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Decarboxylative elimination of enol triflates as a general synthesis of acetylenes †

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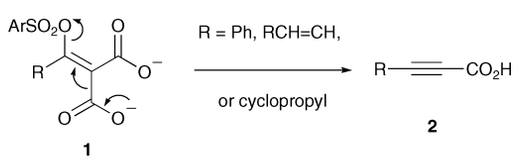
The enol trifluoromethanesulfonates **4**, **8**, **12**, **17** and **20** of *tert*-butyl β-ketodiesters and β-ketoesters can be hydrolysed to the corresponding carboxylic acids by dissolution in trifluoroacetic acid. The dicarboxylic acids undergo mild decarboxylative elimination to give the acetylenic acids **4** and **9** in aqueous sodium bicarbonate solution at room temperature. Similarly, the monocarboxylic acids give the terminal and mid-chain acetylenes **13**, **18**, **21** and **24** by refluxing in acetone with potassium carbonate. One of the substituents on the acetylenes can be methyl, primary alkyl, secondary alkyl or ethynyl, and the other can be a carboxylic acid, hydrogen or primary alkyl, but the enol trifluoromethanesulfonates could not be prepared when one of the substituents was *tert*-butyl, nor when both substituents on the precursor to the acetylene were secondary alkyl.

Introduction

We established long ago in a series of papers[1,2] that enol arenesulfonates **1** derived from acylmalonates underwent concerted decarboxylative elimination in water at room temperature to give acetylenic acids **2**, *provided that the group* R *was cation-stabilising* (Scheme 1). As a measure of how cation-stabilising



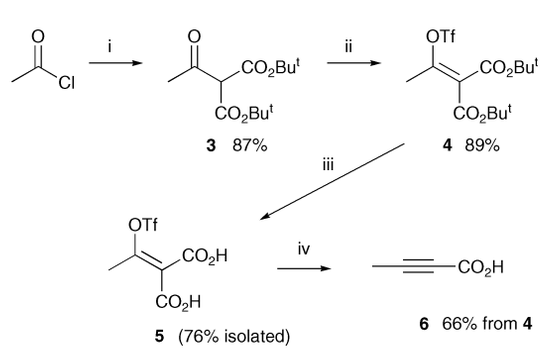
Scheme 1

the group R needed to be, we found that the ρ value from changing the substituents on a phenyl group R, was −3.12.[2] This value showed that a substantial positive charge was developing at the carbon atom carrying the nucleofugal group, but not a full positive charge. In more detail, when the substituent was a *para*-nitro group, the rate of decarboxylative elimination was so slow that hydrolysis of the enol sulfonate took place, giving *p*-nitroacetophenone, at a comparable rate. Thus the reaction only worked if the group R was aryl, as long it was not inappropriately substituted, and it also worked if the group R was vinyl or cyclopropyl. The reaction did not work if R was alkyl or ethynyl, a severe limitation which deterred us at the time from investigating the synthetic potential of this reaction any further. In the meantime, better sulfonate leaving groups have been developed,[3] and so we returned to this remarkably mild reaction, and reported in a preliminary communication[4] that it could be made into a more general synthesis of acetylenes using enol trifluoromethanesulfonates (triflates) in place of enol arenesulfonates. We now report our results in full.

As indications of how much better a triflate might be, we knew that 1-adamantyl triflate undergoes S_N1 solvolysis 10^5 to 10^6 times faster than the corresponding toluene-*p*-sulfonate (tosylate),[5] and ethyl triflate undergoes S_N2 solvolysis in acetic acid 10^4 faster than ethyl tosylate.[6] Furthermore, the ρ value for the decarboxylative elimination **1** ⟶ **2** with a range of *p*-substituted benzenesulfonates was 1.16,[2] which indicated that the elimination was sensitive to how good the leaving group was, but, as expected, less sensitive than an S_N1 reaction, for which a ρ value of 1.76 has been measured for the ionisation of 1-adamantyl arenesulfonates.[7] Putting these facts together implied that enol triflates would undergo decarboxylative elimination significantly faster than enol arenesulfonates, and quite possibly fast enough to work for those cases that had failed before.

Results and discussion

We optimised the sequence in Scheme 2, fully characterising all the intermediates. We used the Rathke procedure for making the acetylmalonate **3**,[8] one of the standard methods using triflic anhydride with triethylamine for making the enol triflate **4**,[9] and dissolution in trifluoroacetic acid to cleave the *tert*-butyl esters to give the dicarboxylic acid **5**. When we dissolved this acid in aqueous sodium bicarbonate solution, and kept the solution overnight, it cleanly gave tetrolic acid **6**, showing that the biggest limitation in our earlier work had been overcome. The dicarboxylic acid **5** was a sensitive compound, and it proved to be easier not to isolate it. Dissolving the enol triflate **4** in trifluoroacetic acid, evaporating the solution after thirty minutes, and dissolving the residue in sodium bicarbonate solution gave tetrolic acid **6** in 66% overall yield, with the decarboxylative elimination complete within four hours.



Scheme 2 *Reagents*: i, $CH_2(CO_2Bu^t)_2$, Et_3N, $MgCl_2$, MeCN, rt 12 h; ii, Tf_2O, Et_3N, CH_2Cl_2, 0 °C, 1 h; iii, TFA, rt, 30 min; iv, $NaHCO_3$, H_2O, rt, 4 h.

A similar sequence (Scheme 3) with other alkyl groups, and minor variations in the details, such as using sodium hydride as the base in the formation of the enol triflates,[10] gave the corresponding acetylenic acids **9**, including one diacetylenic acid **9c**. We now have success with R as a methyl group, a primary alkyl

† We dedicate this paper to the memory of Dr John Harley-Mason, 1920–2003.

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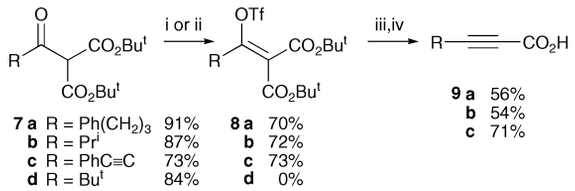
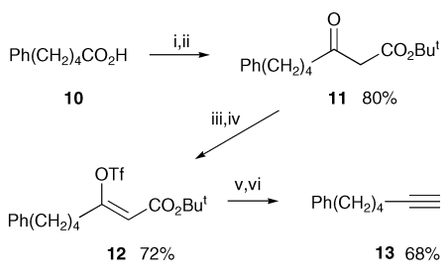


Scheme 3 *Reagents*: i, Tf_2O, Et_3N, CH_2Cl_2, 0 °C ⟶ rt, 3 h; ii, NaH, Et_2O, 0 °C, 1 h, then Tf_2O, 0 °C, then rt, 1 h; iii, TFA, rt, 30 min; iv, $NaHCO_3$, H_2O, rt, 12 h.

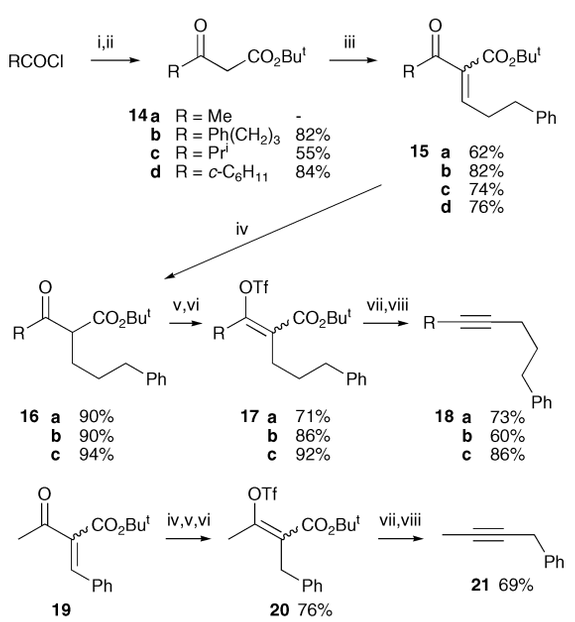
group and a secondary alkyl group, but we were unable to prepare the enol triflate **8d** with a tertiary alkyl group.

