

Oxidative addition of 1,3-dicarbonyl compounds to alkenes mediated by cerium(IV) ammonium nitrate and manganese(III) acetate: a comparative study

Vijay Nair,* Jessy Mathew and K. V. Radhakrishnan

Organic Chemistry Division, Regional Research Laboratory (CSIR), Trivandrum 695 019, India

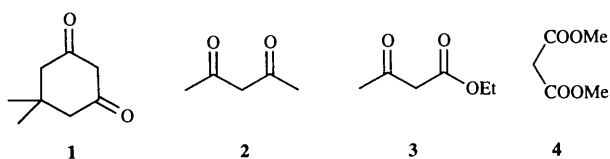
The oxidative addition of dimedone, acetylacetone and ethyl acetoacetate to cyclic and acyclic alkenes mediated by CAN gives dihydrofurans in good yields. Similar addition of the radical generated from dimethyl malonate to alkenes provides lactones. A comparative study of these reactions *vis-à-vis* those mediated by $Mn(OAc)_3$ has shown that the former generally lead to higher yields of products. The milder reaction conditions, experimental simplicity, and the solubility of CAN in common organic solvents like methanol, acetonitrile and THF are other advantages. Thus it appears from this study that CAN is superior to the commonly used $Mn(OAc)_3$.

Introduction

The conceptualization as well as the demonstration¹ that radical methodology offers a powerful alternative to ionic reactions in complex carbocyclic constructions has led to a revival of interest in developing novel reagents and procedures for the generation of radicals.^{2,3} Oxidative methods mediated by salts of Mn^{III} , Cu^{II} , Ag^I , V^V , Fe^{III} , etc. have been explored.⁴ However, among the metal oxidants, $Mn(OAc)_3$ has received the most attention; it has been used in a number of novel approaches to the synthesis of a wide variety of compounds including complex natural products.⁵ In spite of the widespread use of $Mn(OAc)_3$, a number of problems have been associated with this reagent^{5a} and there has been interest in developing newer reagents and procedures for generating radicals.

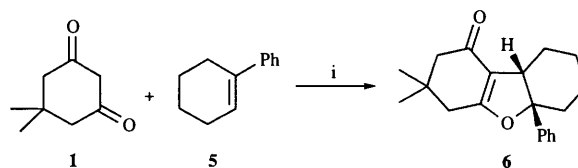
Although it was known from the initial work of Heiba and Dessau⁶ on the oxidative addition of ketones and carboxylic acids to alkenes, and subsequent investigations by Kurz⁷ on aromatic nitromethylation and acetylation, that Ce^{IV} reagents are useful in generating carbon-centred radicals, nothing was done until recently to exploit the synthetic potential of these reagents especially in C–C bond-forming reactions. In 1986, cerium(IV) ammonium nitrate (CAN)-mediated addition of 1,3-dicarbonyl compounds to buta-1,3-diene⁸ and malonylation of arenes⁹ were reported. Subsequently, reports on the oxidative addition of ketones to enol acetates¹⁰ and CAN-mediated cross-coupling of enol silyl ethers¹¹ appeared. Later, allyl phenyl sulfides¹² and enamines¹³ were coupled with enol silyl ethers *via* CAN-mediated processes. Oxidative addition of 1,3-dicarbonyl compounds to styrene¹⁴ and siloxycyclopropane to buta-1,3-diene¹⁵ was also reported. Isolated reports¹⁶ on intramolecular C–C bond-forming reactions have also appeared.

In spite of the above investigations, there has been no information available on the CAN-mediated addition of active methylene compounds to unactivated alkenes; no comparative data on CAN-mediated reactions *vis-à-vis* $Mn(OAc)_3$ existed. We have therefore carried out¹⁷ a systematic investigation of the addition of 1,3-dicarbonyl compounds **1–4** to a number of cyclic and acyclic alkenes mediated by CAN and $Mn(OAc)_3$ and the results are presented here.



Results and discussion

CAN-mediated addition of dicarbonyl compounds **1–3** to cyclic and acyclic alkenes occurs rapidly to afford 2,3-dihydrofurans in moderate to good yields. Scheme 1 is illustrative.



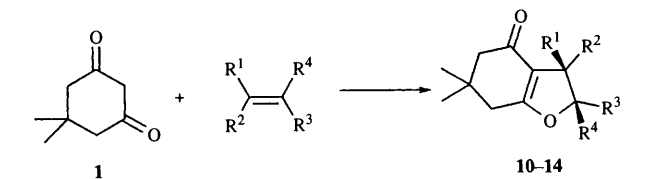
Scheme 1 Reagents and conditions: i, CAN (2 mol equiv.), MeOH, 5 °C, 15 min (98%)

The structure of product **6** was assigned on the basis of its IR and NMR spectral data. The IR spectrum exhibited a carbonyl absorption at 1633 cm^{-1} . In the ^1H NMR spectrum, aromatic protons resonated as a multiplet centred at δ 7.32 and the methine proton resonated as a triplet at δ 3.44. The spectrum also contained two singlets at δ 1.14 and 1.08 due to the protons of the two CH_3 groups. The characteristic resonances at δ_C 194.9, 174.6, 114.9 and 94.1 in the ^{13}C NMR spectrum further confirmed the structure.

Since two mole equivalents of CAN are required for the completion of the reaction, a tentative mechanism for the reaction may be formulated as shown in Scheme 2.

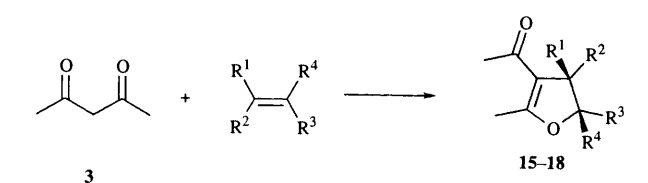
In a comparative experiment, dimedone **1** was treated with 1-phenylcyclohexene **5** in presence of $Mn(OAc)_3$ in refluxing ethanol. Even after 24 h, there was no reaction. However the above product **6** was isolated in 84% yield when the reaction was carried out in refluxing glacial acetic acid. The results of similar reactions of dimedone with a number of alkenes are summarized in Table 1. The J values for the proton geminal to the phenyl group in the products **12**, **13** and **14** are 6.0, 5.0 and 7.1 Hz respectively (see Experimental section). The values calculated by the MMX program for the *cis*-products **12**, **13** and **14** are 6.1, 5.7 and 7.1 Hz whereas the values calculated for the *trans*-products are 10.4, 10.03 and 9.45 Hz, respectively. It is also noteworthy that similar dihydrofurans synthesized by Co(OAc)_2 -mediated reactions¹⁸ have been reported to have *cis*-stereochemistry. Therefore *cis*-stereochemistry has been assigned for all the dihydrofuran derivatives in Table 1.

