Enantioselective Electrochemical Lactonization Using Chiral Iodoarenes as Mediators

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Abstract The enantioselective electrochemical lactonization of diketo acid derivatives using chiral iodoarenes as redox mediators is reported for the first time. Good to high stereoselectivities are observed in the lactonization and also in intermolecular α-alkoxylations of diketo ester derivatives. This enantioselective process was then adapted to an electrochemical flow microreactor where only small amounts of supporting electrolyte were necessary.

Key words electrolysis, flow microreactors, hypervalent iodine, lactonization, stereoselective synthesis

The utility of chiral hypervalent iodine compounds for enantioselective oxidative reactions represents an important and interesting area in organic chemistry.2 Specifically, as a versatile and general oxidation system, the combination of mCPBA as the stoichiometric oxidant and chiral iodoarenes as catalysts has been successfully applied to various transformations, including the asymmetric difunctionalization of alkenes,3 the stereoselective deearomatization of phenol or naphthol derivatives,4 enantioselective oxidative rearrangement5 and the enantioselective synthesis of spirooxindole derivatives.6 Nevertheless, although enantioselective oxidative lactonization has been well developed via the deearomatization of phenol or naphthol derivatives using chiral iodoarenes in combination with mCPBA, direct lactone synthesis through oxidative cyclization of keto acids is underdeveloped, and only moderate enantioselectivities (<51% ee) were achieved (Scheme 1, eq. 1).7

As an efficient and environmentally friendly protocol for organic synthesis, electrochemical conversions have recently gained more attention as often an excess amount of conventional chemical oxidants and reducing reagents can be avoided.8 Although the electrochemical oxidative α-lactonization of γ-keto acids has been reported using n-Bu$_4$NI as the mediator (Scheme 1, eq. 2),9 the enantioselective electrolysnsynthesis of lactones is still unexplored.10 In organic electrochemistry, iodoarenes represent a versatile class of redox mediators, which can generate hypervalent iodine(III) reagents via anodic oxidation to accomplish various transformations without use of a stoichiometric oxidant such as mCPBA. The first electrolysis of iodoarenes described the synthesis of (difluoroiodo)benzene, by Schmidt and Meinert in 1960,11 and subsequently Fuchigami has contributed to the development of different fluorination reactions in electrochemistry.12 Recently, the anodic oxidation of iodoarenes in trifluoroethanol and hexafluoroisopropanol (HFIP) has been reported by Nishiyama and Francke and their co-workers, who accomplished C–N and C–O bond formations.13 Some reviews in this area have recently been published.14

Scheme 1 Different methods for oxidative lactonization

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The anodic oxidation of chiral iodoarenes and subsequent enantioselective synthesis has never been reported, although there are many reported works on stereoselective oxidative functionalizations using hypervalent iodine reagents.\textsuperscript{15} Herein, we report the enantioselective electrochemical $\alpha$-lactonization and $\alpha$-alkoxylation of diketo acid derivatives with chiral iodoarenes as electron-transfer mediators.\textsuperscript{16} These asymmetric reactions have been performed in batch chemistry but can also proceed using an electrochemical flow reactor\textsuperscript{17} with lower amounts of electrolyte (Scheme 1, eq. 3).

Initial reactions were performed using diketo acid 1\textsuperscript{a} as a model substrate for the enantioselective lactonization with chiral iodoarene 2\textsuperscript{b} as redox mediator, and platinum as anode and cathode material, under galvanostatic conditions at 7 mA (Scheme 2). Since fluorinated solvents are known to stabilize iodine(III) reagents by the anodic oxidation, TFE was initially chosen as the solvent.

