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Aerobic epoxidation via alkyl-2-oxocyclopentanecarboxylate co-oxidation with cobalt or manganese Jacobsen-type catalysts

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Abstract

In the presence of methyl, *tert*-butyl, or (−)-menthyl esters of 2-oxocyclopentanecarboxylic acids Jacobsen-type complexes of cobalt(II) and manganese(III) form active catalysts for alkene epoxidation using molecular oxygen. Alkyl-1-hydroxy-2-oxocyclopentanecarboxylates and 1-alkyl-2-oxo-hexanedicarboxylic acids are formed as co-oxidation products. The (−)-menthyl/cobalt system is selective for epoxide production but the products are racemic consistent with radical epoxidation in solution rather than at the cobalt complex. The manganese Jacobsen-type complex gives lower yields of epoxides (40–60%) but for 2,2-dimethylchromene and styrene these are optically active (12–60% ee).

1. Introduction

Asymmetric formation of C–O bonds using molecular oxygen and a homogeneous transition metal catalyst is rare [1]. In a seminal note Nishinaga described the aerobic hydration of styrene (2–38% ee) by cobalt salen-based complexes [2]. Asymmetric aerobic epoxidations of alkenes by bleomycin analogues (5–51% ee) [3] or more successfully by manganese salen-type catalysts in the presence of Bu^{t}CHO (6–92% ee), are also known [4–6]. Finally, asymmetric Baeyer–Villiger oxidations (47–95% ee), again driven by Bu^{t}CHO–O_2, appeared recently using copper(II) catalysts [7]. For one of these processes a patent application has been filed [8].

We are interested in utilising molecular oxygen for asymmetric substrate oxidations [9] using transition metal catalysts and stoichiometric amounts of sacrificial co-reductants other than aldehydes. Cyclic ketones are known to be potent co-oxidants in aerobic processes [10–13]. Iqbal and co-workers reported the oxidation of methyl-2-oxo-cyclopentanecarboxylate **1a** to a tertiary alcohol **2a** during aerobic epoxidations [14]. As **2a** could be dehydrated and hydrogenated back to **1a** the co-reductant can be recycled avoiding the need for bulk production of low value RCO_2H in industrial settings.

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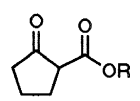
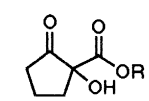
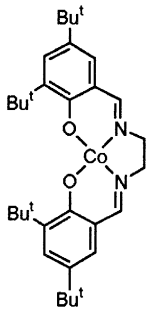
Herein we report the outcome of our study of aerobic epoxidation, including asymmetric epoxidation, utilising the 2-alkyl-2-oxocyclopentanecarboxylates **1a**–**c** together with the cobalt catalysts **3**–**4** and the manganese(III) catalyst (*R*,*R*)-**5**.



1a R = Me
1b R = Bu^t
1c R = (-)-menthyl



2a R = Me
2b R = Bu^t
2c R = (-)-menthyl



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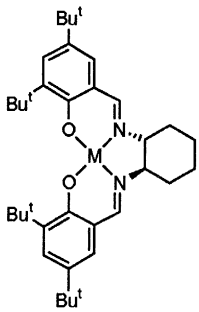