Analogous to the reaction of dimedone, the reactions of acetylacetone and ethyl acetoacetate with alkenes also afforded

Table 1 Oxidative addition of dimedone **1** to alkenes


Entry	Alkene	Product	Yield (%) ^{a,b}
1	R ¹ = H, R ² , R ³ = [CH ₂] ₄ , R ⁴ = CH ₃	10	57 (47)
2	R ¹ = H, R ² = C ₂ H ₅ , R ³ = R ⁴ = CH ₃	11	60 (41)
3	R ¹ = R ⁴ = H, R ² = CH ₂ OCH ₃ , R ³ = Ph	12	65 (55)
4	R ¹ = R ⁴ = H, R ² = CH ₂ OCOCH ₃ , R ³ = Ph	13	45 (37)
5	R ¹ = R ⁴ = H, R ² = CH ₂ OH, R ³ = Ph	14	55 (14)

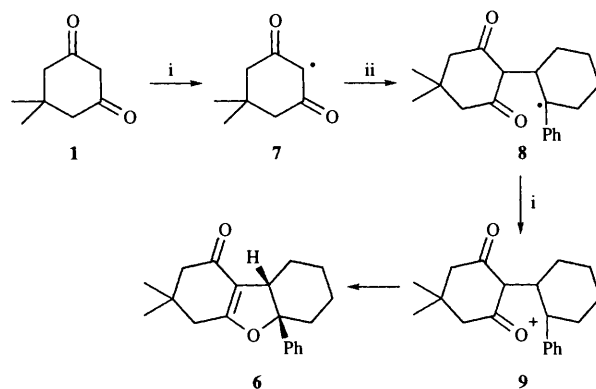
^a Isolated yield. ^b Yields obtained with Mn(OAc)₃-mediated reactions are given in parentheses.

Table 2 Oxidative addition of acetylacetone **2** to alkenes


Entry	Alkene	Product	Yield (%) ^{a,b}
1	R ¹ = H, R ² , R ³ = [CH ₂] ₄ , R ⁴ = Ph	15	96 (83)
2	R ¹ = R ⁴ = H, R ² = CH ₂ OCH ₃ , R ³ = Ph	16	58 (54)
3	R ¹ = H, R ² , R ³ = [CH ₂] ₄ , R ⁴ = CH ₃	17	40 (39)
4	R ¹ = H, R ² = C ₂ H ₅ , R ³ = R ⁴ = CH ₃	18	60 (39)
		19	16 (8)

^a Isolated yield. ^b Yields obtained with Mn(OAc)₃-mediated reactions are given in parentheses.

2,3-dihydrofurans. However, the addition to 2-methylpent-2-ene furnished products **19** and **24** in addition to the dihydrofurans **18** and **23**. The results obtained in these reactions are presented in Tables 2 and 3. In the product **16** the observed *J*-value for the proton geminal to the phenyl group is 3.7 Hz. This is much lower than the corresponding value for the product **12**. However, it is in line with the *J*-value calculated by the MMX program (*i.e.*, 2.3 Hz) for the *cis*-product whereas the value calculated for the *trans*-product is 9.8 Hz. Therefore *cis*-stereochemistry has been assigned to the dihydrofuran derivatives in Table 2. Similarly, the dihydrofuran derivatives **20–22** have been assigned *cis*-stereochemistry. This is based on the fact that the observed *J*-value for the proton geminal to the phenyl group in the product **22** (5.0 Hz) is very close to the value calculated for the *cis*-product (5.3 Hz) by the MMX program. The corresponding value calculated for the *trans*-product is 9.8 Hz.

**Scheme 2** Reagents: i, CAN; ii, **5**

Unlike the CAN-mediated oxidative additions of dicarbonyl compounds **1–3**, the reaction of dimethyl malonate **4** with most of the alkenes took a different course. For example, when dimethyl malonate was treated with 1-phenylcyclohexene **5** or cinnamyl methyl ether under the same conditions described earlier, no addition of malonyl radical to the alkene occurred. However, additions to both these alkenes took place when the experiment was carried out in aq. methanol. Thus the reaction of diester **4** with cinnamyl methyl ether afforded the lactone **29** in 58% yield. Its IR spectrum showed two carbonyl absorptions at 1790 and 1743 cm⁻¹. The ¹H NMR spectrum exhibited a signal at δ 5.20 which could be attributed to the proton geminal to the lactone ring oxygen atom. The characteristic carbon resonances at δ_C 170.4, 167.1 and 81.1 also helped to confirm the structure **29**. The formation of the lactone can be explained as follows. The initial addition of malonyl radical to cinnamyl methyl ether followed by oxidation would produce the cation **25**. Since the reaction is performed in aq. methanol, cation **25** would be easily converted into alcohol **26**, which on loss of methanol would furnish lactone **29**. Alternatively, lactol **28** formed from cation **25** *via* the stabilized cation **27** can lose methanol to afford lactone **29** (Scheme 3).

Similarly the oxidative addition of dimethyl malonate **4** to 1-phenylcyclohexene **5** led to the lactone **30** [equation (1)].

Dimethyl malonate **4** reacted smoothly with 2-methylpent-2-ene in methanol and afforded products **34** and **37**. The mechanistic pathways suggested for this reaction are shown in Scheme 4. The radical **31** generated by CAN from dimethyl malonate undergoes addition to 2-methylpent-2-ene leading to the radical **32**. This radical, on oxidation by CAN, would give the cation **33** which can lose a proton to give product **34** (path a). Alternatively, the cation **33** can undergo cyclization to afford stabilized cation **35** which can lose a proton to furnish the dihydrofuran **36**. The latter on work-up will undergo hydrolysis leading to lactone **37**.

In the Mn(OAc)₃-mediated reaction of dimethyl malonate **4** with 1-phenylcyclohexene **5** and cinnamyl methyl ether, no addition of malonate to the alkenes was observed; instead the alkenes underwent decomposition resulting in intractable products. However, the reaction with 2-methylpent-2-ene furnished compounds **34** and **37** in 17 and 30% yield, respectively.

