Available online at www.sciencedirect.com
SCIENCE DIRECT
Tetrahedron
ELSEVIER
Tetrahedron 62 (2006) 302–310

Chiral *N*-heterocyclic carbenes as asymmetric acylation catalysts

Yumiko Suzuki,* Kazuyuki Muramatsu, Kaori Yamauchi, Yasuko Morie and Masayuki Sato

School of Pharmaceutical Sciences, University of Shizuoka, 52-1 Yada, Suruga-ku, Shizuoka 422-8526, Japan

Received 1 June 2004; revised 31 August 2005; accepted 16 September 2005

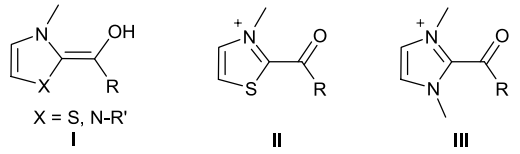
Available online 10 October 2005

Abstract—Chiral *N*-heterocyclic carbenes are generated from C_2-symmetric 1,3-bis(1-arylethyl)imidazolium salts and potassium *tert*-butoxide. These C_2-symmetric imidazolidenyl carbenes catalyze enantioselective acylation of racemic secondary alcohols. The asymmetric acylation of 1-(1-naphthyl)ethanol was achieved in up to 68% ee of the acylated product, using (*R*,*R*)-1,3-bis[(1-naphthyl)ethyl]imidazolium tetrafluoroborate as a precursor of the chiral *N*-heterocyclic carbene and vinyl propionate as the acyl donor.

1. Introduction

The catalytic ability of azolium salts such as thiazolium and imidazolium for benzoin/acyloin condensation was first reported by Ukai et al. in 1943.[1] Subsequently, Breslow proposed a mechanism of azolium-catalyzed benzoin condensation,[2] which is generally accepted at present. An *N*-heterocyclic carbene (NHC), derived from an azolium salt, nucleophilically adds to an aldehyde to form an acyl anion equivalent **I**. This nucleophilic intermediate adds to an aldehyde to produce the benzoin/acyloin. Another important example using this type of umpolung is the Stetter reaction.[3] In this case, the acyl anion equivalent nucleophilically adds to a Michael acceptor to produce 1,4-dicarbonyl compounds. Both reactions are synthetically useful and have been applied to asymmetric synthesis using chiral thiazolium and triazolium salts.[4–7]

The other types of catalytic actions of azolium salts/NHCs are acylation and transesterification reactions. Inoue et al. and Castells et al. reported a thiazolium-catalyzed ester synthesis from aldehydes and alcohols.[8] In this reaction, the acyl anion equivalent derived from thiazolidenyl carbene and aldehyde is oxidized to 2-acylthiazolium salt **II**, and the nucleophilic attack of alcohol on this intermediate at the carbonyl group yields esters. Recently, Nolan et al. and Hedrick et al. reported the NHC-catalyzed transesterification reaction in which acylazolium salts such as **III** are implicated as the key intermediate.[9] In contrast to the development of the asymmetric catalysis of chiral NHCs in benzoin condensation and Stetter reaction, there have been no reports on an asymmetric catalysis using chiral NHCs in this type of acylation reactions.[10,11]



As a part of our efforts focused on the development of NHC-catalysis,[12] we envisioned that the use of chiral NHC in acylation of racemic secondary alcohols could lead to a kinetic resolution. The kinetic resolution of racemic alcohols catalyzed by chiral nucleophilic acylation catalysts is one of the most intensively studied subjects of asymmetric organocatalysis. The organic acylation catalysts that are currently known are tertiary amines, *N*-hetero-aromatic compounds, phosphines, and small-molecule peptides.[4,13] In this paper, we report asymmetric acylation reactions catalyzed by chiral NHCs.

2. Results and discussion

N-heterocyclic carbenes derived from imidazolium and imidazolinium salts were reported to catalyze transesterification.[9] However, the latter has less catalytic ability in the transesterification than the former.[9] Thus, we examined the use of azolium salts **1**–**6** in an acylation of 1-(1-naphthyl)ethanol (**7**).

N-heterocyclic carbenes were generated from imidazolium salts and used in the reactions in situ. A mixture of catalytic amounts of imidazolium salts (3 mol%) and potassium

Keywords: Asymmetric acylation; Chiral *N*-heterocyclic carbene; Imidazolium; Kinetic resolution.
* Corresponding author. Tel./fax: +81 54 264 5755;
e-mail: suzuyumi@u-shizuoka-ken.ac.jp

0040–4020/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2005.09.071

tert-butoxide (*t*-BuOK, 2.5 mol%) in ether/THF was stirred for 30 min and was followed by the addition of vinyl acetate and **7**. The results are summarized in Table 1. Benzimidazolium **2**, triazolium **4**, and imidazolium **6** proved to be effective as a catalyst for acylation of **7**, while thiazolium **1** and pyrido[1,2-*c*]imidazolium **3** had less catalytic ability under these conditions. The low yield of acylated product **8** using **5** is due to the insolubility of **5** in ether.

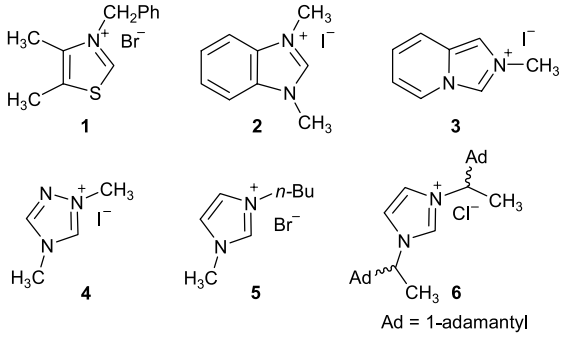
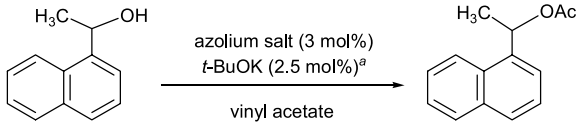


Table 1. The examination of the catalytic ability of various azolium salts[a]



