# Preparation of 1-phenylcyclohexa-2,5-diene-1-carboxylates and their use in free-radical mediated syntheses †

**Paul A. Baguley, Leon V. Jackson and John C. Walton ***

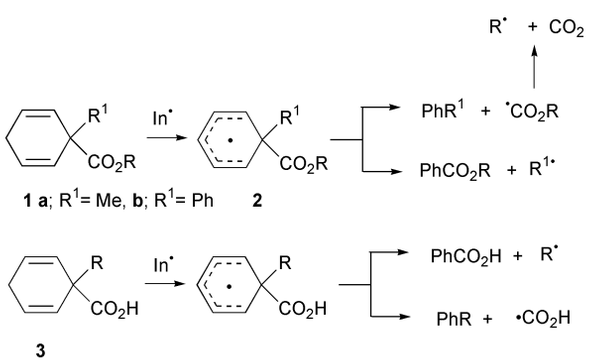
*University of St. Andrews, School of Chemistry, St. Andrews, Fife, UK KY16 9ST*

***Received (in Cambridge, UK) 16th November 2001, Accepted 3rd December 2001***
***First published as an Advance Article on the web 9th January 2002***

Synthetic routes to pure 1-phenylcyclohexa-2,5-diene-1-carboxylic acid and derived esters were developed. Esters containing appropriately unsaturated side chains generated the corresponding alkenyl radicals and hence gave good yields of 5-*exo* ring closure products in organotin-free reactions. Extrusion of phenyl radicals from the intermediate cyclohexadienyl type radicals was not observed, and this alternative β-scission did not compete under any conditions. Yields from alkylations of olefins in analogous intermolecular processes were, however, poor. As a spin-off from the research, it was found that 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (**6**) was a useful source of hydroxyformyl (formate) radicals in organic solvents.

## Introduction

Several series of "pro-aromatic" functionalised cyclohexadienes, containing bisallylic hydrogen atoms, have been investigated as potential 'clean' sources of free radicals.[1,2] For example, alkyl 1-methylcyclohexa-2,5-diene-1-carboxylates (*e.g.* **1a**) afforded cyclohexadienyl radicals **2** which mainly underwent β-scission above *ca.* 80 °C to produce toluene and alkoxycarbonyl radicals (Scheme 1). The latter radical subsequently extruded $CO_2$ to generate the corresponding alkyl radicals that were trapped with moderate efficiency by halogen donors or alkenes. However, loss of a methyl radical from the intermediate cyclohexadienyl radical **2a** to afford an alkyl benzoate was a significant competing β-scission.[1,2]




**Scheme 1**

Similarly, the related acids, *i.e.* 1-alkylcyclohexa-2,5-diene-1-carboxylic acids **3** also functioned as sources of alkyl radicals.[3,4] Again, however, product yields were reduced because of competition from an alternative β-scission leading to an alkylbenzene and the hydroxyformyl (formate) radical. Recently, 1-silylcyclohexadienes were shown to release silyl radicals and hence could be used, in conjunction with alkyl halides[5] or 1,6-dienes,[6] to mediate free-radical syntheses.

We considered that 1-substitution of cyclohexadiene-1-carboxylate with a 1-phenyl substituent (**1b**), instead of a methyl group, should overcome the problem of competing β-scission modes. Loss of a phenyl radical from **2b** would be very disfavoured because $Ph^{\bullet}$ is a thermodynamically destabilised σ-radical. Hence only the desired dissociation mode of **2b**, leading to biphenyl and $R^{\bullet}$, should prevail. A range of 1-phenylcyclohexa-2,5-diene-1-carboxylates was therefore prepared and used in several homolytic processes to test the viability of these compounds as radical precursors in organic syntheses.

## Results and discussion

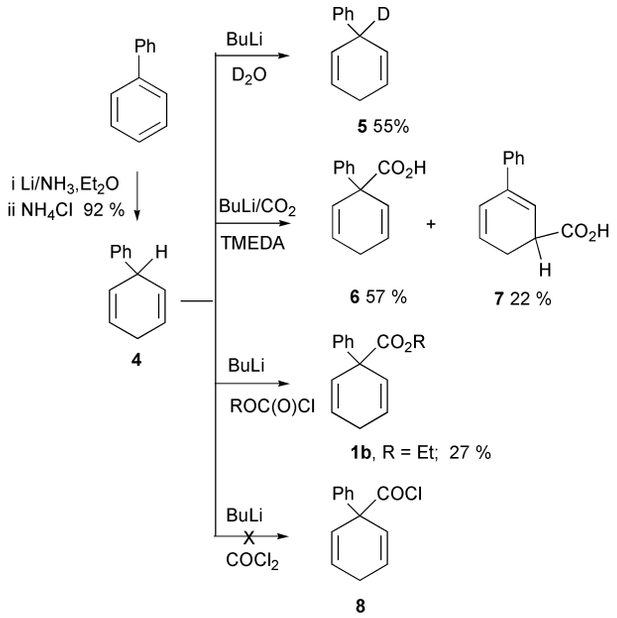
### Preparation of 1-phenylcyclohexa-2,5-diene-1-carboxylates

