Pergamon

Tetrahedron 56 (2000) 9365–9373

TETRAHEDRON

Potassium Ferrate on Wet Alumina: Preparation and Reactivity

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Received 27 June 2000; revised 1 September 2000; accepted 21 September 2000

Abstract—The use of a wet alumina/potassium ferrate system for the oxidation of a range of activated alcohols is described. Studies are presented which delineate the scope and limitation of the procedure and include a new carbon–carbon bond cleavage reaction.

Introduction

The ferrate ion (FeO_4^{2-}) has been identified as an effective mild oxidant and this unusual species shows great promise as a potential alternative to more toxic, less selective, oxidising agents. Such is the interest in ferrate as a non-polluting reagent that it is at present being evaluated for waste water treatment.[1] The best known and most extensively studied of this class is potassium ferrate, principally due to its ease of manufacture, purification and stability.[2] The established method for the preparation of potassium ferrate was first described in detail in 1950 by Hrostowski and Scott[3] and required the precipitation of potassium ferrate from a basic solution of sodium ferrate by addition of potassium hydroxide. Potassium ferrate has been reported to oxidise a variety of organic functionality such as amines[4] and particularly alcohols, for which a number of publications can be found in the literature.[1–11] The reduction potentials for Fe(VI) to Fe(III) have been estimated at 2.20 and 0.72 V for reactions in acidic and basic media, respectively.[5] This is significantly higher than those reduction potentials observed for Mn(VII) and Cr(VI) suggesting that potassium ferrate is potentially the stronger oxidant. Studies involving potassium ferrate generally employ aqueous conditions in which potassium ferrate is very soluble but unstable; it is insoluble in non-aqueous systems. A study by Lee et al. on ferrate degradation concludes that ferrate is particularly unstable in acidic media and has a maximum half-life in basic media (pH 10).[6] The decomposition of the ferrate can be observed as the deep purple colour changes to brown, indicating the reduction of Fe(VI) to Fe(III). There have been studies on potassium ferrate mediated oxidation of alcohols under phase-transfer conditions. Kim and co-workers reported the selective oxidation of allylic and benzylic alcohols in the presence of primary and secondary alcohols.[7] The same authors also reported the selective oxidation of activated alcohols using a solid mixture of potassium ferrate, alumina and copper sulfate pentahydrate.[8] More recently, Laszlo et al. have reported the ferrate-mediated oxidation of alcohols using a non-aqueous solvent with a montmorillonite clay catalyst.[9]

The most comprehensive study on the mechanism of potassium ferrate mediated oxidation of alcohols was carried out by Lee and co-workers.[6] Consistent with this work is the mechanism presented below involving C–H insertion of an Fe=O bond to generate an Fe–C bond. Homolysis of this bond leads to a carbon radical which, on further oxidation gives the resulting carbonyl containing product via a cationic species (Scheme 1).

An alternative ionic mechanism may also be operating and at the present time the detailed chemical processes by which ferrate can mediate the oxidation of allylic alcohols are unclear. Notwithstanding the mechanistic ambiguity, it is certainly the case that, as the search for less toxic oxidants intensifies, potassium ferrate is likely to attract greater attention as a useful reagent, even though at the present time it is not commercially available. This paper describes a new procedure for the preparation of potassium ferrate and the development of its use as a reagent for the oxidation of alcohols.[10] Experiments designed to attempt to clarify the intermediacy of a carbon free-radical are also presented.

Results and Discussion

Preparation of potassium ferrate

An alternative preparation of potassium ferrate using bleach would be highly desirable as it would avoid the requirement of chlorine gas which is commonly employed in most

Keywords: oxidation; iron; alcohols.
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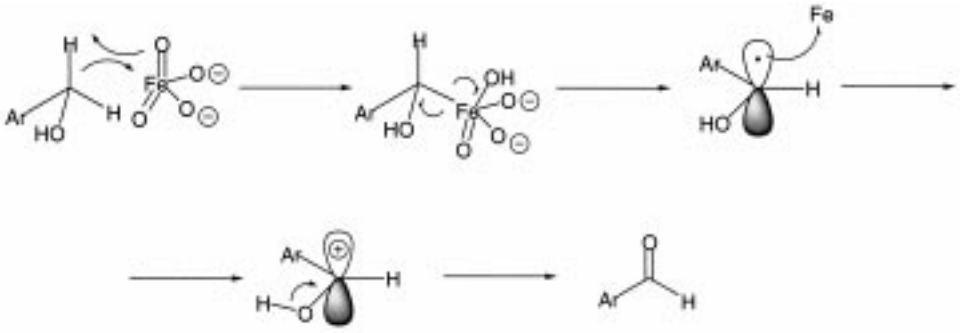
PII: S0040-4020(00)00907-8



Scheme 1.

published procedures. By using relatively strong bleach (12% available chlorine) it has proved possible to prepare potassium ferrate in reasonable yield (20–30%) and purity (>94%). The preparation used is detailed in the experimental section.

Oxidation of alcohols using potassium ferrate with wet alumina

There have been three reports on the oxidation of activated alcohols in non-aqueous solvents, all of which use solid supports. Kim et al. evaluated a variety of supports such as alumina and silica and found the best conversions were achieved using a mixture of alumina and copper sulfate pentahydrate in benzene.[8] Laszlo and co-workers also used a variety of supports such as kaolin, acidic alumina and zeolites and identified optimum conditions using K10 montmorillonite with a non-polar solvent such as pentane.[9] From this work it would appear that water is essential for the success of these oxidations albeit that these are carried out in organic solvent. Our preliminary studies confirmed this and we found that the oxidation of benzyl alcohol **1** using potassium ferrate was very slow in solvents other than water. In order to develop an alternative reagent system, we considered the use of alumina as a support.[11] We studied potassium ferrate mediated oxidation of benzyl alcohol in dichloromethane at room temperature using wet alumina and found that much improved rates of conversion to benzaldehye **2** were achieved using a hydrated additive (Table 1). Optimization studies revealed that alumina containing 30% water provided the highest levels of conversion. When the reactions were carried out in pentane and cyclohexane further improved rates of conversion were achieved. We briefly examined the effectiveness of phase-transfer conditions as it had been previously reported that such additives had a beneficial effect on ferrate-mediated oxidations. However, we found that inclusion of Bu_4NBr had no impact on the yield of reaction.