With a more general reaction now at our disposal, we investigated whether the second carboxylic acid group was necessary. It had always been possible that the second carboxylate ion, present in all our earlier reactions, had accelerated the decarboxylative elimination by a Coulombic repulsion. We prepared the enol triflate **12** (Scheme 4). On treatment successively with trifluoroacetic acid and base this gave the terminal acetylene **13**, showing that the second carboxyl group was unnecessary. In this case, potassium carbonate in refluxing acetone proved to be better for the decarboxylative elimination step than aqueous sodium bicarbonate solution.



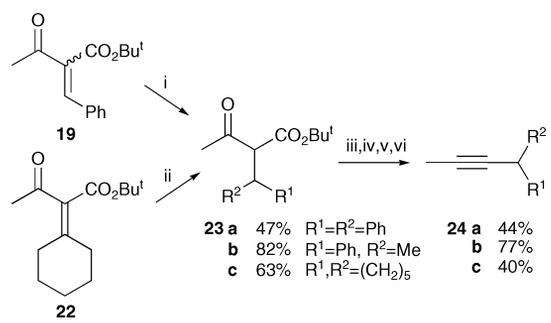
Scheme 4 *Reagents*: i, CDI, THF, rt 1 h; ii, $LiCH_2CO_2Bu^t$, THF, −78 °C, 1 h; iii, NaH, Et_2O, 0 °C, 1 h; iv, Tf_2O, 0 °C, 1 h, rt, 1 h; v, TFA, rt, 30 min; vi, K_2CO_3, Me_2CO, reflux, 4 h.

We also prepared a small range of acetylenes **18a**–**c** and **21** with linear alkyl groups derived from an aldehyde using Knoevenagel condensation and hydrogenation (Scheme 5). We prepared the unsaturated ketoesters **15** using Lehnard's conditions, and the known unsaturated ketoester **19** by piperidine-catalysed condensation between *tert*-butyl acetoacetate and benzaldehyde. Hydrogenation of **15a**–**c** and **19** gave the alkylated β-ketoesters, and the decarboxylative elimination of the enol triflates **17** and **20** using potassium carbonate in acetone as the base gave the acetylenes **18** and **21**. Some of the enol triflates appeared to be pairs of stereoisomers in varying proportions from run to run, but we were unable to separate them, in order to investigate the stereochemistry of the elimination.

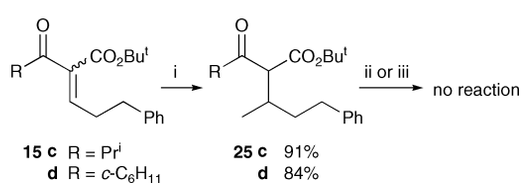


Scheme 5 *Reagents*: i, Meldrum's acid, Py, CH_2Cl_2, rt, 1 h; ii, Bu^tOH, toluene, reflux, 3 h; iii, $Ph(CH_2)_2CHO$, $TiCl_4$, Py, THF, rt, 16 h; iv, H_2, Pd/C, MeOH, rt, 12 h; v, NaH, Et_2O, 0 °C, 1 h; vi, Tf_2O, 0 °C 1 h, rt, 1 h; vii, TFA, rt, 30 min; viii, K_2CO_3, Me_2CO, reflux, 4–5 h.

Finally we prepared a small range of acetylenes **24** with a branched chain derived either by conjugate addition to the Knoevenagel product **19** or by hydrogenation of the Knoevenagel product **22** (Scheme 6). In contrast, we were unable to prepare an enol triflate with branched alkyl groups on *both* sides of the intended triple bond—neither of the β-ketoesters **25** (Scheme 7) gave an enol triflate, even though we were successful with examples having branched chains separately on each side in Schemes 5 and 6.

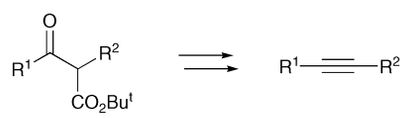


Scheme 6 *Reagents*: i, Ph_2CuLi or Me_2CuLi, THF, −78 °C, 1 h; ii, H_2, Pd/C, MeOH, rt, 16 h; iii, NaH, Et_2O, 0 °C, 1 h; iv, Tf_2O, 0 °C 1 h, rt, 1 h; v, TFA, rt, 30 min; vi, K_2CO_3, Me_2CO, reflux, 4–5 h.



Scheme 7 *Reagents*: i, Me_2CuLi, THF, −78 °C, 1 h; ii, NaH, Et_2O, 0 °C, 1 h followed by Tf_2O; iii, Ph_2NTf.

Except for these limitations, we now have a fairly general synthesis of acetylenes based on a β-ketoester system (Scheme 8), with a wide variety of methods for incorporating or attaching the groups R^1 and R^2 on each side of the ketone group,[11] some of which are illustrated by the standard but far from optimised methods we used in Schemes 3–7. The overall transformation is similar to that achieved by earlier routes from β-keto acid derivatives by way of heterocyclic intermediates,[12] and especially by Zard's intriguing reaction,[13] in which β-ketoesters are treated successively with hydroxylamine and with sodium nitrite and iron(II) sulfate, but the pathway described here is mechanistically more straightforward, and probably less apt to give byproducts. In particular, as he has pointed out, our method works for the synthesis of terminal acetylenes, which his does not. It also bears some resemblance to a fragmentation reaction of an enol triflate studied by Kuwajima, in which the electrofugal group is a tertiary carbocation stabilised by a β-trimethylsilyl group.[14] Both our reaction, with an electrofugal carbon dioxide, and his are completely regioselective in favour of the formation of acetylenes, whereas base-induced elimination of enol triflates derived from ketones can give allenes as well.[15] The success of our reaction



Scheme 8

also suggests that the enol triflates of cyclic β-diketones might undergo fragmentation on treatment with hydroxide or alkoxide ions, analogous to the Eschenmoser fragmentation,[16] provided that conjugate addition leading to hydrolysis can be suppressed.

Experimental

General

Infrared spectra were recorded on a Perkin-Elmer 297 or FT-IR 1620 spectrophotometer and wave numbers measured relative to polystyrene (1603 cm^{-1}), using sodium chloride plates or sodium chloride solution cells (0.1 mm path length). ^{1}H- and ^{13}C-NMR spectra were recorded on Bruker NMR spectrometers (DRX 500, AM 400, DPX 250, AC 250, AC 200). Chemical shifts were measured relative to tetramethylsilane (δ 0.00) or chloroform (δ 7.25) as internal standards. The coupling constants J are expressed in Hertz. In ^{13}C attached proton test (APT) spectra, + denotes a signal in the same direction as the solvent signal. Mass spectra were recorded on AE1 MS 89, Kratos MS 50 or HP 5988A spectrometers and carried out by technical staff. Flash column chromatography was carried out using Merck Kieselgel 60 (230–400 mesh ASTM). Thin layer chromatography (TLC) was performed on glass plates coated to a thickness of 1 mm with Kieselgel 60 PF_{254}. Melting points were determined using a Gallenkamp melting point apparatus and stand uncorrected. Tetrahydrofuran (THF) and ether were freshly distilled from lithium aluminium hydride under argon. Dichloromethane, carbon tetrachloride, acetonitrile, methanol, light petroleum, hexane, and toluene were freshly distilled from calcium hydride under argon. Light petroleum refers to the fraction boiling in the region 40–60 °C. Other solvents and reagents where appropriate were purified before use.