Several commonly used electrolytes were investigated in the electrochemical reaction shown in Scheme 2 (Table 1, entries 1–3); the use of $n$-Bu$_4$NBF$_4$ as the electrolyte gave lactone 3\textsuperscript{a} in good yield (70%) and enantioselectivity (71% ee) (entry 3). Although the reaction does proceed in the absence of trifluoroacetic acid (TFA), both the efficiency and enantioselectivity were decreased (Table 1, entry 4). For this electrochemical process, the solvent HFIP is not a good choice and only results in moderate yield and lower enantioselectivity (Table 1, entry 5); no product was detected using acetonitrile as the solvent. There is also no product formed in the absence of either electrolyte or chiral iodoarene, and with catalytic amounts of 2\textsuperscript{b} only traces of the product were observed (Table 1, entries 6–8). A decrease in the reaction temperature to $–10$ °C did not improve the enantioselectivity, but only resulted in a lower yield of 3\textsuperscript{a} (Table 1, entry 9).

The absolute configuration of the major isomer of 3\textsuperscript{a} was shown to be (S) via X-ray crystallographic analysis (Scheme 2).\textsuperscript{18} Other lactate-based 2-iodoresorcinol derivatives were also employed as potential electron-transfer mediators, including iodoarenes that have previously found applications in the enantioselective oxidative dearmatization of naphthols.\textsuperscript{4} Neither 2\textsuperscript{a} nor 2\textsuperscript{c} gave better results than 2\textsuperscript{b} (Table 1, entries 10 and 11) while the chiral iodoarenes 2\textsuperscript{d} and 2\textsuperscript{e} containing benzyl ester and amide functionalities decomposed after several minutes under the electrochemical reaction conditions.\textsuperscript{19}

To explore the generality and the substrate scope of this electrochemical reaction, some diketo acid derivatives 1 were subjected to the electrolysis conditions (Scheme 3). The electrolysis of substrates bearing electron-rich or -poor groups on the indanone moiety gave the corresponding lactones 3\textsuperscript{b}–3\textsuperscript{d} in moderate yields with reasonable enantioselectivities. For the naphthyl-substituted substrate 1\textsuperscript{e}, the reaction proceeded in high yield leading to the product 3\textsuperscript{e} in 63% ee. Also, tetralone derivatives such as 1\textsuperscript{f} led to the cyclized product 3\textsuperscript{f} in 58% yield and 47% ee, while lactone 3\textsuperscript{g} without an aryl moiety was only formed in 36% yield as a racemate.

When the carbonyl group and carboxylic acid were both fixed to an aromatic ring as 3\textsuperscript{h}, the reaction proceeded well with good selectivity. Unfortunately, the attempted cyclization of the monocarbonyl substrate 5-oxo-5-phenylpentanoic acid 1\textsuperscript{i} failed to give any desired product 3\textsuperscript{i}, which was previously reported in high yield under electrochemical conditions with $n$-Bu$_4$NI as the mediator.\textsuperscript{9}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Entry & Electrolyte & Yield (%) ee (%) \\
\hline
1 & 2\textsuperscript{b} (1.2 eq), LiClO$_4$ & 30 67 \\
2 & 2\textsuperscript{b} (1.2 eq), 0.05 M $n$-Bu$_4$NClO$_4$ & 61 65 \\
3 & 2\textsuperscript{b} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$ & 70 71 \\
4 & 2\textsuperscript{b} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$, no TFA added & 51 61 \\
5 & 2\textsuperscript{b} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$, HFIP instead of TFE & 50 29 \\
6 & 2\textsuperscript{b} (1.2 eq) & 0 – \\
7 & no iodoarene, 0.05 M LiClO$_4$ & 0 – \\
8 & 2\textsuperscript{b} (0.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$ & <5 – \\
9 & 2\textsuperscript{b} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$ & 41 70 \\
10 & 2\textsuperscript{a} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$ & 54 67 \\
11 & 2\textsuperscript{c} (1.2 eq), 0.05 M $n$-Bu$_4$NBF$_4$ & 15 68 \\
\hline
\end{tabular}
\caption{Enantioselective Electrochemical Lactonization of 1\textsuperscript{a} to 3\textsuperscript{a}
Using Chiral Iodoarenes\textsuperscript{a}}
\end{table}