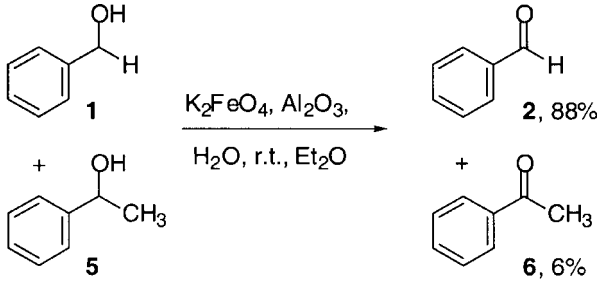
Table 1. Oxidation of benzyl alcohol in dichloromethane, pentane and cyclohexane using potassium ferrate and wet alumina (conversions based on G.C. analysis)

Entry	Solvent	Ferrate (eq)	Additive	Time/h	(%)
1	DCM	1	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	72	94
2	DCM	2	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	96	93
3	DCM	1	$Al_2O_3{\cdot}H_2O$	144	80
4	Pentane	1	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	2	94
5	Pentane	1.5	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	2	92
6	Pentane	1	$Al_2O_3{\cdot}H_2O$	2	93
7	Cyclohexane	1	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	2	92
8	Cyclohexane	1.5	$Bu_4NBr/Al_2O_3{\cdot}H_2O$	2	92
9	Cyclohexane	1	$Al_2O_3{\cdot}H_2O$	2	93

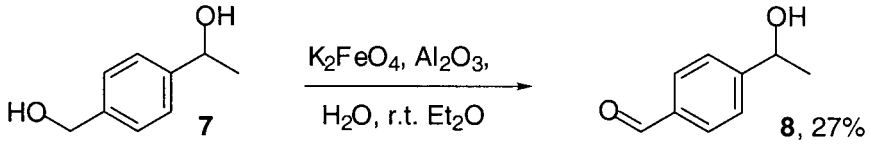
These rates of conversion are consistent with Laszlo's observations that non-polar solvents are most suitable for ferrate-mediated oxidations and that the presence of water is important. It is noteworthy that additional equivalents of ferrate did not result in higher rates of conversion. We used our optimised system to study the oxidation rates of other alcohols. Cinnamyl alcohol **3**, benzhydrol **4** and *sec*-phenethyl alcohol **5** are substrates that have been used to study ferrate oxidation in other systems. We found that our system showed excellent conversion rates for cinnamyl alcohol (77%). By contrast, oxidation of benzhydrol **4** and *sec*-phenethyl alcohol **5** gave only low yields of product ketones (7 and 12% respectively). These results suggest the system may be used for selective oxidation of primary activated alcohols in the presence of secondary activated alcohols. We carried out a competition experiment and found that oxidation of a mixture of benzyl alcohol **1** and *sec*-phenethyl alcohol **5** led to almost exclusive formation of benzaldehyde (**2**, 88%) with very little ketone **6** formed (6%) (Scheme 2).

Moreover, treatment of diol **7** with potassium ferrate in diethyl ether led only to the isolation of alcohol **8** in 27% and recovered starting material (21%). Although we cannot rule out the formation of a ketone (or ketoaldehyde) product derived from **7** because of the poor mass balance, these results do still indicate the possibility of effecting selective oxidation (Scheme 3).

We found that potassium ferrate and wet alumina was also



Scheme 2.



Scheme 3.

effective for the oxidation of thiols. Thus thiophenol **9** and benzyl mercaptan **10** were stirred with one equivalent of potassium ferrate and wet alumina in pentane and gave the corresponding disulphides in good yields without further purification (79% and 82% respectively). Such oxidations are well-known for other ferrate based systems.[9]

Oxidation of heterocyclic alcohols using potassium ferrate and wet alumina

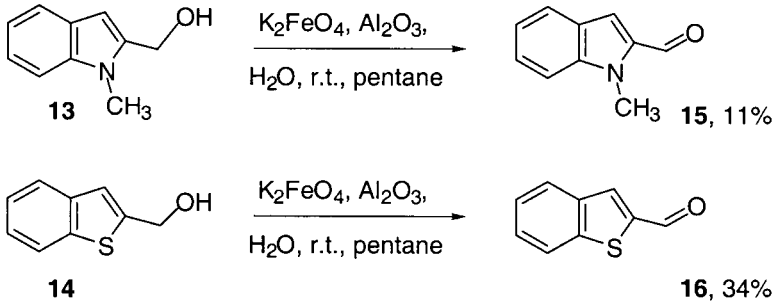
Although many alcohols have been oxidised using potassium ferrate, the range and diversity of these studies has been somewhat limited and we sought to examine the generality of our new reagent system. We examined oxidation of heterocyclic alcohols and somewhat disappointingly found that primary alcohols derived from indole **13** and benzothiophene **14** were oxidised to give **15** and **16** in only modest yields (Scheme 4).

By way of contrast, we did find one case in which reasonably efficient oxidation could be observed; *sec*-furfuryl alcohol **17** was oxidised to ketone **18** in pentane in 61% yield (Scheme 5).