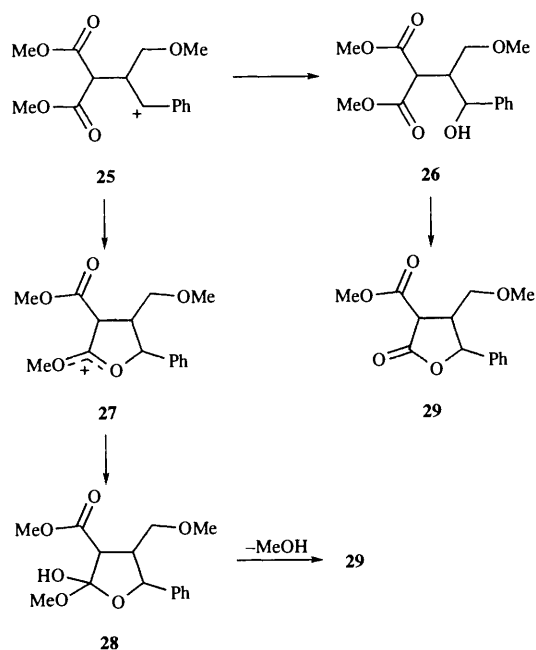
In conclusion, the CAN-mediated addition of dimedone **1**, acetylacetone **2** and ethyl acetoacetate **3** to alkenes offers a simple method for the synthesis of dihydrofurans in good yields, and the addition of dimethyl malonate **4** to alkenes provides lactones in moderate yields. In terms of the solubility of CAN in common organic solvents such as methanol, acetonitrile and tetrahydrofuran (THF), the milder reaction conditions, experimental simplicity and the generally higher yields of products (with the exception of reactions involving ethyl acetoacetate **3**), CAN appears to be superior to the more commonly used Mn(OAc)₃.

Table 3 Oxidative addition of ethyl acetoacetate **3** to alkenes

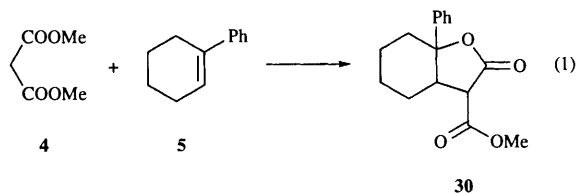
Entry	Alkene	Product	Yield (%) ^{a,b}
1	R ¹ = H, R ² , R ³ = [CH ₂] ₄ , R ⁴ = Ph	20	40 (68)
2	R ¹ = H, R ² , R ³ = [CH ₂] ₄ , R ⁴ = CH ₃	21	20 (33)
3	R ¹ = R ⁴ = H, R ² = CH ₂ OCH ₃ , R ³ = Ph	22	65 (67)
4	R ¹ = H, R ² = C ₂ H ₅ , R ³ = R ⁴ = CH ₃	23	37 (45)

24 (9)

^a Isolated yield. ^b Yields obtained with Mn(OAc)₃-mediated reactions are given in parentheses.

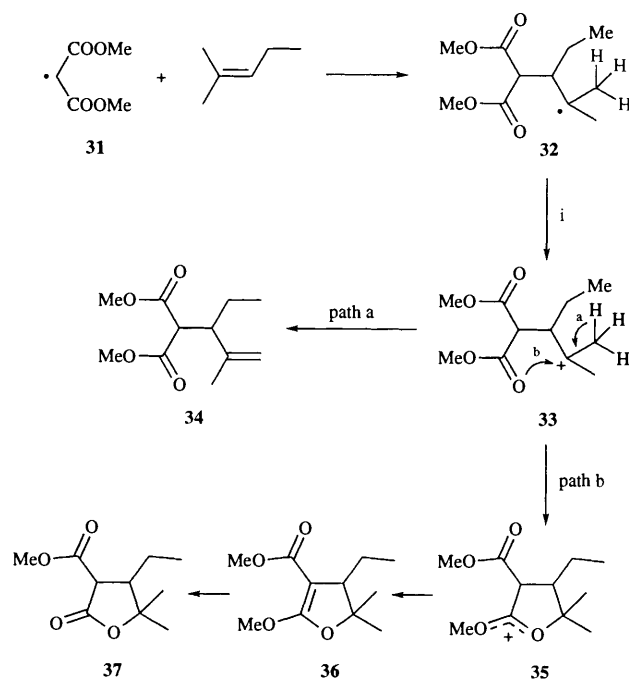


Scheme 3



Experimental

IR spectra were recorded on a Perkin-Elmer Model 882 spectrophotometer. Proton and carbon nuclear resonance spectra were recorded on Nicolet GE-300, JEOL-EX-90 and



Scheme 4 Reagent: i, CAN

Hitachi R24B-60 NMR spectrometers with tetramethylsilane as internal standard. *J*-Values are given in Hz. Mass spectra were recorded on Finnigan MAT 1020 B and Hewlett Packard 5890 mass spectrometers. The relative intensities of the *m/z*-values are given in parentheses. Elemental analyses were performed on a Hewlett Packard 185-B CHN analyser. Light petroleum refers to the fraction boiling between 60 and 80 °C. Silica gel (100–200 mesh) was used for column chromatography. All solvent extracts were dried over anhydrous Na₂SO₄.

Synthesis of dihydrofurans: General procedure

A solution of CAN (2.52 g, 4.6 mmol) in methanol (20 cm³) was added dropwise to an ice-cooled, stirred mixture of a dicarbonyl compound **1**, **2** or **3** (2.4 mmol) and alkene (2.0 mmol) in methanol (10 cm³). In most of the cases the reddish brown colour of CAN disappeared by the time the addition was over (*ca.* 15 min). In the remaining cases it took *ca.* 30–45 min for completion of the reaction. The mixture after decolourization was diluted with water (150 cm³) and extracted with dichloromethane (3 × 40 cm³). The combined organic extracts were washed successively with water and brine, dried over anhydrous Na₂SO₄, and evaporated. The residue obtained was subjected to chromatography on a silica gel column. Elution with 10% ethyl acetate in light petroleum (unless otherwise specified) afforded the dihydrofuran derivative.