\textsuperscript{a} Reaction conditions: Pt cathode, Pt anode, 1 (0.025 M), 2 (0.03 M), electrolyte (0.05 M), TFA (0.075 M), solvent (4 mL), undivided cell (charge passed: 2.6 F). \textsuperscript{b} Determined by HPLC. \textsuperscript{c} The reaction was performed at $–10$ °C.
It has been reported that oxidative lactonization can be achieved with a combination of chiral iodoarenes and mCPBA as stoichiometric oxidant. Therefore, the combination of 2b and mCPBA was compared to the electrochemical reaction conditions, leading to products 3a, 3g and 3i. Compounds 3a and 3g were obtained with similar yields and selectivities, while 3i could be isolated in moderate yield and low enantioselectivity only using the combination of 2b and mCPBA (Scheme 3).

With chiral iodoarene 2b, intermolecular C–O bond functionalization was also investigated using ester 4 as a substrate under the standard electrochemical conditions (Scheme 4). Protonic solvents such as water, alcohols and acetic acid were chosen, together with TFE, due to their conductivity and nucleophilicity.

Pleasingly, the electrochemical reaction of ester 4 in a mixture of TFE/H2O (3:1) with 2b as the chiral mediator gave the desired α-hydroxy product 5a in moderate yield with 31% ee. Although the reaction efficiency was reduced in solvent mixtures of TFE with methanol or ethanol, high enantioselectivities (up to 79% ee) were observed (5b and 5c). However, when the electrolysis was attempted in the solvent TFE/MeOH (3:1), the desired α-acetoxy product 5d was not detected. The absolute configuration of compounds 5 was assigned by analogy to compound 3a.

Compared with batch processes for electrochemical reactions, continuous flow reactors can reduce the amount or avoid the use of electrolytes because of the close distance of the electrodes. We have reported electrochemical flow microreactors for several oxidative transformations. Pleasingly, the present enantioselective lactonization could also be successfully accomplished using an electrochemical flow microreactor with a lower concentration of n-Bu4NB4 (5 mM) (Scheme 5), despite a slight decrease in the efficiency and enantioselectivity. There is no conversion without catalytic amounts of electrolyte and the conversion decreases when the platinum cathode is replaced by graphite. To the best of our knowledge, this is the first enantioselective reaction with iodine(III) reagents generated in an electrochemical flow microreactor.

Additional experiments were carried out to further explore the mechanism of this enantioselective electrolytic lactonization. Initially, a stepwise batch process was performed. After the anodic oxidation of mediator 2b, substrate 1a was added to the reaction mixture. However, this stepwise protocol only led to the desired product 3a in 9% yield (65% ee) (Scheme 6). In the 1H NMR spectra of the electrolyzed 2b in TFE, a downfield peak at around 7.24 ppm was observed indicating the formation of an iodine(III) species, but this peak disappeared after several hours or after removal of the solvent (see the Supporting Information). This indicates the formation of an unstable iodine(III) species Ar–IL2 by electrolysis of iodoarene 2b. In addition, cy-
clic voltammetry in TFE showed a lower potential (1.83 V, vs Ag/AgCl) for 2b than for 1a (2.07 V, vs Ag/AgCl) indicating that 2b is easier oxidized than 1a in the one-pot electrolysis (Figure 1). In summary, we have developed an electrochemical method for enantioselective lactonization using chiral lactate-based iodoarenes as redox mediators. This protocol was also applied to the intermolecular α-alkoxylation of diketo esters with good enantioselectivities. Furthermore, it was demonstrated that this enantioselective transformation could be adapted to an electrochemical flow microreactor with lower supporting electrolyte concentration. Further studies on stereoselective electroosynthesis using chiral iodoarenes are currently in progress.

Based on the investigations from Muñiz, Ishihara and co-workers, two structures for a possible explanation of the observed stereoselectivities are shown in Figure 2. These structures show the intermediates after the reaction of the substrate enolates with the iodine(III) reagent. Due to the steric hindrance between the indanone moiety and the lactate ester, intramolecular cyclization favorably proceeds through intermediate 6 rather than through intermediate 7.