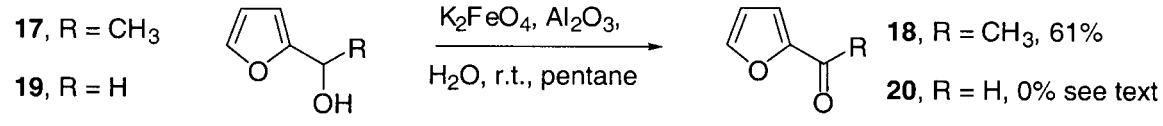
Despite repeated attempts, we were unable to isolate furfuraldehyde **20** by oxidation of furfuryl alcohol **19** in pentane, although we observed a very vigorous exothermic reaction and complete consumption of starting material. This is somewhat surprising particularly in view of our finding that the reaction was successful when carried out using diethyl ether or dichloromethane as reaction solvent. Under these conditions we were able to isolate furfuraldehyde **20** in reasonable yield (34 and 42% respectively).

Oxidation of propargylic alcohols using potassium ferrate and wet alumina

In order to further extend the range of potassium ferrate oxidations with wet alumina we studied the oxidation of propargylic alcohols and the results are summarised in Table 2. The propargyl alcohol derivative **21** was subjected to the usual reaction conditions in pentane and a vigorous, exothermic reaction resulted and appeared to be complete after approximately two minutes. Surprisingly, the sole product from the reaction proved to be 3-tetrahydropyran-2-yl-oxylpropyne **22** resulting from α,β-carbon–carbon bond cleavage (entry 1). A range of alternative work-up procedures were employed to optimise the yield but the terminal alkyne was obtained as the sole product in a reproducible 48–50% yield. When we subjected the silylated derivative **23** to the same conditions the alcohol failed to react and only the starting material was recovered (entry 2). This led us to speculate that the nature of the remote oxygen functionality was a requirement for reactivity. When this remote oxygen functionality was replaced with an alkyl chain we again failed to observe reaction with potassium ferrate (entry 3). These results indicated a strong requirement for the presence of a second oxygen functionality but it was unclear whether the THP motif was essential. A simple experiment showed this not to be the case and when we subjected compound **27** to oxidation we isolated **28** in excellent yields (entry 4, 96–98%). Although the presence of the oxygen moiety is important, the cleavage reaction can still proceed when its position is moved within the chain. Thus when the oxygen atom is moved further from the reacting centre the reaction still proceeds but with reduced yield (entries 5 and 6). This surprising and rather unexpected

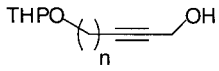
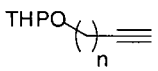
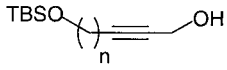
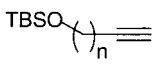
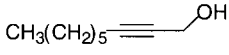
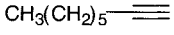
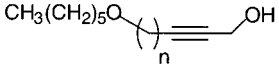
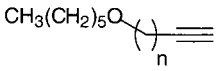
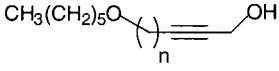
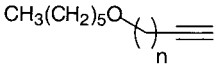
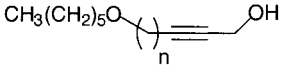
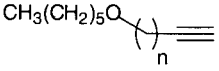
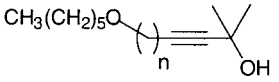
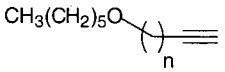
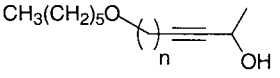
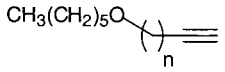
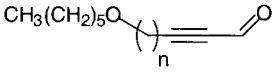
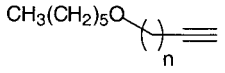


Scheme 4.

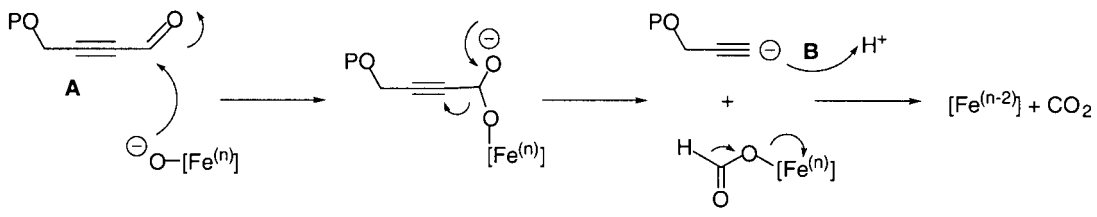


Scheme 5.

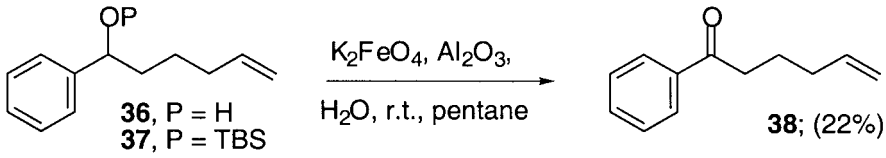
Table 2. Oxidation of propargyl alcohols using potassium ferrate and wet alumina