In the only previous preparation, the methyl ester of **1b** was made by treating 1,4-dihydrobiphenyl **4** with BuLi and then bubbling $CO_2$ into the mixture.[7] However, in our hands, this led to poor yields of **6** which was contaminated with the isomer 3,4-dihydrobiphenyl-3-carboxylic acid (**7**) (Scheme 2). In order to establish whether the *tert*-C was being deprotonated efficiently, **4** was treated with BuLi and quenched with $D_2O$ after 2 h. Analysis by $^1$H NMR spectroscopy indicated the disappearance of the *tert*-H signal and $^2$D NMR showed the formation of a singlet corresponding to the *tert*-D atom in 1-deuterio-1,4-dihydrobiphenyl **5**. It was evident, therefore, that the *tert*-H could be efficiently removed by BuLi to give the corresponding anion. After varying the experimental parameters, the best conditions for formation of **6** were found to involve pouring the solution of the initially formed anion onto crushed dry ice. In this way up to 80% product yields were obtained. However, in this reaction, and under the other conditions tried, a mixture of **6** together with the regioisomer **7** was produced. Unfortunately, it was not possible to separate these two isomers either by chromatography or by recrystallisation.

A possible way round this difficulty involved making esters of **6** and **7** and separating these by chromatography. The mixture of acids **6** and **7** was treated with thionyl chloride to prepare the pair of acid chlorides. This reaction was monitored by NMR spectroscopy, which showed that the acid chloride from **7** was unstable and rapidly aromatised to 3-phenylbenzoyl chloride. Similarly, it was noted that if the mixture of acids **6** and **7** was

† Electronic supplementary information (ESI) available: experimental procedures for the preparation of 1,4-dihydrobiphenyl,[9] 1-deuterio-1,4-dihydrobiphenyl, 1-phenylcyclohexa-2,5-diene-1-carboxylic acid with 3,4-dihydrobiphenyl-3-carboxylic acid, 2-(cyclohex-2-enyloxy)ethyl 1-phenylcyclohexa-2,5-diene-1-carboxylate and non-1-en-6-ol. Experimental details of the reactions of cyclopentyl 1-phenylcyclohexa-2,5-diene-1-carboxylate with cyclohexenone, methyl acrylate, methyl methacrylate, acrylonitrile and cyclohexene are included. See http://www.rsc.org/suppdata/p1/b1/b110527m/

 DOI: 10.1039/b110527m



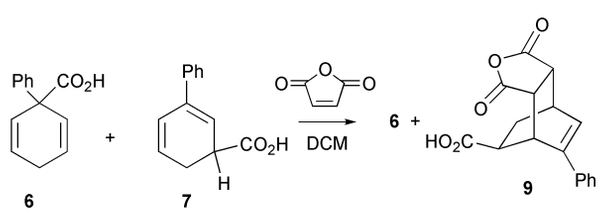

**Scheme 2**

simply refluxed in diethyl ether for 24–48 h, **7** disappeared and the corresponding aromatic acid appeared in its place. The mixture of acid chlorides was esterified with cyclopentanol, but yields were poor and the pure cyclopentyl ester from **6** could not be separated easily by chromatography.

It seemed feasible to go direct from 1,4-dihydrobiphenyl to esters of **6** by deprotonating with base and quenching the resultant anion with an appropriate chloroformate (Scheme 2). When ethyl chloroformate was used in this process a clean reaction was not obtained, although 27% of the ethyl ester (**1b**, R = Et) could be isolated by column chromatography. Further experiments with different reaction conditions, and with other chloroformates, were carried out but better yields could not be obtained.

It appears that efficient reaction of the somewhat sterically congested anion cannot be achieved with chloroformates. Direct preparation of acid chloride **8** was attempted, by treating 1,4-dihydrobiphenyl with BuLi and then adding this mixture to phosgene (Scheme 2). However, work-up yielded only starting material and there was no evidence for the formation of **8**.

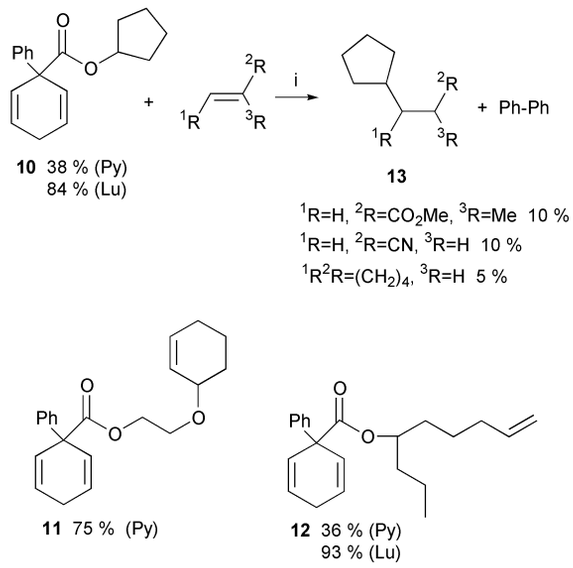
Eventually pure **6** was obtained by refluxing the mixture (**6** + **7**) in DCM with maleic anhydride for 5 h and then treating with NaOH. The mixture was then re-acidified and pure **6** was obtained in *ca.* 35% yield by dry flash chromatography. The regioisomeric acid **7** was a conjugated diene that reacted readily with maleic anhydride to give adduct **9** (Scheme 3). Treatment




**Scheme 3**

of the resulting mixture with NaOH opened the anhydride groups in both this adduct and the excess maleic anhydride. The resulting tri- and di-carboxylic acids were comparatively immobile on silica gel thus enabling the desired acid to elute in pure form.

