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A Series of Cinchona-Derived *N*-Oxide Phase-Transfer Catalysts: Application to the Photo-Organocatalytic Enantioselective α-Hydroxylation of β-Dicarbonyl Compounds

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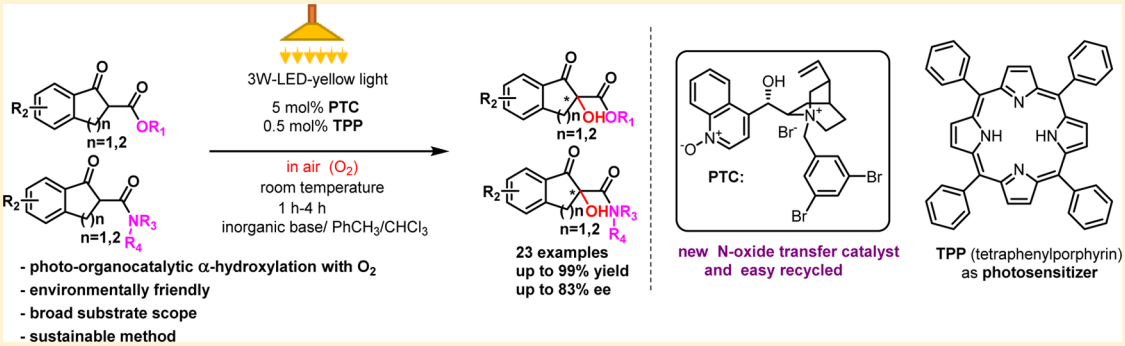
Supporting Information



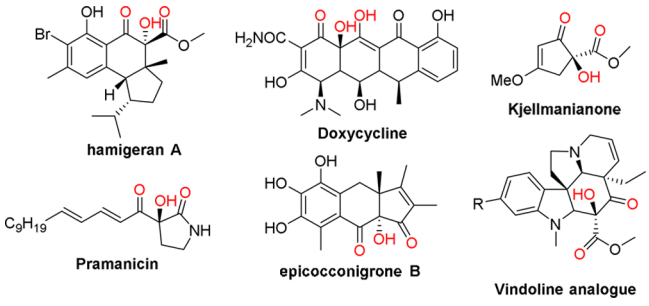
ABSTRACT: A series of cinchona-derived *N*-oxide asymmetric phase-transfer catalysts were synthesized and applied in the enantioselective photo-organocatalytic α-hydroxylation of β-keto esters and β-keto amides (23 examples) using molecular oxygen in excellent yields (up to 98%) and high enantioselectivities (up to 83% ee). These new catalysts could be recycled and reused six times for such a reaction with almost the original reactivity and enantioselectivity.

INTRODUCTION

Over the past few decades, cinchona alkaloids and their derivatives have been demonstrated as privileged chiral catalysts with the sudden explosion of interest in the field of asymmetric catalysis.[1] Moreover, phase-transfer catalysis has been recognized as an effective and sustainable method, and cinchona alkaloid-based phase-transfer catalysts have been applied to many practical asymmetric syntheses.[2] The first example of a highly enantioselective alkylation reaction with a cinchona alkaloid-based phase-transfer catalyst (PTC) was realized by a group at Merck in 1984.[3] After five years, O'Donnell and co-workers reported the enantioselective alkylation of glycine Schiff base with *N*-benzyl cinchonidinium salt.[4] Then, various modified PTCs were prepared for phase-transfer reactions.[5] The structures of cinchona alkaloid-based PTCs were usually modified by the esterification of the C-9 hydroxy group or quaternization of the nitrogen atom in the bridge ring. However, to the best of our knowledge, there are no examples of PTCs in which the quinoline nitrogen was oxidized.[6] Herein, we report the discovery of cinchona-derived *N*-oxide cinchona alkaloids, wherein the quinoline nitrogen (*N*′) was oxidized and the quinuclidine nitrogen was quaternized as a new type of phase-transfer catalyst.

On the other hand, the optically active α-hydroxy-β-dicarbonyl moiety is an intriguing structural motif in a variety of natural products and pharmaceuticals (Scheme 1).[7] Asymmetric

Scheme 1. Examples of α-Hydroxy-β-dicarbonyl Compounds as Key Structures of Natural Products or as Key Synthetic Intermediates



catalysis by chiral metal complexes and organocatalysts were developed rapidly in the last two decades.[8,9] Along these lines, various oxidants, such as *N*-sulfonyloxaziridines, peroxides, dimethyldioxirane, and nitrosobenzene, have been utilized. However, molecular oxygen as the oxygen source has rarely been reported. Considering an economical as well as environmental viewpoint, the use of molecular oxygen as the oxygen

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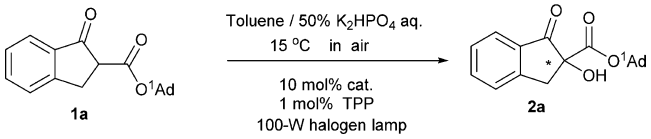
Table 1. Screening of Cinachona Alkaloid Derivatives for α-Hydroxylation of β-Keto Ester 1a[a]



entry	cat.	t [h]	conv. [%][b]	ee [%][c]
1	**Cn-1**	2	90	38
2	**Cn-2**	1	95	19
3	**Cn-3**	1	>99	51
4	**Qd-1**	1	95	43
5	**Qd-2**	5	55	22
6	**Qd-3**	1	>99	54
7	**Qd-4**	0.5	>99	50
8	**Cn-4**	1	>99	56
9	**Cn-5**	1	>99	58
10	**Cn-6**	1	>99	62
11	**Cn-7**	1	>99	72
12	**Cn-8**	1	>99	65
13	**Cn-9**	1	>99	63
14	**Cn-10**	0.5	>99	55

[a]Unless otherwise specified, β-keto ester **1a** (31.0 mg, 0.1 mmol), catalyst (0.01 mmol, 10 mol %), and TPP (0.6 mg, 0.001 mmol) were added to a test tube equipped with a stirring bar and dissolved in toluene (10 mL); then, 50% K_2HPO_4 (4 mL) was added. The mixture was stirred in air with exposure to a 100 W halogen lamp at 15 °C until the reaction was completed. [b]Determined by HPLC analysis with hexane/2-propanol (80:20) as the eluent (Kromasil, SiO_2, 5 m). [c]Determined by HPLC analysis (Chiralcel AD-H) with hexane/2-propanol (80:20) as the eluent.

source would undoubtedly make it an ideal candidate in organic synthesis, especially in the field of asymmetric catalysis.[10]

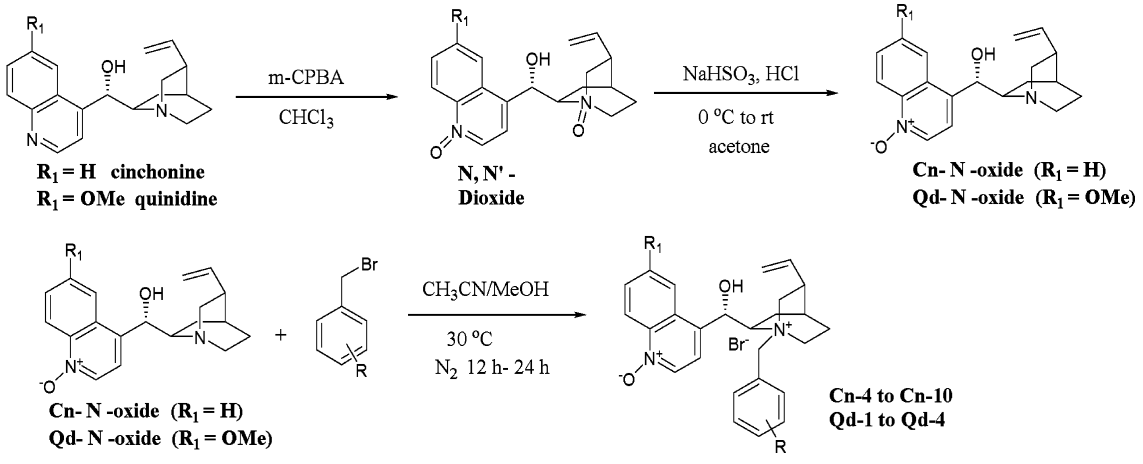
RESULTS AND DISCUSSION

Visible light-driven catalytic asymmetric chemistry has seen tremendous research interest in recent years.[11] Furthermore, molecular oxygen can be transferred from its nonexcited triplet state ($^3O_2$) to its more reactive singlet state ($^1O_2$) by photosensitization. In 2004, the pioneering work of Córdova showed that aldehydes and ketones can be transferred into the corresponding α-hydroxylation products by using singlet oxygen that is activated by photosensitization.[12]

During our studies on the photo-oxygenation of β-keto esters, an enantioselective phase-transfer-catalyzed photo-oxygenation was developed,[13] but the enantioselectivity is moderate (39−75% ee) and the substrate scope is limited to the adamantyl β-keto esters derived from indanone (10 examples). Therefore, we wanted to find more effective phase-transfer catalysts to promote this reaction. First, we attempted the reaction of 1-indanone-derived β-keto ester **1a** (0.1 mmol) in toluene treated with PTC (10 mol %), tetraphenylporphine (TPP; 1 mol %, 0.001 mmol), and K_2HPO_4 (50% aq) in air for enantioselective α-hydroxylation. The simplest catalyst, **Cn-1**, provided **2a** with 38% ee after 2 h (Table 1, entry 1). Then, doubly quaternized catalyst **Cn-2** was synthesized. Although the reaction was completed after 1 h, the enantioselectivity was poor (Table 1, entry 2).