Entry,	n	Substrate	Product (%)
1	1	 **21**	 **22**, (48 - 50)
2	1	 **23**	 **24**, (0)
3	1	 **25**	 **26**, (0)
4	1	 **27**	 **28**, (96 - 98)
5	2	 **29**	 **30**, (23 - 25)
6	3	 **31**	 **32**, (29 - 33)
7	1	 **33**	 **28**, (0)
8	1	 **34**	 **28**, (0)
9	1	 **35**	 **28**, (21)

reactivity of ferrate with propargyl alcohol derivatives is more remarkable when considering the lack of similar transformations in the literature. We could find only one other related example in the literature which involves the base catalysed removal of a tertiary alcohol from an alkyne.[12] In order to ascertain any similarities between the ferrate mediated reaction and this related cleavage reaction we subjected tertiary alcohol **33** to the reaction conditions but no reaction was observed (entry 7). Similarly we observed no reaction with secondary alcohol **34** (entry 8). It is possible however that the lack of reactivity in this case is simply due to the steric effect associated with the tertiary centre and that the successful reactions do proceed via a transient alkynyl anion species. One could envisage a sequence involving oxidation of the alcohol to an intermediate aldehyde **A** followed by nucleophilic attack and elimination of the alkynyl anion **B** with the production of CO_2 (Scheme 6). Indeed, subjection of the aldehyde **35** to potassium ferrate did lead to the isolation of the terminal alkyne **28** albeit in poor yield (entry 9). However we have been unable to confirm the production of CO_2 from our experiments and this postulate does not easily rationalise the effect of remote



Scheme 6.



Scheme 7.

substituent on reactivity. In our opinion a good deal of further work is required before a working mechanism can be proposed with confidence.

Further studies

If, as first postulated by Lee,[6] a radical intermediate is formed during the oxidation of alcohols by potassium ferrate in aqueous media, we reasoned it may be possible to trap the radical using an intra- or inter-molecular radical trap. We decided to prepare a precursor incorporating an alkene as an intramolecular trap.[13] The cyclisation precursor **36** was prepared and subjected to oxidation with one equivalent of potassium ferrate in aqueous media. However, the only product isolated was the ketone (**38**, 22%) along with starting material (68%, Scheme 7). If a carbon-radical species is generated, presumably further oxidation to give the ketone is more rapid than cyclisation. If the earlier hypothesis presented by Lee is correct and involves C–H bond activation and thence radical formation via C–Fe bond homolysis then it may be possible to trap the radical intermediate via oxidation of a protected alcohol substrate. However the silicon protected alcohol **37** gave only starting material in near quantitative yield when subjected to potassium ferrate and wet alumina.

Given our failure to see any evidence of radical intermediates and the recent literature report suggesting an ionic mechanism,[14] we suggest the following mechanistic possibility. Addition of the alkoxide **C** to an iron–oxygen bond results in the formation of an intermediate peroxy species **D**. Inter or intramolecular deprotonation results in the formation of the aldehyde **E** and an iron (IV) species (Scheme 8). This speculation differs from previous mechanistic proposals and may be worthy of consideration.

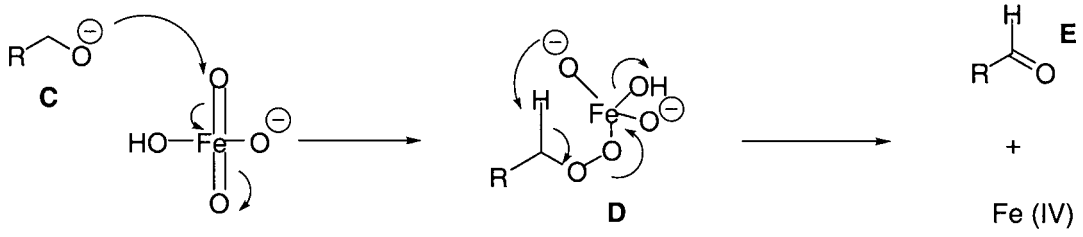
Conclusions

Our work on the use of wet alumina as a solid support for the potassium ferrate mediated oxidation has identified a number of synthetically useful aspects. The procedure is practical, very simple and the reagent system can exhibit chemoselectivity for example in the reaction of primary benzylic alcohols. We have attempted to define the scope of this type of oxidation procedure and have extended the range of alcohols which can be oxidised using this reagent. The results with heterocyclic alcohols are promising but the yields are still to be optimised to enable them to be carried out in a preparatively useful manner; however we believe that it is likely that the underlying reasons for poor efficiency are due to difficulties in identifying an efficient extraction procedure. Further studies on product isolation may lead to an improved procedure. Perhaps the most important part of the study has been the results obtained during our studies on the oxidation of propargylic alcohols. We uncovered an unusual, high yielding, carbon–carbon bond cleavage reaction which takes place under very mild conditions. The importance of the hydroxy group on this mode of reactivity is very unusual and is worthy of further study. Our attempts to trap a proposed radical intermediate using an alkene provided no support for a carbon radical intermediate. This is in agreement with the current consensus that such oxidations are ionic.[14]

Experimental

General

All reactions were performed using oven-dried apparatus under a dry nitrogen atmosphere unless otherwise stated. Proton and carbon NMR spectra were recorder on a Bruker DPX spectrometer at 300 and 75 MHz respectively. Mass spectra were recorded on a Fisons autospec instrument. High resolution mass spectra were recorded at the National Service Centre, University of Wales, Swansea, on a Thermoquest Finnigan MAT900XT spectrometer. Infrared spectra were recorded using a Perkin–Elmer FT-IR 298 spectrometer using a thin film of the pure compound unless otherwise stated. GC studies were carried out using a Perkin–Elmer 8310 machine employing a 50 QC5/BPI 5.0 column. THF and diethyl ether were distilled over sodium benzophenone ketyl prior to use. Dichloromethane, benzene and dimethylformamide were distilled over calcium hydride. Methanol was distilled over magnesium and



Scheme 8.

iodine. Sodium hydride was used as a 60% dispersion in mineral oil. Other solvents were used as supplied (general purpose grade). Column chromatography was performed on silica gel (70–230 mesh, 60 Å). Petrol refers to petroleum ether (boiling range: 40–60°C) Thin layer chromatography was performed on Merck silica gel 60F-254 coated plates and visualisation was achieved using a UV lamp and/or potassium permanganate and anisaldehyde. The term in vacuo refers to solvent removal via rotary evaporation at water aspirator pressure or house vacuum. All coupling constants are given in Hertz and all melting points are uncorrected. Compounds **7**,[15] **8**,[16] **13**–**16**,[17–20] **21**,[21] **22**,[22] **23**,[23] **24**,[24] **28**,[25] **36**,[26] **38**,[26] have been previously reported in the literature; Compounds **1**–**6**, **9**–**12**, **17**–**20**, **25**, **26** can be obtained from commercial sources.