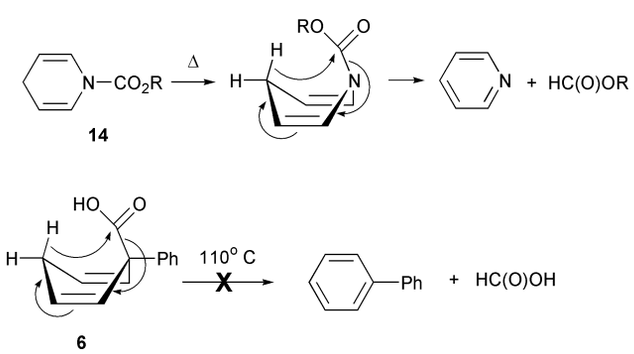
Esters **10**–**12** were prepared from acid chloride **8** with appropriate alcohols. In initial preparations these esterifications were catalysed by pyridine (Py) but low yields were obtained for secondary alcohols, possibly because of crowding around the reaction centre. Yields were significantly improved by use of 2,6-dimethylpyridine (lutidine, Lu) as the base (Scheme 4).




**Scheme 4** i, $PhCO_2O_2CPH$, 0.5 mol equiv., PhH reflux 24 h.

## Homolytic reactions of 1-phenylcyclohexa-2,5-diene-1-carboxylates

We showed previously that *N*-alkoxycarbonyl-1,4-dihydropyridines **14** decomposed thermally in non-radical processes to afford pyridine and formate esters[8] (Scheme 5). It seemed



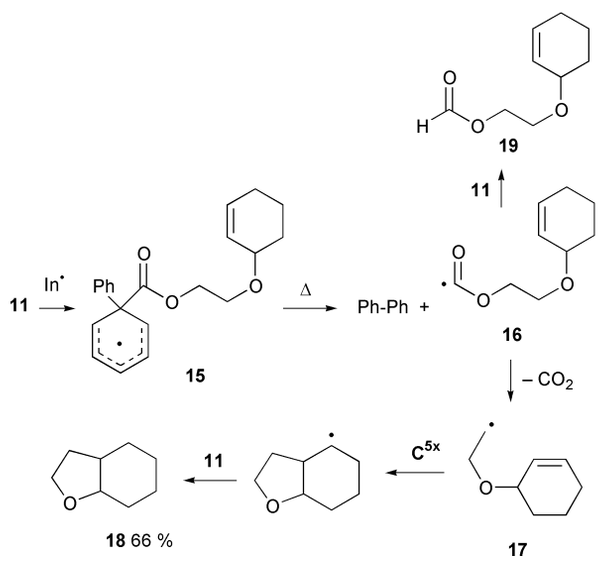

**Scheme 5**

possible that acid **6** might undergo a similar concerted thermal elimination yielding biphenyl and formic acid (Scheme 5). However, when acid **6** (30 mg) in $C_6D_6$ was heated at 110 °C in a sealed tube for 24 h no change in its $^1H$ NMR spectrum was observed and hence this elimination was insignificant under our experimental conditions.

The effectiveness of ester **10** as a source of cyclopentyl radicals for intermolecular additions was examined by reacting it in peroxide initiated chain processes with alkenes. The reaction with cyclohex-2-enone was carried out in refluxing benzene initiated with dibenzoyl peroxide. Under these conditions a low yield of the expected 3-cyclopentylcyclohexanone was obtained, but it was necessary to use *ca.* 0.5 mol equiv. of the initiator to achieve significant conversion of **10**. A slightly improved adduct yield (12%) was obtained by carrying out the reaction photochemically with di-*tert*-butyl peroxide at 70 °C. However, photodimerisation of the alkene became a problem under these conditions. Similar reactions with methyl acrylate, methyl methacrylate, acrylonitrile and cyclohexene all gave low yields (*ca.* 10%) of the corresponding adducts **13**, but significant quantities of the starting ester remained unreacted.

Intramolecular reactions are generally more efficient than their intermolecular analogues and therefore we examined

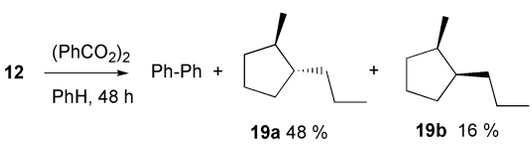
esters **11** and **12**, designed to establish the applicability of the Ph-substituted esters in radical cyclisations. When ester **11** was refluxed in benzene with dibenzoyl peroxide the major products were biphenyl (66%) and 7-oxabicyclo[4.3.0]nonane (**18**, 66%). GC-MS analysis showed a clean chromatogram indicating only minor products from the initiator together with small amounts of formate **19** (<5%) and 2-(cyclohex-2-enyloxy)ethylbenzene (trace). The alkyl group in the intermediate alkoxycarbonyl radical **16** is *primary* and therefore the latter decarboxylated less rapidly than *secondary* or *tertiary* analogues. A small amount of **16** was able to abstract hydrogen to give **19** before $CO_2$ loss (Scheme 6).




**Scheme 6**

None of the benzoic acid ester that would result from loss of a phenyl radical was detectable. Similar reactions of ester **11** were carried out in cyclohexane and 2-methylbutan-2-ol as solvents, and with *tert*-butyl peroxybenzoate as initiator, and similar results were obtained. In 2-methylbutan-2-ol the reflux temperature was 100 °C and at this temperature less **19** was observed because of more efficient decarboxylation. Polymerisation was a potential problem. However, reaction mixtures did not contain detectable polymer or other involatiles.