These results revealed that the stereocontrol of this reaction was sensitive to structural modifications at the N-position of the quinoline ring. **Cn-3** was then provided in which the quinoline nitrogen atom was oxidized, and we were surprised to find that the reaction proceeded at a faster rate (>99% conversion, 1 h) and with higher enantioselectivity (51% ee). After that, a series of *N*-oxide phase-transfer catalysts derived from cinchona alkaloids were prepared. The commercially available cinchona alkaloids could be easily oxidized by *m*-CPBA to form *N*,*N*′-dioxide, and the *N*-oxide can be obtained through a reduction reaction of $NaHSO_3$ and HCl.[14] Then, the new PTCs were readily prepared from *N*-oxide with substitutional benzyl bromide (Scheme 2). Interestingly, **Qd-2** was introduced with electron-donating group OMe in the 3,4,5-position of benzyl, affording **2a** with only 55% conversion and 22% ee after 6 h, whereas **Qd-3** with electron-withdrawing 3,5-$(CF_3)_2$ afforded improved conversion and enantioselectity (Table 1, entries 5 and 6). **Qd-4** bearing a hindering 9-anthracenylmethyl group provided a moderate ee value compared with that of **Qd-3** (Table 1, entry 7). To further optimize the ability to catalyze the α-hydroxylation reaction, we then synthesized a series of cinchonine-derived *N*-oxide PTC catalysts (Scheme 3). A steady improvement in ee value was obtained by the 3,5-$(CF_3)_2$ and 3-NO_2 derivatives **Cn-4** and **Cn-5** (Table 1, entries 8 and 9, respectively). Moreover, we found that the ee value was improved to 62% by introducing a chloride atom at the 3 position (Table 1, entry 10). To our delight, **Cn-7**, which has 3,5-$(Br)_2$ groups in the benzyl position, afforded **2a** with 72% ee and almost quantitative conversion after 1 h (Table 1, entry 11). Unfortunately, 3,5-$(I)_2$ groups and 2,3,4,5-$(F)_4$

Scheme 2. Preparation of *N*-Oxide Phase-Transfer Catalyst



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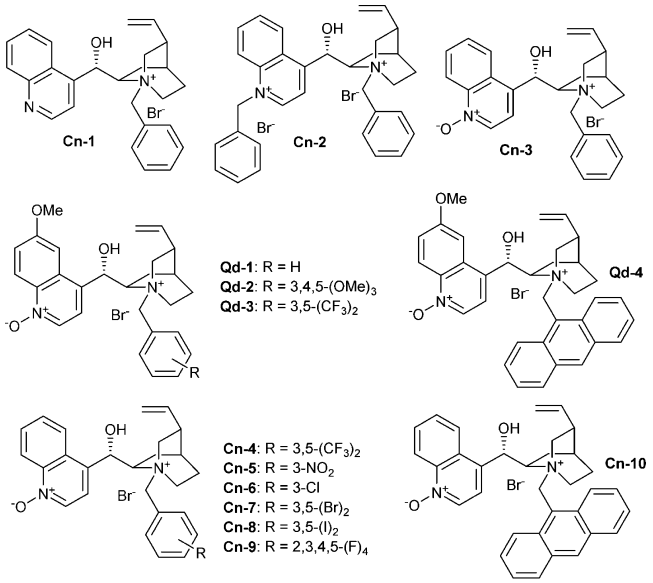
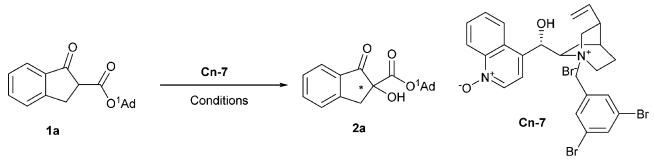
Scheme 3. Cinchona Alkaloid Derivatives Employed for the α-Hydroxylation Reaction



groups in the benzyl position showed slightly lower ee values compared with that of the 3,5-$(Br)_2$ groups (Table 1, entries 12 and 13, respectively). Finally, the bulky *N*-9-anthracenylmethyl group was introduced, but **Cn-10** provided **2a** in only 55% ee, although the reaction time was shortened to 0.5 h (Table 1, entry 14).

After suitable catalyst **Cn-7** was identified, further reaction optimization was undertaken. Table 2 summarizes the effect of several parameters on this reaction. Decreasing concentration of reactants (0.02 to 0.005 M) resulted in no significant improvement for ee value (Table 2, entries 1−3). Then, the effect of different light sources was evaluated. When the 7 W LED blue lamp was used, the ee value decreased to 65% (Table 2, entry 4). The 3 W LED purple lamp also showed poor results (Table 2, entry 5). We think the enantioselectivity was possibly due to the wavelength of the light rather than the wattage. Next, we screened the 3 W LED red and yellow lamps. We were pleased to see that the ee values increased to 76% and 78%, respectively, and the reaction time was shortened to 30 min (Table 2, entries 6 and 7, respectively). In sunlight, the reaction also proceeded well, and oxidation product **2a** was obtained in 74% ee after 45 min (Table 2, entry 8). Correspondingly, nearly no reaction occurred in darkness (Table 2, entry 9). In the solvent screening, we found that the ee value improved to 82% when 8:2 toluene/chloroform was used as the components of the

Table 2. Optimization of the Reaction Conditions for α-Hydroxylation of β-Keto Ester with Catalyst Cn-7[a]



entry	sub (mmol)	light source	solvent	Cn-7 (mol %)	base	sensitizer	T (°C)	reaction time	conv. (%)[b]	ee (%)[c]
1	0.1	100 W halogen lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	60 min	>99	72
2	0.2	100 W halogen lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	40 min	>99	69
3	0.05	100 W halogen lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	120 min	>99	73
4	0.1	7 W LED blue lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	60 min	>99	65
5	0.1	3 W LED purple lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	60 min	>99	62
6	0.1	3 W LED red lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	30 min	>99	76
7	0.1	3 W LED yellow lamp	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	30 min	>99	78
8	0.1	sunlight	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	45 min	>99	74
9	0.1	darkness	PhMe	10	50% K_2HPO_4	TPP (1 mol %)	15	360 min	trace	nd
10	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	50% K_2HPO_4	TPP (0.5 mol %)	15	60 min	>99	82
11	0.1	3 W LED yellow lamp	$CHCl_3$	10	50% K_2HPO_4	TPP (0.5 mol %)	15	60 min	>99	65
12	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	50% K_2HPO_4	rose bengal (1 mol %)	15	60 min	>99	78
13	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	50% K_2HPO_4	$[Ru(bpy)_3]$ Cl_2 (1 mol %)	15	360 min	trace	nd
14	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	25% K_2HPO_4	TPP (1 mol %)	15	120 min	>99	78
15	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	30% K_2CO_3	TPP (1 mol %)	15	30 min	>99	71
16	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	50% K_2HPO_4	TPP (1 mol %)	−5	180 min	>99	81
17	0.1	3 W LED yellow lamp	8:2 PhMe/$CHCl_3$	5	50% K_2HPO_4	TPP (1 mol %)	35	60 min	>99	79

[a]Unless otherwise specified, the reaction was performed with 0.1 mmol of **1a** using the conditions described in Table 2. [b]Determined by HPLC analysis with hexane/2-propanol (80:20) as the eluent (Kromasil, SiO_2). [c]Determined by HPLC analysis (Chiralcel AD-H) with hexane/2-propanol (80:20) as the eluent.

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solvent, and the loading of catalyst **Cn-7** in this α-hydroxylation could be reduced to 5 mol % while still achieving 99% conversion and 82% ee in 60 min at 15 °C (Table 2, entry 10). Pure chloroform was also used and showed poor results (Table 2, entry 11). Other sensitizers such as rose bengal, $[Ru(bpy)_3]Cl_2$, were also tested, and tetraphenylporphyrin (TPP) proved to be the best sensitizer for this reaction (Table 2, entries 12 and 13). Other bases were also tested. Whether the weaker base (25% K_2HPO_4) or stronger base (30% K_2CO_3) was used, the ee value of **2a** was not improved further (Table 2, entries 14 and 15). We also tested the influence of temperature on this reaction; unfortunately, whether at −5 or 35 °C, the enantioselectivity of **2a** was slightly decreased (Table 2, entries 16 and 17).

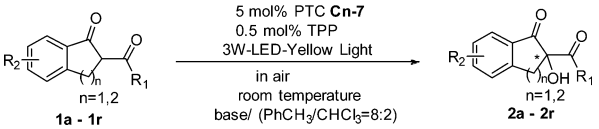
Under the optimized conditions, we explored the substrate scope of the α-hydroxylation reaction shown in Table 3. A series of 1-indanone-derived adamantly β-keto esters were first investigated. Halogenated substrates (Cl, F, and Br) on the benzene ring gave the desired products in high yields and enantioselectivities (Table 3, entries 2−4). However, electron-donating substituents, such as methyl and methoxyl at the phenyl ring, led to a mild decrease in enantioselectivity (Table 3, entries 5−8). Next we investigated the steric influence of the ester group. We found that the enantioselectivities were obviously influenced by the size of substitution in the ester group. For example, **1j**, which contains a *tert*-butyl ester group, provided the α-hydroxylation product with 67% ee (Table 3, entry 10), whereas methy ester **1n** afforded the corresponding product with only 49% ee (Table 3, entry 14). β-Keto esters derived from 1-tetralone are challenging substrates for α-hydroxylation. Then, stronger inorganic base 30% K_2CO_3 was used instead of 50% K_2HPO_4. Gratifyingly, under mild conditions, **2o−2r** were all easily obtained with up to 94% yield and 76% ee (Table 3, entries 15−18).