R,R-**4** M = Co
R,R-**5** M = MnCl

2. Results and discussion

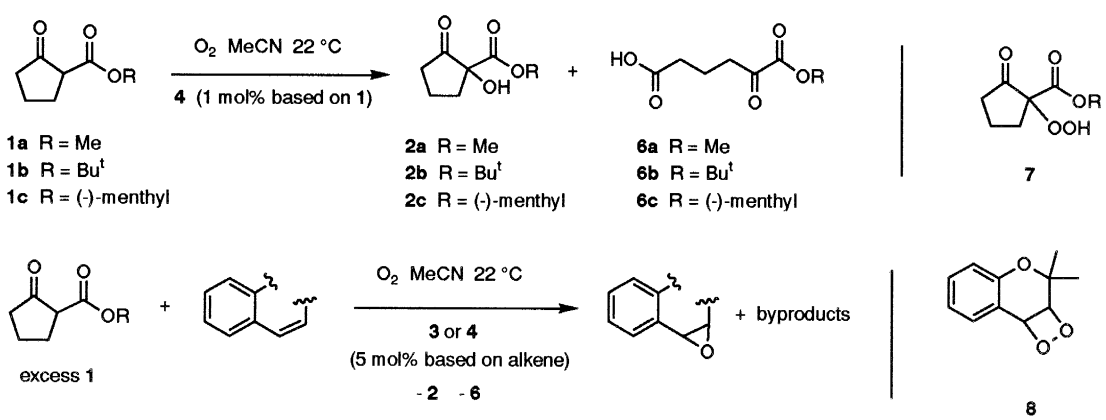
The cyclopentanecarboxylates **1a**–**c** are commercial products or easily prepared [15,16]. Transesterification of **1a** and (−)-menthol may be improved by continuous distillation of MeOH from the reaction mixture; essentially a quantitative yield of **1c** results. The ^{13}C NMR shifts of the C(1) carbons in these compounds in $CDCl_3$ are all very similar to structurally characterised **1c** (δ_C 54.35 **1a**, 55.7 **1b**, 55.15 **1c**) indicating that the carboxylates are largely present in the keto form [16]. Of course given suitable solvents or appropriate bases keto–enol isomerisation is possible for all these carboxylates. The cobalt complexes **3**–**4** are obtained by methods analogous to the preparation of Jacobsen's catalyst **5**, provided the reactions are carried out under inert atmospheres. The low solubility of the ethylenediamine complex **3** somewhat limits its use. Cobalt(II) salen-type complexes often bind oxygen [17,18] but the spectroscopic, elemental analyses, and magnetic moments of **3**–**4** and X-ray crystal structure of **4** are consistent with an O_2-free square planar Co(II) geometry [19].

It is important in radical-based oxygen activation to ascertain if substrate oxidation in the *absence* of transition metal catalysts is viable, a fact not always appreciated by some workers in this field. For example, aerobic alkene epoxidation using aldehyde autoxidation is known to be promoted by both heat and light alone [20,21]. Racemic oxidation products arise from such pathways *even* in the presence of metal-catalysed routes [9,22]. Control reactions were carried out on **1a**, as a representative 2-oxocyclopentanecarboxylate, in MeCN under O_2. Uncatalysed oxygenation leads to degradation of **1a** (0.33 M) within 16 h at room temperature based on ^{1}H NMR analysis of the crude product at this time. The major product of was subsequently identified as the carboxylic acid **6a** (see later). These reactions are, however, not very clean and other unidentified products are always present. Further control reactions show that the uncatalysed reactions are independent of the presence of light. To ascertain if products arising from uncatalysed oxidation of **1** were themselves able to oxidise olefinic substrates extensive test reactions were carried out. Under oxygen, 1,2-dihydronaphthalene (chosen as a substrate susceptible to both epoxidation and H$^\cdot$ abstraction) was not oxidised by **1a** at low substrate concentrations ([alkene] = 0.17 M; [**1a**] = 0.33 M; alkene:**1a** = 1:2) in either light or dark in the absence of catalysts. Similar observations are noted at high concentrations ([alkene] = 1.70 M; [**1a**] = 3.30 M; alkene:**1a** = 1:2) provided adventitious contamination by metal salts is avoided. *In the presence of trace amounts of metal contaminants (typically from non-rigorously cleaned stir bars) highly vari-*

able substrate oxidation is found; none in clean apparatus, up to 100% alkene conversion with some contaminated reactions. Because of these effects subsequent reactions were conducted using highly cleaned apparatus and generally at low substrate concentrations ([alkene] < 0.2 M; [**1a**–**c**] < 0.5 M). Under these conditions oxidation of **1** apparently does not lead to species that are capable of achiral alkene epoxidation.

Cobalt catalysed aerobic oxidation of the alkyl-2-oxocyclopentanecarboxylates **1a**–**c** alone allows the isolation of the alcohols **2a**–**c** and the carboxylic acids **6a**–**c** (Scheme 1). These reactions are more convenient to carry out than their uncatalysed variants, although a number of minor byproducts are still formed. The ^{13}C NMR spectra of **2** and **6** are particularly diagnostic; those of the alcohols **2** contain two high frequency signals, while those of the acid **6** show three. The total mass balance for oxidations of **1a**–**c** to **2a**–**c** and **6a**–**c** are reproducibly high (ca. 85% from **1a**; 95% from **1b**; 65% from **1c**). However, the ^{1}H NMR spectra of all six compounds indicate contamination by small amounts of byproducts (ca. 1–5%). We are unable to completely remove these and therefore have not attempted to obtain analytical data on **2a**–**c** and **6a**–**c**. In the case of **2c** the major impurity can be identified as (−)-menthol. Methyl-2-oxocyclopentanecarboxylate **1a** is suggested to form the hydroperoxide **7** (R = Me) under cobalt catalysis in the absence of alkenes [14]. In our system **2a** and **6a** are the major products. Iodometric titration after 2–6 h of oxidation (0.33 M **1a**, O_2, 1 mol% **4**) indicate only low hydroperoxide concentrations (ca. 0.03 M) are present in the reaction mixture. The alcohol fraction isolated from reactions using **1b** contains no hydroperoxide as neither PPh_3 or NaI-AcOH is oxidised on exposure to crude **2b**. Only limited reports on the preparation of **2** [14] and **6** are available; Cossy and co-workers apparently prepared **6a** via $Cu(ClO_4)_2$ promoted aerobic oxidation of **1a** [23].