In summary, we have developed an electrochemical method for enantioselective lactonization using chiral lactate-based iodoarenes as redox mediators. This protocol was also applied to the intermolecular α-alkoxylation of diketo esters with good enantioselectivities. Furthermore, it was demonstrated that this enantioselective transformation could be adapted to an electrochemical flow microreactor with lower supporting electrolyte concentration. Further studies on stereoselective electroosynthesis using chiral iodoarenes are currently in progress.

All reactions were carried out in oven-dried glassware under an atmosphere of nitrogen/argon using anhydrous solvents. All commercial reagents were used as received. 1H NMR spectra were recorded at 400 or 500 MHz on Bruker DPX 400 or DPX 500 spectrometers. Chemical shifts are reported in parts per million (ppm, δ) relative to TMS (δ 0.00). 1H NMR splitting patterns are designated as singlet (s), doublet (d), doublet of doublet (dd), triplet (t), quartet (q), multiplet (m). 13C NMR spectra were recorded at 100 or 125 MHz. Mass spectra were obtained using a Waters Xevo G2-S ESI mass spectrometers. IR spectra were recorded as neat on a Shimadzu FTIR Affinity-1S spectrophotometer. Melting points were determined using a Gallenkamp hot-stage apparatus and are uncorrected. Optical rotations were measured using a 10.0 mL cell with a 1.0 dm path length on a SCHMIDT + HAENSCH UniPol L polarimeter apparatus and are reported as [α]c in g per 100 mL, solvent at 20 °C.

Methyl 4-Oxo-4-(1-oxo-2,3-dihydro-1H-inden-2-yl)butanoate (4)
To a solution of diisopropylamine (1.6 g, 15.8 mmol) in THF (40 mL) was added 2.5 M n-Buli in hexane (6.9 mL, 17.4 mmol) at –78 °C. The resulting solution was stirred at –78 °C for 30 min and then at room temperature for an additional 30 min. The solution was cooled to –78 °C, and to this solution was added dropwise a solution of 1-iodoarene (1 g, 5 mmol) in THF (10 mL). After 1 h at –78 °C, the solution was added dropwise methyl-4-chloro-4-oxobutyrate (1.36 mL, 11 mmol) in THF (5 mL). The resulting solution was warmed to room temperature over 2 h, and then quenched with saturated NH4Cl solution. The organic phase was separated, and the water phase was extracted with Et2O (3 × 20 mL). The combined organic layers were dried, concentrated and purified by chromatography (petroleum ether/EtOAc, 5:1) to give 4 as a colorless solid; yield: 1.01 g (51%); mp 57–59 °C.

IR (neat): 3025, 1734, 1628, 1545, 1221, 1167, 1038, 779, 731 cm–1.

1H NMR (500 MHz, CDCl3): δ = 7.78 (d, J = 8.0 Hz, 1 H), 7.55–7.48 (m, 2 H), 7.41 (t, J = 7.5 Hz, 1 H), 3.70 (s, 3 H), 3.64 (s, 2 H), 2.82 (t, J = 6.0 Hz, 2 H), 2.75 (t, J = 6.0 Hz, 2 H).

13C NMR (125 MHz, CDCl3): δ = 187.5, 182.4, 173.0, 146.8, 137.7, 132.4, 127.3, 125.6, 122.8, 110.6, 51.9, 30.5, 30.4, 28.9.


4-Oxo-4-(1-oxo-2,3-dihydro-1H-inden-2-yl)butanoic Acid (1a)
Compound 4 (1.2 g, 5 mmol) was dissolved in THF/MeOH/water (3:1:1 v/v/v, 20 mL). To this mixture 1 M LiOH in water (10 mL) was added and the resulting solution stirred overnight. After removal of organic solvent in vacuo, the aqueous phase was acidified with HCl until pH 3. The mixture was extracted with EtOAc (3 × 20 mL). The combined organic fractions were dried with sodium sulfate and con-
centrated in vacuo to give the crude acid 1a, which was recrystallized from EtOAc to give 1a as a white solid; yield: 1.03 g (89%); mp 119–121 °C.