Compared with the β-keto esters, the α-hydroxylation of β-keto amides has been much less explored,[8g,9f] possibly due to the lower acidity of the α-hydrogen, although the amido group is useful for further manipulation.[15] Thus, we then examined the scopes of β-keto amides. The indanone-derived β-keto amide **1s** was nicely converted to **2s** after 1 h in 93% yield with 37% ee (Table 4, entry 1). Then, **1t** was provided with a Br atom at the 5-position to give the corresponding product with a higher ee value (Table 4, entry 2). Next, we tested **1u**, which contains a 4-methylpiperidine group and afforded **2u** with 71% ee, although the reaction time was extended to 4 h (Table 4, entry 3). Compound **1v**, which has methyl and phenyl in the N-position, afforded **2w** in 82% yield with 59% ee (Table 4, entry 4). After all, such a simple and economical method showed good substrate suitability to β-keto esters and β-keto amides.

The absolute configurations of α-hydroxy-β-keto esters **2a**, **2o**, and **2s** were determined to be *S* by comparison of their optical rotations and HPLC spectrograms with literature data.[9c,f]

One major advantage of the *N*-oxide PTC **Cn-7** is that it can be easily separated from the product and TPP because it is nearly insoluble in both the organic phase and water. After the completion of the reaction, the organic layer was removed (α-hydroxylation product and the TPP were all dissolved in it); then, additional **1a** and TPP were added with the toluene and chloroform. The reaction was then started with the light. The PTC **Cn-7** could be reused for up to six runs without any significant loss of reactivity or enantioselectivity (Table 5).

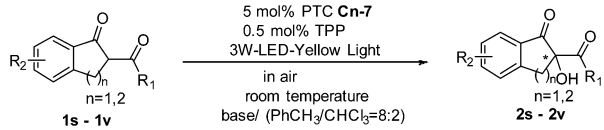
Table 3. Substrate Scope in the Asymmetric α-Hydroxylation of β-Keto Esters and β-Keto Amides[a]



entry	sub	n	R_1	R_2	t [h]	yield (%)[b]	ee (%)[c]
1	**1a**	1	O-^{1}Ad	H	1	97	82
2	**1b**	1	O-^{1}Ad	5-Cl	1	97	83
3	**1c**	1	O-^{1}Ad	6-F	0.5	91	80
4	**1d**	1	O-^{1}Ad	5-Br	1	94	80
5	**1e**	1	O-^{1}Ad	4-OMe	1	96	73
6	**1f**	1	O-^{1}Ad	6-OMe	1	97	71
7	**1g**	1	O-^{1}Ad	6-Me	0.5	95	70
8	**1h**	1	O-^{1}Ad	5,6-di-OMe	3	94	77
9	**1i**	1	O-^{2}Ad	H	1	98	68
10	**1j**	1	O-*t*-Bu	H	0.5	95	67
11	**1k**	1	O-*t*-amyl	H	0.5	95	66
12	**1l**	1	O-*t*-Bu	5,6-di-OMe	2	93	65
13	**1m**	1	O-i-Pr	H	0.5	97	61
14	**1n**	1	O-Me	H	0.5	92	49
15[d]	**1o**	2	O-^{1}Ad	H	1	92	76
16[d]	**1p**	2	O-^{1}Ad	5,7-di-Br	1	76	68
17[d]	**1q**	2	O-^{1}Ad	7-OMe	1	92	75
18[d]	**1r**	2	O-^{1}Ad	6-OMe	1	94	71

[a]The reaction was conducted with substrate (0.1 mmol) in the presence of PTC **Cn-7** (5 mol %) and TPP (0.5 mol %) in a mixture containing 8:2 $PhCH_3/CHCl_3$ (10 mL) and K_2HPO_4 (4 mL, 50% aq) at room temprature with exposure to a 3 W LED yellow lamp for the given reaction period. [b]Yield of isolated product. [c]The enantiomeric excess was determined by HPLC analysis of the product using a chiral column (DAICEL Chiralcel OD-H or AD-H or AS-H) with *n*-hexane/2-propanol as the eluent (see the Experimental Section information for details). [d]Using K_2CO_3 (30% aq) as an inorganic base.

Table 4. Substrate Scope in the Asymmetric α-Hydroxylation of β-Keto Amides[a]



Entry	Sub	n	R_1	R_2	t [h]	Yield (%)[b]	ee (%)[c]
1	**1s**	1		H	1	93	37
2	**1t**	1		5-Br	1	94	50
3[d]	**1u**	1		H	4	77	71
4[d]	**1v**	1		H	4	82	59

[a]The reaction was conducted with substrate (0.1 mmol) in the presence of PTC **Cn-7** (5 mol %) and TPP (0.5 mol %) in a mixture containing 8:2 $PhCH_3/CHCl_3$ (10 mL) and K_2HPO_4 (4 mL, 50% aq) at room temprature with exposure to a 3 W LED yellow lamp for the given reaction period. [b]Yield of isolated product. [c]The enantiomeric excess was determined by HPLC analysis of the product using a chiral column (DAICEL Chiralcel OD-H or AD-H or AS-H) with *n*-hexane/2-propanol as the eluent (see the Experimental Section information for details). [d]Using K_2CO_3 (30% aq) as an inorganic base.

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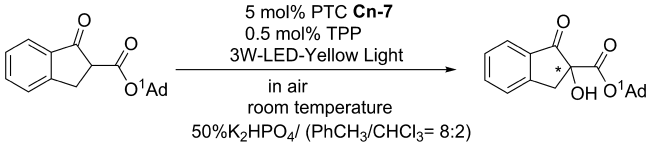
Table 5. Reusability of PTC Cn-7 for the Asymmetric α-Hydroxylation of 1a[a]



run	t [h]	yield [%][b]	ee [%][c]
1	1	96	81
2	1	98	80
3	1	97	80
4	1.5	94	79
5	1.5	93	79
6	2.5	91	78

[a]Unless otherwise specified, the reaction was performed with 0.1 mmol of **1a** by using the same conditions described in Table 3, entry 1. [b]Yield of isolated product. [c]The enantiomeric excess was determined by HPLC analysis of the product using a chiral column (DAICEL Chiralcel AD-H) with *n*-hexane/2-propanol as the eluent.

Finally, an assumed mechanism for this photo-organocatalytic α-hydroxylation was proposed. First, the molecular oxygen was transferred from its nonexcited triplet state ($^3O_2$) to its more reactive singlet state ($^1O_2$) by photosensitization with light; the deprotonation of **1** occurred quickly in the presence of base. Then, the active singlet molecular oxygen could react with ion pair **3**, thereby resulting in the formation of α-hydroperoxide intermediate **4**. This hydroperoxide intermediate, which contains two electron-withdrawing carbonyl groups at the α-position, seemed to be a stronger oxidant than traditional hydrogen peroxide.[16] Thus, α-hydroperoxide intermediate **4** is hard to observe because, in the relatively high temperature, it could be rapidly converted to the final α-hydroxylation product **2** in the second step (Scheme 4).

With further research, we can clearly observe the existence of active intermediate **4a** by TLC when the temperature drops to −20 °C, and the mass spectrum of the reaction solutions could further certify the existence of intermediate **4a**.[17] However, because of the possibly instability of **4a**, we could not separate pure **4a**. However, we still provided some evidence to prove the assumed mechanism (Scheme 5).

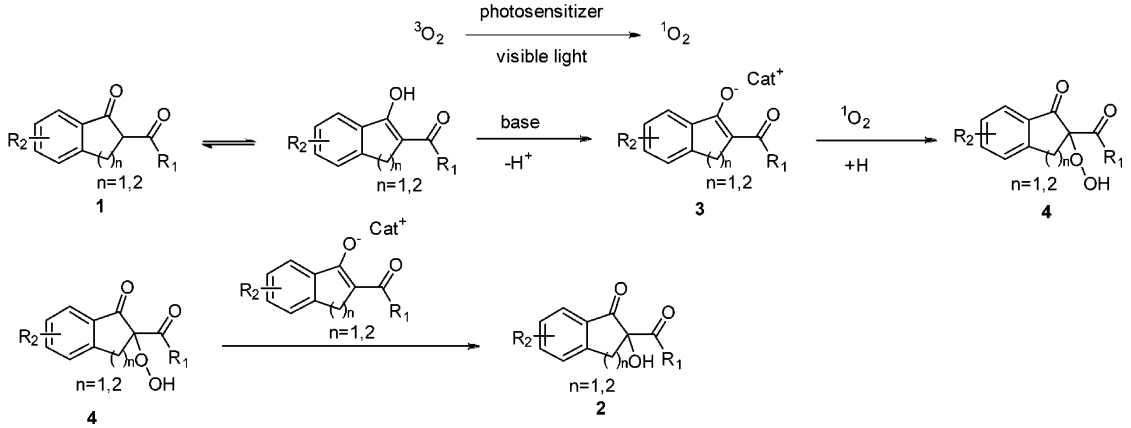
CONCLUSIONS

In conclusion, we developed a series of cinchona-derived *N*-oxide asymmetric phase-transfer catalysts and applied them to the enantioselective photo-organocatalytic α-hydroxylation of β-keto esters and β-keto amides with molecular oxygen in excellent yields (up to 98%) and high enantioselectivities (up to 83% ee). Moreover, these types of phase-transfer catalysts can be easily separated from the product and reused in the reaction without any significant loss of reactivity or enantioselectivity. Finally, an assumed mechanism for this photo-organocatalytic α-hydroxylation was proposed. Further investigations on expanding the applications of asymmetric *N*-oxide asymmetric phase-transfer catalysts are underway in our laboratory.

