t, J=7.5). δ_C (101 MHz, CDCl3): 80.9, 79.9, 46.5, 39.5, 29.1, 27.0, 26.6, 10.4.

4.2.15. 3-Methyl-2-oxaspiro[4.5]decane, ***16***[17]. Colourless oil. δ_H (400 MHz, $CDCl_3$) 4.09–3.97 (1H, m), 3.63 (1H, d, J=8.5), 3.48 (1H, d, J=8.4), 1.86 (1H, dd, J=12.3, 6.3), 1.33–1.52 (11H, m), 1.24 (3H, d, J=6.0). δ_C (101 MHz, $CDCl_3$): 78.6, 74.8, 37.4, 35.9, 26.0, 24.0, 23.6, 21.4.

4.2.16. 3-Ethyl-2-oxaspiro[4.5]decane, ***17***. Colourless oil. δ_H (400 MHz, $CDCl_3$) 3.87–3.76 (1H, m), 3.60 (1H, d, J=8.4), 3.49 (1H, d, J=8.4), 1.83 (1H, dd, J=12.3, 6.4), 1.69–1.32 (12H, m), 1.23 (1H, dd, J=12.3, 9.1), 0.92 (3H, t, J=7.5). δ_C (101 MHz, $CDCl_3$): 80.3, 78.4, 37.2, 35.7, 29.0, 26.0, 24.0, 23.6, 10.5. MS-CI$^+$ (m/z) calcd for $C_{11}H_{20}O$ $[M+NH_4^+]^+$ 186.186, found 186.

4.2.17. 3,8-Dimethyl-2,7-dioxaspiro[4.4]nonane, ***18***. Colourless oil. Obtained as an inseparable mixture of isomers (ratio 1:1:1, by integration of methyl signals). δ_H (400 MHz, $CDCl_3$) 4.15–3.94 (1H, m), 3.84–3.54 (2H, m), 2.19–1.96 (1H, m), 1.60–1.46 (1H, m), 1.32–1.20 (3H, m). δ_C (101 MHz, $CDCl_3$) 77.6, 76.5, 75.3, 75.3, 75.2, 51.9, 45.2, 45.0, 44.2, 21.2. MS-CI$^+$ (m/z) calcd for $C_9H_{16}O_2$ $[M+NH_4^+]^+$ 174.149, found 174.

4.2.18. ((3-Allyl-5-methyltetrahydrofuran-3-yl)methoxy)-triisopropylsilane, ***19***. Colourless oil. Exists as an inseparable mixture of diastereomers δ_H (400 MHz, $CDCl_3$) 5.88–5.71 (1H, m), 5.14–5.02 (2H, m), 4.07–3.93 (1H, m), 3.84–3.38 (4H, d, J=8.9), 2.36–2.18 (2H, m), 1.99–1.79 (1H, m), 1.31–1.17 (7H, m), 1.13–0.98 (18H, m). δ_C (101 MHz, $CDCl_3$) 135.1, 117.6, 75.4, 74.5, 67.8, 66.9, 49.4, 49.3, 41.7, 41.3, 40.3, 38.9, 21.1, 18.1, 12.0. TOF MS ES$^+$ (m/z) calcd for $C_{18}H_{36}O_2Si$ $(M+H)^+$ 313.2563, found 313.2553.

Acknowledgements

The authors are grateful to Fundación Caixa Galicia (Becas Postgrado 2008) and Xunta Galicia (Ángeles Alvariño) for postdoctoral support (LAA), Ministerio de Educación y Ciencia (project number CTQ2006-15621-C02-01/BQU), for a collaborative grant, and EPSRC/GSK for studentship support (JGT).

Supplementary data

Preparation of non-commercially available acyclic precursors and copies of ^1H and ^{13}C NMR spectra are provided as Supplementary Material. Supplementary data associated with this article can be found in online version, at doi:10.1016/j.tet.2009.10.055.