3,3-Dimethyl-5a-phenyl-1,2,3,4,5a,6,7,8,9,9a-decahydrodibenzofuran-1-one 6. A mixture of dimedone **1** (0.336 g, 2.4 mmol) and 1-phenylcyclohexene **5** (0.316 g, 2.0 mmol) was treated with CAN (2.52 g, 4.6 mmol) as described in the general procedure to afford *title compound 6* (0.579 g, 98%) as a viscous liquid (Found: C, 81.4; H, 8.25. C₂₀H₂₄O₂ requires C, 81.04; H, 8.16%); ν_{max}(CH₂Cl₂)/cm⁻¹ 2959, 2872, 1633, 1401 and 1239; δ_H(300 MHz; CDCl₃) 7.39–7.24 (5 H, m, ArH), 3.44 (1 H, t, *J* 5.1, >CHCH₂), 2.39 (2 H, d, *J* 1.4), 2.19 (2 H, s), 2.02–1.91 (4 H, m, CH₂), 1.65–1.44 (4 H, m, CH₂), 1.14 (3 H, s, CH₃) and 1.08 (3 H, s, CH₃); δ_C(22.4 MHz; CDCl₃) 194.9 (C=O), 174.6 (=C–O), 146.2, 128.6, 127.1, 124.3, 114.9 (olefinic), 94.1 (C–O), 51.2, 44.4, 37.8, 33.5, 33.2, 28.5, 27.9, 23.8 and 17.5; *m/z* (EI-MS) 296 (M⁺, 100%), 279 (10), 205 (16), 185 (15), 169 (10), 157 (75) and 130 (60).

3,3,5a-Trimethyl-1,2,3,4,5a,6,7,8,9,9a-decahydrodibenzofuran-1-one 10. The reaction of dimedone **1** (0.420 g, 3.0

mmol) and 1-methylcyclohexene (0.240 g, 2.5 mmol) with CAN (3.15 g, 5.75 mmol) as described in the general procedure afforded *title compound 10* (0.331 g, 57%) as a viscous liquid; δ_{H} (300 MHz; CDCl_3) 2.85 (1 H, t, J 5.6, $>\text{CHCH}_2$), 2.25 (2 H, d, J 1.3), 2.22 (2 H, s), 1.87–1.59 (4 H, m), 1.49–1.38 (4 H, m), 1.35 (3 H, s, CH_3) and 1.10 (6 H, s, CH_3); δ_{C} (75.5 MHz; CDCl_3) 194.98 (C=O), 175.38 (=C–O), 115.26 (olefinic), 91.88 (C–O), 51.21, 43.71, 38.18, 34.01, 32.11, 29.02, 28.27, 27.22, 24.15 and 18.56; m/z (GC-MS) 234 (M^+ , 100%), 219 (72), 201 (41), 191 (38), 166 (43), 154 (49), 135 (48) and 122 (30).

3-Ethyl-2,2,6,6-tetramethyl-2,3,4,5,6,7-hexahydro-1-benzofuran-4-one 11. The oxidative addition of dimedone **1** (0.420 g, 3.0 mmol) to 2-methylpent-2-ene (0.211 g, 2.5 mmol) in the presence of CAN (3.15 g, 5.75 mmol) was carried out following the general procedure. Pure *product 11* (0.334 g, 60%) was obtained as a pale yellow oil; δ_{H} (60 MHz; CCl_4) 2.81–2.40 (1 H, m, $>\text{CHCH}_2$), 2.25 (2 H, s), 2.12 (2 H, s), 1.75–1.50 (2 H, m), 1.35 (6 H, s, CH_3), 1.13 (6 H, s, CH_3) and 0.89–0.69 (3 H, m, CH_3); δ_{C} (22.4 MHz; CDCl_3) 194.1 (C=O), 173.9 (=C–O), 114.5 (olefinic), 92.2, 50.8, 48.5, 37.4, 32.5, 29.2, 28.1, 27.5, 21.4, 21.1 and 11.5 (Found: M^+ , 222.1613. $\text{C}_{14}\text{H}_{22}\text{O}_2$ requires M , 222.1619).

3-Methoxymethyl-6,6-dimethyl-2-phenyl-2,3,4,5,6,7-hexahydro-1-benzofuran-4-one 12. A mixture of dimedone **1** (0.420 g, 3.0 mmol) and cinnamyl methyl ether (0.371 g, 2.5 mmol) on reaction with CAN (3.15 g, 5.75 mmol) as described in the general procedure furnished *title compound 12* (0.465 g, 65%) as a pale yellow oil; δ_{H} (60 MHz; CCl_4) 7.02 (5 H, s, ArH), 5.41 (1 H, d, J 6.0, $>\text{CHPh}$), 3.60–3.32 (2 H, m, OCH_2), 3.21 (4 H, s, OCH_3 , $>\text{CHCH}_2$), 2.20 (2 H, s), 2.02 (2 H, s) and 1.05 (6 H, s, CH_3); δ_{C} 193.5 (C=O), 176.2 (=C–O), 140.3, 128.1, 127.5, 124.5, 110.4 (olefinic), 89.1 (C–O), 72.2, 59.3, 50.8, 48.9, 37.6, 33.4, 28.0 and 27.5; m/z (GC-MS) 286 (M^+ , 18%), 271 (12), 254 (48), 241 (100), 199 (35), 165 (18), 157 (29) and 128 (25).

3-Acetoxyethyl-6,6-dimethyl-2-phenyl-2,3,4,5,6,7-hexahydro-1-benzofuran-4-one 13. A mixture of dimedone **1** (0.336 g, 2.4 mmol) and cinnamyl acetate (0.352 g, 2.0 mmol) was treated with CAN (2.52 g, 4.6 mmol) as described in the general procedure to afford *title compound 13* (0.282 g, 45%) as a pale yellow oil; δ_{H} (60 MHz; CCl_4) 7.11 (5 H, s, ArH), 5.35 (1 H, d, J 5.0, $>\text{CHPh}$), 4.42–4.10 (2 H, m, OCH_2), 3.45–3.25 (1 H, m, $>\text{CHCH}_2$), 2.32 (2 H, s), 2.10 (2 H, s), 1.91 (3 H, s, COCH_3) and 1.10 (6 H, s, CH_3); δ_{C} (22.4 MHz; CDCl_3) 194.4 (C=O), 176.7 (=C–O), 140.7, 128.5, 127.9, 125.2, 110.9 (olefinic), 89.5 (C–O), 72.6, 58.7, 51.1, 48.60, 37.8, 34.0, 28.6 and 28.2; m/z (GC-MS) 271 (M^+ – COCH_3 , 10%), 254 (46), 241 (100), 199 (35), 165 (18), 157 (28), 128 (25) and 115 (46).