IR (neat): 3025, 1699, 1624, 1549, 1404, 1067, 972, 775 cm⁻¹.

1H NMR (500 MHz, CD₂OD): δ (two isomers) = 7.70 (d, J = 7.5 Hz, 0.77 H) (major), 7.68–7.60 (m, 1 H), 7.57–7.52 (m, 2 H), 7.44–7.35 (m, 1.23 H), 3.66 (s, 1.54 H) (major), 3.60 (d, J = 16.5 Hz, 0.46 H), 3.28–3.25 (m, 0.23 H), 3.19 (d, J = 16.5 Hz, 0.46 H), 2.98–2.90 (m, 0.46 H), 2.83 (t, J = 6.5 Hz, 1.54 H) (major), 2.70 (t, J = 6.5 Hz, 1.63 H) (major), 2.63–2.50 (m, 0.77 H).

13C NMR (125 MHz, CD₂OD): δ = 204.4, 202.1, 176.3, 156.2, 148.7, 139.1, 136.8, 136.5, 133.7, 128.9, 128.5, 128.0, 127.0, 125.3, 123.6, 112.3, 83.6, 31.6, 31.5, 29.9, 29.3, 28.8.


4-Oxo-4-(1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoic Acid (1b)
Yield: 406 mg (31%); white solid; mp 132–134 °C.

IR (neat): 3003, 1718, 1647, 1576, 1492, 1375, 1024, 877, 788 cm⁻¹.

1H NMR (500 MHz, DMSO-d₆): δ (two isomers) = 12.2 (br s, 1 H), 7.52 (d, J = 8.4 Hz, 0.40 H), 7.40 (d, J = 8.4 Hz, 0.60 H) (major), 7.29 (dd, J = 8.4, 2.8 Hz, 0.40 H), 7.25–7.20 (m, 0.60 H) (major), 7.15 (dd, J = 8.4, 2.8 Hz, 0.60 H) (major), 7.09 (dd, J = 2.8 Hz, 0.40 H), 4.25 (dd, J = 8.0, 2.8 Hz, 0.60 H) (major), 3.81 (s, 2 H), 3.79 (s, 1 H), 3.56 (br s, 1.40 H), 3.37 (dd, J = 13.2, 2.8 Hz, 0.60 H) (major), 3.20–3.07 (m, 1 H), 2.92–2.80 (m, 1.60 H) (major), 2.56 (t, J = 2.8 Hz, 1.40 H), 2.43 (t, J = 6.8 Hz, 0.60 H) (major).

13C NMR (100 MHz, DMSO-d₆): δ = 202.8, 199.8, 173.7, 173.6, 159.2, 158.9, 147.0, 136.1, 127.7, 126.6, 124.3, 119.6, 112.5, 105.4, 105.1, 61.4, 55.6, 55.4, 37.1, 31.6, 30.1, 28.4, 27.6, 27.4.


4-(6-Methoxy-1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoic Acid (1c)
Yield: 677 mg (55%); white solid; mp 138–140 °C.

IR (neat): 2950, 1703, 1614, 1544, 1207, 1165, 1111, 1031 cm⁻¹.

1H NMR (400 MHz, DMSO-d₆): δ (two isomers) = 12.1 (br s, 1 H), 7.57–7.37 (m, 3 H), 4.23 (dd, J = 8.0, 3.2 Hz, 0.40 H), 3.60 (s, 1.3 H) (major), 3.43 (dd, J = 17.6, 3.2 Hz, 0.40 H), 3.24–3.10 (m, 1 H), 2.95–2.75 (m, 1.60 H) (major), 2.57 (t, J = 6.4 Hz, 1.40 H), 2.44 (t, J = 6.4 Hz, 1.40 H), 2.39 (m, 3 H).

13C NMR (100 MHz, DMSO-d₆): δ = 202.9, 199.9, 173.7, 173.6, 151.7, 137.3, 136.6, 135.0, 126.5, 125.5, 123.6, 122.0, 61.0, 37.1, 31.5, 30.4, 27.7, 27.6, 20.9, 20.5.