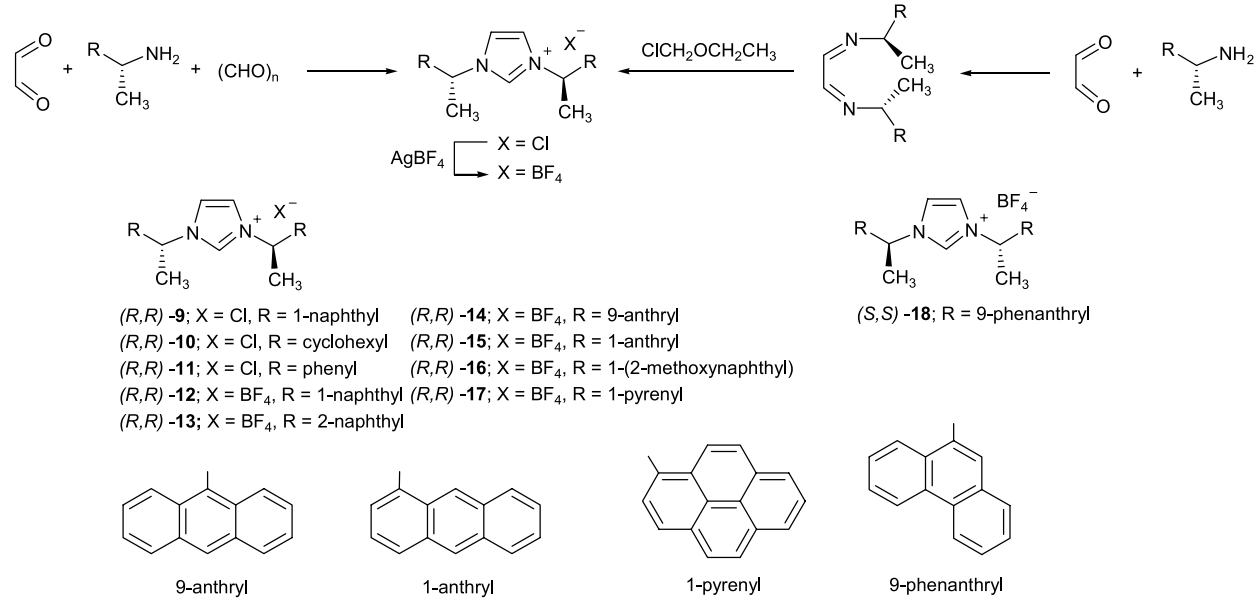
Entry	Azolium salt	Conditions	Yield (%)
1	**1**	THF, room temperature, 16 h	19
2	**2**	Ether, room temperature, 1 h	39
3	**3**	Ether, room temperature, 2 h	13
4	**4**	Ether, room temperature, 2.5 h	35
5	**5**	Ether, room temperature, 1 h	17
6	**6**	THF, room temperature, 1 h	61

[a] THF (1.0 M) solution was used.

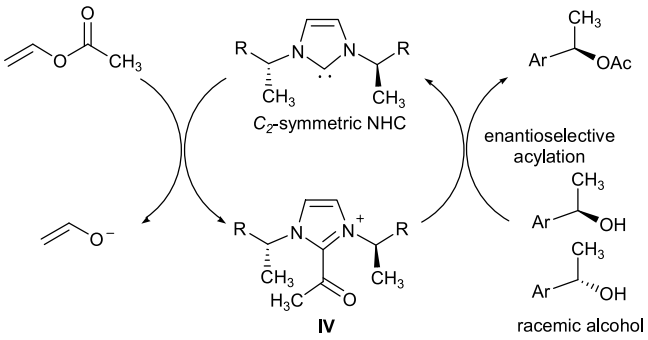
After obtaining these results, we selected C_2-symmetric imidazolidenyl carbenes as catalysts for asymmetric acylation. C_2-symmetric imidazolium salts can be readily prepared from inexpensive materials in one step or in two steps (Scheme 1).[14,15] We hypothesized that C_2-symmetric intermediate **IV**, which is formed from NHC and vinyl acetate, has sufficient enantio selectivity to react with the preferred enantiomer of racemic secondary alcohols (Scheme 2). The first choice was imidazolium salts (*R*,*R*)-**9**–**13**, which can be synthesized from commercially available chiral amines. Imidazolium tetrafluoroborates were prepared from the corresponding chlorides by a reaction with silver tetrafluoroborate.

The results of the kinetic resolution of the secondary alcohols catalyzed by (*R*,*R*)-**9**–**13** are summarized in Table 2. The acylation of **7** using (*R*,*R*)-**9**[14] at room temperature provided acetate **8** in 21% yield with 42% ee (entry 1). The unreacted **7** was recovered in 69% yield with 21% ee. At 0 °C with (*R*,*R*)-**9**, the selectivity was improved (entry 2). Under the same conditions at room temperature, the acylation of 1-phenylethanol (**19**) produced acetate **22** in 29% with 31% ee, and **19** was recovered in 36% yield with 20% ee (entry 13). The reaction rate increased when tetrafluoroborate (*R*,*R*)-**12** was used in the acylation of **7** (entry 5), instead of chloride (*R*,*R*)-**9**. The catalysts (*R*,*R*)-**10**,[14]**11**, **13** had lower selectivities than (*R*,*R*)-**9**, (*R*,*R*)-**12** (entries 3, 4, and 7). When an *N*-substituent of carbene is an (*R*)-1-arylethyl group, the acylation of 1-arylethanols proceeded with *R*-selectivities, and in the case of an (*R*)-1-cyclohexylethyl group, the reaction proceeded with *S*-selectivities.

These results led us to assume that an aromatic substituent on the *N*-ethyl group of the NHC is required to be bulkier than the 1-naphthyl group in order to achieve a better selectivity. Hence, imidazolium salts (*R*,*R*)-**14**, (*R*,*R*)-**15**, (*R*,*R*)-**16**, (*R*,*R*)-**17**, and (*S*,*S*)-**18** that have aromatic substituents 9-anthryl, 1-anthryl, 1-(2-methoxynaphthyl),



Scheme 1. C_2-symmetric imidazolium salts.