Di-*tert*-butyl acetylmalonate 3

Following Rathke and Cowan,[8] triethylamine (1.96 g, 19.4 mmol) was added to di-*tert*-butyl malonate (2.00 g, 9.3 mmol) and magnesium chloride (0.95 g, 10 mmol) in dry acetonitrile (15 cm^3) under argon, and the mixture was stirred for 15 min at 0 °C. Acetyl chloride (0.81 g, 10 mmol) was added dropwise, the mixture was stirred at 0 °C for 1 h, and at room temperature for 12 h. The mixture was quenched with saturated aqueous ammonium chloride solution (20 cm^3), and the aqueous layer was extracted with ether (3 × 20 cm^3). The combined organic fractions were washed with brine (40 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–hexane, 2 : 98) to give the *acylmalonate* (2.05 g, 87%); R_f(EtOAc–light petroleum, 1 : 9) 0.6; ν_{max}(film)/cm^{-1} 3300–2500 br (OH), 1720 (C=O) and 1625 (C=C of enol); δ_H(250 MHz; $CDCl_3$) 2.1 and 2.28 (3 H total, s, MeCO of keto and enol forms) and 1.48 (18 H, s, Bu^t) (Found: C, 60.72; H, 8.64. $C_{13}H_{22}O_5$ requires C, 60.45; H. 8.58%).

The other acylmalonates

Typically, following Breslow, Baumgarten and Hauser,[17] di-*tert*-butyl malonate (9.3 mmol) was added slowly to a stirred mixture of magnesium ethoxide (11 mmol) in dry ether (15 cm^3) and refluxed for 20 min. The acid chloride (11 mmol) was added dropwise to the mixture, and refluxing continued for 20 min. The mixture was cooled and quenched with saturated aqueous ammonium chloride solution (15 cm^3). The mixture was extracted with ether (3 × 20 cm^3) The combined organic fractions were washed with brine (30 cm^3), dried ($MgSO_4$), and concentrated under reduced pressure. Chromatography (SiO_2, EtOAc–hexane, 2 : 98) gave the acylmalonate.

The following acylmalonates were prepared by this method.

Di-*tert*-butyl 5-phenylvalerylmalonate 7a (91%). R_f(EtOAc–light petroleum, 1 : 9) 0.64; ν_{max}(film)/cm^{-1} 1724 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.66 (2 H, t, J 7.3, PhCH_2), 2.40 (2 H, t, J 7.4, CH_2CH$_2$CH$_2$Ph), 1.96 (2 H, m, CH$_2$CH_2CH$_2$), 1.50 (9 H, s, Bu^t) and 1.46 (9 H, s, Bu^t); *m*/*z* (EI) 306 (11%, M − C_4H_8), 250.1 [78, M − (C_4H_8)$_2$] and 57 (80, C_4H_9) (Found: M^+ − C_4H_8, 306.1466. $C_{21}H_{30}O_5$ requires M − C_4H_8, 306.1467).

Di-*tert*-butyl isobutyrylmalonate 7b (87%). R_f(EtOAc–light petroleum, 1 : 9) 0.6; ν_{max}(film)/cm^{-1} 1725 (C=O); δ_H(250 MHz; $CDCl_3$) 2.80 (1 H, m, Me$_2$CH), 1.48 (18 H, s, Bu^t) and 1.14 (6 H, m, Me_2CH); *m*/*z* (EI) 230 (40%, M − C_4H_8), 174 [72, M − (C_4H_8)$_2$] and 57 (100, C_4H_9) (Found: M^+ − C_4H_8, 230.1156. $C_{15}H_6O_5$ requires M − C_4H_8, 230.1154).

Di-*tert*-butyl phenylpropioloylmalonate 7c (89%). R_f(EtOAc–light petroleum, 1 : 9) 0.65; ν_{max}(film)/cm^{-1} 2208 (C≡C) and 1730 (C=O); δ_H(250 MHz; $CDCl_3$) 7.60–7.30 (5 H, m, Ph) and 1.58 (18 H, s, Bu^t); *m*/*z* (EI) 288 (50%, M − C_4H_8), 232 [30, M − (C_4H_8)$_2$] and 57 (100, C_4H_9) (Found: M^+ − C_4H_8, 288.0997. $C_{20}H_{24}O_5$ requires M − C_4H_8, 288.0998).

Di-*tert*-butyl pivaloylmalonate 7d (84%). R_f(EtOAc–light petroleum, 1 : 9) 0.67; ν_{max}(film)/cm^{-1} 1734 (C=O); δ_H(250 MHz; $CDCl_3$) 1.46 (18 H, s, Bu^t) and 1.10 (9 H, s, Me). *m*/*z* (EI) 301 (20%, M + H) and 57 (100, C_4H_9) (Found: M^+ + H, 301.2012. $C_{16}H_{28}O_5$ requires M + H, 301.2014).

tert-Butyl 3-oxo-7-phenylheptanoate 11

tert-Butyl acetate (2.14 g, 18.4 mmol) was added to lithium *N*,*N*-diisopropylamide (LDA) (18.4 mmol) in THF (15 cm^3) under argon at −78 °C and the mixture kept for 1 h. Carbonyl diimidazole (CDI) (1.6 g, 10 mmol) and 5-phenylvaleric acid (1.5 g, 8.4 mmol) were stirred in THF (15 cm^3) under argon for 1 h at room temperature, and then transferred by cannula to the solution of *tert*-butyl lithioacetate at −78 °C over 10 min. The mixture was stirred for 1 h and quenched with saturated aqueous ammonium chloride solution. The aqueous layer was extracted with ether (2 × 30 cm^3). The combined organic layers were washed with hydrochloric acid solution (3 mol dm^{-3}, 30 cm^3), brine (30 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–light petroleum, 4 : 96) to give the *ester* as an oil (1.85 g, 80%); R_f(EtOAc–light petroleum, 2 : 8) 0.73; ν_{max}(film)/cm^{-1} 1736 (C=O), 1714 (C=O) and 1642 (Ph); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 3.32 (2 H, s, COCH_2CO), 2.62 (2 H, t, J 7.4, PhCH_2), 2.55 (2 H, t, J 7.3, CH$_2$CH_2CO), 1.71–1.60 [4 H, m, PhCH$_2$(CH_2)$_2$] and 1.48 (9 H, s, Bu^t); *m*/*z* (EI) 277 (38%, M + H), 202 (100, M − Bu^{t}OH) and 161 [20, Ph(CH$_2$)$_4$CO] (Found: M^+ + H, 277.1811. $C_{17}H_{24}O_3$ requires M − H, 277.1803).

The β-keto esters 14

Following Oikawa *et al.*,[18] pyridine (207 mmol) was added to a stirred solution of Meldrum's acid[19] (69.4 mmol) in dry dichloromethane (50 cm^3) at 0 °C. The acid chloride (90.0 mmol) was added dropwise, and the mixture was stirred at 0 °C for 1 h and at room temperature for 1 h. The mixture was quenched with saturated aqueous ammonium chloride solution (50 cm^3). The mixture was extracted with dichloromethane (3 × 50 cm^3). The combined organic fractions were washed with aqueous hydrochloric acid (3 mol dm^{-3}, 3 × 50 cm^3) and brine (50 cm^3), dried ($MgSO_4$), and concentrated under reduced pressure. The residue, which was refluxed in a mixture of toluene (50 cm^3) and *tert*-butanol (207 mmol) for 3 h. The mixture was poured into water (50 cm^3), and extracted with ether (2 × 50 cm^3). The combined organic fractions were washed with brine (50 cm^3), dried ($MgSO_4$), and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–light petroleum, 4 : 96) to give the esters.

The following esters were prepared by this method.

***tert*-Butyl 3-oxo-6-phenylhexanoate 14b (82%).** R_f(EtOAc–light petroleum, 2 : 8) 0.70; ν_{max}(film)/cm^{-1} 1738 and 1715 (C=C); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 3.31 (2 H, s, COCH_2CO), 2.63 (2 H, t, *J* 7.4, PhCH_2), 2.53 (2 H, t, *J* 7.3, CH_2CH_2CO) and 1.93 (2 H, qn, *J* 7.3, $CH_2CH_2CH_2$); *m*/*z* (EI) 262 (5%, M$^+$), 206 (50, M − C_4H_8), 188 [45, M − (C_4H_8 + H_2O)], 91 (80, $PhCH_2$) and 57 (100, C_4H_9) (Found: M$^+$, 262.1561. $C_{16}H_{22}O_3$ requires *M,* 262.1568).