4-(6-Chloro-1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoic Acid (1d)
Yield: 373 mg (28%); white solid; mp 134–136 °C.

IR (neat): 2950, 1701, 1626, 1541, 1217, 1078, 813, 748 cm⁻¹.

1H NMR (500 MHz, CDCl₃): δ (two isomers) = 8.00 (dd, J = 7.5, 1.0 Hz, 0.5 Hz), 7.82 (br s, 0.5 H), 7.76 (dd, J = 8.0, 0.55 Hz) (major), 7.74–7.52 (m, 5 H), 7.48 (d, J = 7.5, 0.55 Hz) (major), 7.43 (t, J = 7.5, 0.55 H) (major), 7.36 (t, J = 8.0, 0.55 Hz) (major), 3.46–3.15 (m, 2 H).

13C NMR (125 MHz, CDCl₃): δ = 189.7, 169.8, 155.4, 139.1, 138.7, 136.7, 134.0, 133.4, 131.1, 129.8, 128.6, 127.9, 127.0, 124.8, 123.7, 112.8, 32.4, 30.5.

4-Oxo-4-(2-oxycyclopentyl)butanoic Acid (1g)
A mixture of cyclopentanone (2.6 mL, 30 mmol) and pyrrolidine (3.0 mL, 36 mmol) in benzene (12 mL) was refluxed using a Dean–Stark apparatus overnight. The solvents and excess pyrrolidine were removed in vacuo. The crude enamine and dry triethylamine (4.6 mL, 33 mmol) were dissolved in benzene (10 mL), and to this solution was added dropwise methyl 3,5-dihydroxy-4-iodobenzoate (5.9 g, 20.0 mmol), triphenylphosphine (13 g, 50 mmol, 2.5 eq) and methyl diisopropyl azodicarboxylate (10 mL, 50 mmol, 2.5 eq) was added dropwise via syringe over 30 min to a stirred suspension of methyl triphenylphosphonium chloride (74.1 mg, 0.2 mmol). After stirring for 24 h at room temperature, the mixture was filtered through Celite and washed with chloroform. The combined organic extracts were dried, the solvent was removed and the residue was purified by column chromatography (petroleum ether/EtOAc, 3:1) to give 2b as a white solid; yield: 13 mg (54%); mp 166–168 °C; 61% ee (determined by HPLC).

IR (neat): 2924, 1749, 1707, 1606, 1411, 1271, 1215, 1090, 972, 768 cm⁻¹.

HRMS (ESI): m/z calc for C_{13}H_{11}O_{4} [M + H]^+: 231.0675; found: 231.0676.

HPLC (YMC Chiral Amylose-C S-5 μm (25 cm), hexane/i-PrOH, 90:10, 0.8 mL/min, 10 °C, 254 nm): t<sub>R</sub> (minor) = 35.4 min, t<sub>R</sub> (major) = 39.8 min.

(5)-6-Methyl-4′,5′-dihydrospiro[indene-2,2′-pyran]-1,3′,6′(3H)-trione (3c)
A 10-mL three-necked round-bottomed flask was equipped with a magnetic stirrer, and platinum plate (1 cm²) electrode as the working electrode and counter electrode. The substrate 1a (23 mg, 0.1 mmol), chiral idobenzene 2b (56 mg, 0.12 mmol), TFA (34 mg, 0.3 mmol) and supporting electrolyte n-Bu4NBF4 (66 mg, 0.2 mmol) were added to the solvent TFE (4 mL). The resulting mixture was stirred and electrolyzed under galvanostatic conditions (7 mA/cm²) at room temperature for 1 h. The solvent was removed in vacuo and the residue purified by column chromatography (petroleum ether/EtOAc, 3:1) to give 3a as a white solid; yield: 16 mg (70%); mp 162–164 °C; 71% ee (determined by HPLC).

IR (neat): 2922, 1749, 1707, 1606, 1411, 1271, 1215, 1090, 972, 768 cm⁻¹.