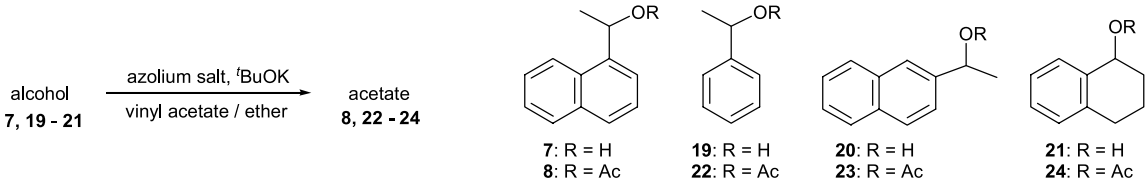
Scheme 2. Proposed mechanism for asymmetric acylation.

1-pyrenyl, and 9-phenanthryl, were synthesized and used in acylation reaction of **7**. Contrary to our prediction, (*R*,*R*)-**14**, (*R*,*R*)-**16** had lower selectivities, and the reaction rates were slow (entries 8, 10). 9-Anthryl and 1-(2-methoxynaphthyl) groups seem to hinder the attack of alcohol on the carbonyl carbon of the intermediate **IV** (Scheme 2). (*R*,*R*)-**15**, (*R*,*R*)-**17**, and (*S*,*S*)-**18** showed enantio selectivities comparable to (*R*,*R*)-**9**, (*R*,*R*)-**12** (entries 9, 11, and 12).

Next, we examined the effects of various vinyl esters as acyl donors. Vinyl propionate, vinyl butyrate, and vinyl benzoate were employed in the reaction. The results are shown in Table 3. In the acylation of **7** using (*R*,*R*)-**12** as catalysts, vinyl propionate functioned well as an acyl donor to increase the enantiomeric excess of produced ester up to 68% ee with *s* factor 6.1.

Very recently, Maruoka et al. have reported kinetic resolution of secondary alcohols by chiral NHC catalysis.[16] Using 5 mol% of (*R*,*R*)-**12** and bulkier vinyl esters (e.g.,

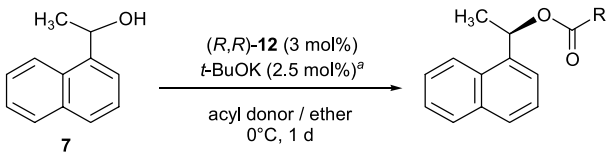
Table 2. Kinetic resolution of secondary alcohols



Entry	Racemic alcohol	Azolium salt		Condition		Acetate		Alcohol		*s*
		X				Yield (%)[a]	ee (%)[b]	Yield (%)[a]	ee (%)[b]	
1	**7**	(*R*,*R*)-**9**	Cl	Room temperature, 2 days	**8**	21	42 (*R*)	69	21 (*S*)	3.0
2	**7**	(*R*,*R*)-**9**	Cl	0 °C, 2 days	**8**	21	51 (*R*)	79	11 (*S*)	3.4
3	**7**	(*R*,*R*)-**10**	Cl	Room temperature, 18 h	**8**	15	19 (*S*)	83	1 (*R*)	1.5
4[c]	**7**	(*R*,*R*)-**11**	Cl	Room temperature, 16 h	**8**	52	18 (*R*)	47	17 (*S*)	1.7
5	**7**	(*R*,*R*)-**12**	BF_4	0 °C, 1 day	**8**	33	45 (*R*)	56	22 (*S*)	3.3
6	**7**	(*R*,*R*)-**12**	BF_4	−15 °C, 3 days	**8**	14	58 (*R*)	85	8 (*S*)	4.1
7	**7**	(*R*,*R*)-**13**	BF_4	0 °C, 18 h	**8**	43	14 (*R*)	47	14 (*S*)	1.5
8	**7**	(*R*,*R*)-**14**	BF_4	0 °C, 2 days	**8**	6	23 (*R*)	80	5 (*S*)	1.7
9[c]	**7**	(*R*,*R*)-**15**	BF_4	Room temperature, 4 days	**8**	17	50 (*R*)	83	—	—
10[c]	**7**	(*R*,*R*)-**16**	BF_4	0 °C, 2.5 days and then room temperature, 2 h	**8**	4	13 (*R*)	84	<1	—
11	**7**	(*R*,*R*)-**17**	BF_4	0 °C, 12 h	**8**	27	49 (*R*)	73	20 (*S*)	3.5
12	**7**	(*S*,*S*)-**18**	BF_4	0 °C, 18 h	**8**	37	39 (*S*)	60	23 (*R*)	2.8
13	**19**	(*R*,*R*)-**9**	Cl	Room temperature, 3 days	**22**	29	31 (*R*)	36	20 (*S*)	2.3
14	**20**	(*R*,*R*)-**12**	BF_4	0 °C, 18 h	**23**	44	44 (*R*)	49	37 (*S*)	3.6
15	**21**	(*R*,*R*)-**12**	BF_4	0 °C, 2 days	**24**	14	9	84	2	1.2

[a] Isolated yield.
[b] Enantioselectivities were measured by HPLC using a Chiralcel OD column or a Chiralpac AS column.
[c] THF (1.0 M) solution of ^{t}BuOK was used.

Table 3. Acylation with various acyl donors[a]



Entry	Acyl donor	R	Ester (ee %)[b]	Alcohol (ee %)[b]	Conversion (%)	*s*
1	Vinyl acetate	Me	48	16	25	3.3
2	Vinyl propionate	Et	68	16	19	6.1
3	Vinyl butyrate	*n*-Pr	66	11	14	5.4
4	Vinyl benzoate	Ph	33	17	34	2.3

[a] THF (1.0 M) solution was used.
[b] Enantioselectivities were measured by HPLC using a Chiralcel OD column, a Chiralcel OD-H column or a Chiralpac AD-H column.

vinyl diphenylacetylate) at −78 to −20 °C in THF, enantioselectivities improved up to 96% ee in asymmetric acylation of **7**, **19**, **20**, and related secondary alcohols.