Having established the identity of the **1a**–**c** oxidation products, 1,2-dihydronaphthalene, styrene, and 2,2-dimethylchromene were selected as model alkenes and oxidised in the presence of **1a**–**c** and the cobalt catalysts **3**–**4** (Table 1). Due to its higher solubility complex **4** is the preferred catalyst for most runs. The reaction mixtures undergo a series of colour changes from an orange suspension to green and finally yellow–brown solutions but no intermediates could be isolated. If catalyst **3** is used dissolution is very slow in the early stages of the oxidation. The colour change to green is assigned to oxidation of the cobalt(II) precatalyst to an active cobalt(III) species. The methyl and *tert*-butyl esters **1a**–**b** lead to aggressive



Scheme 1.

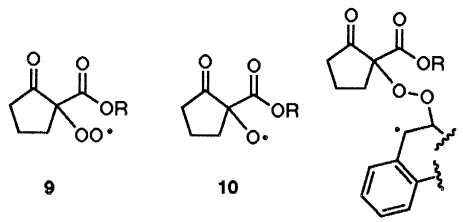
oxidation systems and only low yields of epoxide are realised (runs 1–6). Control reactions show that the product epoxide is consumed in these reactions. Resin formation accounts for most of the mass balance, probably via $H^{\cdot}$ abstraction routes as use of 1,2-dihydronaphthalene leads to significant yields of naphthalene (runs 1–3). Only C–C bond cleavage is noted with styrene (run 7). The 2,2-dimethylepoxychromene produced from oxidation with **1b** co-elutes with a second product. Proton NMR and mass spectra of the mixture suggest that the additional compound is a dioxetane of type **8** although corroboration of this hypothesis is prevented by the high reactivity of the material isolated. The epoxide chemoselectivity may be dramatically improved by using the (−)-menthyl ester **1c**. Essentially quantitative yields of 2,2-dimethylepoxychromene are realised with no formation of 2,2-dimethylchromanone [24] but excess **1c** is required (runs 8–10). Under these optimal conditions 1,2-dihydronaphthalene gives a 77% yield of epoxide (run 11). No naphthalene is formed suggesting that $H^{\cdot}$ abstraction is minimised.

Several factors support a radical autoxidation mechanism for these cobalt-catalysed reactions: the susceptibility to adventitious promotion at high concentrations by impurities, the formation of a number of low yield byproducts, and the absence of any optical induction in the reaction products. The optical yield of the isolated epoxides is $< 1\%$, while **2c** is isolated as a 1:1 mixture of diastereomers. Metal-centred epoxidation of 2,2-dimethylchromene using the ligand set in complexes (*R*,*R*)-**4**–**5** normally proceeds with detectable, often high, enantiomeric excess [25–27]. Only degradation of (*R*,*R*)-**4** to achiral species or a metal-free epoxidation pathway are consistent with our observations. A radical chain operating via **9**–**11** and/or $HO_n^{\cdot}$ ($n = 1, 2$) is most in accord with the experimental data. These ideas are supported by the work of Drago [28], Kochi [29], and others [30]. Cobalt catalysed O_2 activation by **1** (R = Et) has been proposed to proceed by a bound enolate-hydroperoxide complex [11,12]. The only role we can see for such enolates in our chemistry is during the onset of reaction. Apparently the major function of the cobalt complex in this chemistry is as a typical autoxidation chain initiator where **3**–**4** either remain intact or are degraded under the reaction conditions [31]. For whatever reason (degradation or inappropriate ligand/reaction condition choice) (*R*,*R*)-**4** is ineffective at chiral catalysis.