3-Hydroxymethyl-6,6-dimethyl-2-phenyl-2,3,4,5,6,7-hexahydro-1-benzofuran-4-one 14. The reaction of dimedone **1** (0.420 g, 3.0 mmol) and cinnamyl alcohol (0.335 g, 2.5 mmol) with CAN (3.15 g, 5.75 mmol) as described in the general procedure furnished *title compound 14* (0.353 g, 52%) as a viscous liquid (Found: C, 74.95; H, 7.4. $\text{C}_{17}\text{H}_{20}\text{O}_3$ requires C, 74.96; H, 7.41%). δ_{H} (60 MHz; CCl_4) 7.11 (5 H, s, ArH), 5.30 (1 H, d, J 7.1, $>\text{CHPh}$), 4.32 (1 H, br s, OH), 3.50 (2 H, d, J 6.0, CH_2OH), 3.32–3.03 (1 H, m, $>\text{CHCH}_2\text{OH}$), 2.25 (2 H, s), 2.08 (2 H, s) and 1.0 (6 H, s, CH_3); δ_{C} (22.4 MHz; CDCl_3) 195.9 (C=O), 177.8 (=C–O), 139.9, 128.5, 128.1, 125.3, 113.49 (olefinic), 88.5 (C–O), 63.5, 51.1, 50.3, 37.5, 34.2 and 28.3; m/z (GC-MS) 272 (M^+ , 10%), 254 (12), 241 (100), 199 (40), 185 (30), 166 (90), 157 (25) and 128 (40).

3-Acetyl-2-methyl-7a-phenyl-3a,4,5,6,7,7a-hexahydrobenzofuran 15. The reaction of CAN (3.15 g, 5.75 mmol) with a mixture of acetylacetone **2** (0.30 g, 3.0 mmol) and 1-phenylcyclohexene **5** (0.396 g, 2.5 mmol) as described in the general procedure afforded *title compound 15* as a pale yellow, viscous liquid (0.614 g, 96%) (Found: C, 79.6; H, 7.85. $\text{C}_{17}\text{H}_{20}\text{O}_2$ requires C, 79.65; H, 7.86%); δ_{H} (60 MHz; CCl_4) 7.05 (5 H, s, ArH), 3.17 (1 H, t, J 5.9, $>\text{CHCH}_2$), 2.15 (3 H, s, CH_3),

1.90 (3 H, s, COCH_3) and 1.61–1.12 (8 H, m, CH_2); δ_{C} 194.1 (C=O), 166.5 (=C–O), 147.2, 128.3, 126.8, 124.1, 118.5 (olefinic), 90.0 (C–O), 46.9, 34.1, 28.9, 26.8, 19.3, 18.8 and 15.2; m/z (EI-MS) 256 (M^+ , 20%), 238 (11), 213 (38), 195 (32), 156 (28), 141 (20), 129 (30) and 105 (100).

4-Acetyl-3-methoxymethyl-5-methyl-2-phenyl-2,3-dihydrofuran 16. A mixture of acetylacetone **2** (0.240 g, 2.4 mmol) and cinnamyl methyl ether (0.296 g, 2.0 mmol) in acetonitrile (10 cm^3) was treated with a solution of CAN (2.52 g, 4.6 mmol) in acetonitrile (20 cm^3) as described in the general procedure to afford *compound 16* (0.418 g, 85%) as a pale yellow oil; δ_{H} (300 MHz; CDCl_3) 7.41–7.26 (5 H, m, ArH), 5.49 (1 H, d, J 3.7, $>\text{CHPh}$), 3.66–3.64 (1 H, t, J 5.9, $>\text{CHCH}_2$), 3.48–3.41 (2 H, m, CH_2OCH_3), 3.39 (3 H, s, OCH_3), 2.36 (3 H, s, CH_3) and 2.26 (3 H, s, COCH_3); δ_{C} (75.5 MHz; CDCl_3) 193.84 (C=O), 168.63 (=C–O), 141.20, 128.57, 127.92, 125.07, 113.03 (olefinic), 86.19 (C–O), 73.81, 58.92, 51.97, 29.26 and 15.58; m/z (EI-MS) 246 (M^+ , 10%), 214 (8), 201 (100), 155 (27), 129 (8), 121 (12) and 115 (12).

3-Acetyl-2,7a-dimethyl-3a,4,5,6,7,7a-hexahydrobenzofuran 17. The reaction of acetylacetone **2** (0.30 g, 3.0 mmol) and 1-methylcyclohexene (0.240 g, 2.5 mmol) with CAN (3.15 g, 5.75 mmol) as described in the general procedure furnished *title compound 17* (0.151 g, 40%) as an oil; δ_{H} (60 MHz; CCl_4) 2.77–2.52 (1 H, m, $>\text{CHCH}_2$), 2.13 (3 H, s, CH_3), 2.08 (3 H, s, COCH_3), 1.87–1.29 (8 H, m, CH_2) and 1.22 (3 H, s, CH_3); δ_{C} (22.4 MHz; CDCl_3) 193.7 (C=O), 166.5 (=C–O), 117.8 (olefinic), 86.4 (C–O), 45.8, 31.5, 28.5, 26.5, 26.1, 19.5 and 14.9; m/z (EI-MS) 194 (M^+ , 72%), 179 (38), 161 (90), 151 (60), 137 (35), 133 (100) and 123 (65).

Oxidative addition of acetylacetone to 2-methylpent-2-ene

A mixture of acetylacetone **2** (0.30 g, 5.0 mmol) and 2-methylpent-2-ene (0.250 g, 3.25 mmol) was treated with CAN (3.15 g, 5.75 mmol) as described in the general procedure. The residue obtained on careful chromatography using ethyl acetate in light petroleum (2% and 3%, respectively) as eluent furnished compounds **19** (0.075 g, 16%) and **18** (0.272 g, 60%) as oils.