***tert*-Butyl 4-methyl-3-oxo-pentanoate 14c[20] (55%).** R_f(EtOAc–light petroleum, 2 : 8) 0.61; ν_{max}(film)/cm^{-1} 1720 and 1713 (C=C); δ_H(250 MHz; $CDCl_3$) 3.38 (2 H, s, COCH_2CO), 2.70 (1 H, septet, *J* 7.0, Me_2CH), 1.44 (9 H, s, Bu^t), 1.12 (3 H, d, *J* 7.0, CHMe_AMe$_B$) and 1.11 (3 H, d, *J* 7.0, CHMe$_A$$Me_B$).

***tert*-Butyl 3-cyclohexyl-3-oxo-propionate 14d[21] (84%).** R_f(EtOAc–light petroleum, 2 : 8) 0.75; ν_{max}(film)/cm^{-1} 1738 and 1709 (C=C); δ_H(250 MHz; $CDCl_3$) 3.36 (2 H, s, COCH_2CO), 1.88–1.75 (6 H, m, cyclohexyl), 1.44 (9 H, s, Bu^t) and 1.36–1.23 (5 H, m, cyclohexyl); *m*/*z* (EI) 226 (20%, M$^+$), 170 (50, M − C_4H_8) and 54 (100, C_4H_9) (Found: M$^+$, 226.1568. $C_{13}H_{22}O_3$ requires *M*, 226.1569).

(*E* and *Z*)-*tert*-Butyl 2-benzylidene-3-oxobutanoate[22]

tert-Butyl acetoacetate (5 g, 31.6 mmol), benzaldehyde (3.35 g, 31.6 mmol), piperidine (1 cm^3) and ethanol (1 cm^3) were kept at 5 °C for 24 h. Ether (50 cm^3) was added. The organic layer was washed with aqueous hydrochloric acid solution (3 mol dm^{-3}, 50 cm^3), brine (50 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–light petroleum 4 : 96) to give the ester (3.81 g, 50%, 2 : 1 mixture of geometrical isomers) as needles, mp 84–85 °C (from EtOAc) (lit.,[22] 84–85 °C); R_f(EtOAc–light petroleum, 2 : 8) 0.74 (one isomer) and 0.58 (other isomer); ν_{max}(Nujol)/cm^{-1} 1723, 1655 (C=O) and 1575 (Ph); δ_H(250 MHz; $CDCl_3$) 7.50–7.30 (5 H, m, Ph, both isomers), 7.26 (1 H, s, PhC*H*, both isomers), 2.41 (3 H, s, *Me*CO, one isomer), 2.19 (3 H, s, *Me*CO, other isomer), 1.52 (9 H, s, Bu^t, one isomer) and 1.12 (9 H, s, Bu^t, other isomer).

The other unsaturated β-ketoesters

Typically, following Lehnert,[23] the ester (18.8 mmol) and aldehyde (18.8 mmol) in THF (10 cm^3), followed by pyridine (75 mmol) in THF (10 cm^3), were added dropwise to titanium tetrachloride (1 mol dm^{-3} in CH_2Cl_2, 37.6 mmol) in dry THF (35 cm^3) under argon at 0 °C over 30 min, and the mixture stirred at room temperature for 16 h. The mixture was quenched with saturated aqueous ammonium chloride solution and extracted with ether (3 × 50 cm^3). The combined organic fractions were washed with aqueous hydrochloric acid (3 mol dm^{-3}, 2 × 50 cm^3) and brine (10 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–hexane, 4 : 96) to give the α-alkylidene esters as *ca*. 1.5 : 1 mixtures of geometrical isomers.

The following esters were prepared by this method.

(*E* and *Z*)-*tert*-Butyl 2-acetyl-5-phenylpent-2-enoate 15a (62%). R_f(EtOAc–light petroleum, 2 : 8) 0.51 (one isomer) and 0.43 (other isomer); ν_{max}(film)/cm^{-1} 1722 and 1697 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 6.83 (1 H, t, *J* 7.8, CH=C, one isomer), 6.76 (1 H, t, *J* 7.5, CH=C other isomer), 2.81 (2 H, t, *J* 8.0, PhCH_2, one isomer), 2.76 (2 H, t, *J* 7.8, PhCH_2, other isomer), 2.65 (2 H, q, *J* 7.8, $PhCH_2CH_2$, one isomer), 2.53 (2 H, q, *J* 7.6, $PhCH_2CH_2$, other isomer), 2.27 (3 H, s, MeCO, one isomer), 2.17 (3 H, s, MeCO, other isomer), 1.52 (9 H, s, Bu^t, one isomer) and 1.48 (9 H, s, Bu^t, other isomer); *m*/*z* (EI) 218 (60%, M − C_4H_8) and 91 (100, $PhCH_2$) (Found: M$^+$ − C_4H_8, 218.0942. $C_{17}H_{22}O_3$ requires *M* − C_4H_8, 218.0942).

(*E* and *Z*)-*tert*-Butyl 3-oxo-6-phenyl-2-(3-phenylpropylidene)-hexanoate 15b (82%). R_f (EtOAc–light petroleum, 2 : 8) 0.76 (one isomer) and 0.72 (other isomer); ν_{max}(film)/cm^{-1} 1720 br (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (10 H, m, Ph), 6.84 (1 H, t, *J* 7.8, C=CH, one isomer), 6.74 (1 H, t, *J* 7.7, C=CH, other isomer), 2.77 (2 H, m, C=CHCH_2, one isomer), 2.83 (2 H, m, C=CHCH_2, other isomer), 2.62 (2 H, t, *J* 7.8, PhCH_2, one isomer), 2.51–2.43 (4 H, m, PhCH_2 and CH_2CO, one isomer), 2.70–2.52 (6 H, m, PhCH_2 and CH_2CO, other isomer), 1.98 (2 H, quintet, $CH_2CH_2CH_2$, one isomer), 1.89 (2 H, quintet, *J* 7.4, $CH_2CH_2CH_2$, other isomer), 1.46 (9 H, s, Bu^t, one isomer) and 1.54 (9 H, s, Bu^t, other isomer); *m*/*z* (EI) 305 (15%, M − C_4H_9O) (Found: M$^+$ − C_4H_9O, 305.1541. $C_{25}H_{30}O_3$ requires *M* − C_4H_9O, 305.1541).

(*E* and *Z*)-*tert*-Butyl 2-isobutyryl-5-phenylpent-2-enoate 15c (74%). R_f (EtOAc–light petroleum, 1 : 5) 0.63 (one isomer) and 0.66 (other isomer); ν_{max}(film)/cm^{-1} 1717 and 1697 (C=O); δ_H(250 MHz; $CDCl_3$) 7.40–7.10 (5 H, m, Ph), 6.86 (1 H, t, *J* 7.8, CH=C, one isomer), 6.69 (1 H, t, *J* 7.6, CH=C, other isomer), 3.02 (1 H, septet, *J* 6.8, Me_2CH, one isomer), 2.90–2.34 (5 H, m, PhCH_2 and $PhCH_2CH_2$, both isomers and Me_2CH, other isomer), 1.52 (9 H, s, Bu^t, one isomer) and 1.48 (9 H, s, Bu^t, other isomer); *m*/*z* (EI) 302 (5%, M$^+$), 246 (65, M − C_4H_8), 91 (100, $PhCH_2$) and 57 (100, C_4H_9) (Found: M$^+$, 302.1893. $C_{19}H_{26}O_3$ requires *M*, 302.1882).

(*Z*)-*tert*-Butyl 2-(cyclohexanecarbonyl)-5-phenylpent-2-enoate 15d (82%, predominantly one isomer). R_f(EtOAc–light petroleum, 2 : 8) 0.69; ν_{max}(film)/cm^{-1} 1720 and 1697 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 6.68 (1 H, t, *J* 7.6, C=CH), 2.83–2.72 (2 H, m, $PhCH_2CH_2$), 2.63 (2 H, t, *J* 6.9, PhCH_2), 1.80–1.77 (5 H, m, cyclohexyl), 1.52 (9 H, s, Bu^t) and 1.32–1.23 (6 H, m, cyclohexyl); *m*/*z* (EI) 342 (5%, M$^+$), 91 (100, $PhCH_2$) and 57 (80, C_4H_9) (Found: M$^+$, 342.2194. $C_{22}H_{30}O_3$ requires *M*, 342.2195).