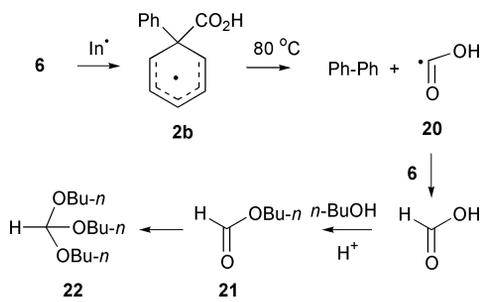
The benzoyl peroxide induced reaction of nonenyl ester **12** under similar conditions afforded biphenyl together with 1-methyl-2-propylcyclopentane (**19**) (64%) as a 2.9 : 1 mixture of the *trans*- and *cis*-isomers (Scheme 7). None of the nonenyl




**Scheme 7**

benzoate, from competing loss of a phenyl radical from the intermediate cyclohexadienyl radical, was detected. These reactions demonstrated that 1-phenyl esters of type **1b** could indeed be effective mediators of free-radical ring closure processes giving products in yields approaching those obtainable *via* organotin hydride methodology.

Previous work with 1-substituted cyclohexa-2,5-diene-1-carboxylic acids showed that some hydroxyformyl radical formation always accompanied the main production of alkyl radicals.[4] The 1-phenyl acid **6** appeared, therefore, to be a potential 'clean' source of hydroxyformyl radicals (**20**), because phenyl extrusion from the intermediate cyclohexadienyl radical **2b** would be strongly disfavoured. To test for hydroxyformyl radical production, reactions of acid **6** in the presence of various alkenes as traps, were examined. The dibenzoyl peroxide initiated reaction of **6** with butyl vinyl ether was carried out in cyclohexane as solvent and in *tert*-amyl alcohol (2-methylbutan-2-ol). The main products in both cases were *n*-butanol (trace), *n*-butyl formate (**21**), 1,1-di-*n*-butoxyethane ($CH_3CH(OBu\text{-}n)_2$, **23**), benzoic acid, biphenyl and 1-(di-*n*-butoxymethoxy)butane (**22**). Some water was always present because commercial dibenzoyl peroxide is moistened with this. The benzoic acid was a side product from thermolysis of this initiator. It is probable that the butyl vinyl ether was extensively hydrolysed under these conditions giving *n*-butanol and ethanal. The latter was then converted to its di-*n*-butyl acetal (**23**). The hydroxyformyl radical (**20**) will readily abstract hydrogen from acid **6** giving formic acid and hence the production of *n*-butyl formate (**21**) is explained (Scheme 8). It is




**Scheme 8**

probable that the ortho-ester **22** was formed from butanol and formate **21**, although there seems little precedent for direct condensations of this type. In any case, the observation of **21** and **22** as major products was good evidence that hydroxyformyl radicals were key intermediates released from **6**.

The reaction of **6** with phenyl vinyl sulfide was carried out under similar homolytic conditions. As judged by GC-MS analysis, the main product, formed in up to 50% yield, was the adduct 3-(phenylthio)propanoic acid, although this compound was not isolated. These results supported the conclusion that **6** can be used to generate hydroxyformyl radicals in organic solvents.

We conclude that 1-phenylcyclohexa-2,5-diene-1-carboxylic esters function with good efficiency as alkyl radical sources. Good yields were obtained from intramolecular 5-*exo* ring closure reactions that were free of tin or other metal contaminants. Yields from alkylations of olefins were poor. However, it is normal in free-radical alkylations to use a large excess of olefin. In this work one equivalent (occasionally two) was used, and the low adduct yields should be evaluated in the light of this restriction. Products from competing loss of a phenyl radical from the intermediate cyclohexadienyl radicals were not observed in any situation. As a spin-off from the research, it was found that 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (**6**) can be a useful source of hydroxyformyl radicals in organic solvents.

## Experimental

$^1$H NMR spectra were recorded at 200 or 300 MHz and $^{13}$C NMR spectra at 75 MHz, in $CDCl_3$ solution with tetramethylsilane ($\delta_H = \delta_C = 0$) as reference. Coupling constants are expressed in Hz. Ether refers to diethyl ether. Light petroleum refers to the fraction boiling in the range 40–60 °C. EI mass spectra were obtained with 70 eV electron impact ionisation and CI spectra with isobutane as the target gas on a VG Autospec spectrometer. GC-MS analyses were run on a Finnigan Incos 50 quadrupole instrument coupled to a Hewlett Packard HP 5890 chromatograph fitted with a 25 m HP 17 capillary column (50% phenyl methyl silicone). For the calculation of yields from GC data, the detector response was calibrated with known

amounts of authentic materials (or close analogues) and *n*-hexadecane, *n*-heptane or 3,3-dimethylbutan-2-one were added as a standard. Chromatographic purifications were carried out using either Sorbsil C60 40/60A or BDH 40–63 μm silica gel eluting with the given solvent mixture. Ammonia was obtained from BOC and used directly from the cylinder; drying and distillation had no perceptible effect on the yields. Experimental procedures for the preparation of 1,4-dihydrobiphenyl,[9] 1-deuterio-1,4-dihydrobiphenyl, 1-phenylcyclohexa-2,5-diene-1-carboxylic acid with 3,4-dihydrobiphenyl-3-carboxylic acid (**6** + **7**), 2-(cyclohex-2-enyloxy)ethyl 1-phenylcyclohexa-2,5-diene-1-carboxylate (**11**) from (**6** + **7**) and non-1-en-6-ol are given in the supplementary information.† Experimental details of the reactions of cyclopentyl 1-phenylcyclohexa-2,5-diene-1-carboxylate with cyclohexenone, methyl acrylate, methylmethacrylate, acrylonitrile and cyclohexene are also given in the supplementary information.†