3. Conclusion

We have demonstrated that chiral *N*-heterocyclic carbenes catalyze the enantioselective acylation of racemic secondary alcohols. We used simple C_2-symmetric carbenes, which were readily synthesized from chiral amines, glyoxal, and formaldehyde or chloromethyl ethyl ether. Further investigations to broaden the scope of this asymmetric acylation are ongoing in our laboratory.

4. Experimental

4.1. General

Melting points are determined using a Yazawa Micro Melting Point Apparatus without correction. ^{1}H NMR (500 MHz) and ^{13}C NMR (126 MHz) spectra were recorded on a JEOL ECA-500 NMR spectrometer. IR spectra were recorded on a JASCO FT/IR-8000 spectrometer and a SHIMADZU IR Prestige-21. HRMS (FAB) spectra were recorded on a JEOL MStation JMS-700 mass spectrometer using *m*-nitrobenzyl alcohol as a matrix. Column chromatography was performed with Merck Silica Gel 60 and Silica Gel 60 N (spherical, neutral, Kanto Chemical Co., Inc.). Optical rotations were measured using a JASCO DIP-360 or a JASCO P-1030 polarimeter.

4.2. Preparation of imidazolium chlorides: general procedure

4.2.1. Glyoxal-bis-[1-(1-adamantyl)ethyl]imine. A mixture of 40% aqueous solution of glyoxal (145 mg, 1 mmol), 1-propanol (0.16 mL), and water (0.4 mL) was added to a solution of racemic 1-(1-adamantyl)ethylamine (360 mg, 2 mmol) in 1-propanol (1.4 mL) at room temperature. The mixture was stirred at 70 °C for 2 h. Water was added to the mixture, and the resulting colorless precipitates were filtered, washed with water, and dried. The precipitates were identified as imine (335 mg, 88%) by ^{1}H NMR spectroscopy, and used in the subsequent reaction without further purification.

4.2.2. 1,3-Bis-[1-(1-adamantyl)ethyl]imidazolium chloride 6. A solution of glyoxal-bis-[1-(1-adamantyl)ethyl]imine (337 mg, 0.89 mmol) and one drop of water in THF (1.9 mL) was added to a solution of chloromethyl ethyl ether (96%, 88 mg, 0.89 mmol) and THF (0.2 mL) in a 10 mL single-necked flask. The flask was sealed under nitrogen with a septum and the mixture was stirred at room temperature for 24 h, and then at 40 °C for 15 h. Water and dichloromethane were added to the reaction mixture. The organic layer was taken, dried over $MgSO_4$, and evaporated. The residue was purified by silica gel column chromatography using dichloromethane/methanol as an eluent to afford **6** as a solid (145 mg, 39%). This product is assumed to comprise a mixture of meso and racemic forms.

4.3. General procedure for *N*-heterocyclic carbene-catalyzed acetylation of 1-(1-naphthyl)ethanol

Potassium *tert*-butoxide (0.25 mmol) was added to a suspension of azolium salt (0.3 mmol) in ether or THF (2 mL). The mixture was stirred at room temperature for 30 min. To the mixture were added vinyl acetate (1.2 mmol) and **7** (1 mmol). The resulting mixture was stirred at room temperature for 1–16 h (Table 2). The solvent was evaporated and the residue was purified by silica gel column chromatography using ethyl acetate/*n*-hexane as an eluent.

4.3.1. 1,3-Bis-[(*R*)-1-cyclohexylethyl]imidazolium chloride (*R*,*R*)-10. Paraformaldehyde (120 mg, 4 mmol) with ice cooling was added to a solution of (*R*)-(−)-cyclohexylethylamine (595 μL, 4 mmol) in toluene (4 mL). After stirring for 30 min, another equivalent of the amine was added; subsequently, 3.3 N HCl (1.2 mL) was added dropwise at 0 °C. 40% aqueous gyloxal solution (580 μL, 4 mmol) was added dropwise at room temperature. The mixture was stirred for 20 h at 35 °C. Dichloromethane and water were added to the reaction mixture. The organic layer was taken, dried over $MgSO_4$, and evaporated to yield crude (*R*,*R*)-**10** as a solid. Recrystallization from acetonitrile/ether afforded (*R*,*R*)-**10** as colorless prisms (364 mg, 29%); mp 188–190.5 °C; $[\alpha]_D^{24}$ +11.2 (*c* 1.0, $CHCl_3$, 21.8 °C); ^{1}H NMR ($CDCl_3$) δ: 1.14 (8H, m), 1.57–1.83 (14H, m), 4.59 (2H, quintet, J=7.4 Hz), 7.13 (2H, d, J=1.7 Hz, imidazole C4-H, C5-H), 11.32 (1H, s, imidazole C2-H); ^{13}C NMR ($CDCl_3$) δ: 18.5, 25.6, 25.7, 25.8, 29.2, 29.2, 29.3, 43.7, 62.1, 119.6, 137.9; HRMS (FAB) *m*/*z* calcd for $C_{19}H_{33}N_2$ (M^+): 289.2644, found: 289.2661.

4.3.2. 1,3-Bis-[(*R*)-1-(1-naphthyl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-12. $AgBF_4$ (90%) in hexane (476 mg, 2.2 mmol) was added to a solution of 1,3-bis-[(*R*)-1-(1-naphthyl)ethyl]imidazolium chloride (413 mg, 1 mmol) in dichloromethane (5 mL). The mixture was stirred for 2 h at room temperature. The resulting precipitates were filtered. The filtrate was purified by silica gel column chromatography using dichloromethane/methanol as an eluent to yield (*R*,*R*)-**12** (279 mg, 60%) as a coloreless solid; $[\alpha]_D^{24}$ −88.7 (*c* 1.0, $CHCl_3$, 21.7 °C); ^{1}H NMR ($CDCl_3$) δ: 2.13 (6H, d, J=6.5 Hz, CH_3CH), 6.85 (2H, q, J=6.5 Hz, CH_3C*H*), 6.90 (2H, s), 7.41–7.54 (8H, m), 7.83–7.84 (4H, m), 8.15 (2H, d, J=8.5 Hz), 11.59 (1H, s, imidazole C2-H); ^{13}C NMR ($CDCl_3$) δ: 21.6, 56.2, 120.6, 122.4, 124.5, 125.3, 126.5, 127.8, 129.2, 130.4, 130.5, 133.0, 134.0, 137.3.