Table 1
Cobalt catalysed aerobic alkene oxidations in the presence of oxocyclopentane carboxylate esters **1a**–**c** [a]

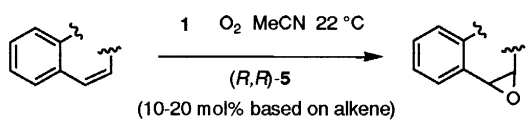
Run	Alkene (A) [molarity]	Co-oxidant **1** [molarity]	A:**1** ratio	Catalyst	Conversion	Isolated product yields (%)
1	dihydronap. [b] [1.65]	**1a** [3.3]	1:2	**4**	> 95	epoxide 3, naphthalene 10
2	dihydronap. [0.17]	**1a** [0.33]	1:2	**4**	> 95	epoxide 34, naphthalene 9
3	dihydronap. [0.08]	**1a** [0.33]	1:2	**4**	> 95	epoxide 32, naphthalene 7
4	chromene [c] [0.17]	**1a** [0.50]	1:3	**4**	78	epoxide 4
5	chromene [0.35]	**1a** [1.75]	1:5	**4**	> 95	epoxide 8
6	chromene [0.08]	**1b** [0.37]	1:5	**4**	> 95	epoxide 7
7	styrene [0.17]	**1a** [0.33]	1:2	**4**	73	PhCHO 19
8	chromene [0.13]	**1b** [0.37]	1:3	**3**	71	epoxide 55
9	chromene [0.08]	**1c** [0.37]	1:5	**3**	> 95	epoxide 98
10	chromene [0.08]	**1c** [0.37]	1:5	**4**	> 95	epoxide 95
11	dihydronap. [0.08]	**1c** [0.37]	1:5	**4**	> 95	epoxide 77

[a] Alkene (0.25–0.50 mmol) and **1** (0.5–2.50 mmol) in MeCN (variable ca. 0.3–3.0 cm^3 depending on concentrations) with **3** or **4** (5 mol% based on alkene) for 16 h.
[b] Dihydronap. = 1,2-dihydronaphthalene.
[c] Chromene = 2,2-dimethylchromene.



9 10 11

A report of aerobic oxidation of β-isophorone to an enedione by Mn(II)(salen) [32] led us to try some epoxidations using **1** and (*R*,*R*)-**5** (Scheme 2). Attempted epoxidation of 2,2-dimethylchromene using (*R*,*R*)-**5** in the presence of *N*-methylimidazole and a five fold excess of **1c** under O_2 results in precipitation of free chiral ligand which is isolated in 63% yield. The fate of the manganese(III) is not known but we note that the reaction mixture becomes very pale coloured during decomplexation from **5**. The manganese(III) catalyst derived from (*R*,*R*)-**5** (d^4 electronic configuration) is expected to be more substitution labile than the active cobalt(III) catalysts (substitution inert low spin d^6) derived from **3**–**4**. We chose to overcome these difficulties by adding **1c** slowly via a syringe pump over four hours and were rewarded by a significant yields of chromene epoxide (ca. 50%) with some asymmetric induction (ca. 20%). As the mass balance in these reactions was not very good initial attempts were made to improve the chemical yield of epoxide (Table 2) before concentrating on the enantioselectivity of the epoxidation. However, altering the reaction conditions does not dramatically change the epoxide chemical yield. Reducing the amount of **1c** lowers the alkene conversion but similar amounts of epoxide are formed (runs 1–3). Either slowing or increasing the rate of addition of **1c** (0.5–16 h) lowers the chemical yield of epoxide (runs 1 and 4–6). Changing the amount of *N*-methylimidazole from 20 to 80 mol% had little affect but in its absence the chemical yield is suppressed (runs 1 and 7–9). With five equivalents of **1** alkene conversions are very good (> 95%) but the yield of epoxide remains less than 60%. Control reactions indicate that 2,2-dimethylepoxychromene is stable in the presence of **1** under catalytic conditions, that no 2,2-dimethylchromanone is formed, and that no appreciable polymerisation products are present (GPC analysis). Mild basification of the reaction mixture ($NaHCO_3$) indicates that C–C bond cleavage of the chromene to carboxylic acids accounts for the at least some of the converted alkene. A complex mixture of **6** and at least two chromene derived products is isolated. Further purification was not attempted.



Scheme 2.