### 1-Phenylcyclohexa-2,5-diene-1-carboxylic acid (6)

1,4-Dihydrobiphenyl (13.3 g, 83.3 mmol) was dissolved in dry THF (350 $cm^3$) containing TMEDA (10.7 g, 83.3 mmol) under an atmosphere of $N_2$. To this was added BuLi (5.9 g, 92.2 mmol) at −40 °C and the resulting deep red solution was stirred for 80 min as the temperature was allowed to rise to 0 °C. The mixture was cooled to −70 °C and poured into a conical flask containing crushed dry ice causing immediate decolorisation. The THF was evaporated to yield a solid, to which ether (100 $cm^3$) and NaOH (70 $cm^3$) were added. The layers were separated and the ether layer was extracted with NaOH (2 × 70 $cm^3$). The alkaline fractions were combined and neutralised with excess HCl. The product was extracted with ether (3 × 150 $cm^3$). The ethereal extracts were combined, dried ($MgSO_4$) and the solvent was evaporated to yield a white solid (12 g) consisting of the title compound (7.8 g, 45%) and carboxylic acid **7** (4.2 g, 24%); $\delta_H$ 2.50–2.62 (2 H, m, allylic-H, **7**), 2.68–2.78 (2 H, m, allylic-H, **6**), 3.43–3.59 (1 H, m, *t*-H, **7**), 5.95–6.17 (6 H, m, CH=, **6**, **7**), 6.31–6.40 (1 H, d, *J* 10, CH=, **7**), 7.23–7.46 (10 H, m, ArH, **6**, **7**). This mixture was dissolved in dichloromethane (100 $cm^3$) to which maleic anhydride (5.56 g, 56.7 mmol) was added, and refluxed for 5 h. The mixture was extracted with NaOH (4 × 40 $cm^3$), the alkaline fractions were combined and neutralised with excess HCl. The product was extracted with ether (3 × 100 $cm^3$), the ethereal extracts were combined, dried ($MgSO_4$) and the solvent was evaporated to yield an orange liquid (15.41 g). Dichloromethane (50 $cm^3$) and silica gel were added to the product and the solvent was removed. The product adsorbed onto silica gel, was added to a sinter funnel packed with silica gel and the column was eluted with 30% ethyl acetate in light petroleum. The title compound was obtained as a white solid (6.2 g, 35%), mp 122–124 °C (Found: C, 78.27; H, 6.26. Calc. for $C_{13}H_{12}O_2$: C, 77.98, H, 6.04%); $\delta_H$ 2.68–2.78 (2 H, m, allylic-H), 5.94–6.14 (4 H, m, CH=) 7.21–7.40 (5 H, m, ArH); $\delta_C$ (50 MHz) 25.9 (allylic-C), 52.4 (C), 125.0, 126.6, 127.2, 129.0 (9 × CH), 143.3 (C), 180.0 (CO); *m*/*z* (rel. intensity) 200 (2), 156 (12), 155 (100), 154 (27), 153 (24), 152 (14), 128 (12), 115 (16), 77 (54), 76 (18), 51 (31).

### Cyclopentyl 1-phenylcyclohexa-2,5-diene-1-carboxylate (10)

Thionyl chloride (2.38 g, 0.02 mol) was added to 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (1.0 g, 0.005 mol) dissolved in dry dichloromethane (20 $cm^3$). This mixture was refluxed under nitrogen for 6 h and the solvent evaporated to give the acid chloride. The acid chloride was dissolved in dry dichloromethane (10 $cm^3$) and added dropwise to a mixture of cyclopentanol (0.43 g, 0.005 mol), 2,6-lutidine (0.54 g, 0.005 mol) and a catalytic amount of DMAP, in dry dichloromethane (10 $cm^3$) and the resultant mixture was refluxed under nitrogen for 6 h. The contents were washed with NaOH (2 × 50 $cm^3$) followed by HCl (2 × 50 $cm^3$) and water (2 × 50 $cm^3$). The organic layer was dried ($MgSO_4$) and the solvent evaporated to yield a yellow oil (1.4 g). The title compound was obtained as a slightly yellow oil by column chromatography, eluting with 2.5% ethyl acetate in light petroleum (1.20 g, 84%). $\delta_H$ 1.52–1.95 (8 H, m, 4 × $CH_2$), 2.70–2.77 (2 H, m, allylic-H), 5.21–5.28 (1 H, m, *t*-H), 5.91–6.15 (4 H, m, CH=), 7.20–7.40 (5 H, m, ArH); $\delta_C$ 23.6, 25.8, 32.4, 52.4, 78.0, 124.8, 126.4, 126.8, 127.9, 128.7, 144.2, 173.4; *m*/*z* (rel. intensity) 201 (2), 156 (100), 155 (25), 128 (6), 115 (8), 77 (44), 69 (42), 51 (19), 41 (68), 39 (19). The ester was obtained in 38% yield using pyridine as base. MS and microanalysis indicated minor contamination by biphenyl.