4.4. Preparation of 1,3-bis-[(*R*)-1-(2-naphthyl)ethyl]-imidazolium tetrafluoroborate (*R*,*R*)-13

4.4.1. Glyoxal-bis-[(*R*)-1-(2-naphthyl)ethyl]imine. Following the general procedure given for the glyoxal-bis-imine, (*R*)-(+)-1-(2-naphthyl)ethylamine (342 mg, 2 mmol) was reacted with glyoxal for 4 h at 60 °C. The crude imine (362 mg, 99%) was extracted with ether. The product was used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) δ: 1.72 (6H, d, J=6.9 Hz, CH_3CH), 4.73 (2H, q, J=6.9 Hz, CH_3C*H*), 7.45–7.50 (4H,

m), 7.53 (2H, dd, J=8.6, 1.7 Hz), 7.82–7.86 (8H, m), 8.2 (2H, s).

4.4.2. 1,3-Bis-[(*R*)-1-(2-naphthyl)ethyl]imidazolium chloride. Following the general procedure given for **6**, glyoxal-bis-[(*R*)-1-(2-naphthyl)ethyl]imine (362 mg, 0.995 mmol) was reacted with chloromethyl ethyl ether at 40 °C for 18 h to afford imidazolium chloride (122 mg, 30%) as a yellow amorphous solid; $[\alpha]_D^{24}$+49.9 (*c* 1.0, $CHCl_3$, 22.8 °C); ^{1}H NMR ($CDCl_3$) δ: 2.03 (6H, d, J= 6.9 Hz, C*H*$_3$CH), 6.16 (2H, q, J=6.9 Hz, CH$_3$C*H*), 7.22 (2H, d, J=1.2 Hz), 7.40–7.45 (4H, m), 7.48 (2H, dd, J= 8.5, 1.9 Hz), 7.71–7.78 (6H, m), 7.90 (2H, s), 11.32 (1H, s, imidazole C2-H); ^{13}C NMR ($CDCl_3$) δ: 21.2, 60.0, 120.7, 124.2, 126.6, 126.9, 127.1, 127.8, 128.3, 129.6, 133.1, 133.4, 135.3, 136.6; $C_{27}H_{25}N_2$ (M^+): 377.2018, found: 477.2056.

4.4.3. 1,3-Bis-[(*R*)-1-(2-naphthyl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-13. Following the procedure given for (*R*,*R*)-**12**, 1,3-bis-[(*R*)-1-(2-naphthyl)ethyl]imidazolium chloride was treated with $AgBF_4$ to yield (*R*,*R*)-**13** (70%) as a yellow amorphous solid. This compound was used in the acylation reaction without further purification.

4.5. Preparation of 1,3-bis-[(*R*)-1-(9-anthryl)ethyl]-imidazolium tetrafluoroborate (*R*,*R*)-14

4.5.1. Glyoxal-bis-[(*R*)-1-(9-anthryl)ethyl]imine. Following the general procedure given for glyoxal-bis-imine, (*R*)-(+)-1-(9-anthryl)ethylamine[17] (221 mg, 1 mmol), was reacted with glyoxal for 2 h at 60 °C. The crude imine (202 mg, 87%) was extracted with dichloromethane. The product was used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) δ: 1.97 (6H, d, J=7.4 Hz, C*H*$_3$CH), 6.08 (2H, d, J=7.4 Hz, CH$_3$C*H*), 7.38–7.40 (8H, m), 7.94–7.96 (4H, m), 8.08 (2H, s), 8.34 (2H, s), 8.42 (4H, br).

4.5.2. 1,3-Bis-[(*R*)-1-(9-anthryl)ethyl]imidazolium chloride. Following the general procedure given for **6**, glyoxal-bis-[(*R*)-1-(9-anthryl)ethyl]imine (223 mg, 0.48 mmol) was reacted with chloromethyl ethyl ether at 40 °C for 64 h. The addition of water to the reaction mixture afforded precipitates of imidazolium chloride (224 mg, 91%). Slight brown granules (dichloromethane/ether); mp 161–162.5 °C; $[\alpha]_D^{24}$−88.7 (*c* 1.0, $CHCl_3$, 21.7 °C); ^{1}H NMR ($CDCl_3$) δ: 2.51 (6H, d, J=6.9 Hz, C*H*$_3$CH), 6.75 (2H, d, J=1.7 Hz), 7.29 (2H, q, J=6.9 Hz, CH$_3$C*H*), 7.46–7.52 (8H, m), 8.03–8.11 (8H, m), 8.53 (2H, s), 10.10 (1H, s); ^{13}C NMR ($CDCl_3$) δ: 21.3, 56.4, 120.8, 122.5, 123.1, 123.6, 126.2, 127.2, 127.3, 127.8, 128.1, 128.9, 129.3, 130.5, 130.7, 130.9, 131.2, 136.6; HRMS (FAB) *m*/*z* calcd for $C_{35}H_{29}N_2$ (M^+): 477.2331, found: 477.2310.

4.5.3. 1,3-Bis-[(*R*)-1-(9-anthryl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-14. Following the procedure given for (*R*,*R*)-**12**, 1,3-bis-[(*R*)-1-(9-anthryl)ethyl]imidazolium chloride was treated with $AgBF_4$ to yield (*R*,*R*)-**14** (61%) as a slight brown solid. This compound was used in the acylation reaction without further purification.