Preparation of 4 hexyloxybut-2-yn-1-ol 27. Sodium hydride (930 mg, 23.3 mmol) was added to a solution of butane-1,4-diol (1.0 g, 11.6 mmol) in dry THF (50 mL) at 0°C. The mixture was stirred for thirty minutes after which the evolution of hydrogen gas had subsided. *t*-Butylammonium bromide (747 mg, 2.3 mmol) and 1-bromohexane (3.22 mL, 35 mmol) were then added and the reaction mixture was heated at reflux for two hours. The mixture was allowed to cool to room temperature prior to addition of water (50 mL). The mixture was extracted with ether (3×100 mL) and the combined organic extracts dried with magnesium sulfate. The mixture was then filtered and the solvent removed in vacuo. The crude product was purified using flash column chromatography (5:1 petrol/ether) to give the *alcohol* **27** as a colourless oil (3.0 g, 78%). ν_{max} 3399, 2931, 2859, 1456, 1353, 1124, 1094, 1019, 733 cm^{-1}; δ_H ($CDCl_3$) 1.06 (3H, t, J=6.0 Hz, C**H**$_3$), 1.49–1.58 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.73–1.82 (2H, m, C**H**$_2$), 2.62 (1H, s, CH$_2$O**H**), 3.68 (2H, t, J=6.0 Hz, C**H**$_2$O), 4.36 (2H, s, C**H**$_2$OH), 4.49 (2H, s, OC**H**$_2$); δ_C ($CDCl_3$) 14.5, 19.1, 23.0, 29.0, 31.8, 51.8, 53.9, 78.7, 87.0, 126.3; HRMS calculated for $C_{10}H_{17}O_2$, 169.1229, found 169.1230 $(M-H)^+$.

Preparation of 5-hexyloxypent-2-yne-1-ol 29. *n*-Butyllithium (1.30 mL of a 2.5 M solution in hexanes, 3.25 mmol) was added dropwise to a solution of the *alkyne* **30** (500 mg, 3.25 mmol) in dry THF (10 mL) at −78°C. The reaction mixture was stirred for one hour prior to addition of solid *p*-formaldehyde (195 mg, 6.50 mmol). The reaction mixture was stirred for one hour and then allowed to warm to room temperature, after which stirring was continued for a further hour. Aqueous ammonium chloride solution (20 mL) was then added. The mixture was extracted with diethyl ether (3×30 mL) and the extracts dried over magnesium sulfate. The mixture was then filtered and the solvent removed in vacuo. The crude product was purified using flash chromatography (5:1 petrol/diethyl ether) to give the *alcohol* **29** as a colourless oil (253 mg, 42%). ν_{max} 3397, 2930, 2860, 1457, 1374, 1106, 1017, 911, 733 cm^{-1}; δ_H ($CDCl_3$) 0.79 (3H, t, J=7.0 Hz, C**H**$_3$), 1.20–1.28 (6H, m, 6H, C**H**$_2$C**H**$_2$C**H**$_2$), 1.44–1.50 (2H, m, C**H**$_2$), 1.89 (1H, s, O**H**), 2.43 (2H, t, J=7.0 Hz, C**H**$_2$), 3.35 (2H, t, J=7.0 Hz, OC**H**$_2$), 3.44 (2H, t, J=7.0 Hz, OC**H**$_2$), 4.15 (2H, s, C**H**$_2$OH); δ_C (75 MHz) 14.5, 20.5, 23.0, 26.2, 23.9, 32.0, 51.7, 69.2, 71.6, 79.8, 83.6; HRMS calculated for $C_{11}H_{24}NO_2$, 202.1807, found 202.1809 $(M+NH_4)^+$.

Preparation of 4-hexyloxybut-1-yne 30. Sodium hydride (1.2 g, 30.0 mmol) was added to a solution of *hex-3-ynol* (2.0 g, 28.6 mmol) in dry THF (20 mL) at 0°C and the mixture was stirred for thirty minutes. *t*-Butylammonium bromide (461 mg, 1.43 mmol) and hexylbromide (4.40 mL, 30.3 mmol) were then added and the reaction mixture heated at reflux for two hours. The mixture was allowed to cool to room temperature and water (50 mL) added. The mixture was extracted with diethyl ether (3×100 mL) and the combined organic extracts washed with brine (20 mL) then dried with magnesium sulfate. The mixture was then filtered and the solvent removed in vacuo. The crude product was purified using flash column chromatography (3:1 petrol/diethyl ether) to give the *alkyne* **30** as a colourless oil (3.83 g, 87%). ν_{max} 3314, 2932, 2861, 1116 cm^{-1}; δ_H ($CDCl_3$) 1.11–1.15 (3H, m, C**H**$_3$), 1.51–1.61 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.80–1.85 (2H, m, C**H**$_2$), 2.23 (1H, t, J=3.0 Hz, CC**H**), 2.70 (2H, dd, J=7.0, 3.0 Hz, CC**H**$_2$), 3.70 (2H, t, J=7.0 Hz, C**H**$_2$O), 3.80 (2H, t, J=7.0 Hz, C**H**$_2$O); δ_C ($CDCl_3$) 14.5, 20.2, 23.0, 26.2, 30.0, 32.1, 51.7, 69.1, 69.6, 71.6, 81.8; HRMS calculated for $C_{10}H_{17}O$, 153.1357, found 153.1360 $(M-H)^+$.