HRMS (ESI): m/z calc for C_{13}H_{11}O_{4} [M + H]^+: 231.0652; found: 231.0653.

HPLC (YMC Chiral Amylose-C S-5 μm (25 cm), hexane/i-PrOH, 90:10, 0.8 mL/min, 20 °C, 254 nm): t<sub>R</sub> (minor) = 35.4 min, t<sub>R</sub> (major) = 39.8 min.
(5)-6-Chloro-4,5′-dihydropyridin-2′-pyran]-1,3′,6′(3'H)-trione (3d)
Yield: 10 mg (40%); white solid; mp 172–174 °C; 68% ee (determined by HPLC).
IR (neat): 3420, 2924, 2360, 1763, 1715, 1450, 1307, 1254, 1105, 982, 872 cm−1.
1H NMR (500 MHz, CDCl3): δ = 7.71 (d, J = 2.0 Hz, 1 H), 7.66 (dd, J = 8.5, 0.2 Hz, 1 H), 7.46 (d, J = 8.0 Hz, 1 H), 7.37 (d, J = 16.5 Hz, 1 H), 3.69–3.62 (m, 1 H), 3.27 (d, J = 17.0 Hz, 1 H), 3.01 (dt, J = 17.0, 4.5 Hz, 1 H), 2.86–2.82 (m, 2 H).
13C NMR (125 MHz, CDCl3): δ = 129.4, 128.9, 128.7, 127.2, 88.2, 43.1, 31.6, 27.7, 24.7.

(5)-4′,5′-Dihydrospiro[cyclopenta[a]naphthalene-2,2′-pyran]-1,3′,6′(3'H)-trione (3e)
Yield: 24 mg (87%); white solid; mp 200–202 °C; 63% ee (determined by HPLC).
IR (neat): 3420, 2924, 2360, 1763, 1715, 1450, 1307, 1254, 1105, 982, 872 cm−1.
1H NMR (500 MHz, CDCl3): δ = 8.58 (d, J = 8.5 Hz, 1 H), 8.16 (d, J = 8.5 Hz, 1 H), 7.92 (d, J = 8.5 Hz, 1 H), 7.70 (td, J = 8.0, 1.0 Hz, 1 H), 7.60 (td, J = 8.0, 1.0 Hz, 1 H), 7.54 (d, J = 8.5 Hz, 1 H), 3.85 (d, J = 17.0 Hz, 1 H), 3.84–3.76 (m, 1 H), 3.42 (d, J = 17.0 Hz, 1 H), 3.07–3.01 (m, 1 H), 2.89–2.85 (m, 2 H).
13C NMR (125 MHz, CDCl3): δ = 135.9, 134.2, 131.0, 130.9, 129.5, 128.6, 126.9, 123.8, 123.0, 92.9, 39.1, 33.5, 27.2.

6-Oxaspiro[4.5]decane-1,7,10-trione (3g)
Yield: 7 mg (36%); yellow oil; 0% ee (determined by HPLC).
IR (neat): 2924, 1743, 1713, 1456, 1265, 1142, 1103, 1051, 1009, 970, 872 cm−1.
1H NMR (500 MHz, CDCl3): δ = 3.34–3.25 (m, 1 H), 2.94–2.87 (m, 1 H), 2.80–2.68 (m, 2 H), 2.65–2.57 (m, 1 H), 2.55–2.40 (m, 2H), 2.30–2.07 (m, 3 H).
13C NMR (125 MHz, CDCl3): δ = 209.9, 203.2, 168.9, 191.7, 35.8, 34.3, 33.8, 27.0, 18.2.
HRMS (ESI): m/z calcd for C10H10O4 [M + H]+: 283.0652; found: 283.0651.