Hydrogenation of the unsaturated β-keto esters

Typically, palladium on carbon (10% w/w, 140 mg) was stirred with the α-alkylidene ester (4.6 mmol) in methanol (10 cm^3) for 24 h at room temperature under hydrogen delivered from a balloon. The mixture was filtered through Celite, dried ($MgSO_4$) and concentrated under reduced pressure to give the α-substituted β-keto ester.

The following esters were prepared by this method.

***tert*-Butyl 2-benzyl-3-oxobutanoate[24] (87%).** R_f(EtOAc–light petroleum, 2 : 8) 0.70; ν_{max}(film)/cm^{-1} 1731 and 1715 (C=C) and 1604 (Ph); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 3.68 (1 H, t, *J* 7.9, COCHCO), 3.10 (2 H, d, *J* 8.0, PhCH_2), 2.2 (3 H, s, MeCO) and 1.38 (9 H, s, Bu^t).

***tert*-Butyl 2-acetyl-5-phenylpentanoate 16a (90%).** R_f(EtOAc–light petroleum, 2 : 8) 0.6; ν_{max}(film)/cm^{-1} 1731 and 1713 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 3.31 (1 H, t, *J* 7.4, COCHCO), 2.74 (2 H, t, *J* 7.6, PhCH_2), 2.18 (3 H, s, MeCO), 1.95–1.80 (2 H, m, CHCH_2), 1.70–1.53 (2 H, m, $PhCH_2CH_2$) and 1.44 (9 H, s, Bu^t); *m*/*z* (TES) 299 (100%, M + Na) (Found: M$^+$ + Na, 299.1652. $C_{17}H_{24}O_3$ requires *M* + Na, 299.1623).

***tert*-Butyl 3-oxo-6-phenyl-2-(3-phenylpropyl)hexanoate 16b (90%).** R_f(EtOAc–light petroleum, 2 : 8) 0.78; ν_{max}(film)/cm^{-1} 1733 and 1717 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (10 H, m, Ph), 3.31 (1 H, t, *J* 7.2, COCHCO), 2.61–2.46 [8 H, m, 2 × PhCH_2, CHCH_2 and CH_2CO], 1.93–1.80 (4 H, m, C$H_2$$CH_2$CO and $CHCH_2CH_2$) and 1.40 (9 H, s, Bu^t); *m*/*z* (EI) 322 (50%,

M − C_4H_9) and 233 (100, M − C_4H_8 − $PhCH_2$) (Found: M^+ − C_4H_9, 322.1587. $C_{25}H_{32}O_3$ requires *M* − C_4H_9, 322.1568).

***tert*-Butyl 4-methyl-3-oxo-2-(3-phenylpropyl)pentanoate 16c (94%).** R_f(EtOAc–light petroleum, 2 : 8) 0.66; ν_{max}(film)/cm^{-1} 1739 and 1712 (C=O); δ_H(250 MHz; $CDCl_3$) 7.40–7.10 (5 H, m, Ph), 3.52 (1 H, t, *J* 7.1, COCHCO), 2.78 (1 H, septet, *J* 6.9, Me_2CH), 2.63 (2 H, td, *J* 7.5 and 3.2, CH_2CHCO), 2.18 (2 H, t, *J* 7.5, $PhCH_2$), 1.85 (2 H, m, $PhCH_2CH_2$), 1.43 (9 H, s, Bu^t), 1.10 (3 H, d, *J* 6.6, $CHMe_AMe_B$) and 1.08 (3 H, d, *J* 7, $CHMe_AMe_B$); *m*/*z* (EI) 304 (10%, M^+), 248 (85, M − C_4H_8), 91 (85, $PhCH_2$) and 57 (100, C_4H_9) (Found: M^+, 304.2027. $C_{19}H_{28}O_3$ requires *M*, 304.2038).

***tert*-Butyl 2-cyclohexyl-3-oxobutanoate 23c (63%).** R_f(EtOAc–light petroleum, 1 : 9) 0.5; ν_{max}(film)/cm^{-1} 1709 br (C=O); δ_H(250 MHz; $CDCl_3$) 3.07 (1 H, d, *J* 9.7, COCHCO), 2.14 (3 H, s, MeCO), 1.69–1.56 (5 H, m, cyclohexyl), 1.40 (9 H, s, Bu^t) and 1.30–0.85 (6 H, m, cyclohexyl); *m*/*z* (EI) 241 (20%, M^+ + H) and 185 (80, M − C_4H_8 + H) (Found: M^+ + H, 241.1808. $C_{14}H_{24}O_3$ requires *M* + H, 241.1803).

***tert*-Butyl 2-diphenylmethyl-3-oxobutanoate 23a**

Phenyllithium (1.3 mol dm^{-3} solution in hexane, 18.75 cm^3, 24.39 mmol) was added dropwise to a suspension of copper(I) cyanide (1.08 g, 12.2 mmol) in THF (10 cm^3) under argon at 0 °C and the mixture stirred for 1 h. The mixture was cooled to −78 °C and the enone **19** (2 g, 8.13 mmol) in THF (10 cm^3) was added dropwise, and the mixture stirred for 1 h. Saturated basic aqueous ammonium chloride solution was added, and the mixture was extracted with ether (2 × 20 cm^3). The combined organic fractions were washed with brine (50 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–hexane, 4 : 96) to give the *ester* (1.23 g, 47%) as needles, mp 117–120 °C (from Et_2O); R_f(EtOAc–light petroleum, 2 : 8) 0.66; ν_{max}($CHCl_3$)/cm^{-1} 1736 and 1708 (C=O); δ_H(250 MHz; $CDCl_3$) 7.50–7.00 (10 H, m, Ph), 4.68 (1 H, d, *J* 12.2, COCHCO), 4.43 (1 H, d, *J* 12.2 PhC*H*Ph), 4.33 (1 H, s, PhC*H*Ph, of enol form), 2.10 and 1.74 (3 H, s, MeCO, of keto and enol forms), 1.18 and 1.02 (9 H, s, Bu^t, of keto and enol forms) (Found: C, 77.28; H, 7.47; M^+ + Na, 347.1621. $C_{21}H_{24}O_3$ requires C, 77.75; H, 7.46%; *M* + Na, 347.1623).

***tert*-Butyl 3-oxo-2-(1-phenylethyl)butanoate 23b**

Methyllithium (1.4 mol dm^{-3} solution in ether, 71.4 cm^3, 0.101 mol) was added dropwise to a suspension of copper(I) iodide (19.3 g, 0.101 mol) in THF (100 cm^3) under argon at 0 °C and the mixture stirred for 1 h. The mixture was cooled to −78 °C and the enone **19** (10 g, 0.04 mol) in THF (50 cm^3) was added dropwise, and the mixture stirred for 1 h. Basic saturated ammonium chloride solution was added, and the mixture extracted with ether (2 × 100 cm^3). The combined organic fractions were washed with brine (50 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–light petroleum, 4 : 96) to give the *ester* (7.73 g, 82%) as a 1.8 : 1 mixture of diastereoisomers; R_f(EtOAc–light petroleum, 2 : 8) 0.75; ν_{max}(film)/cm^{-1} 1737 and 1708 (C=O); δ_H(250 MHz; $CDCl_3$) 7.40–7.20 (5 H, m, Ph), 3.70 (1 H, d, *J* 7.9, COCHCO, one isomer), 3.68 (1 H, d, *J* 8.1, COCHCO, other isomer), 3.48 (1 H, m, PhC*H*Me, both isomers), 2.29 (3 H, s, MeCO, one isomer), 1.94 (3 H, s, MeCO, other isomer), 1.48 (9 H, s, Bu^t, one isomer), 1.27 (3 H, d, *J* 6.8, PhCH*Me*, one isomer), 1.17 (3 H, d, *J* 6.9, PhCH*Me*, other isomer) and 1.12 (9 H, s, Bu^t, other isomer); δ_C($CDCl_3$) 202.6+, 167.7+, 167.2+, 143.5+, 143.4+, 128.6−, 128.3−, 127.6−, 127.3−, 126.7−, 126.6−, 82.0+, 81.6+, 68.6−, 68.0−, 39.8−, 39.7−, 29.5−, 29.1−, 27.9−, 27.4−, 20.8−, 20.5−; *m*/*z* (EI) 206 (20%, M^+ − C_4H_8), 188 (100, M − C_4H_8 − H_2O) and 145 (50, M − C_4H_8 − H_2O − MeCO) (Found: M^+ − C_4H_8, 206.0948. $C_{16}H_{22}O_3$ requires *M* − C_4H_8, 206.0947).