Preparation of 6-hexyloxyhex-2-yn-1-ol 31. *n*-Butyllithium (2.4 mL of a 2.5 M solution in hexanes, 6.0 mmol) was added dropwise to a solution of the *alkyne* **32** (1.0 g, 5.95 mmol) in dry THF (10 mL) at 0°C. The reaction mixture was stirred for thirty minutes and *p*-formaldehyde (476 mg, 11.90 mmol) added. Stirring was continued for two hours before adding aqueous ammonium chloride (10 mL). The mixture was extracted with ether (3×30 mL) and the extracts were combined and dried over magnesium sulfate. The solvent was removed in vacuo and the crude product purified by flash column chromatography (5:1 petrol/diethyl ether) to give the *alcohol* **31** as a colourless oil (849 mg, 72%). ν_{max} 3409, 2931, 2860, 1635, 1375, 1112, 1015, 910, 732 cm^{-1}; δ_H ($CDCl_3$) 0.82 (3H, t, J=6.0 Hz, C**H**$_3$), 1.20–1.40 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.49 (2H, t, J=7.0 Hz, C**H**$_2$), 1.68–1.74 (3**H**, m, O**H** and C**H**$_2$), 2.22–2.27 (2H, m, C**H**$_2$), 3.34 (2H, t, J=7.0 Hz, OC**H**$_2$), 3.41 (2H, t, J=6.0 Hz, OC**H**$_2$), 4.18 (2H, s, C**H**$_2$OH); δ_C ($CDCl_3$) 14.5, 15.6, 23.0, 26.2, 29.1, 30.1, 32.1, 51.8, 69.6, 71.5, 78.0, 86.2; *m/z* (EI) 198 $(M)^+$.

Preparation of 5-hexyloxy-1-pentyne 32. Sodium hydride (524 mg, 13.1 mmol) was added to a solution of the *pent-4-ynol* (1.00 g, 11.9 mmol) in dry THF (20 mL) at 0°C. The mixture was stirred for thirty minutes. *t*-Butylammonium bromide (190 mg, 0.59 mmol) and 1-bromohexane (1.84 mL, 13.1 mmol) was then added and the reaction mixture heated at reflux for two hours. The mixture was allowed to cool to room temperature and water was added (50 mL). The mixture was extracted with diethyl ether (3×100 mL) and the combined organic extracts dried with magnesium sulfate. The mixture was then filtered and the solvent removed in vacuo. The crude product was purified using flash column chromatography (10:1 petrol/ether) to give the *ether* **32** as a colourless oil (1.76 g, 88%). ν_{max} 3313, 933, 2859, 1467, 1376, 1116, 630 cm^{-1}; δ_H ($CDCl_3$) 0.73–0.79 (3H, m, C**H**$_3$), 1.12–1.26 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.44 (2H, t, J=7.0 Hz, CCC**H**$_2$), 1.66–1.78 (2H, m, C**H**$_2$), 1.82 (1H, t, J=3.0 Hz, CC**H**), 2.14–2.19 (2H, m, C**H**$_2$), 3.28 (2H, t, J=7.0 Hz, OC**H**$_2$), 3.37 (2H, t,

J=6.0 Hz, OC**H**$_2$); δ_C ($CDCl_3$) 14.1, 15.3, 22.7, 25.9, 28.7, 29.8, 31.8, 68.4, 69.1, 71.2, 84.2; HRMS calculated for $C_{11}H_{19}O$, 167.436, found 167.442 $(M-H)^+$.

Preparation of 5-hexyloxy-2-methylpent-3-yn-2-ol 33. *n*-Butyllithium (2.9 mL of a 2.5 M solution in hexanes, 7.25 mmol) was added dropwise to a solution of the *alkyne* **28** (1.0 g, 7.14 mmol) in dry THF (10 mL) at 0°C. The reaction mixture was stirred for 30 min, cooled to −78°C and acetone (1.24 g, 21.4 mmol) was added. Stirring was continued for two hours, the reaction allowed to warm to room temperature and saturated aqueous ammonium chloride solution (10 mL) was added. The mixture was extracted with diethyl ether (3×30 mL) and the extracts were combined and dried with magnesium sulfate. The solvent was removed in vacuo and the crude product purified by flash column chromatography (5:1 petrol/diethyl ether) to give the *alcohol* **33** as a colourless oil (295 mg, 21%). ν_{max} 3385, 2931, 2859, 1464, 1360, 1234, 1168, 1103, 950 cm^{-1}; δ_H ($CDCl_3$) 0.68 (3H, t, J=7.0 Hz, C**H**$_3$), 1.13–1.24 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.32 (6H, s, C(C**H**$_3$)$_2$OH), 1.36–1.38 (2H, m, C**H**$_2$), 1.78 (1H, s, (CH$_3$)$_2$O**H**), 3.27 (2H, t, J=7.0 Hz, OC**H**$_2$), 3.93 (2H, s, C**H**$_2$O); δ_C ($CDCl_3$) 12.0, 12.0, 20.5, 23.7, 27.1, 27.4, 29.3, 29.6, 63.1, 68.2, 76.2, 88.6; HRMS calculated for $C_{12}H_{21}O_2$, 197.1542 found 197.1537 $(M-H)^+$.