[R]-Spino[inden-2,3′-isochroman]-1′,4′(3'H)-trione (3h)
Yield: 18 mg (64%); white solid; mp 140–142 °C; 67% ee (determined by HPLC).
IR (neat): 2924, 1743, 1713, 1456, 1265, 1142, 1103, 1051, 1009, 970, 872 cm−1.
1H NMR (500 MHz, CDCl3): δ = 3.56 (dd, J = 8.0, 1.0 Hz, 1 H), 8.00 (dd, J = 7.5, 1.0 Hz, 1 H), 7.91 (td, J = 7.5, 1.0 Hz, 1 H), 7.80 (td, J = 8.0, 1.0 Hz, 1 H), 7.75–7.69 (m, 2 H), 7.59 (dt, J = 8.0, 1.0 Hz, 1 H), 7.44 (t, J = 8.0 Hz, 1 H), 4.20 (d, J = 16.5 Hz, 1 H), 3.47 (d, J = 16.5 Hz, 1 H).
13C NMR (125 MHz, CDCl3): δ = 195.5, 187.9, 161.6, 152.2, 137.0, 135.9, 134.2, 131.5, 130.9, 129.5, 128.6, 126.6, 126.4, 126.0, 94.0, 37.4.

(S)-Methyl 4-(2-Hydroxy-1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoate (5a)
Yield: 17 mg (66%); colorless oil; 31% ee (determined by HPLC).
IR (neat): 1726, 1705, 1609, 1211, 1092, 733 cm−1.
1H NMR (500 MHz, CDCl3): δ = 7.82 (d, J = 9.0 Hz, 1 H), 7.70 (t, J = 7.5 Hz, 1 H), 7.55 (d, J = 7.5 Hz, 1 H), 7.46 (t, J = 7.5 Hz, 1 H), 4.42 (s, 1 H), 3.82 (d, J = 17.5 Hz, 1 H), 3.65 (s, 3 H), 3.24 (d, J = 17.5 Hz, 1 H), 2.82–2.66 (m, 2 H), 2.54–2.43 (m, 2 H).
13C NMR (125 MHz, CDCl3): δ = 205.1, 201.5, 172.7, 152.2, 136.5, 134.3, 128.5, 126.8, 125.3, 87.1, 52.0, 38.9, 31.3, 27.5.
HRMS (ESI): m/z calcd for C14H12O3 [M + H]+: 263.0914; found: 263.0916.

(S)-Methyl 4-(2-Methoxy-1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoate (5b)
Yield: 10 mg (38%); colorless oil; 77% ee (determined by HPLC).
IR (neat): 2953, 2926, 1730, 1707, 1609, 1458, 1209, 1132, 1101, 1020, 771 cm−1.
1H NMR (500 MHz, CDCl3): δ = 7.73 (d, J = 7.5 Hz, 1 H), 7.64 (t, J = 7.5 Hz, 1 H), 7.50 (d, J = 8.0 Hz, 1 H), 7.39 (t, J = 7.5 Hz, 1 H), 3.68 (d, J = 17.0 Hz, 1 H), 3.64 (s, 3 H), 3.41 (s, 3 H), 3.23–3.08 (m, 3 H), 2.62–2.46 (m, 2 H).

13C NMR (125 MHz, CDCl3): δ = 205.8, 199.5, 173.0, 152.5, 136.2, 134.1, 128.0, 126.5, 124.8, 93.7, 53.6, 51.7, 33.6, 32.6, 27.5.


HPLC (Daicel Chiralcel OD-H column (25 cm), hexane/i-PrOH, 95:5, 1.0 mL/min, 20 °C, 254 nm): tR (minor) = 20.3 min, tR (major) = 24.1 min.

(S)-Methyl 4-(2-Ethoxy-1-oxo-2,3-dihydro-1H-inden-2-yl)-4-oxobutanoate (5c)

Yield: 12 mg (40%); colorless oil; 79% ee (determined by HPLC).

[α]D 20 = +31 (c 0.70, CHCl3).

IR (neat): 2924, 1728, 1707, 1609, 1437, 1213, 1161, 1105, 1038, 772 cm⁻¹.

For mass spectrometric analysis.

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References

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(10) For molecules containing chiral keto lactones, see:


(16) For selected enantioselective electrochemical processes, see:


(18) CCDC 1834441 (3a) contains the supplementary crystallographic data for this paper. The data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/getstructures.