***tert*-Butyl 4-methyl-3-oxo-2-(4-phenylbut-2-yl)pentanoate 25c**

Methyllithium (1.6 mol dm^{-3} solution in ether, 6.2 cm^3, 10 mmol) was added dropwise to a suspension of copper(I) cyanide (0.44 g, 5.0 mmol) in THF (5 cm^3) under argon at 0 °C and stirred for 1 h. The mixture was cooled to −78 °C and the enone **15c** (1.13 g, 3.3 mmol) in THF (5 cm^3) was added dropwise, and the mixture stirred for 1 h. Basic aqueous saturated ammonium chloride solution was added, and the mixture extracted with ether (2 × 20 cm^3). The combined organic fractions were washed with brine (25 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–hexane, 4 : 96) to give the *ester* (0.958 g, 91%) as a 1 : 1 mixture of diastereoisomers; R_f(EtOAc–light petroleum, 2 : 8) 0.76; ν_{max}(film)/cm^{-1} 1738 and 1712 (C=O); δ_H(250 MHz; $CDCl_3$) 7.27–7.10 (5 H, m, Ph), 3.44 (1 H, d, *J* 9.5, COCHCO), 2.81–2.28 (6 H, m, $PhCH_2$, $PhCH_2CH_2$, MeC*H*, and Me_2CH), 1.45 (9 H, s, Bu^t, one isomer), 1.42 (9 H, s, Bu^t, other isomer), 1.10 (3 H, d, *J* 6.9, $CHMe_AMe_B$ one isomer), 1.09 (3 H, d, *J* 6.9, $CHMe_AMe_B$, other isomer), 1.07 (3 H, d, *J* 7.0, $CHMe_AMe_B$, one isomer) (the $CHMe_AMe_B$ signal for the other isomer was obscured), 1.03 (3 H, d, *J* 7.6, *Me*CH, one isomer) and 0.95 (3 H, d, *J* 6.7 *Me*CH, other isomer). This compound was not fully characterised.

***tert*-Butyl 2-(cyclohexanecarbonyl)-3-methyl-5-phenylpentanoate 25d**

Similarly, the enone **15d** (2.5 g, 7.3 mmol) gave the *ester* (2.21 g, 84%) as a 1 : 1 mixture of diastereoisomers; R_f(EtOAc–light petroleum, 2 : 8) 0.76; ν_{max}(film)/cm^{-1} 1739 and 1709 (C=O); δ_H(250 MHz; $CDCl_3$) 7.32–7.10 (5 H, m, Ph), 3.43 (1 H, d, *J* 9.3, COCHCO, one isomer), 3.42 (1 H, d, *J* 9.3, COCHCO, other isomer), 2.78–2.25 (5 H, m, $PhCH_2$, $PhCH_2CH_2$ and MeC*H*), 1.79–1.76 (6 H, m, cyclohexyl), 1.44 (9 H, s, Bu^t, one isomer), 1.41 (9 H, s, Bu^t, other isomer), 1.23 (5 H, m, cyclohexyl), 1.02 (3 H, d, *J* 6.7, *Me*CH, one isomer) and 0.94 (3 H, d, *J* 6.7 *Me*CH, other isomer); *m*/*z* (EI) 358 (20%, M^+), 302 (85, M − C_4H_8), 91 (80 $PhCH_2$) and 57 (100, C_4H_9) (Found: M^+, 358.2512. $C_{23}H_{34}O_3$ requires *M*, 358.2507).

The enol triflates

Method A. Typically the di-*tert*-butyl acylmalonate (1.96 mmol) was dissolved in dry dichloromethane (10 cm^3) and cooled to 0 °C. Trifluoromethanesulfonic (triflic) anhydride (2.35 mmol) was added slowly, followed by triethylamine (3.92 mmol). The mixture was stirred for 1 h at 0 °C and allowed to warm to room temperature. Saturated aqueous ammonium chloride solution was added, and the mixture was extracted with dichloromethane (3 × 10 cm^3). The combined organic fractions were washed with hydrochloric acid solution (3 mol dm^{-3}, 50 cm^3) and brine (50 cm^3), dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–light petroleum, 2 : 98) to give the enol triflate.

Method B. Typically the di-*tert*-butyl acylmalonate or the α-substituted β-keto ester (1.96 mmol) in dry ether (5 cm^3) was added dropwise to a prewashed suspension of sodium hydride (60% dispersion in mineral oil, 2.94 mmol) in dry ether (10 cm^3) at 0 °C and stirred for 1 h. Triflic anhydride (2.35 mmol) was added and the mixture was stirred for 1 h at 0 °C and 1 h at room temperature. The mixture was worked up in the same as for Method A.

The following enol triflates were prepared by either or both of these methods. The enol triflates were unstable, and, except for the first, were not fully characterised before being used in the next step.

1,1-Di-*tert*-butoxycarbonylpropen-2-yl trifluoromethanesulfonate 4 (89% by method A, 85% by method B). R_f(EtOAc–light petroleum, 1 : 9) 0.65; ν_{max}(film)/cm^{-1} 1720 (C=O); δ_H(250 MHz; $CDCl_3$) 2.48 (3 H, s, Me) and 1.50 (18 H, s, 2 × Bu^t); δ_C($CDCl_3$) 161.4+, 161.1+, 156.7+, 83.8+, 83.6+, 27.9−, 27.7− and 17.8−; *m*/*z* (EI) 391 (15%, M + H), 335 (70, M + H − 2Bu^t) and 57 (100, C_4H_9) (Found: M$^+$ + H, 391.1045. $C_{14}H_{21}F_3O_7S$ requires *M* + H, 391.1038).

1,1-Di-*tert*-butoxycarbonyl-5-phenylpenten-2-yl trifluoromethanesulfonate 8a (70% by method A). R_f(EtOAc–light petroleum, 1 : 9) 0.69; ν_{max}(film)/cm^{-1} 1729 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.68 (2 H, t, *J* 7.5, CH_2CH_2-CH_2Ph), 2.56 (2 H, t, *J* 7.5, PhCH_2), 1.94 (2 H, qn, *J* 7.7, CH_2CH_2CH_2), 1.52 (9 H, s, Bu^t) and 1.48 (9 H, s, Bu^t).

1,1-Di-*tert*-butoxycarbonyl-3-methylbuten-2-yl trifluoromethanesulfonate 8b (72% by method A). R_f(EtOAc–light petroleum, 1 : 9) 0.65; ν_{max}(film)/cm^{-1} 1731 (C=O); δ_H(250 MHz; $CDCl_3$) 3.17 (1 H, septet, *J* 7.2, C*H*Me$_2$), 1.47 (18 H, s, 2 × Bu^t) and 1.26 (3 H, d, *J* 7.1, *Me*CH).

1,1-Di-*tert*-butoxycarbonyl-4-phenylbuten-3-yn-2-yl trifluoromethanesulfonate 8c (73% by method A). R_f(EtOAc–light petroleum, 1 : 9) 0.65; ν_{max} (film)/cm^{-1} 2208 (C≡C) and 1732 (C=O); δ_H(250 MHz; $CDCl_3$) 7.60–7.30 (5 H, m, Ph) and 1.58 (18 H, s, Bu^t).