4.6. Preparation of 1,3-bis-[(*R*)-1-(1-anthryl)ethyl]-imidazolium tetrafluoroborate (*R*,*R*)-9

4.6.1. (*R*)-(+)-1-(1-anthryl)ethylamine. A solution of 1-(1-anthranyl)ethylamine[18] (312 mg, 1.41 mmol) and (*R*)-16-hydroxy-14-oxabicyclo[11.2.2]heptadecane-1(16), 13(17)-diene-2,15-dione[19,20] (392 mg, 1.41 mmol) in benzene (14 mL) was refluxed for 2 h. After evaporation of the solvent, the residue was purified by column chromatography on neutral silica gel by using hexane/ethyl acetate 4:1 as an eluent to first yield (*R*,*R*)-2-[1-(1-anthranyl)ethylamino]-14-oxabicyclo[11.2.2]heptadecane-1(2),13(17)-diene-15,16-dione (428 mg, 33%), and then (*R*,*S*)-2-[1-(1-anthranyl)-ethylamino]-14-oxabicyclo[11.2.2]heptadecane-1(2), 13(17)-diene-15,16-dione (147 mg, 20%).

(R,R)-2-[1-(1-anthranyl)ethylamino]-14-oxabicyclo[11.2.2] heptadecane-1(2),13(17)-diene-15,16-dione. Colorless needles (dichloromethane/ether); mp 199–202 °C; $[\alpha]_D^{24}$− 327.9 (*c* 1.0, $CHCl_3$, 21.6 °C); ^{1}H NMR ($CDCl_3$) δ: 1.11–1.34 (10H, m), 1.44–1.52 (2H, m), 1.61–1.72 (3H, m), 1.78–1.90 (4H, m), 2.18–2.24 (2H, m), 2.60 (1H, dt, J= 14.3, 4.5 Hz), 4.05 (1H, br), 5.82–5.86 (2H, m), 7.42–7.45 (2H, m), 7.50–7.54 (2H, m), 7.96–7.98 (1H, m), 8.02–8.08 (2H, m), 8.49 (1H, s), 8.51 (1H, s), 14.37 (1H, br, NH); HRMS (FAB) *m*/*z* calcd for $C_{32}H_{36}NO_3$ (M+1): 437.2229, found: 437.2230.

(R,S)-2-[1-(1-anthranyl)ethylamino]-14-oxabicyclo[11.2.2] heptadecane-1(2),13(17)-diene-15,16-dione. Colorless prisms (ether); mp 146–149 °C; $[\alpha]_D^{24}$+677.6 (*c* 1.0, $CHCl_3$, 22.1 °C); ^{1}H NMR ($CDCl_3$) δ: 0.62–1.03 (7H, m), 1.08–1.23 (5H, m), 1.26–1.34 (1H, m), 1.42–1.49 (1H, m), 1.58–1.67 (1H, m), 1.72–1.82 (1H, m), 1.85 (3H, d, J= 6.5 Hz), 2.16–2.22 (1H, m), 2.59 (1H, dt, J=13.6, 4.5 Hz), 2.72 (1H, br), 4.35 (1H, br), 5.83 (1H, s), 5.95–6.01 (1H, m), 7.44 (1H, dd, J=7.8, 7.1 Hz), 7.49–7.56 (3H, m), 7.94 (1H, d, J=8.4 Hz), 8.00 (1H, d, J=7.8 Hz), 8.08 (1H, d, J= 7.8 Hz), 8.47 (1H, s), 8.52 (1H, s), 14.50 (1H, br, NH); ^{13}C NMR ($CDCl_3$) δ: 23.9, 26.1, 26.6, 26.8, 28.5, 28.6, 33.9, 51.4, 98.7, 108.8, 120.6, 122.4, 125.0, 126.1, 126.2, 128.0, 128.1, 128.5, 128.9, 131.6, 132.0, 137.6, 164.6, 166.1, 178.0, 183.7; HRMS (FAB) *m*/*z* calcd for $C_{32}H_{36}NO_3$ (M+ 1): 437.2229, found: 437.2230.

A solution of (*R*,*R*)-2-[1-(anthranyl)amino]-14-oxabicyclo[11.2.2]heptadecane-1(2),13(17)-diene-15,16-dione (384 mg, 0.8 mmol) and KOH (179 mg, 3.2 mmol) in THF (10 mL)/H_2O (10 mL) was stirred for 20 h at room temperature. The mixture was alkalized with 10% aqueous KOH solution and extracted with dichloromethane. The organic layer was washed with brine, dried over K_2CO_3, and concentrated to give (*R*)-amine (176 mg, 99%). Colorless needles (ether); mp 62–64 °C; $[\alpha]_D^{24}$+4.8 (*c* 0.6, $CHCl_3$, 21.2 °C).

4.6.2. Glyoxal-bis-[(*R*)-1-(1-anthryl)ethyl]imine. Following the general procedure given for glyoxal-bis-imine, (*R*)-(+)-1-(1-anthryl)ethylamine (177 mg, 0.8 mmol) was reacted with glyoxal for 2 h at 70 °C. The crude imine (202 mg, 87%) was extracted with ethyl acetate. This product was used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) δ: 1.79 (6H,

d, J=6.3 Hz, CH_3CH), 5.56 (2H, q, J=6.3 Hz, CH$_3$CH), 7.41–7.48 (6H, m), 7.62 (2H, d, J=6.9 Hz), 7.91 (2H, d, J=8.6 Hz), 7.97–8.03 (4H, m), 8.22 (2H, s), 8.43 (2H, s), 8.65 (2H, s).

4.6.3. 1,3-Bis-[(*R*)-1-(1-anthryl)ethyl]imidazolium chloride. Following the general procedure given for 1,3-bis-[1-(1-adamantyl)ethyl]imidazolium chloride, glyoxal-bis-[(*R*)-1-(1-anthryl)ethyl]imine (171 mg, 0.37 mmol) was reacted with chloromethyl ethyl ether at 40 °C for 15 h. After addition of THF (2 mL), the mixture was refluxed for 8 h to afford imidazolium chloride (112 mg, 60%) as a yellow solid; mp 162–166 °C (dichloromethane/ether); $[\alpha]_D^{24}$ −298.6 (*c* 0.26, $CHCl_3$, 21.7 °C); ^{1}H NMR (DMSO-d_6) 2.09 (6H, d, J=6.9 Hz, CH_3CH), 6.73 (2H, q, J=6.9 Hz, CH$_3$CH), 7.37 (2H, d, J=8.0 Hz), 7.41–7.45 (4H, m), 7.51 (2H, t, J=7.5 Hz), 7.83–7.84 (2H, m), 8.05 (2H, d, J=8.6 Hz), 8.09 (2H, d, J=8.0 Hz), 8.61 (2H, s), 8.65 (2H, s), 9.89 (1H, s); ^{13}C NMR ($CDCl_3$) δ: 21.4, 56.3, 120.0, 121.5, 124.0, 124.0, 126.2, 126.3, 127.4, 127.5, 128.2, 129.0, 130.6, 131.5, 131.6, 132.4, 132.7, 137.8; HRMS (FAB) *m*/*z* calcd for $C_{35}H_{29}N_2$ (M^+): 477.2331, found: 477.2310.