References and notes

1. (a) Coulombel, L.; Duñach, E. *Green Chem.* **2004**, 499–501; (b) Coulombel, L.; Duñach, E. *Synth. Commun.* **2005**, *35*, 153–160; (c) Zhou, Y.; Woo, L. K.; Angelici, R. J. *Appl. Catal., A* **2007**, *333*, 238–244.
2. (a) Qian, H.; Han, X.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2004**, *126*, 9536–9537; (b) Coulombel, L.; Faviera, I.; Duñach, E. *Chem. Commun.* **2005**, 2286–2288; (c) Coulombel, L.; Rajzmann, M.; J-Pons, M.; Olivero, S.; Duñach, E. *Chem.—Eur. J.* **2006**, *12*, 6356–6365; (d) Kamiya, I.; Tsunoyama, H.; Tsukuda, T.; Sakurai, H. *Chem. Lett.* **2007**, *36*, 646–647.
3. (a) Yang, C. G.; Reich, N. W.; Shi, Z.; He, C. *Org. Lett.* **2005**, *7*, 4553–4556; (b) Komeyama, K.; Mieno, Y.; Yukawa, S.; Morimoto, T.; Takaki, K. *Chem. Lett.* **2007**, *36*, 752–753; (c) Komeyama, K.; Morimoto, T.; Nakayama, Y.; Takaki, K. *Tetrahedron Lett.* **2007**, *48*, 3259–3261.
4. (a) Taylor, J. G.; Whittall, N.; Hii, K. K. *Chem. Commun.* **2005**, 5103–5105; (b) Taylor, J. G.; Whittall, N.; Hii, K. K. *Org. Lett.* **2006**, *8*, 3561–3564; (c) Adrio, L. A.; Hii, K. K. *Chem. Commun.* **2008**, 2325–2327.
5. Monophosphines (PPh_3 and P(*o*-tolyl)$_3$) and 2,2′-bipy inhibited the reaction completely, while diphosphines (dppe, dppp, dppb, Xantphos and BINAP) did not lead to any acceleration in turnover.
6. 4-Pentenol and 5-hexenol were not included, due to the volatility of their cyclised products.
7. For example, see: (a) Wabnitz, T. C.; Yu, J. Q.; Spencer, J. B. *Chem.—Eur. J.* **2004**, *10*, 484–493; (b) Rosenfeld, D. C.; Shekhar, S.; Takemiya, A.; Utsunomiya, M.; Hartwig, J. F. *Org. Lett.* **2006**, *8*, 4179–4182.
8. A TIPS-protected substrate was reported to be unstable in the presence of 5% TfOH (giving <10% product yield): Ref. 3a.
9. The following handling, storage and precautions were recommended by the 'Encyclopedia of Reagents for Organic Synthesis' (Ed. L. A. Paquette, Wiley & Sons, 2006): '(trifluoromethanesulfonic acid) is a stable, hygroscopic liquid, which fumes copiously on exposure to moist air. Transfer under dry nitrogen is recommended. Contact with cork, rubber and plasticised materials will cause rapid discolouration of the acid and deterioration of the materials. Samples are best stored in sealed glass ampules or glass bottles with Kel-FTM or PTFE plastic screw cap linings. Use in a fume hood.'
10. In most cases, particularly for intermolecular reactions, excess amounts of triflic acid can lead to competitive poly/oligomerisation of the alkene precursor, leading to lower yields of the desired product (see Ref. 7b, also 4a and 4b).
11. Shimizu, H.; Onitsuka, S.; Egami, H.; Katsuki, T. *J. Am. Chem. Soc.* **2005**, *127*, 5396–5413.
12. Muñoz, M. P.; Lloyd-Jones, G. C. *Eur. J. Org. Chem.* **2009**, 516–524.
13. Fittig, H. *Liebigs Ann. Chem.* **1883**, *216*, 63–69.
14. Maslak, V.; Matović, R.; Saičić, R. N. *Tetrahedron* **2004**, *60*, 8957–8966.
15. Larchevegue, M.; Debal, A. *Synth. Commun.* **1980**, *10*, 49–58.
16. Mazet, M.; Desmaison-Brut, M. *Bull. Soc. Chim. Fr.* **1971**, 2656–2662.
17. Picard, P.; Moulines, J.; Lecoustre, M. *Bull. Soc. Chim. Fr.* **1984**, 65–70.