Having confirmed that our initial choice of conditions were close to optimal, investigations into asymmetric epoxidations were carried out with **1a**–**c** (Table 3). Assay of the optical purity of 2,2-epoxychromene by chiral GC has to be carried out in the presence of excess **1b**–**c** as this is present in the reaction mixture. Prior

Table 2
Aerobic epoxidation of 2,2-dimethylchromene by manganese catalyst (*R*,*R*)-**5** in the presence of (−)-(1*R*,2*S*,5*R*)-menthyl-(1*R*)-2-oxocyclopentanecarboxylate **1c**

Run	Alkene:**1c** ratio	Me-Imid (mol%)	Addition time (h)	Yield epoxide (%) [a]
1	1:5	20	4.0	56
2	1:2.5	20	4.0	44
3	1:1.5	20	4.0	40
4	1:5	20	0.5	25
5	1:5	20	2.0	32
6	1:5	20	16.0	44
7	1:5	0	4.0	30
8	1:5	40	4.0	56
9	1:5	80	4.0	52

[a] 2,2-dimethylchromene (0.25 mmol) in MeCN (1 cm^3) containing *N*-methylimidazole (Me-Imid, variable amounts), PhCN internal standard and (*R*,*R*)-**5** (10 mol% based on alkene) was treated with **1c** (0.38–1.25 mmol).
[b] Determined by GC on a BP-20 column, based on averages of multiple runs.

chromatographic separation is unhelpful as the epoxide and **1b–c** co-elute on both alumina and silica in all solvent systems tried so far. No such problems are encountered with **1a** and hence its use is preferred for most runs. Quantified GC analysis of a typical reaction mixture reveals smooth formation of chiral epoxide suggesting catalyst deactivation is not a major problem. Addition of extra catalyst after 1.5 h does not lead to the formation of significant extra amounts of epoxide (such behaviour is expected if the catalytic system is inactivated). Nevertheless the higher optical yield attained is strongly suggestive of competing achiral epoxidation pathways. The optimised procedure has some utility: cyclohexene (runs 9–10), styrene (runs 11–12), and *trans*-stilbene (run 14) participate to various degrees.

Reaction mixtures containing alkene, **1**, (*R*,*R*)-**5**, and *N*-methylimidazole develop a characteristic green–brown colour when active although initially some precipitation may be evident. At high concentrations of **1** the reaction becomes deep green in colour but attempted isolation of this intermediate is hampered by apparent reformation of brown (*R*,*R*)-**5**. For 2,2-dimethylchromene a predominance of the (+)-(3*R*, 4*R*) epoxide (identical to oxidations using NaOCl [33] or Bu^tCHO/O_2/*N*-alkylimidazoles [1,5]) is detected implicating a common manganese(V) oxo species. Oxidations of 2,2-dimethylchromene using (*R*,*R*)-**5** in the presence of ROOH ($R = Bu^t$, CMe_2Ph; five fold excess added over 4 h) give only very low yields of epoxide suggesting that free hydroperoxides of type **7** do not effect the O-atom transfer to (*R*,*R*)-**5**. However, typical preparations (Table 3, run 4) do contain 0.08 ± 0.01

Table 3
Aerobic oxidations catalysed by the manganese salen-type complex (*R*,*R*)-**5** in the presence of **1** [a]

Run	Alkene (A)	Co-oxidant **1**	A:**1** ratio	Time (h)	Convertion (%)	Epoxide (%) [b]	ee (%) [c]
1	chromene [d]	**1c**	1:5	4	> 95	55	23
2	chromene	**1c**	1:5	4	> 95	52	60 [e]
3	chromene	**1b**	1:5	4	> 95	57	45
4	chromene	**1a**	1:5	4	> 95	40	14
5	chromene	**1a**	1:2.5	4	63	39	42
6	chromene	**1a**	1:1.5	4	55	19	52
7	chromene	**1a**	1:1	4	32	16	42
8	chromene	**1a**	1:2.5	7	79	50	45
9	cyclohexene	**1a**	1:2.5	7	> 93	55 [f]	—
10	cyclohexene	**1a**	1:2.5	7	> 89	52 [g]	—
11	styrene	**1a**	1:2.5	7	76	41 [h]	17 [i]
12	styrene	**1a**	1:2.5	14	80	38 [j]	12 [i]
13	1-hexene	**1a**	1:2.5	7	66	< 5	— [k]
14	*trans*-stilbene	**1a**	1:2.5	14	70	44	< 5 [l]

[a] Alkene (0.25 mmol) in MeCN (1 cm^3) containing *N*-methylimidazole (Me-Imid, 0.05 mmol), PhCN internal standard and (*R*,*R*)-**5** (10 mol% based on alkene) was treated with **1** (0.25–1.25 mmol).
[b] Determined by GC on a BP-20 column, based on averages of multiple runs.
[c] Determined by GC on a Cyclodex-B column, ±3% maximum error bar.
[d] Indicates 2,2-dimethylchromene.
[e] Extra catalyst (10 mol%) and *N*-methylimidazole (0.05 mmol) added after 1.5 h.
[f] 2-cyclohexene-1-ol (21%) and 2-cyclohexen-1-one (17%) also produced.
[g] In acetonitrile containing radical suppressant (50 ppm, *t*-butylcatechol); 2-cyclohexene-1-ol (18%) and 2-cyclohexen-1-one (19%) also produced.
[h] Benzaldehyde (4%) also produced.
[i] (*R*)-styrene oxide.
[j] Benzaldehyde (7%) also produced.
[k] Not determined.
[l] Determined using $Eu(hfc)_3$.