4.6.4. 1,3-Bis-[(*R*)-1-(1-anthryl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-15. Following the procedure given for 1,3-bis-[(*R*)-1-(1-naphthyl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-**12**, 1,3-bis-[(*R*)-1-(1-anthryl)ethyl]imidazolium chloride was treated with $AgBF_4$ to give (*R*,*R*)-**15** (80%) as a slight brown solid. This compound was used in the acylation reaction without further purification.

4.7. Preparation of 1,3-bis-{(*R*)-1-[1-(2-methoxynaphthyl)]ethyl}imidazolium tetrafluoroborate (*R*,*R*)-10

4.7.1. 1-[1-(2-Methoxynaphthyl)]ethylamine. Diethyl azodicarboxylate (40% in toluene, 2 mL) at room temperature was added to a solution of 1-[1-(2-methoxynaphthyl)] ethanol[21] (727 mg, 3.6 mmol), phthalimide (573 mg, 4 mmol), and triphenylphosphine (1.05 g, 4 mmol) in dry THF (20 mL). The mixture was stirred overnight at room temperature. The solvent was evaporated and the residue was purified by silica gel column chromatography using hexane/ethyl acetate 2:1 as an eluent to yield *N*-1-[1-(2-methoxynaphthyl)]ethylphthalimide (989 mg, 83%). Colorless needles (ethyl acetate/hexane); mp 144–145 °C; ^{1}H NMR ($CDCl_3$) δ: 2.12 (3H, d, J=7.4 Hz, CH_3CH), 3.95 (3H, s, CH$_3$O), 6.31 (1H, q, J=7.4 Hz, CH$_3$CH), 7.27 (1H, d, J=8.6 Hz), 7.31–7.34 (1H, m), 7.51 (1H, t, J=7.4 Hz), 7.63–7.64 (2H, m), 7.75–7.79 (4H, m), 8.25 (1H, d, J=9.2 Hz); ^{13}C NMR ($CDCl_3$) δ: 18.5, 46.9, 56.8, 114.4, 121.5, 122.6, 123.0, 123.5, 27.1, 129.0, 129.4, 130.0, 132.1, 132.2, 133.8, 155.9, 168.9; HRMS (FAB) *m*/*z* calcd for $C_{21}H_{17}NO_3$ (M^+): 331.1208, found: 331.1203.

A solution of *N*-1-[1-(2-methoxynaphthyl)]ethylphthalimide (993 mg, 3 mmol) and hydrazine monohydrate (0.3 mL) in THF (30 mL) was refluxed for 3.5 h. Ether was added to the reaction mixture and the resulting precipitates were filtered. The filtrate was alkalized with KOH aqueous solution to pH 11. The organic layer was taken and extracted with 10% aqueous solution. The aqueous layer was taken, alkalized with NaOH aqueous solution, and extracted with ether. The organic layer was washed with brine, dried over K_2CO_3, and evaporated to yield the amine (424 mg, 70%). Colorless prisms (ether); mp 49–51 °C; ^{1}H NMR ($CDCl_3$) δ: 1.59 (3H, d, J=6.9 Hz, CH_3CH), 2.11 (2H, br, NH_2), 3.95 (3H, s, CH$_3$O), 4.97 (1H, q, J=6.9 Hz, CH$_3$CH), 7.26 (1H, d, J=9.2 Hz), 7.33 (1H, t, J=7.4 Hz), 7.47 (1H, dd, J=8.6, 7.4 Hz), 7.73 (1H, d, J=9.2 Hz), 7.78 (1H, d, J=8.0 Hz), 8.16 (1H, d, J=8.6 Hz); ^{13}C NMR ($CDCl_3$) δ: 23.2, 45.5, 56.2, 114.0, 122.9, 123.4, 126.5, 128.0, 128.5, 128.8, 129.5, 131.7, 155.1; HRMS (FAB) *m*/*z* calcd for $C_{13}H_{16}NO$ (M+1): 202.1232, found: 202.1228.

4.7.2. (*R*)-(+)-1-[1-(2-methoxynaphthyl)]ethylamine. Following the procedure given for (*R*)-(+)-1-(1-anthryl) ethylamine, racemic 1-(2-methoxynaphthyl)ethylamine was resoluted. The (*R*,*R*)- and (*R*,*S*)-diastereomers were purified by column chromatography on neutral silica gel by using dichloromethane/hexane/ether 10:5:1 as an eluent.

(R,R)-2-{1-[1-(2-methoxynaphthyl)]ethylamino}-14-oxabicyclo[11.2.2]heptadecane-1(2),13(17)-diene-15,16-dione. Yield 32%; colorless needles (dichloromethane/ether); mp 149–150 °C; $[\alpha]_D^{24}$ −271.4 (*c* 1.0, $CHCl_3$, 21.7 °C); ^{1}H NMR ($CDCl_3$) δ: 0.97–1.42 (12H, m), 1.48–1.55 (3H, m), 1.62–1.86 (4H, m), 2.05 (1H, t, J=12.0 Hz), 2.30–2.46 (2H, m), 3.93 (3H, d, J=2.9 Hz), 4.00 (1H, br), 5.65 (1H, s), 5.79 (1H, br), 7.20 (1H, dd, J=9.2, 2.9 Hz), 7.28 (1H, t, J=6.9 Hz), 7.45 (1H, t, J=6.9 Hz), 7.72–7.75 (2H, m), 7.84 (1H, d, J=8.0 Hz), 14.1 (1H, br, NH); ^{13}C NMR ($CDCl_3$) δ: 20.6, 24.0, 25.48, 26.5, 27.1, 27.2, 27.5, 28.2, 28.6, 28.8, 33.9, 47.9, 56.4, 98.0, 109.0, 113.6, 121.3, 123.7, 127.8, 129.4, 130.5, 131.0, 164.9, 165.1, 165.4, 183.3; HRMS (FAB) *m*/*z* calcd for $C_{29}H_{36}NO_4$ (M+1): 462.2644, found: 462.2655.