1-*tert*-Butoxycarbonyl-6-phenyl-hexen-2-yl trifluoromethanesulfonate 12 (72% by method B). One isomer; R_f(EtOAc–light petroleum, 2 : 8) 0.76; ν_{max}(film)/cm^{-1} 1725 (C=O) and 1676 (C=C); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 5.63 (1 H, s, C=CH), 2.64 (2 H, t, *J* 7.2, PhCH_2), 2.36 (2 H, t, *J* 7.2, CH_2C=CH), 1.7–1.5 (4 H, m, CH_2CH_2CH$_2$Ph) and 1.49 (9 H, s, Bu^t).

3-*tert*-Butoxycarbonyl-6-phenylhex-2-en-2-yl trifluoromethanesulfonate 17a (71% by method B). R_f(EtOAc–light petroleum, 2 : 8) 0.64; ν_{max}(film)/cm^{-1} 1714 (C=C); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.67 and 2.65 (2 H, t, *J* 7.5, PhCH_2), 2.42–2.18 (2 H, m, C=CCH_2), 2.06 and 1.98 (3 H, s, MeCO), 1.92–1.70 (2 H, m, PhCH$_2$CH_2) and 1.50 (9 H, s, Bu^t); *m*/*z* (EI) 335 (80%, M − C_4H_8 − 16) and 91 (75, PhCH_2) and 57 (100, C_4H_9) (Found: M$^+$ − C_4H_8, 335.0564. $C_{18}H_{23}F_3O_5S$ requires *M* − C_4H_8O, 335.0559).

5-*tert*-Butoxycarbonyl-1,8-diphenyloct-4-en-4-yl trifluoromethanesulfonate 17b (86% by method B). ν_{max}(film)/cm^{-1} 1722 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (10 H, m, Ph), 2.60 (4 H, t, *J* 7.4 2 × PhCH_2), 2.44–2.18 (4 H, m, 2 × C=CCH_2), 1.94–1.66 (4 H, m, 2 × CH$_2$CH_2CH$_2$) and 1.51 and 1.40 (9 H, s, Bu^t); *m*/*z* (EI) 455 (10%, M − C_4H_9), 91 (100, PhCH_2) and 57 (80, C_4H_9) (Found: M$^+$ − C_4H_9, 455.1129. $C_{26}H_{31}F_3O_5S$ requires *M* − C_4H_9, 455.1139).

4-*tert*-Butoxycarbonyl-2-methyl-7-phenylhept-3-en-3-yl trifluoromethanesulfonate 17c (92% by method B). R_f(EtOAc–light petroleum, 2 : 8) 0.71; ν_{max}(film)/cm^{-1} 1722 (C=O); δ_H(250 MHz; $CDCl_3$) 7.40–7.10 (5 H, m, Ph), 2.82 and 2.78 (1 H, 2 × septets, *J* 6.9, Me$_2$C*H*), 2.68 and 2.66 (2 H, 2 × t, *J* 7.4, PhCH_2), 2.43–2.30 (2 H, m, C=CCH_2), 1.90–1.73 (2 H, m, CH$_2$CH_2CH$_2$), 1.49 and 1.30 (9 H, 2 × s, Bu^t), 1.15 and 1.13 (3 H, 2 × d, *J* 6.9, CH*Me*$_2$) (Found: M$^+$ − C_4H_9O, 363.0876. $C_{20}H_{27}F_3O_5S$ requires *M* − C_4H_9O, 363.0872).

2-*tert*-Butoxycarbonyl-1-phenylbut-2-en-3-yl trifluoromethanesulfonate 20 (87% by method B). R_f(EtOAc–light petroleum, 2 : 8) 0.74; ν_{max}(film)/cm^{-1} 1723 (C=C); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 3.75 and 3.66 (2 H, s, PhCH_2), 2.24 and 2.17 (3 H, s, MeCO) and 1.34 (9 H, s, Bu^t).

3-*tert*-Butoxycarbonyl-3-cyclohexylprop-2-en-2-yl trifluoromethanesulfonate (48% by method B). R_f(EtOAc–light petroleum, 2 : 8) 0.63; δ_H(250 MHz; $CDCl_3$) 2.40–2.20 (1 H, m, cyclohexyl CH), 2.15 and 2.05 (3 H, s, MeC=C), 1.85–1.58 (11 H, m, cyclohexyl) and 1.45 (9 H, s, Bu^t).

3-*tert*-Butoxycarbonyl-4-phenylpent-2-en-2-yl trifluoromethanesulfonate (85% by method B). R_f(EtOAc–light petroleum, 2 : 8) 0.77; ν_{max}(film)/cm^{-1} 1721 (C=O) and 1602 (Ph); δ_H(250 MHz; $CDCl_3$) 7.30–7.20 (5 H, m, Ph), 3.96 and 3.86 (1 H, q, *J* 7.3, PhC*H*), 2.12 and 2.10 (3 H, s, MeC=C), 1.57 (3 H, d, *J* 7.2, *Me*CH) and 1.31 (9 H, s, Bu^t).

2-*tert*-Butoxycarbonyl-1,1-diphenylbut-2-en-3-yl trifluoromethanesulfonate (73% by method B). One isomer; R_f(EtOAc–light petroleum, 2 : 8) 0.7; ν_{max}(film)/cm^{-1} 1717 (C=O); δ_H(250 MHz; $CDCl_3$) 7.50–7.00 (10 H, m, Ph), 5.15 (1 H, s, PhC*H*Ph), 2.06 (3 H, s, MeC=C) and 1.13 (9 H, s, Bu^t) (Found: M$^+$ + H, 457.1318. $C_{20}H_{27}F_3O_5S$ requires *M* + H, 457.1297).

1-Trifluoromethanesulfonyloxyethylidenemalonic acid 5

Triflate **4** (0.3 g, 0.76 mmol) was dissolved in trifluoroacetic acid (5 cm^3) and stirred for 20 min at room temperature. The excess trifluoroacetic acid was removed under reduced pressure, and the residue crystallised from ether–light petroleum to give the *dicarboxylic acid* (0.162 g, 76%), mp 80–82 °C (from Et$_2$O-light petroleum); ν_{max}(Nujol)/cm^{-1} 3449 (COOH) and 1761 (C=O); δ_H(250 MHz; $CDCl_3$) 2.05 (3 H, s, Me) (Found: C, 25.84; H, 1.74. $C_6H_5F_3O_7S$ requires C, 25.91; H, 1.81%). The diacid is unstable and decomposes in a few hours.

The acetylenic acids

Typically, the enol triflate (0.75 mmol) was stirred in trifluoroacetic acid (5 cm^3) at room temperature for 30 min. The excess trifluoroacetic acid was removed under reduced pressure. The residue was dissolved in saturated aqueous sodium hydrogen carbonate (10 cm^3) and was stirred for 4 h. The mixture was washed with ether (5 cm^3), and the aqueous layer was carefully acidified with concentrated hydrochloric acid solution. The mixture was extracted with ether (3 × 10 cm^3). The combined organic fractions were washed with brine (30 cm^3), dried ($MgSO_4$), and concentrated under reduced pressure to give the acetylenic acid.

The following compounds were prepared by this method.

2-Butynoic acid 6 (66%). [0.043 g, 66% from enol triflate **5** (0.3 g)], mp 75–76 °C (from light petroleum) (lit.,[25] 78–80 °C); ν_{max}(Nujol)/cm^{-1} 2918 (COOH), 2246 (C≡C) and 1711 (C=O); δ_H(250 MHz; $CDCl_3$) 2.11 (3 H, s, Me).

6-Phenylhex-2-ynoic acid 9a (56%). ν_{max} (film)/cm^{-1} 2236 (C≡C) and 1720 (C=O); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.74 (2 H, t, *J* 7.3, PhCH_2), 2.36 (2 H, t, *J* 7.1, CH_2CH$_2$CH$_2$Ph) and 1.92 (2 H, qn, *J* 7.3, CH$_2$CH_2CH$_2$); δ_C($CDCl_3$) 158.2+, 140.7+, 128.5−, 126.2−, 112.6−, 91.8+, 73.2+, 34.6+, 28.9+ and 18.1+; *m*/*z* (EI) 188.1 (34%, M$^+$), 170.1 (55, M − H_2O) and 91 (100, PhCH_2) (Found: M$^+$, 188.0835. $C_{12}H_{12}O_2$ requires *M*, 188.0837).