EXPERIMENTAL SECTION

General Procedure for the Synthesis of Cn-*N*-oxide. Cinchonine (7.35 g, 25 mmol) was dissolved in chloroform (100 mL), and the solution was cooled to 0 °C. Then, *m*-chloroperoxybenzoic acid (85%, 12.7 g, 62 mmol) was added in portions under stirring. The resulting suspension was allowed to warm to rt and stirred for 3 h. The reaction was quenched with 10% NaOH solution until reaching a pH of 10. The mixture was extracted with a mixed solvent of $CHCl_3$/MeOH (10:1, 50 mL × 10). The organic layer was combined and dried over Na_2SO_4. Then, the solvent was evaporated in vacuo to give a light yellow foam as Cn-*N*,*N*′-dioxide (8.14 g, 99% yield). This crude product was used directly in the next step without any further purification; 8.60 g of $NaHSO_3$ was added to 62.4 mL of 1 mol/L HCl and stirred for 1 h. Then, Cn-*N*,*N*′-dioxide (8.14 g, 25.0 mmol) in acetone (100 mL) at 0 °C was added dropwise. After the solution was added completely, the resulting mixture was warmed to rt. The resulting mixture was stirred for 12 h. Then, the acetone was removed under a vacuum, and ammonium hydroxide was added until reaching a pH of 9. Chloroform (50 mL × 5) was used to extract the aqueous layer. The organic layers were combined, washed with brine (50 mL), dried over Na_2SO_4, and concentrated in vacuo. The residue was subjected to silica gel column chromatography (40% EtOAc, 10% MeOH, 2% Et_3N in PE) to afford Cn-*N*-oxide as a white solid (4.86 g, 63% yield). Mp 233−235 °C. $[\alpha]_D^{25}$ +187.6 (*c* 0.17, MeOH). ^1H NMR (500 MHz, chloroform- *d*) δ 8.60−8.40 (m, 1H), 7.87 (m, 2H), 7.53 (ddd, *J* = 8.7, 6.9, 1.2 Hz, 1H), 7.39−7.30 (m, 1H), 7.10 (d, *J* = 6.2 Hz, 1H), 6.30−5.97 (m, 2H), 5.28 (d, *J* = 5.8 Hz, 1H), 5.14−5.01 (m, 2H), 3.17 (ddd, *J* = 13.9, 7.9, 2.2 Hz, 1H), 2.92 (td, *J* = 8.8, 5.7 Hz, 1H), 2.87−2.61 (m, 3H), 2.23 (t, *J* = 8.5 Hz, 1H), 2.06 (ddd, *J* = 13.4, 8.4, 2.2 Hz, 1H), 1.78 (dt, *J* = 4.3, 2.2 Hz, 1H), 1.59−1.33 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 143.6, 140.7, 139.6, 135.5, 130.2, 128.4, 127.2, 123.9, 119.5, 118.1, 114.5, 71.1, 60.7, 49.8, 49.3, 40.2, 28.1, 26.5, 22.5. HRMS calcd for $[C_{19}H_{22}N_2O_2 + H]^+$ requires *m*/*z* 311.1760, found *m*/*z* 311.1754.

Scheme 4. Proposed Mechanism for the Photo-Oxygenation of β-Dicarbonyl Compounds



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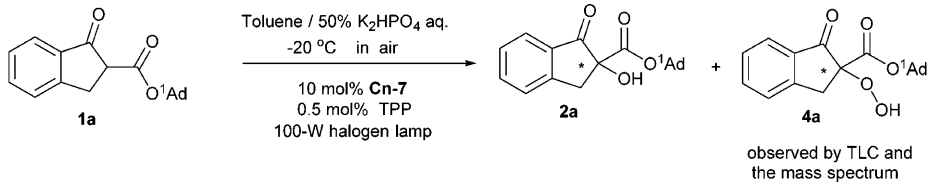
Scheme 5. Control Experiment



Catalyst Qd-*N*-oxide was synthesized by the same procedure as mentioned above for catalyst Cn-*N*-oxide from quinidine as a white solid (5.54 g, 83% yield). Mp 180−182 °C. $[\alpha]_D^{25}$ +234.8 (*c* 0.09, MeOH). ^{1}H NMR (500 MHz, chloroform- *d*) δ 8.40 (d, *J* = 9.5 Hz, 1H), 7.86 (d, *J* = 6.2 Hz, 1H), 7.26−7.07 (m, 2H), 6.84 (d, *J* = 2.7 Hz, 1H), 6.27−5.95 (m, 2H), 5.28−4.98 (m, 3H), 3.84 (s, 3H), 3.39−3.10 (m, 1H), 2.95−2.63 (m, 4H), 2.29−1.97 (m, 2H), 1.76 (dt, *J* = 4.6, 2.0 Hz, 1H), 1.59−1.19 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.7, 142.4, 140.8, 135.2, 133.8, 128.6, 122.4, 121.0, 118.4, 114.4, 101.8, 71.1, 60.2, 55.6, 50.0, 49.5, 40.2, 28.2, 26.6, 22.1. HRMS calcd for $[C_{20}H_{24}N_2O_3 + H]^+$ requires *m*/*z* 341.1865, found *m*/*z* 341.1858.

General Procedure for the Synthesis of Phase-Transfer Catalysts. PTC **Cn-1** was prepared according to our previous paper[10e] and used directly.

Cn-2: The catalyst was synthesized following known procedures.[6] A slurry of cinchonine (0.74 g, 2.5 mmol) and benzyl bromide (1.07 g, 6.25 mmol) in IPA (0.5 mL) and DMF (3 mL) was degassed, heated to 70 °C under nitrogen atmosphere, and held for 12 h. The reaction mixture was cooled to 15 °C, and EtOAc (50 mL) was added over 10 min with vigorous stirring. The resulting slurry was aged at 15 °C for 1 to 2 h, filtered, rinsed with EtOAc (twice, 20 mL each) and hexanes (twice, 20 mL each). The solid was dried under a vacuum to give 1.38 g of **Cn-2** as a yellow solid in 87% yield. Mp 228−230 °C. $[\alpha]_D^{25}$ +119.6 (*c* 0.05, MeOH). ^{1}H NMR (500 MHz, DMSO- d_6) δ 9.80 (d, *J* = 6.1 Hz, 1H), 8.80 (d, *J* = 8.2 Hz, 1H), 8.57 (dd, *J* = 27.0, 7.5 Hz, 2H), 8.28 (ddd, *J* = 8.7, 7.0, 1.2 Hz, 1H), 8.19−8.09 (m, 1H), 7.77 (dd, *J* = 6.6, 3.0 Hz, 2H), 7.60 (q, *J* = 3.2, 2.7 Hz, 3H), 7.46−7.34 (m, 5H), 6.81 (d, *J* = 3.6 Hz, 1H), 6.42 (d, *J* = 2.4 Hz, 2H), 6.03 (ddd, *J* = 17.4, 10.6, 7.0 Hz, 1H), 5.33−5.19 (m, 3H), 4.92 (d, *J* = 13.0 Hz, 1H), 4.17 (d, *J* = 8.1 Hz, 1H), 4.03 (d, *J* = 10.4 Hz, 2H), 3.53 (s, 1H), 2.98 (d, *J* = 10.2 Hz, 1H), 2.69 (t, *J* = 8.7 Hz, 1H), 2.28 (s, 1H), 1.92−1.69 (m, 3H), 1.27−1.18 (m, 1H). ^{13}C NMR (126 MHz, DMSO) δ 158.1, 149.5, 137.1, 136.9, 135.3, 133.8, 130.5, 130.2, 129.1, 128.9, 128.8, 127.7, 127.3, 127.0, 126.3, 121.5, 119.9, 117.1, 66.8, 65.3, 62.2, 60.0, 56.1, 53.8, 36.6, 26.2, 22.8, 20.5. HRMS calcd for $[(C_{33}H_{36}N_2OBr_2 - 2Br)/2]^+$ requires *m*/*z* 238.1409, found *m*/*z* 238.1410.

Cn-3: To a flame-dried flask equipped with a magnetic stirring bar and a reflux condenser was added Cn-*N*-oxide (0.46 g), CH_3CN (3 mL), MeOH (0.75 mL), and benzyl bromide (0.31 g). The mixture was heated to 30 °C under N_2 for 12 h and then cooled to room temperature. The reaction mixture was cooled to 15 °C, and EtOAc (50 mL) was added over 10 min with vigorous stirring. The resulting slurry was aged at 15 °C for 1−2 h, filtered, and rinsed with EtOAc (twice, 20 mL each) and hexanes (twice, 20 mL each). The solid was dried under vacuum to afford **Cn-3** as a white solid (0.47 g, 68% yield). Mp 264−266 °C. $[\alpha]_D^{25}$ +150.1 (*c* 0.08, MeOH). ^{1}H NMR (500 MHz, DMSO- d_6) δ 8.76−8.59 (m, 2H), 8.40 (d, *J* = 8.4 Hz, 1H), 7.89 (ddd, *J* = 14.5, 7.9, 1.8 Hz, 2H), 7.79−7.69 (m, 3H), 7.62−7.54 (m, 3H), 6.88 (d, *J* = 4.0 Hz, 1H), 6.43 (t, *J* = 3.2 Hz, 1H), 5.99 (ddd, *J* = 17.3, 10.8, 6.9 Hz, 1H), 5.29−5.18 (m, 2H), 5.09 (d, *J* = 12.3 Hz, 1H), 4.88 (d, *J* = 12.4 Hz, 1H), 4.27−4.14 (m, 1H), 3.89 (m, 2H), 3.47 (t, *J* = 11.4 Hz, 1H), 3.01−2.88 (m, 1H), 2.65 (d, *J* = 9.1 Hz, 1H), 2.26 (t, *J* = 11.7 Hz, 1H), 1.89 (s, 1H), 1.81−1.73 (m, 2H), 1.26−1.15 (m, 1H). ^{13}C NMR (126 MHz, DMSO) δ 140.3, 137.1, 134.6, 133.8, 133.6, 130.1, 129.4, 128.9, 127.9, 126.5, 124.9, 120.9, 119.5, 116.9, 67.0, 64.4, 62.1, 55.9, 53.7, 36.6, 26.4, 22.9, 20.5. HRMS calcd for $[C_{26}H_{29}N_2O_2\ Br - Br]^+$ requires *m*/*z* 401.2224, found *m*/*z* 401.2226.