mmol of active oxygen at 2 h as determined iodometrically. Monitoring the oxidation of cyclohexene reveals that 2-cyclohexene-1-ol and 2-cyclohexen-1-one are only produced in the first 100 min of oxidation (epoxide is also generated). After this time their concentration remains approximately constant while cyclohexene epoxide continues to grow in. Allylic oxidation products are often indicative of radical oxidation processes but this may not be the case in the present reaction. The final ratio of epoxide:alcohol:enone for aerobic oxidation of cyclohexene (59:23:17) is essentially independent of the presence of radical inhibitor (*tert*-butylcatechol, 50 ppm).

Presently we cannot make an unequivocally statement for the mechanism of aerobic catalysis by (*R,R*)-**5**. The similarity of the product yields and distributions in cyclohexene oxidation in the presence and absence of a radical inhibitor suggest a minor role for solution-based $RO_n^{\cdot}$ ($n = 1, 2$) radicals. However, the observed enantioselectivities in the epoxidation of 2,2-dimethylchromene indicate that ca. 25% of the epoxide is formed by a non-selective epoxidation radical pathway. The manganese(V) oxo species derived from (*R,R*)-**5** normally epoxidises chromenes in 90–98% ee (a value which is often largely independent of reaction conditions). If only this species is responsible for selective chromene epoxidation a ca. 40% ee is calculated if a quarter of the epoxidation manifold is racemic. Detailed kinetic analyses of this reaction is currently underway to define the intermediates present in this reaction and improve the enantioselectivity of the reaction.

3. Experimental

3.1. General

All manipulations were carried out in air except where noted. Acetonitrile was dried over 4 Å molecular sieves. All other reagents were used as supplied. The light petroleum used had bp 40–60°C. Column chromatography and preparative TLC were run on activated silica gel; Rhône-Poulenc Sorbsil C60 40/60H and Merck Kieselgel 60 $HF_{254+366}$ respectively. Infrared spectra were recorded using a Perkin-Elmer 983G instrument. Proton NMR spectra (270 MHz) and ^{13}C NMR spectra (67.8 MHz) were recorded on a Jeol-270 spectrometer at ambient temperature in $CDCl_3$. Mass spectra were obtained on a Finnigan 1020 (electron impact ionisation, EI) machine. Catalytic runs were monitored by TLC or GC analysis using a Perkin-Elmer 8320 equipped with a 24 m capillary BP-20 column. Optical activities were assayed by GC analysis on a 24 m cyclodex-B column, or by NMR spectroscopy [$Eu(hfc)_3$]. The compounds 2,2-dimethylchromene [34], *tert*-butyl-2-oxocyclopentanecarboxylate [15], 2,4-di-*tert*-butylsalicylaldehyde [26], and complex (*R,R*)-**5** [26] were prepared by literature methods. The carboxylate **1c** were prepared by a standard method [16].

3.2. Cobalt catalysts *3* and *(R,R)-4*

For **3** ethylenediamine (0.22 cm^3, 3.26 mmol) was added to 2,4-di-*tert*-butylsalicylaldehyde (1.58 g, 6.64 mmol) dissolved in ethanol (100 cm^3) and the solution heated (60°C) under a nitrogen atmosphere until precipitation of the yellow ligand was complete (30 min). A solution of KOH (15 cm^3 of 0.50 M EtOH solution, 7.50 mmol) was added followed by further EtOH (50 cm^3) and the mixture stirred at 60°C until a yellow solution was obtained. A solution of $Co(OAc)_2 \cdot 4H_2O$ (0.91 g, 3.67 mmol) in deoxygenated water (15 cm^3) was added over a few minutes causing the precipitation of the orange–red product. The reaction was allowed to cool to ambient temperature and stirred (16 h). The product was isolated by filtration, washed with water (5×25 cm^3), and dried under vacuum to yield **3** as an orange–red powder 1.32 g (67%): mp > 300°C; ν_{max} (KBr disc) (cm^{-1}) 2947s, 2901m, 2867m ($3 \times CH$), 1595s (C=N); μ_{eff} (corr., 24.0°C) = $2.59\mu_B$.