Preparation of 5-hexyloxy-pent-3-yn-2-ol 34. *n*-Butyllithium (1.57 mL of a 2.5 M solution in hexanes, 3.93 mmol) was added dropwise to a solution of *alkyne* **28** (500 mg, 3.57 mmol) in dry THF (10 mL) at 0°C. The mixture was stirred for twenty minutes and then cooled to −78°C. Acetaldehyde (471 mg, 10.71 mmol) was added and the reaction mixture stirred for thirty minutes. The mixture was allowed to warm slowly to room temperature, stirred for one hour and saturated aqueous ammonium chloride solution (20 mL) was added. The mixture was extracted with diethyl ether (3×30 mL) and the extracts combined and dried over magnesium sulfate. The mixture was filtered and the solvent removed in vacuo. The crude material was purified using flash column chromatography (5:1 petrol/diethyl ether) to give the *alcohol* **34** as a colourless oil (300 mg, 46%). ν_{max} 3370, 2931, 2860, 1456, 1358, 1330, 1149, 1102, 996 cm^{-1}; δ_H ($CDCl_3$) 0.71 (3H, t, J=7.0 Hz, C**H**$_3$), 1.08–1.19 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.28 (3H, d, J=7.0 Hz, C**H**$_3$), 1.36–1.43 (2H, m, C**H**$_2$), 1.72 (1H, s, O**H**), 3.30 (2H, t, J=7.0 Hz, OC**H**$_2$), 3.97, (2H, s, C**H**$_2$O), 4.36–4.41 (1H, m, C**H**(OH)); δ_C (75 MHz, $CDCl_3$) 14.5, 23.0, 24.6, 26.2, 29.9, 32.1, 58.8, 63.6, 70.8, 80.7, 88.3; *m/z* (EI) 184 $(M)^+$.

Preparation of 4-hexyloxybut-2-ynal 35. Pyridinium chlorochromate (1.90 g, 8.82 mmol) was added to a solution of *alcohol* **27** (500 mg, 2.94 mmol) in dichloromethane (20 mL) at room temperature. The mixture was stirred for three hours prior to addition of diethyl ether (20 mL); and then stirring was continued for a further five minutes. The solvent was decanted and a further portion of diethyl ether (20 mL) was added to the residue and stirring was continued for twenty minutes. The solvent was decanted again and this procedure repeated until the residue became a dark, granular solid. The combined ether layers were removed in vacuo and the crude mixture purified using flash column chromatography (5:1 petrol/diethyl ether) to give the *aldehyde* **35** as a colourless liquid (244 mg, 51%). ν_{max} 3441, 2932, 2859, 1675, 1634, 1436, 1256, 1113 cm^{-1}; δ_H ($CDCl_3$) 0.68 (3H, t, J=6.0 Hz, C**H**$_3$), 1.10–1.18 (6H, m, C**H**$_2$C**H**$_2$C**H**$_2$), 1.35–1.42 (2H, m, C**H**$_2$), 3.32 (2H, t, J=7.0 Hz, OC**H**$_2$), 4.13 (2H, s, C**H**$_2$), 9.04 (1H, s, C**H**O); δ_C ($CDCl_3$) 14.4, 23.0, 3.1, 29.8, 32.0, 58.4, 71.1, 85.7, 93.1, 176.8; HRMS calculated for $C_{10}H_{16}O_2$, 168.1150, found 168.1145 $(M)^+$.

Preparation of *tert*-butyldimethyl-(1-phenylhex-5-enyloxy)-silane 37. *t*-Butyldimethylsilyl chloride (103 mg, 0.68 mmol) was added to the *alcohol* **36** (100 mg, 0.57 mmol), imidazole (103 mg, 1.4 mmol) and DMF (2 mL). The mixture was stirred for four hours at room temperature and then water (10 mL) was added. The mixture was extracted with diethyl ether (3×10 mL) and the solvent removed in vacuo. The crude mixture was purified using flash column chromatography (10:1 petrol/diethyl ether) to give the *silyl ether* **37** as a colourless oil (145 mg, 88%). ν_{max} 2929, 2857, 1472, 1256, 1090, 836, 776, 699 cm^{-1}; δ_H ($CDCl_3$) −0.17 (3H, s, Si(C**H**$_3$)$_2$), 0.00 (3H, s, Si(C**H**$_3$)$_2$), 0.86 (9H, s, SiC(C**H**$_3$)$_3$), 1.27–1.71 (4H, m, C**H**$_2$C**H**$_2$), 2.03 (2H, m, C=CC**H**$_2$), 4.62 (1H, t, J=7.0 Hz, C**H**(O–Si)), 4.89–4.98 (2H, m, C**H**=C**H**$_2$), 5.69–5.80 (1H, m, CH=C**H**$_2$), 7.17–7.28 (5H, m, Ar–**H**); δ_C ($CDCl_3$) 17.9, 24.6, 25.4, 25.5, 33.3, 40.1, 74.6, 114.1, 125.5, 126.4, 127.6, 138.5, 145.5; HRMS calculated for $C_{17}H_{27}OSi$, 275.1831, found 275.1832 $(M-Me)^+$.

Potassium ferrate[2]