Qd-1: Catalyst **Qd-1** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Qd-*N*-oxide as a light yellow solid (0.71 g, 76% yield). Mp 193−196 °C. $[\alpha]_D^{25}$ +181.1 (*c* 0.07, MeOH). ^{1}H NMR (500 MHz, DMSO- d_6) δ 8.65−8.48 (m, 2H), 7.76−7.68 (m, 3H), 7.57 (dd, *J* = 6.3, 3.0 Hz, 4H), 7.49 (d, *J* = 2.6 Hz, 1H), 6.88 (s, 1H), 6.47 (s, 1H), 6.02 (ddd, *J* = 17.4, 10.0, 7.0 Hz, 1H), 5.29−5.18 (m, 2H), 5.00 (d, *J* = 12.6 Hz, 1H), 4.76 (d, *J* = 12.5 Hz, 1H), 4.27−4.16 (m, 1H), 4.10 (s, 3H), 3.97 (dd, *J* = 9.8, 2.6 Hz, 1H), 3.84 (t, *J* = 9.6 Hz, 1H), 3.49 (t, *J* = 11.5 Hz, 1H), 2.95−2.86 (m, 1H), 2.67 (d, *J* = 8.8 Hz, 1H), 2.43−2.31 (m, 1H), 1.92 (s, 1H), 1.79 (dt, *J* = 19.6, 11.7 Hz, 2H), 1.24 (td, *J* = 8.5, 4.2 Hz, 1H). ^{13}C NMR (126 MHz, DMSO) δ 159.1, 137.2, 135.5, 134.3, 133.6, 133.2, 130.1, 129.0, 128.1, 127.8, 122.1, 121.4, 121.2, 116.9, 103.7, 67.2, 64.3, 63.1, 59.7, 56.0, 53.7, 36.7, 26.4, 23.1, 20.5. HRMS calcd for $[C_{27}H_{31}N_2O_3\ Br - Br]^+$ requires *m*/*z* 431.2329, found *m*/*z* 431.2329.

Qd-2: Catalyst **Qd-2** was synthesized by the same procedure as mentioned above for catalyst **Qd-1** from Qd-*N*-oxide as a yellow solid (0.78 g, 66% yield). Mp 211−213 °C. $[\alpha]_D^{25}$ +172.5 (*c* 0.10, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.54 (dd, *J* = 19.0, 7.9 Hz, 2H), 7.68 (d, *J* = 6.2 Hz, 1H), 7.62−7.45 (m, 2H), 7.08 (s, 2H), 6.91−6.76 (m, 1H), 6.45 (s, 1H), 6.04 (ddd, *J* = 17.3, 10.4, 6.8 Hz, 1H), 5.25 (dd, *J* = 13.9, 9.4 Hz, 2H), 4.98 (d, *J* = 12.3 Hz, 1H), 4.73 (d, *J* = 12.4 Hz, 1H), 4.21 (t, *J* = 6.9 Hz, 1H), 4.11 (s, 3H), 3.87 (s, 6H), 3.74 (s, 5H), 3.59 (t, *J* = 11.5 Hz, 1H), 2.96 (q, *J* = 10.2 Hz, 1H), 2.68 (d, *J* = 8.8 Hz, 1H), 2.37 (t, *J* = 11.5 Hz, 1H), 1.97−1.72 (m, 3H), 1.28 (m, 1H). ^{13}C NMR (126 MHz, DMSO) δ 159.0, 152.9, 138.8, 137.4, 135.9, 132.8, 128.1, 123.0, 121.5, 121.4, 121.4, 116.9, 111.2, 103.6, 67.4, 64.3, 63.4, 60.0, 56.3, 56.0, 54.9, 53.9, 36.8, 26.4, 23.2, 20.5. HRMS calcd for $[C_{30}H_{37}N_2O_6Br - Br]^+$ requires *m*/*z* 521.2652, found *m*/*z* 521.2642.

Qd-3: Catalyst **Qd-3** was synthesized by the same procedure as mentioned above for catalyst **Qd-1** from Qd-*N*-oxide and subjected to silica gel column chromatography (15:1 $CHCl_2$/MeOH) to afford **Qd-3** as a brown solid (0.45 g, 48% yield). Mp 208−210 °C. $[\alpha]_D^{25}$ +164.1 (*c* 0.08, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.65−8.47 (m, 4H), 8.38 (s, 1H), 7.67 (d, *J* = 6.4 Hz, 1H), 7.58 (dd, *J* = 9.5, 2.5 Hz, 1H), 7.48 (d, *J* = 2.6 Hz, 1H), 6.78 (d, *J* = 3.4 Hz, 1H), 6.37 (d, *J* = 3.7 Hz, 1H), 6.02 (ddd, *J* = 17.3, 10.1, 6.9 Hz, 1H), 5.25 (ddd, *J* = 14.6, 3.0, 1.4 Hz, 2H), 5.10 (d, *J* = 12.9 Hz, 1H), 4.98 (d, *J* = 12.6 Hz, 1H), 4.29 (ddd, *J* = 11.8, 8.3, 2.7 Hz, 1H), 4.06−4.00 (m, 1H), 3.75 (s, 1H), 3.47 (t, *J* = 11.4 Hz, 1H), 3.01 (d, *J* = 9.7 Hz, 1H), 2.63 (dd, *J* = 12.2, 5.4 Hz, 1H), 2.44−2.31 (m, 1H), 1.92 (s, 1H), 1.88−1.71 (m, 2H), 1.32 (d, *J* = 14.0 Hz, 1H). ^{13}C NMR (126 MHz, DMSO) δ 159.1, 137.2, 135.9, 134.6, 132.6, 131.3, 130.9, 130.6, 128.1, 124.2, 122.1, 121.5, 121.5, 121.2, 117.00, 103.9, 67.9, 64.3, 61.0, 56.1, 55.6, 54.0, 36.8, 26.5, 23.1, 20.5. HRMS calcd for $[C_{29}H_{29}F_6N_2O_3Br - Br]^+$ requires *m*/*z* 567.2082, found *m*/*z* 567.2073.

Qd-4: Catalyst **Qd-4** was synthesized by the same procedure as mentioned above for catalyst **Qd-1** from Qd-*N*-oxide as a yellow solid (1.15 g, 94% yield). Mp 198−201 °C. $[\alpha]_D^{25}$ +404.5 (*c* 0.11, MeOH). ^{1}H NMR (500 MHz, chloroform-*d*) δ 9.02 (d, *J* = 9.0 Hz, 1H), 8.55 (m, 2H), 8.29 (s, 1H), 8.18 (s, 1H), 8.10−7.92 (m, 2H), 7.82 (t, *J* = 8.8 Hz, 2H), 7.71−7.52 (m, 2H), 7.51−7.32 (m, 3H), 7.18 (d, *J* = 9.0 Hz, 1H), 6.86 (s, 1H), 6.40 (s, 2H), 5.76 (m, 1H), 5.14 (d, *J* = 10.4 Hz, 1H), 5.07−4.93 (m, 2H), 4.69−4.43 (m, 2H), 3.98 (s, 3H), 2.86 (t, *J* = 11.6 Hz, 1H), 2.33 (q, *J* = 10.1, 9.2 Hz, 2H), 1.94 (m, 3H), 1.74 (s, 1H), 1.48 (t, *J* = 11.9 Hz, 1H), 1.15 (s, 1H). ^{13}C NMR (126 MHz, DMSO) δ 158.9, 137.3, 136.0, 132.9, 132.8, 132.7, 132.6, 133.0, 131.1, 129.8, 129.6, 128.1, 127.8, 127.6, 125.5, 124.8, 124.2, 121.9, 121.6, 121.3, 118.7, 116.9, 104.1, 67.2, 65.2, 56.0, 55.9, 55.2, 55.1, 37.1, 25.6, 23.6, 21.0. HRMS calcd for $[C_{35}H_{35}N_2O_3Br - Br]^+$ requires *m*/*z* 531.2648, found *m*/*z* 531.2638.

Cn-4: Catalyst **Cn-4** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide and subjected to silica gel column chromatography (40% EtoAc, 10% MeOH, 2% Et_3N in PE) to afford **Cn-4** as a white solid (0.35 g, 76% yield). Mp 205−208 °C.

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$[\alpha]_D^{25}$ +112.0 (*c* 0.05, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.77−8.59 (m, 4H), 8.46 (dd, *J* = 6.0, 3.5 Hz, 1H), 8.37−8.34 (m, 1H), 7.98−7.86 (m, 2H), 7.73 (d, *J* = 6.3 Hz, 1H), 6.87 (t, *J* = 3.1 Hz, 1H), 6.43 (t, *J* = 3.1 Hz, 1H), 6.09−5.90 (m, 1H), 5.44 (dd, *J* = 12.8, 6.3 Hz, 1H), 5.24 (m, 3H), 4.40−4.30 (m, 1H), 4.14 (d, *J* = 10.5 Hz, 1H), 3.90 (t, *J* = 9.7 Hz, 1H), 3.50 (t, *J* = 11.4 Hz, 1H), 3.08 (m, 8.7 Hz, 2H), 2.63 (d, *J* = 8.8 Hz, 1H), 2.28 (t, *J* = 11.7 Hz, 1H), 1.94−1.74 (m, 3H), 1.26 (m, 1H).^{13}C NMR (126 MHz, DMSO) δ 140.4, 137.1, 134.6, 133.4, 131.3, 130.8, 130.6, 130.1, 129.4, 126.5, 124.7, 124.3, 122.1, 120.9, 119.6, 117.0, 79.2, 67.8, 64.4, 60.26, 55.6, 54.1, 45.6, 36.8, 26.4, 23.0, 20.4. HRMS calcd for $[C_{28}H_{27}F_6N_2O_2Br - Br]^+$ requires *m*/*z* 537.1977, found *m*/*z* 537.1964.