### 2-(Cyclohex-2-enyloxy)ethyl 1-phenylcyclohexa-2,5-diene-1-carboxylate (11)

Thionyl chloride (7.14 g, 60 mmol) was added to 1-phenylcyclohexa-2,5-diene-1-carboxylic acid **6** (3 g, 15 mmol) in dry dichloromethane (30 $cm^3$). This was refluxed for 6 h and the solvent was evaporated to yield acid chloride **8** (3.3 g); $\delta_H$ 2.74–2.80 (2 H, m), 6.07–6.14 (4 H, s), 7.24–7.47 (5 H, m). The acid chloride was dissolved in dichloromethane (15 $cm^3$) and added dropwise to a mixture of 3-(2-hydroxyethoxy)cyclohexene (1.92 g, 13.5 mmol), pyridine (1.2 g, 15 mmol) and a catalytic amount of DMAP, in dry dichloromethane (30 $cm^3$) and the mixture was refluxed for 2.5 h. The contents were washed with NaOH (2 × 20 $cm^3$) followed by HCl (2 × 20 $cm^3$). The organic layer was dried ($MgSO_4$) and the solvent was evaporated to yield an orange oil (4.8 g). The title compound was obtained as a pale yellow liquid by column chromatography eluting with 20% ethyl acetate in light petroleum (3.48 g, 75%); $\delta_H$ 1.51–2.05 (6 H, m, 3 × $CH_2$), 2.65–2.75 (2 H, m, allylic-H), 3.55–3.95 (3 H, m, $CH_2$, *t*-H), 4.28–4.32 (2 H, t, *J* 4.9, $CH_2$), 5.61–6.15 (6 H, m, CH=), 7.18–7.25 (5 H, m, ArH); $\delta_C$ 19.1, 25.2, 25.8, 28.1, 52.4, 64.7, 65.7, 73.1, 124.8, 125.5, 126.3, 126.8, 127.6, 128.6, 131.0, 143.8, 173.5; *m*/*z* (rel. intensity) 324 ($M^+$, 1 %), 242 (6), 228 (6), 225 (7), 181 (5), 155 (100), 128 (10), 115 (10), 81 (36), 77 (27) (Found: $M^+$, 324.1737. $C_{21}H_{24}O_3$ requires 324.1725).

### Ethyl 1-phenylcyclohexa-2,5-diene-1-carboxylate

To 1,4-dihydrobiphenyl (2 g, 12.8 mmol) in dry THF (75 $cm^3$) under an atmosphere of $N_2$ was added BuLi (0.95 g, 14 mmol) at −40 °C and the resulting dark red solution was left stirring for 80 min as the temperature was allowed to rise to 0 °C. The mixture was quenched with ethyl chloroformate (1.53 g, 14 mmol) in dry THF (5 $cm^3$) causing the solution to turn pale red. Another addition of ethyl chloroformate (1.53 g, 14 mmol) caused the solution to turn yellow and this mixture decolorised overnight. The solvent was evaporated, ether (150 $cm^3$) was added to the residue and this was washed with $H_2O$ (2 × 100 $cm^3$). The ether layer was dried ($MgSO_4$) and the solvent was evaporated to give an orange oil (3.47 g). The title compound was obtained as a slightly discolored liquid by column chromatography eluting with 15% ethyl acetate in light petroleum (0.78 g, 27%); $\delta_H$ 1.23–1.31 (3 H, t, *J* 7.2, $CH_3$), 2.93–3.00 (2 H, m, allylic-H), 4.18–4.30 (2 H, q, *J* 7.2, $CH_2$), 5.98–6.38 (4 H, m, CH=), 7.29–7.50 (5 H, m, ArH).

### Attempted preparation of 1-phenylcyclohexa-2,5-diene-1-carboxylates with phosgene

To 1,4-dihydrobiphenyl (1 g, 6.41 mmol) in dry THF (50 $cm^3$) under an atmosphere of $N_2$ was added BuLi (0.45 g, 7.04 mmol) at −78 °C and the resulting dark red solution was left stirring for 80 min at −60 °C to −78 °C. Using a cannula, the mixture was added to phosgene (0.76 g, 7.7 mmol) in toluene cooled to −78 °C, and the resulting mixture was left stirring overnight. The solvent was evaporated and ether (50 $cm^3$) was added to the residue and this was washed with $H_2O$ (50 $cm^3$). The ether layer was dried ($MgSO_4$) and the solvent was evaporated to give

a liquid which was shown by $^1$H NMR to be a mixture of unreacted 1,4-dihydrobiphenyl and biphenyl.