4-Acetyl-3-ethyl-2,2,5-trimethyl-2,3-dihydrofuran 18; δ_{H} (90 MHz; CDCl_3) 2.72 (1 H, t, J 5.4, $>\text{CHCH}_2$), 2.23 (3 H, s, CH_3), 2.18 (3 H, s, CH_3), 1.71–1.48 (2 H, m, CH_2), 1.39 (3 H, s, CH_3), 1.31 (3 H, s, CH_3) and 0.87 (3 H, t, J 7.2, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 194.3 (C=O), 165.9 (=C–O), 117.3 (olefinic), 88.3 (C–O), 51.7, 29.1, 28.9, 22.6, 21.6, 15.4 and 11.7 (GC-MS) m/z 182 (M^+ , 26%), 167 (8), 153 (65), 149 (8), 139 (10), 125 (10) and 111 (100).

3-(1'-Ethyl-2'-methylpent-2'-enyl)pentane-2,4-dione 19; δ_{H} (90 MHz; CDCl_3) 4.75 (2 H, d, J 7.9, olefinic), 3.75 (1 H, d, J 11.6), 2.92–2.64 (1 H, m, $>\text{CHCH}_2$), 2.11 (3 H, s, COCH_3), 2.01 (3 H, s, COCH_3), 1.54 (3 H, s, CH_3), 1.27–1.09 (2 H, m, CH_2) and 0.71 (3 H, t, J 8.2, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 204.1 (C=O), 203.4 (C=O), 143.2, 114.8, 48.8, 30.3, 29.6, 23.5, 18.6 and 11.2; m/z (GC-MS) 182 (M^+ , 5%), 164 (7), 153 (12), 139 (50), 121 (32) and 111 (100).

2-Methyl-7a-phenyl-3a,4,5,6,7,7a-hexahydrobenzofuran-3-carboxylic acid ethyl ester 20. A mixture of ethyl acetoacetate **3** (0.390 g, 3.0 mmol) and 1-phenylcyclohexene **5** (0.396 g, 2.5 mmol) was treated with CAN (3.15 g, 5.75 mmol) as described in the general procedure to afford *title compound 20* (elution with 2% ethyl acetate in light petroleum; 0.262 g, 40%) as a viscous liquid (Found: C, 75.6; H, 7.75. $\text{C}_{18}\text{H}_{22}\text{O}_3$ requires C, 75.50; H, 7.74%); δ_{H} (60 MHz; CCl_4) 7.23–6.88 (5 H, m, ArH), 3.95 (2 H, q, J 7.1, OCH_2CH_3), 3.17 (1 H, t, J 4.9, $>\text{CHCH}_2$), 2.17 (3 H, s, CH_3), 2.0–1.41 (8 H, m) and 1.12 (3 H, t, J 7.1, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 167.1 (C=O), 165.8 (=C–O), 147.4, 127.9, 126.5, 124.1, 107.2 (olefinic), 89.5 (C–O), 58.5, 47.2, 34.1, 26.2, 19.0, 18.3 and 14.2; m/z (GC-MS) 286 (M^+ , 5%), 244 (77), 212 (20), 197 (31), 169 (76), 156 (100), 141 (70) and 115 (50).

2,7a-Dimethyl-3a,4,5,6,7,7a-hexahydrobenzofuran-3-carboxylic acid ethyl ester 21. The reaction of ethyl acetoacetate **3** (0.390 g, 3.0 mmol) and 1-methylcyclohexene (0.250 g, 2.5 mmol) with CAN (3.15 g, 5.75 mmol) as described in the general procedure furnished compound **21** (elution with 2% ethyl acetate in light petroleum; 0.211 g, 38%) as an oil; δ_{H} (60 MHz; CCl_4) 4.12 (2 H, q, J 7.2, OCH_2), 2.65 (1 H, t, J 6.9, $>\text{CHCH}_2$), 2.05 (3 H, s, CH_3) and 1.80–1.05 (14 H, m); δ_{C} (22.4 MHz; CDCl_3) 167.7 (C=O), 162.0 (=C–O), 107.9 (olefinic), 87.5 (C–O), 59.1, 50.5, 46.4, 32.1, 27.2, 26.1, 19.0, 14.6 and 14.1; m/z (GC-MS) 224 (M^+ , 16%), 206 (5), 195 (7), 182 (26), 163 (10), 151 (22), 135 (55), 122 (24), 107 (30) and 94 (100).

4-Methoxymethyl-2-methyl-5-phenyl-4,5-dihydrofuran-3-carboxylic acid ethyl ester 22. The reaction of ethyl acetoacetate **3** (0.390 g, 3.0 mmol) and cinnamyl methyl ether (0.372 g, 2.5 mmol) with CAN (3.15 g, 5.75 mmol) as described in the general procedure furnished *title compound* **22** (elution with 5% ethyl acetate in light petroleum; 0.454 g, 65%) as a pale yellow oil (Found: C, 69.65; H, 7.3. $\text{C}_{16}\text{H}_{20}\text{O}_4$ requires C, 69.55; H, 7.30%); δ_{H} (60 MHz; CCl_4) 7.01 (5 H, s, ArH), 5.25 (1 H, d, J 5.0, $>\text{CHPh}$), 3.92 (2 H, q, J 7.2, OCH_2), 3.40–3.15 (3 H, m, 3 H, $>\text{CHCH}_2$), 3.12 (3 H, s, OCH_3), 2.11 (3 H, s, CH_3), 1.03 (3 H, t, J 7.2, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 168.8 (C=O), 164.9 (=C–O), 141.7, 128.1, 127.3, 124.5, 101.2 (olefinic), 86.1 (C–O), 73.3, 59.1, 58.2, 51.3, 49.5 and 13.9; m/z (EI-MS) 276 (M^+ , 26%), 244 (5), 231 (38), 203 (10), 158 (30), 115 (28) and 105 (100).

Oxidative addition of ethyl acetoacetate to 2-methylpent-2-ene

A mixture of ethyl acetoacetate **3** (0.390 g, 3.0 mmol) and 2-methylpent-2-ene (0.210 g, 2.5 mmol) was treated with CAN (3.15 g, 5.75 mmol) as described in the general procedure. The residue obtained on column chromatography using ethyl acetate in light petroleum (2% and 3%, respectively) as eluent afforded compounds **23** (0.195 g, 37%) and **24** (0.106 g, 22%) as oils.

4-Ethyl-2,5,5-trimethyl-4,5-dihydrofuran-3-carboxylic acid ethyl ester 23; δ_{H} (60 MHz; CCl_4) 4.03 (2 H, q, J 7.1, OCH_2), 2.73–2.40 (1 H, m, $>\text{CHCH}_2$), 2.12 (3 H, s, CH_3), 1.70–1.12 (8 H, m) and 0.85 (6 H, t, J 7.1, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 166.2 (C–O), 166.1, 105.3 (olefinic), 87.8 (C–O), 58.3, 51.1, 29.6, 22.2, 21.1, 14.2, 13.8 and 11.6 (Found: M^+ , 212.1402. $\text{C}_{12}\text{H}_{20}\text{O}_3$ requires M , 212.1412).