Sodium hydroxide (180 g, 4.5 mol) was added to sodium hypochlorite solution (600 mL supplied by BDH-12 % available chlorine, 1.0 mol). The mixture was allowed to cool to 25°C and the precipitated salt filtered and discarded. Ferric nitrate nonahydrate (40 g, 0.1 mol) was added slowly to the filtrate (over thirty minutes) with vigorous stirring and the mixture allowed to stir at room temperature for two hours. Sodium hydroxide (100 g, 2.5 mol) was added slowly, maintaining the temperature below 30°C. The mixture was then filtered using a large, coarse glass filter (grade 1) and the filtrate of sodium ferrate was collected as a deep purple solution in concentrated sodium hydroxide solution. Saturated potassium hydroxide (100 mL) was added to the ferrate solution and the mixture allowed to stand for ten minutes. The mixture was then filtered using a large coarse glass filter (grade 1) and the crude solid potassium ferrate collected. The solid was leeched on the filter using 3 M potassium hydroxide solution (5×20 mL). The 3 M potassium hydroxide portions were used to dissolve the ferrate, and the filtrate was allowed to pass through the crude solid into saturated potassium hydroxide solution (50 mL). The solid remaining on the frit was discarded. The resulting reprecipitated potassium ferrate was then collected using a medium frit (grade 3) and the solid further purified by another leeching/reprecipitation stage using 3 M potassium hydroxide solution (5×5 mL). The solid was collected and washed with dry benzene (3×20 mL), dry methanol (3×20 mL), and dry diethyl ether (3×20 mL) and stored in a vacuum dessicator overnight. The potassium ferrate was obtained as a dark purple crystalline solid (6.4 g, 30%). The potassium ferrate produced comparable IR spectra with those published in

the literature and chromite analysis[27] showed the product to be 94% pure.

Oxidation using potassium ferrate. *General Procedure A: Oxidation under aqueous conditions:* Potassium ferrate (198 mg, 1.0 mmol) was added to a mixture of *substrate* (1.0 mmol) and aqueous sodium hydroxide solution (10 mL, pH 10.0) at room temperature. The mixture was shaken until the reaction was complete as indicated by the colour change from purple to brown (indicating the formation of iron(III) from iron(VI)) and a pH of 13.5 was recorded on completion. The reaction mixture was acidified with 1N HCl (5 mL) and extracted with diethyl ether (3×30 mL). The solvent was removed in vacuo to give the crude product which was then purified using flash column chromatography or distillation to give the *product*.

General Procedure B: Oxidation of alcohols using potassium ferrate and wet alumina: Potassium ferrate (1 equiv.) was added to a mixture of *substrate* (1 equiv.) and wet alumina (500 mg/mmol) in pentane (5 mL/mmol) at room temperature and the mixture was stirred vigorously until the reaction was complete. The reaction mixture was filtered through a glass frit and the residue washed with ether (3×20 mL). The solvent was removed in vacuo and the crude product was then purified.

All products were purified using flash column chromatography (FCC), distillation, recrystallisation or were sufficiently pure in their crude form to enable structure characterisation. Where appropriate product structures were confirmed by comparison of their IR, ^{1}H NMR, ^{13}C NMR spectroscopy and mass spectra with authentic commercial samples or literature data. The following compounds were obtained by oxidation using these general procedures (substrate, procedure, scale, reaction time, purification, yield).

Benzaldehyde **2**; (**1**, A, 1 mmol, 10 min., FCC, 47%). *Benzaldehyde* **2**; (**1**, B, 0.5 mmol, 2 h., crude, 93%). *Cinnamaldehyde;* (**3**, B, 0.5 mmol, 6 h., FCC, 77%). *Acetophenone* **6**; (**5**, B, 0.5 mmol, 48 h., FCC, 12%). *Acetophenone* **6**; (**5**, A, 1 mmol, 10 min., FCC, 74%). *Benzophenone;* (**4**, A, 1 mmol, 15 min., FCC, 5%). *1-Methyl-indole-2 carbaldehyde* **15**;[21] (**13**, B, 0.5 mmol, 48 h., FCC, 30%). *Benzothiophen-2-carbaldehyde* **16**; (**14**, B, 1 mmol, 24 h., FCC, 34%). *Diphenyl disulfide* **11**; (**9**, B, 1 mmol, 0.5 h., crude, 79%). *Dibenzyl disulfide* **12**; (**10**, B, 1 mmol, 0.5 h., crude, 82%). *1-Furan-2-yl-ethanone* **18**; (**17**, B, 1 mmol, 1 h, FCC, 61%). *Furan-2-carbaldehyde* **20**; (**19**, B/CH_2Cl_2, 1 mmol, 2 h., FCC, 34%). *1-Phenyl-hex-5-en-1-one* **38**. (**41**, B, 1 mmol, 15 min., FCC, 22%). *2-Prop-2-ynyloxytetrahydropyran* **22**; (**21**, B, 1.2 mmol, 2 min., FCC, 50%). *3-Hexyloxypropyne* **28**; (**27**, 1 mmol/2 ferrate, 24 h., FCC, 98%). *4-Hexyloxybutyne* **30**; (**29**, 0.3 mmol/2 ferrate, 48 h., FCC, 25%). *5-Hexyloxy-pent-1-yne* **32**; (**31**, 0.3 mmol/2 ferrate, 48 h., FCC, 36%).

Oxidation of a mixture of benzyl alcohol 1 and 1-phenylethanol 5. *sec*-Phenethyl alcohol (61 mg, 0.5 mmol) and benzyl alcohol (54 mg, 0.5 mmol) were added via syringe to a mixture of potassium ferrate (99 mg. 0.5 mmol) and wet alumina in pentane (5 mL) under nitrogen at room temperature with stirring. After 48 h the reaction mixture was filtered and washed with diethyl ether (2×5 mL). The solvent was removed in vacuo and the product purified by column chromatography (5:1 petrol/diethyl ether). The *aldehyde* and *ketone* were obtained as a mixture (47 mg, 88%) and (4 mg, 6%) as estimated by ^{1}H NMR spectroscopy and *sec*-phenethyl alcohol was also recovered (51 mg, 84%).

Acknowledgements

We gratefully acknowledge funding from the EPSRC and Rhone Poulenc Rorer. We are also grateful to AstraZeneca, GlaxoWellcome, SmithKline Beecham and Novartis for support of our programme. We acknowledge the EPSRC Mass Spectrometry Service at Swansea and Dr Abdul Sada and Avent for assistance and Dr J. R. Hanson for valuable discussions.

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