### Non-1-en-6-yl 1-phenylcyclohexa-2,5-diene-1-carboxylate (12)

Thionyl chloride (2.38 g, 0.02 mol) was added to the 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (1.0 g, 0.005 mol) in dry dichloromethane (20 cm$^3$). This mixture was refluxed under nitrogen for 6 h and the solvent evaporated to give the acid chloride (some biphenyl was also formed). The acid chloride was dissolved in dry dichloromethane (10 cm$^3$) and added dropwise to a mixture of non-1-en-6-ol (0.71 g, 0.005 mol), 2,6-lutidine (0.54 g, 0.005 mol) and a catalytic amount of DMAP, in dry dichloromethane (10 cm$^3$) and the resultant mixture was refluxed under nitrogen for 6 h. The contents were washed with NaOH (2 × 50 cm$^3$) followed by HCl (2 × 50 cm$^3$) and water (2 × 50 cm$^3$). The organic layer was dried ($MgSO_4$) and the solvent evaporated to yield a yellow oil (1.50 g, 93%). Ester **12** was also obtained in 36% yield, after Kugelrohr distillation, using pyridine as base. $\delta_H$ 0.80–0.92 (3 H, m, $CH_3$), 1.20–1.59 (8 H, m, $(CH_2)_4$–$CH_2CH$=$CH_2$), 1.92–2.0 (2H, m, $CH_2$–CH=$CH_2$), 2.64–2.75 (2 H, m, bisallylic H), 4.89–5.00 (2 H, m, overlapping peak of $CH_3(CH_2)_2$–$CH$–$(CH_2)_3CH$=$CH_2$), 5.65–5.78 (1 H, m, CH= in nonenol chain), 5.85–6.15 (4 H, m, CH= in diene), 7.20–7.38 (5 H, m, ArH); $\delta_C$ 13.8, 18.2, 24.1, 25.7, 33.1, 33.3, 35.9, 52.4, 74.7, 114.6, 124.9, 125.3, 125.8, 126.2, 126.3, 126.7, 127.1, 127.2, 127.7, 138.4, 143.9, 173.9; *m*/*z* (rel. intensity) 200 (2), 156 (12), 155 (100), 154 (23), 153 (10), 128 (5), 115 (7), 83 (16), 77 (24), 69 (33), 55 (40), 41 (35). Ester **12** was also purified by column chromatography, eluting with 2.5% ethyl acetate in light petroleum.

### Thermal treatment of 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (6) in $C_6D_6$

Acid **6** (0.03 g, 0.14 mmol) in $C_6D_6$ (0.5 cm$^3$), in a sealed NMR tube, was placed into an oven at 110 °C and monitored by NMR at various intervals. After a total of 24 h at 110 °C, no change was observed in the $^1$H NMR spectrum.

### Benzoyl peroxide induced fragmentation of ester 11

Ester **11** (0.43 g, 1.3 mmol) and dibenzoyl peroxide (0.24 g, 56 wt%) were dissolved in benzene (2.5 cm$^3$) and refluxed for 24 h. A sample of the reaction mixture was submitted for GC-MS; *peak no. 248*, 7-oxabicyclo[4.3.0]nonane (**18**), *m*/*z* (rel. intensity) 126 ($M^+$) (11), 83 (100), 55 (35), 41 (28), 39 (31), 29 (22), 27 (32); *peak no. 353*, 2-(cyclohex-2-enyloxy)ethyl formate (**19**) and benzoic acid; *peak no. 404*, biphenyl; *peak no. 491*, *m*/*z* (rel. intensity) 202 ($M^+$, 4), 105 (100), 97 (15), 81 (36), 79 (60), 77 (64), 51 (37), 41 (24), 27 (20), 18 (11), 3-(2-phenylethoxy)cyclohexene. Ether (10 cm$^3$) was added to the reaction flask and the contents were washed with NaOH (2 × 10 cm$^3$). The alkaline fractions were combined and washed with light petroleum (10 cm$^3$). The organic fractions were combined, dried over ($MgSO_4$) and the solvents were removed by atmospheric distillation using a Vigreux column. Bicyclic ether **18** was difficult to isolate because its boiling point was not sufficiently different from that of the solvents. Residual benzene was still present and the yield of 7-oxabicyclo[4.3.0]nonane was estimated by GC to be 31%, using added 9-methylene-7-oxabicyclo[4.3.0]nonane as a standard; $\delta_H$ (lit.[4]) 1.2–2.1 (11 H, m), 3.78–3.92 (2 H, m), 3.92–4.05 (1 H, q, *J* 7.8).

### Radical-induced fragmentation of ester 11 in *tert*-amyl alcohol

Ester **11** (0.49 g, 1.4 mmol) and hexadecane (0.105 g, 0.46 mmol) were dissolved in *tert*-amyl alcohol (5 cm$^3$) to which *tert*-butyl peroxybenzoate (0.24 g, 50 wt%) was added. This mixture was refluxed for 15 h and a sample was analysed by GC-MS; *peak no. 236*, 7-oxabicyclo[4.3.0]nonane (**18**); *peak no. 346*, *m*/*z* (rel. intensity) 142 (1), 125 (1), 97 (12), 81 (28), 79 (21), 74 (41), 73 (100), 45 (35), 41 (26), 39 (21), 28 (27), 2-(cyclohex-2-enyloxy)ethyl formate (**19**); *peak no. 387*, biphenyl. None of the starting ester remained according to the GC-MS analysis when the reaction was terminated. Using hexadecane as standard the yields of cyclic ether **18** and biphenyl were calculated by NMR to be 66% and 62% respectively. The solvent was evaporated to give predominantly biphenyl and hexadecane, *i.e.* no polymer or similar involatiles were detected. A repeat experiment yielded similar results.