2-(1'-Ethyl-2'-methylpent-2'-enyl)-3-oxobutanoic acid ethyl ester 24; this product is a mixture of isomers; δ_{H} (90 MHz; CDCl_3) 4.84–4.75 (2 H, m, olefinic), 4.11 (2 H, q, J 7.3, OCH_2), 3.51 (2 H, dd, J 2.4 and 2.2), 2.92–2.61 (1 H, m, $>\text{CHCH}_2$), 2.20 and 2.15 (together 3 H, s, COCH_3), 1.65–1.54 (2 H, m), 1.36–1.08 (6 H, m, CH_3) and 0.91–0.66 (3 H, m, CH_3); δ_{C} (22.4 MHz; CDCl_3) 202.3 (C=O), 202.1 (C=O), 168.7 (C=O), 168.1 (C=O), 143.3, 114.4, 114.2, 84.8, 64.3, 61.1, 60.9, 48.4, 48.1, 29.1, 27.9, 23.5, 23.4, 18.7, 18.5, 13.9, 13.8, 11.2 and 11.0 (Found: M^+ , 212.1404. $\text{C}_{12}\text{H}_{20}\text{O}_3$ requires M , 212.1412).

4-Methoxymethyl-2-oxo-5-phenyltetrahydrofuran-3-carboxylic acid methyl ester 29. A mixture of cinnamyl methyl ether (0.220 g, 1.5 mmol) and dimethyl malonate **4** (0.237 g, 1.8 mmol) was dissolved in methanol (5 cm^3). Aq. CAN (1.89 g, 3.45 mmol in 15 cm^3) was added dropwise and the mixture was stirred in an ice-bath for 1 h and further stirred at room temperature for 2 h. The reaction mixture was worked up and the residue was subjected to column chromatography. Elution with light petroleum–chloroform–ethyl acetate (16:3:1) furnished compound **29** (0.230 g, 58%) as a viscous liquid; $\nu_{\text{max}}(\text{CH}_2\text{Cl}_2)/\text{cm}^{-1}$ 2936, 1790, 1743, 1459 and 1269; δ_{H} (60 MHz; CCl_4) 7.25 (5 H, s, ArH), 5.20 (1 H, d, J 9.9, $>\text{CHPh}$), 3.85–3.58 (4 H, m) and 3.52–2.95 (6 H, m); δ_{C} (22.4 MHz; CDCl_3) 170.4 (C=O), 167.1 (C=O), 136.8, 128.9, 128.1, 125.7, 81.1 (C–O), 68.3, 58.2, 51.6, 49.4 and 48.1; m/z (GC-MS) 264 (M^+ , 5%), 232 (6), 219 (3), 200 (7), 173 (30), 163 (30) and 105 (100).

Oxidative addition of dimethyl malonate to 1-phenylcyclohexene

A mixture of dimethyl malonate **4** (0.330 g, 2.5 mmol) and 1-phenylcyclohexene **5** (0.475 g, 3.0 mmol) was dissolved in methanol (10 cm^3). Aq. CAN (3.15 g, 5.75 mmol in 25 cm^3) was added dropwise and the mixture was stirred in an ice-bath for 1 h and then at room temperature for 1 h. The reaction mixture was worked up, and solvent was evaporated off, the crude product was dissolved in methanol and treated with 10% HCl before being worked up as usual and purified by column chromatography. Elution with 10% ethyl acetate in light petroleum afforded lactone **30** (0.276 g, 40%) as a pale yellow viscous liquid; $\nu_{\text{max}}(\text{CH}_2\text{Cl}_2)/\text{cm}^{-1}$ 2938, 1790, 1736, 1454 and 1165; δ_{H} (90 MHz; CDCl_3) 8.11–7.20 (5 H, m, ArH), 3.92–2.85 (5 H, m, CO_2CH_3 , CH) and 2.15–1.30 (8 H, m, CH_2); δ_{C} (90 MHz; CDCl_3) 170.5 (C=O), 167.1 (C=O), 141.5, 128.3, 127.8, 127.6, 125.3, 123.8, 86.2 (C–O), 52.1, 51.8, 43.2, 36.2, 25.7, 21.1 and 20.3; m/z (GC-MS) 274 (M^+ , 12%), 242 (5), 215 (16), 199 (10), 173 (6), 128 (12) and 105 (82).

Oxidative addition of dimethyl malonate to 2-methylpent-2-ene

A solution of CAN (3.15 g, 5.75 mmol) in methanol (30 cm^3) was added to an ice-cooled mixture of dimethyl malonate **4** (0.330 g, 2.5 mmol) and 2-methylpent-2-ene (0.252 g, 3.0 mmol) in methanol (10 cm^3). The reaction mixture was stirred in an ice-bath for 1 h and at room temperature for 3 h. Work up gave a residue, which was subjected to column chromatography. Elution with 10% ethyl acetate in light petroleum furnished compounds **34** (0.103 g, 20%) and **37** (0.206 g, 41%) as pale yellow oils.

2-(1'-Ethyl-2'-methylpent-2'-enyl)propanedioic acid dimethyl ester 34; δ_{H} (60 MHz; CCl_4) 4.70 (2 H, m, olefinic), 3.62 (3 H, s, CO_2CH_3), 3.50 (3 H, s, CO_2CH_3), 3.35–3.21 (1 H, m), 2.91–2.40 (1 H, m), 1.85 (3 H, s, CH_3), 1.52–1.20 (2 H, m, CH_2CH_3) and 0.90 (3 H, t, J 7.0, CH_2CH_3); δ_{C} (22.4 MHz; CDCl_3) 168.8 (C=O), 168.1 (C=O), 143.29 (olefinic), 114.5 (olefinic), 56.1, 52.3, 48.2, 23.3, 18.8 and 11.2 (Found: M^+ , 214.1252. $\text{C}_{11}\text{H}_{18}\text{O}_4$ requires M , 214.1205).