Cn-5: Catalyst **Cn-5** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a white solid (0.42 g, 82% yield). Mp 289−292 °C. $[\alpha]_D^{25}$ +163.9 (*c* 0.06, MeOH).^{1}H NMR (500 MHz, DMSO-d_6) δ 8.78−8.60 (m, 3H), 8.43 (dd, *J* = 8.2, 2.0 Hz, 2H), 8.23 (d, *J* = 7.6 Hz, 1H), 7.90 (ddd, *J* = 13.3, 8.1, 3.1 Hz, 3H), 7.72 (d, *J* = 6.4 Hz, 1H), 6.84 (d, *J* = 3.9 Hz, 1H), 6.44 (t, *J* = 3.1 Hz, 1H), 5.99 (ddd, *J* = 17.3, 10.8, 6.9 Hz, 1H), 5.38−5.16 (m, 3H), 5.12−4.97 (m, 1H), 4.24 (td, *J* = 9.2, 8.8, 4.3 Hz, 1H), 4.03−3.97 (m, 1H), 3.87 (s, 1H), 3.52 (d, *J* = 11.4 Hz, 1H), 3.34 (s, 1H), 3.03−2.89 (m, 1H), 2.60 (d, *J* = 8.8 Hz, 1H), 2.28 (d, *J* = 12.1 Hz, 1H), 1.94−1.72 (m, 3H), 1.24 (m, 1H). ^{13}C NMR (126 MHz, DMSO) δ 148.0, 140.4, 140.3, 137.0, 134.6, 133.4, 130.5, 130.2, 129.9, 129.3, 128.4, 126.5, 124.9, 124.8, 120.9, 119.6, 117.0, 67.5, 64.4, 60.9, 55.8, 53.9, 36.7, 26.5, 23.0, 20.4. HRMS calcd for $[C_{26}H_{28}N_3O_4Br - Br]^+$ requires *m*/*z* 446.2080, found *m*/*z* 446.2071.

Cn-6: Catalyst **Cn-6** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a white solid (0.43 g, 84% yield). Mp 256−258 °C. $[\alpha]_D^{25}$ +148.9 (*c* 0.05, MeOH).^{1}H NMR (500 MHz, DMSO-d_6) δ 8.70−8.61 (m, 2H), 8.41 (dd, *J* = 8.3, 1.4 Hz, 1H), 7.96−7.82 (m, 3H), 7.79−7.56 (m, 4H), 6.82 (s, 1H), 6.41 (t, *J* = 3.1 Hz, 1H), 5.99 (ddd, *J* = 17.4, 10.1, 6.9 Hz, 1H), 5.30−5.19 (m, 2H), 5.19−5.10 (m, 1H), 4.89 (d, *J* = 12.4 Hz, 1H), 4.21 (ddd, *J* = 11.8, 8.4, 2.7 Hz, 1H), 4.03−3.90 (m, 1H), 3.84 (t, *J* = 9.7 Hz, 1H), 3.57−3.44 (m, 1H), 2.98 (dt, *J* = 11.7, 9.2 Hz, 1H), 2.68 (d, *J* = 8.8 Hz, 1H), 2.32−2.20 (m, 1H), 1.90 (d, *J* = 4.7 Hz, 1H), 1.81−1.71 (m, 2H), 1.21 (tt, *J* = 9.6, 3.1 Hz, 1H). ^{13}C NMR (126 MHz, DMSO) δ 140.9, 137.6, 135.1, 134.0, 133.9, 133.8, 133.0, 131.2, 130.7, 130.7, 130.6, 129.8, 127.0, 125.3, 121.4, 120.1, 117.5, 67.9, 64.9, 61.8, 56.4, 54.5, 37.1, 26.8, 23.5, 20.9. HRMS calcd for $[C_{26}H_{28}ClN_2O_2Br - Br]^+$ requires *m*/*z* 435.1839, found *m*/*z* 435.1830.

Cn-7: Catalyst **Cn-7** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a white solid (0.56 g, 88% yield). Mp >300 °C. $[\alpha]_D^{25}$ +138.3 (*c* 0.04, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.66 (dd, *J* = 9.7, 7.3 Hz, 2H), 8.39 (d, *J* = 8.3 Hz, 1H), 8.20−8.03 (m, 3H), 7.98−7.83 (m, 2H), 7.70 (d, *J* = 6.4 Hz, 1H), 6.78 (d, *J* = 3.9 Hz, 1H), 6.37 (t, *J* = 3.1 Hz, 1H), 6.07−5.92 (m, 1H), 5.35−5.21 (m, 2H), 5.13 (d, *J* = 12.4 Hz, 1H), 4.87 (d, *J* = 12.5 Hz, 1H), 4.22 (ddd, *J* = 11.9, 8.4, 2.7 Hz, 1H), 3.94 (dd, *J* = 9.4, 4.9 Hz, 1H), 3.80 (t, *J* = 9.7 Hz, 1H), 3.51 (t, *J* = 11.4 Hz, 1H), 3.03 (dt, *J* = 11.8, 9.2 Hz, 1H), 2.75−2.58 (m, 1H), 2.25 (t, *J* = 11.6 Hz, 1H), 1.95−1.71 (m, 3H), 1.22 (s, 1H). ^{13}C NMR (126 MHz, DMSO) δ 140.4, 137.1, 135.4, 135.1, 134.6, 133.3, 132.4, 130.2, 129.3, 126.5, 124.6, 122.8, 120.8, 119.6, 117.0, 67.6, 64.4, 60.5, 55.9, 54.9, 54.2, 36.7, 26.3, 23.0, 20.4. HRMS calcd for $[C_{26}H_{27}N_2O_2Br_3 - Br]^+$ requires *m*/*z* 557.0439, found *m*/*z* 557.0430.

Cn-8: Catalyst **Cn-8** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a white solid (0.59 g, 81% yield). Mp >300 °C. $[\alpha]_D^{25}$ +108.7 (*c* 0.02, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.75−8.52 (m, 2H), 8.43−8.26 (m, 2H), 8.18 (d, *J* = 1.5 Hz, 2H), 8.00−7.83 (m, 2H), 7.69 (d, *J* = 6.4 Hz, 1H), 6.73 (d, *J* = 3.7 Hz, 1H), 6.35 (s, 1H), 6.20−5.84 (m, 2H), 5.37−5.15 (m, 2H), 4.97 (d, *J* = 12.5 Hz, 1H), 4.18 (t, *J* = 10.2 Hz, 1H), 3.88−3.70 (m, 2H), 3.48 (t, *J* = 11.5 Hz, 1H), 2.99 (q, *J* = 10.0 Hz, 1H), 2.72−2.64 (m, 1H), 2.24 (t, *J* = 11.6 Hz, 1H), 1.98−1.69 (m, 3H), 1.22 (d, *J* = 13.7 Hz, 1H). HRMS calcd for $[C_{26}H_{27}I_2N_2O_2Br - Br]^+$ requires *m*/*z* 653.0162, found *m*/*z* 653.0152. (We failed to obtain the ^{13}C NMR of **Cn-8** because it has poor solubility in most of the deuterated solvents, even in the high polarity solvents such as dimethyl sulfoxide and dimethylformamide.)

Cn-9: Catalyst **Cn-9** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a white solid (1.10 g, 97% yield). Mp 220−223 °C. $[\alpha]_D^{25}$ +134.8 (*c* 0.06, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.74−8.59 (m, 2H), 8.53−8.43 (m, 1H), 7.89 (ddd, *J* = 13.0, 8.3, 1.4 Hz, 2H), 7.73 (d, *J* = 6.4 Hz, 1H), 6.99 (d, *J* = 3.3 Hz, 1H), 6.39 (d, *J* = 3.3 Hz, 1H), 6.01 (ddd, *J* = 17.3, 10.4, 6.9 Hz, 1H), 5.23 (dd, *J* = 21.3, 14.1 Hz, 3H), 5.06 (d, *J* = 13.9 Hz, 1H), 4.24−4.09 (m, 2H), 3.84 (t, *J* = 10.8 Hz, 1H), 3.46 (m, 2H), 2.58 (t, *J* = 8.3 Hz, 1H), 2.22 (t, *J* = 11.9 Hz, 1H), 1.95−1.77 (m, 3H). ^{13}C NMR (126 MHz, DMSO) δ 140.4, 136.8, 134.6, 133.1, 130.3, 129.2, 126.6, 124.9, 121.0, 119.5, 117.1, 67.0, 65.0, 55.9, 54.1, 50.4, 37.2, 25.8, 23.2, 20.7. HRMS calcd for $[C_{26}H_{24}F_5N_2O_2Br - Br]^+$ requires *m*/*z* 491.1758, found *m*/*z* 491.1749.