### Radical induced cyclisation of non-1-en-6-yl 1-phenylcyclohexa-2,5-diene-1-carboxylate (12)

The nonenol ester **12** (0.05 g, 0.15 mmol) and dibenzoyl peroxide (0.02 g, 50 wt%) were dissolved in benzene (0.5 cm$^3$). The mixture was refluxed for 24 h before a further portion of dibenzoyl peroxide (0.02 g) was added. After a total of 48 h reflux, the solvent was evaporated and the products analysed. GC-MS: *peak no. 184*, *m*/*z* (rel. intensity) 126 ($M^+$, 18), 97 (28), 84 (48), 83 (55), 78 (85), 70 (50), 63 (100), 57 (95), 45 (35), 41 (72), *cis*-1-methyl-2-propylcyclopentane (library fit 986), 16.3%; *peak 198*, *m*/*z* (rel. intensity) 126 (12), 98 (15), 97 (25), 84 (28), 83 (55), 70 (50), 69 (38), 63 (30), 56 (72) 55 (100), 41 (65), *trans*-1-methyl-2-propylcyclopentane (library fit 997), 47.5%. The chromatogram also showed benzoic acid, biphenyl and a minor amount of unreacted **12**.

### The radical-initiated reaction of 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (6) with butyl vinyl ether in cyclohexane

Acid **6** (0.05 g, 0.25 mmol), butyl vinyl ether (0.05 g, 0.5 mmol) and dibenzoyl peroxide (0.01 g, 50 wt%) were dissolved in cyclohexane (0.5 cm$^3$). The mixture was refluxed for 24 h before a further portion of dibenzoyl peroxide (0.01 g) was added. After a total of 48 h reflux the solvent was evaporated and the products analysed by GC-MS. *Peak no. 153*, *n*-butanol; *peak no. 618*, *m*/*z* (rel. intensity) 159 (7), 101 (58), 83 (6), 57 (92), 45 (100), 43 (22), 41 (66), 1,1-di-*n*-butoxyethane (**23**, library fit 978); *peak no. 791*, benzoic acid; *peak no. 850*, biphenyl; *peak no. 1240*, *m*/*z* (rel. intensity) 221 (4), 165 (2), 159 (12), 105 (39), 103 (22), 77 (20), 57 (100), 41 (35), 1-(di-*n*-butoxymethoxy)-butane (**22**, library fit 961).

### The radical-initiated reaction of 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (6) with butyl vinyl ether in *tert*-amyl alcohol

Acid **6** (0.05 g, 0.25 mmol), butyl vinyl ether (0.05 g, 0.5 mmol) and dibenzoyl peroxide (0.01 g, 50 wt%) were dissolved in *tert*-amyl alcohol (0.5 cm$^3$). The mixture was refluxed for 24 h before a further portion of dibenzoyl peroxide (0.01 g) was added. After a total of 48 h reflux, the solvent was evaporated and the products analysed by GC-MS; *peak no. 404*; *m*/*z* (rel. intensity) 101 ($M - H^+$, 3), 87 (13), 57 (100), 56 (22), 41 (50), 29 (43), 28 (68), *n*-butyl formate (**21**); *peak no. 624*, 1,1-di-*n*-butoxyethane (**23**); *peak no. 811*, benzoic acid; *peak no. 856*, biphenyl; *peak no. 1239*, 1-(di-*n*-butoxymethoxy)butane (**22**).

### The radical-initiated reaction of 1-phenylcyclohexa-2,5-diene-1-carboxylic acid (6) with phenyl vinyl sulfide

Acid **6** (0.025 g, 0.125 mmol), phenyl vinyl sulfide (0.04 g, 0.25 mmol) and dibenzoyl peroxide (0.01 g, 50 wt%) were dissolved in benzene (0.5 cm$^3$). The mixture was refluxed for 24 h before a further portion of dibenzoyl peroxide (0.01 g) was added. After a total of 48 h reflux, the solvent was evaporated and the products analysed by GC-MS; the chromatogram showed starting sulfide, benzoic acid, biphenyl and *peak no. 463*, *m*/*z* (rel. intensity) 176 (2), 152 (12), 137 (6), 135 (13), 125 (12), 123 (14), 109 (32), 104 (100), 97 (20), 91 (18), 78 (71), 77 (65), 51 (88) 3-(phenylthio)propanoic acid (25% based on *tert*-butylbenzene added as reference); *peak no. 645* diphenyl disulfide (20%). The reaction was repeated adding the peroxide

slowly over 48 h. The adduct yield increased to 50% and PhSH (library fit 976) was identified as a trace product. In cyclohexane as solvent the adduct yield was greatly reduced.

## Acknowledgements

We thank the EPSRC for financial support of this research (grants GR/L49185 and GR/J28315).

## References

1 G. Binmore, J. C. Walton and L. Cardellini, *J. Chem. Soc., Chem. Commun.*, 1995, 27.
2 G. Binmore, L. Cardellini and J. C. Walton, *J. Chem. Soc., Perkin Trans. 2*, 1997, 757.
3 P. A. Baguley, G. Binmore, A. Milne and J. C. Walton, *Chem. Commun.*, 1996, 2199.
4 P. A. Baguley and J. C. Walton, *J. Chem. Soc., Perkin Trans. 1*, 1998, 2073.
5 A. Studer and S. Amrein, *Angew. Chem., Int. Ed.*, 2000, **39**, 3080.
6 S. Amrein, A. Timmermann and A. Studer, *Org. Lett.*, 2001, **3**, 2357.
7 B. M. Ratnayake Bandara, A. J. Birch, B. Chauncy and L. F. Kelly, *J. Organometal. Chem.*, 1981, **208**, C31.
8 P. A. Baguley and J. C. Walton, *J. Chem. Soc., Perkin Trans. 2*, 1998, 1423.
9 D. F. Lindow, C. N. Cortez and R. G. Harvey, *J. Am. Chem. Soc.*, 1972, **94**, 5406.