MS (EI) m/z 550 (M^+). Anal. found: C, 69.9; H, 8.1; N, 4.9. Calc. for $C_{32}H_{46}CoN_2O_2$: C, 69.9; H, 8.4; N, 5.1%. The compound was too insoluble to allow solution NMR and polarimetry studies.

For (R,R)-**4** a literature procedure [19] is used but starting from (R,R)-1,2-cyclohexyldiamine (0.18 g, 1.58 mmol), 2,4-di-*tert*-butylsalicylaldehyde (0.73 g, 3.12 mmol), and $Co(OAc)_2 \cdot 4H_2O$ (0.40 g, 1.61 mmol) to yield red–orange microneedles 0.72 g (79%) of (R,R)-**4**: mp > 300°C; ^{1}H NMR: δ_H-0.31 (s, $W_{1/2} = 45$ Hz), 7.83 (s, $W_{1/2} = 90$ Hz), 11.00 (s, $W_{1/2} = 125$ Hz), 14.36 (s, $W_{1/2} = 80$ Hz), 16.83 (s, $W_{1/2} = 505$ Hz), 18.36 (s, $W_{1/2} = 560$ Hz); ν_{max} (KBr disc) (cm^{-1}) 2950s, 2904m, 2862m (3 × CH), 1592s (C=N); μ_{eff} (corr., 20.8°C) = 2.44 μ_B. MS(EI) m/z 604 (M^+). Anal. Found: C, 71.3; H, 8.9; N, 4.6. Calc. for $C_{36}H_{52}CoN_2O_2$: C, 71.6; H, 8.7; N, 4.6%. Solutions of (R,R)-**4** were too dark to allow accurate polarimetry studies.

*3.3. Representative procedures for cobalt-catalysed oxidation of alkyl-2-oxocyclopentanecarboxylates **1***

Solid **3** or (R,R)-**4** (0.025 mmol, 1 mol% based on **1**) was added to a solution of the appropriate alkyl-2-oxocyclopentanecarboxylate **1a**–**c** (2.50 mmol) dissolved in acetonitrile (6.5 cm^3) and the mixture stirred under oxygen (1 atm, 16 h). The reaction turned first bottle green and then brown. The solvent was removed and the residue chromatographed.

For **1a** elution with light petroleum–Et_2O (3:2) gave 0.25 g (62%) of **2a**: ^{1}H NMR: δ_H 2.04–2.18 (m, 3 H, ring CH_2), 2.42–2.55 (m, 3 H, ring CH_2), 3.66 (s, br, 1 H, OH), 3.81 (s, 3 H, OMe); ^{13}C NMR: δ_C 18.3, 34.8, 35.8, 53.2, 79.8, 172.0 (C=O), 213.3 (C=O); ν_{max} (thin film) (cm^{-1}) 3465br (OH), 1751s, 1730s (2 × CO); MS(EI) m/z 158 (M^+). Continued elution gave 96 mg (22%) of **6a**: ^{1}H NMR: δ_H 1.98 (apparent quintet, $J = 7$ Hz, 2 H, central CH_2), 2.45 (apparent t, $J = 7$ Hz, 2 H, CH_2), 2.97 (apparent t, $J = 7$ Hz, 2 H, CH_2), 3.88 (s, 3 H, OMe), CO_2H gives a broad signal at 9.0–9.5 depending on water contamination of the NMR solvent; ^{13}C NMR: δ_C 17.8, 32.5, 38.2, 53.0, 161.2 (C=O), 178.5 (C=O), 193.3 (C=O); ν_{max} (thin film) (cm^{-1}) 3400vbr (OH), 1728s (CO); MS(EI) m/z 158 (M^+).