Cn-10: Catalyst **Cn-10** was synthesized by the same procedure as mentioned above for catalyst **Cn-3** from Cn-*N*-oxide as a light yellow solid (0.39 g, 51% yield). Mp 190−192 °C. $[\alpha]_D^{25}$ +250.0 (*c* 0.06, MeOH). ^{1}H NMR (500 MHz, DMSO-d_6) δ 8.96 (d, *J* = 10.9 Hz, 2H), 8.81−8.72 (m, 2H), 8.71−8.67 (m, 1H), 8.61 (d, *J* = 9.1 Hz, 1H), 8.28 (dd, *J* = 8.5, 1.3 Hz, 2H), 8.06−7.93 (m, 2H), 7.89−7.75 (m, 3H), 7.73−7.57 (m, 3H), 6.87 (t, *J* = 3.4 Hz, 1H), 6.26 (d, *J* = 14.1 Hz, 1H), 6.16−6.01 (m, 1H), 5.93 (ddd, *J* = 17.4, 10.4, 7.0 Hz, 1H), 5.15 (d, *J* = 1.2 Hz, 1H), 5.02 (dt, *J* = 17.2, 1.3 Hz, 1H), 4.48−4.33 (m, 2H), 4.24 (d, *J* = 11.3 Hz, 1H), 3.00 (t, *J* = 11.2 Hz, 1H), 2.86−2.69 (m, 1H), 2.30 (dt, *J* = 18.6, 10.0 Hz, 2H), 1.74 (d, *J* = 22.0 Hz, 2H), 1.59 (d, *J* = 11.8 Hz, 1H), 1.31−1.14 (m, 2H). ^{13}C NMR (126 MHz, DMSO) δ 140.4, 137.2, 134.6, 134.0, 133.2, 132.9, 131.9, 131.1, 131.0, 130.2, 129.6, 129.5, 129.3, 127.6, 127.4, 126.8, 125.4, 125.4, 124.5, 121.1, 119.5, 119.1, 116.8, 66.8, 65.4, 56.5, 54.5, 54.2, 37.0, 25.5, 23.5, 21.3. HRMS calcd for $[C_{34}H_{33}N_2O_2Br - Br]^+$ requires *m*/*z* 501.2537, found *m*/*z* 501.2533.

General Procedure for the Asymmetric α-Hydroxylation of β-Keto Esters and β-Keto Amides. The reaction was conducted with substrates **1a**−**1v** (0.1 mmol) in the presence of PTC **Cn-7** (5 mol %) and tetraphenylporphine (TPP) (0.5 mol %) in a mixture containing 8:2 $PhCH_3/CHCl_3$ (10 mL) and K_2HPO_4 (4 mL, 50% aq) or K_2CO_3 (4 mL, 30% aq) at room temprature with exposure to a 3 W LED yellow lamp for the given reaction period. After completion of the reaction (confirmed by TLC analysis), the mixture was diluted with EtOAc (50 mL), washed with water (3 × 20 mL), dried over anhydrous Na_2SO_4, filtered, and concentrated in vacuo. The residue was purified by flash chromatography to give **2a**−**2v**, respectively. The ee of the product was determined by chiral HPLC.

*1-Adamantyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-inde-ne-2-carboxylate (**2a**).*[13] Colorless oil (31.8 mg, 97% yield, 82% ee). $[\alpha]_D^{25}$ +26.5 (*c* 0.40, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ 7.86−7.53 (m, 2H), 7.53−7.33 (m, 2H), 4.07 (s, 1H), 3.66 (d, *J* = 17.1 Hz, 1H), 3.21 (d, *J* = 17.1 Hz, 1H), 2.20−1.86 (m, 9H), 1.59 (m, 6H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1 mL/min, 254 nm, τ_R (major) = 11.3 min, τ_R (minor) = 18.3 min.

*1-Adamantyl 2-Hydroxy-5-chloro-1-oxo-2,3-dihydro-1H-indene-2-carboxylate(**2b**).*[13] White solid (35.0 mg, 97% yield, 83% ee). Mp 152−156 °C. $[\alpha]_D^{25}$ +62.4 (*c* 0.51, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ 7.74 (d, *J* = 8.2 Hz, 1H), 7.46 (dd, *J* = 35.3, 1.6 Hz, 2H), 4.02 (s, 1H), 3.64 (d, *J* = 17.3 Hz, 1H), 3.21 (d, *J* = 17.3 Hz, 1H), 2.24−2.09 (m, 3H), 1.99 (m, 6H), 1.62 (m, 6H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1 mL/min, 254 nm, τ_R (major) = 13.0 min, τ_R (minor) = 16.3 min.

*1-Adamantyl 2-Hydroxy-5-bromine-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2c**).* White wax (37.6 mg, 94% yield, 80% ee). $[\alpha]_D^{25}$ +62.1 (*c* 0.65, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ 7.77−7.53 (m, 3H), 4.04 (s, 1H), 3.64 (d, *J* = 17.2 Hz, 1H), 3.21 (d, *J* = 17.2 Hz, 1H), 2.22−2.09 (m, 3H), 1.98 (m, 6H), 1.62 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 200.2, 169.8, 153.8, 132.9, 131.6, 131.3, 129.6, 126.1, 84.3, 80.4, 40.9, 39.2, 35.8, 30.8. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1 mL/min, 254 nm, τ_R (major) = 12.9 min, τ_R (minor) = 21.5 min. HRMS calcd for $[C_{20}H_{21}BrO_4 + Na]^+$ requires *m*/*z* 427.0521, found *m*/*z* 427.0530.

*1-Adamantyl 2-Hydroxy-4-methoxyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2d**).*[13] White wax (34.0 mg, 96% yield, 73% ee). $[\alpha]_D^{25}$ +35.6 (*c* 0.65, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ

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7.44−7.35 (m, 2H), 7.10 (s, 1H), 4.01 (s, 1H), 3.92 (d, J = 1.5 Hz, 3H), 3.60 (dd, J = 17.4, 1H), 3.08 (d, J = 17.4, 1H), 2.13 (s, 3H), 1.99 (m, 6H), 1.61 (m, 6H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 14.3 min, τ_R (minor) = 19.4 min.

*1-Adamantyl 2-Hydroxy-6-methoxyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2e**).*[13] White wax (34.6 mg, 97% yield, 71% ee). $[\alpha]_D^{25}$ +15.3 (c 0.42, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.37 (d, J = 8.3 Hz, 1H), 7.27−7.19 (m, 2H), 4.03 (s, 1H), 3.86 (s, 3H), 3.58 (d, J = 16.7 Hz, 1H), 3.14 (d, J = 16.7 Hz, 1H), 2.13 (s, 3H), 1.99 (m, 6H), 1.61 (m, 6H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 13.1 min, τ_R (minor) = 22.5 min.

*1-Adamantyl 2-Hydroxy-6-fluorine-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2f**).* Colorless oil (31.5 mg, 91% yield, 80% ee). $[\alpha]_D^{25}$ +16.5 (c 0.55, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.53−7.32 (m, 3H), 4.05 (s, 1H), 3.62 (d, J = 16.9 Hz, 1H), 3.37−3.08 (d, J = 16.9 Hz, 1H), 2.19−2.11 (m, 3H), 1.97 (m, 6H), 1.61 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 200.6, 169.8, 163.4, 161.4, 147.8, 135.7, 127.7, 123.6, 110.8, 84.2, 81.2, 40.9, 39.0, 35.8, 30.8. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 9.2 min, τ_R (minor) = 17.0 min. HRMS calcd for $[C_{20}H_{21}FO_4 + Na]^+$ requires m/z 367.1322, found m/z 367.1307.

*1-Adamantyl 2-Hydroxy-6-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2g**).* White wax (32.4 mg, 95% yield, 70% ee). $[\alpha]_D^{25}$ +31.2 (c 0.45, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.59 (s, 1H), 7.47 (d, J = 7.8 Hz, 1H), 7.36 (d, J = 7.8 Hz, 1H), 4.00 (s, 1H), 3.62 (d, J = 16.9 Hz, 1H), 3.17 (d, J = 16.9 Hz, 1H), 2.42 (s, 3H), 2.20−2.08 (m, 3H), 1.98 (m, 6H), 1.61 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 200.5, 169.3, 148.8, 136.8, 136.1, 133.1, 124.9, 123.9, 82.8, 79.8, 39.9, 38.2, 34.9, 29.8, 20.1. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 10.3 min, τ_R (minor) = 18.5 min. HRMS calcd for $[C_{21}H_{24}O_4 + Na]^+$ requires m/z 363.1572, found m/z 363.1560.

*1-Adamantyl 2-Hydroxy-5,6-dimethoxyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2h**).*[13] Yellow solid (36.5 mg, 94% yield, 77% ee). Mp 145−148 °C. $[\alpha]_D^{25}$ +52.8 (c 0.53, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.18 (s, 1H), 6.88 (s, 1H), 4.01 (s, 1H), 3.98 (s, 3H), 3.91 (s, 3H), 3.58 (d, J = 16.8 Hz, 1H), 3.11 (d, J = 16.8 Hz, 1H), 2.19−2.09 (m, 3H), 1.99 (m, 6H), 1.60 (m, 6H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 20.4 min, τ_R (minor) = 33.8 min.

*2-Adamantyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2i**).*[9c] White wax (31.9 mg, 98% yield, 77% ee). $[\alpha]_D^{25}$ +18.4 (c 0.51, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.81 (d, J = 7.6 Hz, 1H), 7.76−7.64 (m, 1H), 7.63−7.38 (m, 2H), 4.97 (t, J = 3.5 Hz, 1H), 4.06 (s, 1H), 3.72 (d, J = 17.0 Hz, 1H), 3.31 (d, J = 17.0 Hz, 1H), 2.00−1.53 (m, 10H), 1.41−1.16 (m, 4H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 12.1 min, τ_R (minor) = 15.2 min.

*tert-Butyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2j**).*[13] White solid (24.1 mg, 95% yield, 67% ee). Mp 128−129 °C. $[\alpha]_D^{25}$ +21.3 (c 0.20, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.81 (d, J = 7.6 Hz, 1H), 7.66 (d, J = 1.2 Hz, 1H), 7.49 (dt, J = 7.7, 0.9 Hz, 1H), 7.46−7.37 (m, 1H), 4.02 (s, 1H), 3.67 (d, J = 17.0 Hz, 1H), 3.24 (d, J = 17.0 Hz, 1H), 1.38 (s, 9H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 0.8 mL/min, 254 nm, τ_R (major) = 8.6 min, τ_R (minor) = 9.6 min.