4-Ethyl-5,5-dimethyl-2-oxofuran-3-carboxylic acid methyl ester 37; δ_{H} (300 MHz; CDCl_3) 3.82 (3 H, s, CO_2CH_3), 3.38 (1 H, d, J 12.1, $>\text{CHCO}_2\text{CH}_3$), 2.71–1.62 (1 H, m, $>\text{CHCH}_2$), 1.60–1.42 (5 H, m, CH_2CH_3 and CH_3), 1.26 (3 H, s, CH_3) and 0.93 (3 H, t, J 7.4, CH_2CH_3); δ_{C} 170.69 (C=O), 169.02 (C=O), 86.13 (C–O), 53.56, 53.01, 51.65, 27.86, 22.68, 22.60 and 12.62 (Found: M^+ , 200.1026. $\text{C}_{10}\text{H}_{16}\text{O}_4$ requires M , 200.1048).

Preparation of dihydrofurans mediated by $\text{Mn}(\text{OAc})_3$; General procedure

A mixture of the dicarbonyl compound (2.0 mmol), alkene (2.4 mmol) and $\text{Mn}(\text{OAc})_3$ (4.6 mmol) in acetic acid (30 cm^3) was refluxed until the brown colour of $\text{Mn}(\text{OAc})_3$ disappeared (15 min). It was cooled, diluted with water (200 cm^3) and extracted with diethyl ether (3 \times 75 cm^3). The combined organic extracts were repeatedly washed successively with NaHCO_3 and then water, dried and evaporated. The residue obtained on column chromatography using 10% ethyl acetate in light petroleum as eluent afforded the dihydrofuran. The yields obtained in individual cases are given in Tables 1–3.

Acknowledgements

J. M. and K. V. R. thank CSIR for the award of research fellowships. We thank Professor S. Chandrasekaran, IISc, Bangalore, Professor G. Mehta, University of Hyderabad, Dr A. V. Rama Rao, ICT, Hyderabad and Dr T. V. Rajan Babu, Dupont Experimental station, USA for providing elemental analysis and mass spectra, and Mr George Morton, American Cynamid Company, Pearl River, USA for high-resolution NMR.

References

- 1 G. Stork and N. H. Baine, *J. Am. Chem. Soc.*, 1982, **104**, 2321; G. Stork and P. M. Sher, *J. Am. Chem. Soc.*, 1983, **105**, 6765; G. Stork, in *Current Trends in Organic Synthesis*, ed. H. Nozaki, Pergamon Press, Oxford, 1983, p. 359.
- 2 M. Julia, *Acc. Chem. Res.*, 1971, **4**, 386; *Pure Appl. Chem.*, 1974, **40**, 553.
- 3 For reviews see: B. Giese in *Radicals in Organic Synthesis: Formation of Carbon-Carbon Bonds*, Pergamon Press, Oxford, 1986; D. H. R. Barton, *Aldrichim. Acta*, 1990, **23**, 3; D. P. Curran in *Comprehensive Organic Synthesis*, ed. B. M. Trost and I. Fleming, Pergamon Press, New York, 1991, vol. 4, p. 715; A. L. J. Beckwith, *Chem. Soc. Rev.*, 1993, **22**, 143.
- 4 W. J. De Klein, in *Organic Synthesis by Oxidation with Metal Compounds*, ed. W. J. Mijs and C. R. H. de Jonge, Plenum, New York, 1986, p. 261.
- 5 (a) G. G. Melikyan, *Synthesis*, 1993, 833; (b) J. Iqbal, B. Bhatia and N. K. Nayyar, *Chem. Rev.*, 1994, **94**, 519.
- 6 E. I. Heiba and R. M. Dessau, *J. Am. Chem. Soc.*, 1971, **93**, 524, 995; *J. Am. Chem. Soc.*, 1972, **94**, 2888; E. I. Heiba, R. M. Dessau and P. G. Rodewald, *J. Am. Chem. Soc.*, 1974, **96**, 7977.
- 7 M. E. Kurz and P. Ngoviwatchai, *J. Org. Chem.*, 1981, **46**, 4672; M. E. Kurz, V. Baru and P. N. Nguyen, *J. Org. Chem.*, 1984, **49**, 1603.
- 8 E. Baciocchi and R. Ruzziconi, *J. Org. Chem.*, 1986, **51**, 1645.
- 9 E. Baciocchi, R. Ruzziconi and D. D. Aira, *Tetrahedron Lett.*, 1986, **27**, 2763; L. M. Wienstock, E. Corley, N. L. Abramson, A. O. King and S. Karady, *Heterocycles*, 1988, **27**, 2627.
- 10 E. Baciocchi, A. Casu and R. Ruzziconi, *Tetrahedron Lett.*, 1987, **28**, 5357; E. Baciocchi and R. Ruzziconi, *Synth. Commun.*, 1988, **18**, 1841.
- 11 E. Baciocchi, A. Casu and R. Ruzziconi, *Tetrahedron Lett.*, 1989, **30**, 3707; *Synlett*, 1990, 679.
- 12 K. Narasaka and T. Okauchi, *Chem. Lett.*, 1991, 515.
- 13 K. Narasaka, T. Okauchi, K. Tanaka and M. Murakami, *Chem. Lett.*, 1992, 2099.
- 14 E. Baciocchi and R. Ruzziconi, *J. Org. Chem.*, 1991, **56**, 4772.
- 15 A. B. Paolobelli, F. Gioacchini and R. Ruzziconi, *Tetrahedron Lett.*, 1993, **34**, 6333.
- 16 B. B. Snider and T. Kwon, *J. Org. Chem.*, 1990, **55**, 4786; A. Citterio, R. Sebastiano and A. Marion, *J. Org. Chem.*, 1991, **56**, 5328; A. Citterio, R. Sebastiano and M. C. Carvayal, *J. Org. Chem.*, 1991, **56**, 5335.
- 17 A preliminary communication of this work has been published: V. Nair and J. Mathew, *J. Chem. Soc., Perkin Trans. 1*, 1995, 187. For our related work on CAN-mediated C-C bond-forming reactions see: V. Nair and J. Mathew, *J. Chem. Soc., Perkin Trans. 1*, 1995, 1881; V. Nair, J. Mathew and S. Alexander, *Synth. Commun.*, 1995, **25**, 3981.
- 18 J. Iqbal, B. Bhatia and N. K. Nayyar, *Tetrahedron*, 1991, **47**, 6457.

Paper 5/06313B

Received 25th September 1995

Accepted 5th February 1996