For **1b** elution with light petroleum–Et_2O (4:1) gave 0.24 g (48%) of **2b**: ^{1}H NMR: δ_H 1.48 (s, 9 H, Bu^t), 2.01–2.14 (m, 3 H, ring CH_2), 2.37–2.49 (m, 3 H, ring CH_2), 3.70 (s, br, 1 H, OH); ^{13}C NMR: δ_C 18.4, 27.8, 34.9, 35.5, 79.7, 83.9, 170.8 (C=O), 213.8 (C=O); ν_{max} (thin film) (cm^{-1}) 3480br (OH), 1750s, 1723s (2 × CO); MS(EI) m/z 183 (M^+–OH). Continued elution gave 0.25 g (47%) of **6b**: ^{1}H NMR: δ_H 1.56 (s, 9 H, Bu^t), δ_H 1.96 (apparent quintet, $J = 7$ Hz, 2 H, central CH_2), 2.44 (apparent t, $J = 7$ Hz, 2 H, CH_2), 2.89 (apparent t, $J = 7$ Hz, 2 H, CH_2), CO_2H gives a broad signal at 9.0–9.5 depending on water contamination of the NMR solvent; ^{13}C NMR: δ_C 17.9, 27.7, 32.6, 37.9, 84.1, 160.3 (C=O), 178.5 (C=O), 194.7 (C=O); ν_{max} (thin film) (cm^{-1}) 3400vbr (OH), 1719s (CO); MS(EI) m/z 161 (M^+ + 1-isobutylene).

For **1c** elution with light petroleum–Et_2O (7:3) gave 0.30 g (45%) of **2c** as two diastereoisomers: ^{1}H NMR: δ_H 0.72 and 0.77 (2 × d, $J = 7$ Hz, 3 H, menthyl), 0.82–1.13 (m, 8 H, menthyl), 1.32–1.76 (m, 5 H, menthyl), 1.78–2.18 (m, 5 H, menthyl and ring CH_2), 2.38–2.54 (m, 3 H, ring CH_2), 3.67 (s, br, 1 H, OH), 4.78 (m, 1 H, CHO-menthyl); ^{13}C NMR: δ_C 15.8, 15.9, 18.4, 20.6, 20.75, 21.75, 21.8, 25.7, 26.1, 31.3, 34.0, 34.55, 34.9, 35.7, 35.9, 40.1, 40.6, 46.85, 46.9, 76.7, 76.8, 79.55, 79.6, 171.15 (C=O), 171.2 (C=O), 213.25 (C=O), 213.3 (C=O); ν_{max} (thin film) (cm^{-1}) 3470br (OH), 1752s, 1724s (2 × CO); MS(EI) m/z 282 (M^+). Continued elution gave 0.14 g (21%) of **6c**: ^{1}H NMR: δ_H 0.76 (d, $J = 7$ Hz, 3 H, menthyl), 0.90 (d, $J = 7$ Hz, 3 H, menthyl), 0.91 (d, $J = 7$ Hz, 3 H, menthyl), 0.93–1.28 (m, 2 H), 1.43–1.59 (m, 3 H, menthyl), 1.65–2.06 (m, 6 H, menthyl and central CH_2), 2.45

(apparent t, $J = 7$ Hz, 2 H), 2.93 (apparent t, $J = 7$ Hz, 2 H), 4.82 (apparent dt, $J = 10.5$, 4.5 Hz, 1 H, CHO-menthyl), CO_2H gives a broad signal at 9.0–9.5 depending on water contamination of the NMR solvent; ^{13}C NMR: δ_C 16.1, 17.85, 20.6, 21.85, 23.3, 26.2, 31.4, 32.6, 34.0, 38.2, 40.3, 46.7, 77.0, 160.6 (C=O), 178.6 (C=O), 193.9 (C=O); ν_{max} (thin film) (cm^{-1}) 3400vbr (OH), 1718 (CO); MS(EI) m/z 139 (menthyl$^+$); $[\alpha]_D$-56 (c 1.22, $CHCl_3$).

*3.4. General procedure for alkene oxidation using cobalt catalysts **3**–**4***

Solid **3** or (*R,R*)-**4** (5 mol% based on alkene) was added to a mixture of alkene (0.25–0.50 mmol) and **1** in MeCN at the concentrations and alkene:**1**, ratios given in Table 1. After stirring under oxygen (1 atm, 16 h) products were isolated by chromatography on elution with 4:1 light petroleum:Et_2O and identified by comparison with authentic samples.

*3.5. General procedure for alkene oxidation using manganese catalyst (R,R)-**5***

Co-reductant **1c** (0.63–1.25 mmol) in MeCN (1.5 cm^3) was added by syringe pump to a stirred solution of alkene (0.25 mmol), catalyst (*R,R*)-**5** (25 μmol, 10 mol% based on alkene), *N*-methylimidazole (0.00–0.20 mmol, 0–80 mol% based on alkene) and internal standard (PhCN, 100 μL) under oxygen as indicated in Tables 2 and 3. After the addition of **1** was complete the reaction was stirred for a further 0.5 h. Chemical yields were determined by GC analysis. The reaction mixture was filtered through silica twice and the enantioselectivity determined by GC (epoxychromene and styrene oxide) or NMR methods (*trans*-stilbene).

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