*tert-Pentyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2k**).*[9h] Colorless oil (24.7 mg, 95% yield, 66% ee). $[\alpha]_D^{25}$ +26.5 (c 0.35, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.79 (dd, J = 7.6, 2.4 Hz, 1H), 7.64 (dd, J = 7.6, 2.4 Hz, 1H), 7.52−7.37 (m, 2H), 4.02 (s, 1H), 3.64 (d, J = 17.1, 1H), 3.24 (d, J = 17.1, 1H), 1.60 (dd, J = 7.8, 2.3 Hz, 2H), 1.35 (dd, J = 5.8, 2.5 Hz, 6H), 0.68−0.53 (m, 3H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 95:5, 0.8 mL/min, 254 nm, τ_R (major) = 11.3 min, τ_R (minor) = 12.2 min.

*tert-Butyl 2-Hydroxy-5,6-dimethoxyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2l**).*[9c] Light yellow oil (28.6 mg, 93% yield, 65% ee). $[\alpha]_D^{25}$ +43.7 (c 0.30, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.20 (d, J = 2.0 Hz, 1H), 6.89 (s, 1H), 4.00 (s, 3H), 3.92 (s, 3H), 3.57 (d, J = 16.5 Hz, 1H), 3.12 (d, J = 16.5 Hz, 1H), 1.39 (s, 9H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 38.4 min, τ_R (minor) = 42.4 min.

*Isopropyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2m**).*[13] White solid (22.7 mg, 97% yield, 61% ee). Mp 68−71 °C. $[\alpha]_D^{25}$ +23.3 (c 0.21, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.72 (d, J = 7.7 Hz, 1H), 7.64−7.56 (m, 1H), 7.45−7.40 (m, 1H), 7.35 (t, J = 7.5 Hz, 1H), 5.00 (pd, J = 6.3, 1.0 Hz, 1H), 3.93 (s, 1H), 3.62 (d, J = 17.2 Hz, 1H), 3.17 (d, J = 17.2 Hz, 1H), 1.09 (m, 6H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 95:5, 1.0 mL/min, 254 nm, τ_R (major) = 9.9 min, τ_R (minor) = 10.9 min.

*Methyl 2-Hydroxy-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (**2n**).*[9h] White solid (20.2 mg, 98% yield, 49% ee). Mp 134−136 °C. $[\alpha]_D^{25}$ +35.2 (c 0.20, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.81 (d, J = 7.8 Hz, 1H), 7.68 (td, J = 7.5, 1.6 Hz, 1H), 7.54−7.40 (m, 2H), 3.99 (s, 1H), 3.86−3.67 (m, 4H), 3.26 (d, J = 17.3 Hz, 1H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 13.2 min, τ_R (minor) = 15.8 min.

*1-Adamantyl 2-Hydroxy-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (**2o**).*[13] Colorless oil (29.7 mg, 92% yield, 76% ee). $[\alpha]_D^{25}$ −6.4 (c 0.49, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 8.04 (d, J = 7.8 Hz, 1H), 7.51 (d, J = 7.6 Hz, 1H), 7.35 (d, J = 7.6 Hz, 1H), 7.26 (d, J m, 1H), 4.23 (s, 1H), 3.12 (t, J = 6.4 Hz, 2H), 2.65 (dt, J = 13.4, 5.2 Hz, 1H), 2.30−2.18 (m, 1H), 2.13 (s, 3H), 2.01 (s, 6H), 1.61 (s, 6H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 7.5 min, τ_R (minor) = 10.3 min.

*1-Adamantyl 2-Hydroxy-5,7-dibromine-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (**2p**).* Colorless oil (37.5 mg, 76% yield, 68% ee). $[\alpha]_D^{25}$ −2.1 (c 0.25, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 8.14 (s, 1H), 7.93 (s, 1H), 4.12 (s, 1H), 3.21−2.89 (m, 2H), 2.70−2.58 (m, 1H), 2.29−2.19 (m, 1H), 2.15 (s, 3H), 2.01 (s, 6H), 1.63 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 192.8, 169.0, 141.7, 139.8, 133.5, 130.1, 125.3, 121.0, 84.1, 41.0, 35.9, 31.6, 30.8, 26.4. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 9.7 min, τ_R (minor) = 16.5 min. HRMS calcd for $[C_{21}H_{22}Br_2O_4 + Na]^+$ requires m/z 518.9783, found m/z 518.9775.

*1-Adamantyl 2-Hydroxy-7-methoxyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (**2q**).* Light yellow wax (34.2 mg, 92% yield, 75% ee). $[\alpha]_D^{25}$ −18.4 (c 0.45, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 7.50 (d, J = 2.5 Hz, 1H), 7.20−7.07 (m, 2H), 4.22 (s, 1H), 3.85 (s, 3H), 3.05 (dd, J = 7.5, 5.3 Hz, 2H), 2.62 (dd, J = 13.5, 1.7 Hz, 1H), 2.28−2.18 (m, 1H), 2.13 (s, 3H), 2.02 (s, 6H), 1.61 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 194.9, 169.8, 158.4, 136.5, 131.4, 130.0, 122.6, 109.6, 83.4, 55.5, 41.0, 36.0, 33.1, 30.8, 25.0. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 12.6 min, τ_R (minor) = 20.6 min. HRMS calcd for $[C_{22}H_{26}O_5 + Na]^+$ requires m/z 393.1678, found m/z 393.1667.

*1-Adamantyl 2-Hydroxy-6-methoxyl-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (**2r**).* Light yellow wax (34.7 mg, 94% yield, 71% ee). $[\alpha]_D^{25}$ −7.5 (c 0.50, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 8.01 (d, J = 8.8 Hz, 1H), 6.86 (d, J = 8.8, 1H), 6.70 (d, J = 2.6 Hz, 1H), 4.38−4.15 (m, 1H), 3.87 (s, 3H), 3.21−2.97 (m, 2H), 2.70−2.45 (m, 1H), 2.27−2.11 (m, 4H), 2.03 (s, 6H), 1.61 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 193.5, 169.9, 164.2, 146.5, 130.5, 124.1, 113.6, 112.6, 83.3, 55.5, 41.0, 36.0, 32.8, 30.8, 26.1. HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1.0 mL/min, 254 nm, τ_R (major) = 17.9 min, τ_R (minor) = 25.0 min. HRMS calcd for $[C_{22}H_{26}O_5 + Na]^+$ requires m/z 393.1678, found m/z 393.1666.

*2-Hydroxy-1-oxo-N-phenyl-2,3-dihydro-1H-indene-2-carboxamide (**2s**).*[9h] White solid (24.8 mg, 93% yield, 37% ee). Mp 150−151 °C. $[\alpha]_D^{25}$ +2.8 (c 0.25, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-d) δ 8.73 (s, 1H), 7.89−7.29 (m, 8H), 7.12 (d, J = 7.4 Hz, 1H), 3.87 (d, J = 16.8 Hz, 1H), 3.20 (d, J = 16.8 Hz, 1H). HPLC conditions: Chiralcel OD-H

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column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 9.1 min, τ_R (minor) = 14.2 min.

*5-Bromo-2-hydroxy-1-oxo-N-phenyl-2,3-dihydro-1H-indene-2-carboxamide (**2t**).*[9h] White solid (32.5 mg, 94% yield, 50% ee). Mp 187−189 °C. $[\alpha]_D^{25}$ +37.2 (*c* 0.51, MeOH). ^{1}H NMR (400 MHz, chloroform-*d*) δ 8.72 (s, 1H), 8.14−7.95 (m, 1H), 7.72−7.29 (m, 6H), 7.14 (d, *J* = 7.5 Hz, 1H), 3.84 (d, *J* = 16.9 Hz, 1H), 3.18 (d, *J* = 16.9 Hz, 1H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 80:20, 1 mL/min, 254 nm, τ_R (major) = 11.7 min, τ_R (minor) = 15.3 min.

*2-Hydroxy-1-oxo-N-phenyl-N-4-methylpiperidine-2,3-dihydro-1H-indene-2-carboxamide (**2u**).*[9g] Colorless oil (21.4 mg, 77% yield, 71% ee). $[\alpha]_D^{25}$ −15.8 (*c* 0.25, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ 7.85 (d, *J* = 7.7 Hz, 1H), 7.67 (t, *J* = 7.5 Hz, 1H), 7.53−7.43 (m, 2H), 5.54 (s, 1H), 4.59 (d, *J* = 45.9 Hz, 1H), 3.45 (d, *J* = 17.7 Hz, 1H), 3.33 (s, 1H), 3.16−2.98 (m, 1H), 2.92−2.68 (m, 2H), 1.83−1.41 (m, 4H), 0.99−0.88 (m, 4H). HPLC conditions: Chiralcel AD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 31.97 min, τ_R (minor) = 28.1 min.

*2-Hydroxy-1-oxo-N-phenyl-N-methyl-2,3-dihydro-1H-indene-2-carboxamide (**2v**).*[9g] White wax (20.5 mg, 82% yield, 59% ee). $[\alpha]_D^{25}$ −15.2 (*c* 0.22, $CHCl_3$). ^{1}H NMR (500 MHz, chloroform-*d*) δ 7.39 (m, 2H), 7.25−6.76 (m, 7H), 5.40 (s, 1H), 3.55 (d, *J* = 18.0 Hz, 1H), 3.34 (s, 3H), 3.12 (d, *J* = 18.0 Hz, 1H). HPLC conditions: Chiralcel OD-H column (250 × 4.6 mm), hexane/*i*-PrOH = 90:10, 1.0 mL/min, 254 nm, τ_R (major) = 27.9 min, τ_R (minor) = 24.6 min.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00856.

Characterization data (including ^{1}H NMR, ^{13}C NMR, and HPLC spectra) for catalysts and all α-hydroxylation products (PDF)

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Notes

The authors declare no competing financial interest.

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