4-Methylpent-2-ynoic acid 9b[26] (54%). ν_{max}(film)/cm^{-1} 2979 (COOH), 2231 (C≡C) and 1693 (C=O); δ_H(250 MHz; $CDCl_3$) 2.72 (1 H, septet, *J* 6.9, C*H*Me$_2$) and 1.24 (6 H, d, *J* 6.9 CH*Me*$_2$); δ_C($CDCl_3$) 158.7, 97.3, 71.8, 29.7, and 21.6; *m*/*z* (EI) 111 (50%, M − H), 97 (56, M − H − Me) and 67 (100, M − H − CO_2) (Found: M$^+$ − H, 111.0446. $C_6H_8O_2$ requires *M* − H, 111.0446).

5-Phenylpenta-2,4-diynoic acid 9c[27] (71%). mp 142–144 °C (from Et$_2$O–hexane) (lit.,[27] 143–144 °C); ν_{max}(film)/cm^{-1} 3445

(COOH), 2226 (C≡C) and 1732 (C=O); δ_H(250 MHz; $CDCl_3$) 7.60–7.30 (5 H, m, Ph); δ_C($CDCl_3$) 157.4+, 133.2−, 130.8−, 128.7−, 85.1+, 73.9+, and 70.9+.

The other acetylenes

Typically, the enol triflate (2.29 mmol) was stirred in trifluoroacetic acid (5 cm^3) at room temperature for 30 min. The excess trifluoroacetic acid was removed under reduced pressure. The residue was dissolved in anhydrous acetone (20 cm^3), potassium carbonate (6.87 mmol) was added and the mixture refluxed for 4 h. The mixture was cooled, poured into water and extracted with ether (2 × 20 cm^3). The combined organic fractions were washed with brine (30 cm^3), dried ($MgSO_4$), and concentrated under reduced pressure. The residue was chromatographed (SiO_2, EtOAc–hexane, 2 : 98) to give the acetylene.

The following compounds were prepared by this method.

6-Phenylhexyne 13 (68%). R_f(EtOAc–light petroleum, 2 : 8) 0.87; ν_{max}(film)/cm^{-1} 3300 C≡C-H) and 2238 (C≡C); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.64 (2 H, t, *J* 7.3, PhCH_2), 2.22 (2 H, td, *J* 7.0 and 2.6, CH_2C≡C), 1.94 (1 H, t, *J* 2.6, C≡CH), 1.75 (2 H, m, $PhCH_2CH_2$) and 1.57 (2 H, m, CH_2CH_2C≡C); *m*/*z* (EI) 157 (10%, M − H) and 91 (12, $PhCH_2$) (Found: M^+ − H, 157.1014. $C_{12}H_{14}$ requires *M* − H, 157.1017).

6-Phenylhex-2-yne 18a[28] (73%). R_f(EtOAc–light petroleum, 1 : 9) 0.72; ν_{max}(film)/cm^{-1} 1603 (Ph); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (5 H, m, Ph), 2.72 (2 H, t, *J* 7.8, PhCH_2), 2.16 (2 H, m, C≡CCH_2) and 1.84–1.78 (5 H, m, MeC≡C and $PhCH_2CH_2$); *m*/*z* (EI) 158 (95%, M^+), 143 (95, M − Me) and 91 (100, Ph) (Found: M^+, 158.1088. $C_{12}H_{14}$ requires *M*, 158.1096).

1,8-Diphenyloct-4-yne 18b (60%). R_f(EtOAc–light petroleum, 1 : 9) 0.85; ν_{max}(film)/cm^{-1} 1602 (Ph); δ_H(250 MHz; $CDCl_3$) 7.30–7.10 (10 H, m, Ph), 2.76 (4 H, t, *J* 7.4, 2 × PhCH_2), 2.22 (4 H, t, *J* 7.0, 2 × CH_2C≡C) and 1.84 (4 H, qn, *J* 6.9, 2 × $PhCH_2CH_2$); δ_C($CDCl_3$) 141.8+, 128.5−, 128.3−, 125.8−, 80.3+, 34.8+, 30.7+ and 18.2+; *m*/*z* (EI) 262 (25%, M^+), 171 (10, M − $PhCH_2$) and 91 (100, $PhCH_2$) (Found: M^+, 262.1721. $C_{20}H_{22}$ requires *M,* 262.1721).

2-Methyl-7-phenylhept-3-yne 18c (86%). R_f(EtOAc–light petroleum, 2 : 8) 0.80; ν_{max}(film)/cm^{-1} 1603 (Ph); δ_H(250 MHz; $CDCl_3$) 7.40–7.10 (5 H, m, Ph), 2.72 (2 H, t, *J* 7.3, PhCH_2), 2.55 (1 H, septet t, *J* 6.8 and 2.1, Me_2CH), 2.18 (2 H, td *J* 7.3 and 2.1, C≡CCH_2), 1.8 (2 H, qn, *J* 7.3, $PhCH_2CH_2$) and 1.17 (6 H, d, *J* 6.8, Me_2CH); δ_C($CDCl_3$) 141.9+, 128.5−, 128.2−, 125.7−, 86.6+, 78.8+, 34.7+, 31.4−, 30.7+, 23.4−, 20.5– and 18.1+; *m*/*z* (EI) 186 (35%, M^+), 171 (40, M − Me) and 91 (70, $PhCH_2$) (Found: M^+, 186.1408. $C_{14}H_{18}$ requires *M*, 186.1409).

1-Phenylbut-2-yne 2[29] (69%). R_f(EtOAc–light petroleum, 2 : 8) 0.85; ν_{max}(film)/cm^{-1} 2204 (C≡C); δ_H(250 MHz; $CDCl_3$) 7.40–7.10 (5 H, m, Ph), 3.55 (2 H, q, *J* 2.6, PhCH_2) and 1.85 (3 H, t, *J* 2.6, Me).

1,1-Diphenylbut-2-yne 24a (60%). R_f(EtOAc–light petroleum, 1 : 9) 0.76; ν_{max}(film)/cm^{-1} no characteristic peaks; δ_H(250 MHz; $CDCl_3$) 7.46–6.98 (10 H, m, Ph), 4.96 (1 H, br s, PhCHPh) and 1.92 (3 H, d, *J* 2.4, MeC≡C); δ_C($CDCl_3$) 142.3+, 128.4+, 127.8+, 126.6+, 80.3+, 79.6+, 43.2− and 3.79−; *m*/*z* (EI) 206 (35%, M^+) and 77 (32, C_6H_5) (Found: M^+, 206.1095. $C_{16}H_{14}$ requires *M*, 206.1095).

4-Phenylpent-2-yne 24b[30] (91%). R_f(EtOAc–light petroleum, 2 : 8) 0.85; ν_{max}(film)/cm^{-1} 1596 (Ph); δ_H(250 MHz; $CDCl_3$) 7.40–7.20 (5 H, m, Ph), 3.72 (1 H, m, PhCH), 1.88 (3 H, d, *J* 2.5, MeC≡C) and 1.47 (3 H, d, *J* 7.2, MeCH); δ_C($CDCl_3$) 144+, 128.4−, 126.8−, 126.4−, 82.0+, 77.5+, 31.9−, 24.6− and 3.6−.

1-Cyclohexylpropyne 24c[31] (84%). R_f(EtOAc–light petroleum, 2 : 8) 0.85; ν_{max}(film)/cm^{-1} no characteristic peaks; δ_H(250 MHz; $CDCl_3$) 2.25 (1 H, m, C≡CCH), 1.77 (3 H, d, *J* 2.4, MeC≡C) and 1.67–1.23 (11 H, m, cyclohexyl); δ_C($CDCl_3$) 83.7+, 75.0+, 33.1+, 29.2−, 25.9+, 25.0+, 3.45−.

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