(R,S)-2-{1-[1-(2-methoxynaphthyl)]ethylamino}-14-oxabicyclo[11.2.2]heptadecane-1(2),13(17)-diene-15,16-dione. Yield 24%; colorless powder (ether); mp 127–128 °C; $[\alpha]_D^{24}$ +206.9 (*c* 1.0, $CHCl_3$, 21.2 °C); ^{1}H NMR ($CDCl_3$) δ: 0.74–1.17 (12H, m), 1.34–1.44 (1H, br), 1.50–1.63 (2H, m), 1.68–1.80 (4H, m), 2.08–2.14 (1H, m), 2.55 (1H, dt, J=13.6, 4.5 Hz), 2.72 (1H, br), 4.08 (3H, s, CH$_3$O), 4.20 (1H, br), 5.69 (1H, s), 5.92–5.94 (1H, m), 7.31 (1H, d, J=9.1 Hz), 7.36 (1H, t, J=7.1 Hz), 7.53–7.57 (1H, m), 7.81–7.84 (2H, m), 7.97 (1H, d, J=9.1 Hz), 14.2 (1H, br, NH); HRMS (FAB) *m*/*z* calcd for $C_{29}H_{36}NO_4$ (M+1): 462.2644, found: 462.2655.

(R)-(+)-1-[1-(2-methoxynaphthyl)]ethylamine. $[\alpha]_D^{24}$ +30.7 (*c* 1.0, $CHCl_3$, 24.4 °C).

4.7.3. Glyoxal-bis-{(*R*)-1-[1-(2-methoxynaphthyl)]ethyl}-imine. Following the general procedure given for glyoxal-bis-imine, (*R*)-(+)-1-[1-(2-methoxynaphthyl)]ethylamine was reacted with glyoxal for 2 h at 60 °C. The crude imine (brown oil, 98%) was extracted with dichloromethane. This product was used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) δ: 1.80 (6H, d, J=6.9 Hz, CH_3CH), 3.86 (6H, s, CH$_3$O), 5.73 (2H, q, J=6.9 Hz, CH$_3$CH), 7.21 (2H, dd, J=9.2, 1.7 Hz), 7.29 (2H, t, J=6.9 Hz), 7.37 (2H, dd, J=8.6, 6.9 Hz), 7.72–7.75 (4H, m), 8.03 (2H, s), 8.21 (2H, d, J=8.6 Hz).

4.7.4. 1,3-Bis-{(*R*)-1-[1-(2-methoxynaphthyl)]ethyl}-imidazolium chloride. Following the general procedure given for **6**, glyoxal-bis-{(*R*)-1-[1-(2-methoxynaphthyl)]-ethyl}imine (212 mg, 0.5 mmol) was reacted with chloromethy ethyl ether at 40 °C for 20 h. After addition of THF (2 mL), the mixture was refluxed for 24 h to afford imidazolium chloride (104 mg, 44%) as a brown amorphous solid; $[\alpha]_D^{24}$ −96.6 (*c* 0.54, $CHCl_3$, 20.8 °C); ^{1}H NMR ($CDCl_3$) *δ*: 2.19 (6H, d, *J*=6.3 Hz, C*H*$_3$CH), 3.69 (6H, s, CH_3O), 6.74 (2H, q, *J*=6.3 Hz, CH_3C*H*), 7.09 (2H, s), 7.18 (2H, d, *J*=9.2 Hz), 7.31 (2H, dd, *J*=8.0, 6.9 Hz), 7.50 (2H, t, *J*=6.9 Hz), 7.75 (2H, d, *J*=8.0 Hz), 7.82 (2H, d, *J*=8.6 Hz), 8.16 (2H, br), 10.47 (1H, s, imidazole C2-H); ^{13}C NMR ($CDCl_3$) *δ*: 19.4, 53.6, 56.2, 113.3, 118.2, 120.9, 122.0, 124.2, 128.3, 129.1, 129.3, 131.69, 131.8, 136.7, 155.8; HRMS (FAB) *m*/*z* calcd for $C_{29}H_{29}N_2O_2$ (M^+): 437.2229, found: 437.2230.

4.7.5. 1,3-Bis-{(*R*)-1-[1-(2-methoxynaphthyl)]ethyl}-imidazolium tetrafluoroborate (*R*,*R*)-16. Following the procedure given for (*R*,*R*)-**12**, 1,3-bis-{(*R*)-1-[1-(2-methoxynaphthyl)]ethyl}imidazolium chloride was treated with $AgBF_4$ to give (*R*,*R*)-**16** (77%) as a solid. This compound was used in the acylation reaction without further purification.

4.8. Preparation of 1,3-bis-(*R*)-1-1-pyrenylimidazolium tetrafluoroborate (*R*,*R*)-11

4.8.1. Glyoxal-bis-[(*R*)-1-(1-pyrenyl)ethyl]imine. Following the general procedure given for glyoxal-bis-imine, (*R*)-(+)-1-(1-pyrenyl)ethylamine[22] (245 mg, 2 mmol) was reacted with glyoxal at 60 °C for 3 h. The extraction with dichloromethane yielded the crude imine quantitively as a slight brown solid. The product was used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) *δ*: 1.85 (6H, d, *J*=6.9 Hz, C*H*$_3$CH), 5.71 (2H, q, *J*=6.9 Hz, CH_3C*H*), 7.97 (2H, t, *J*=7.4 Hz), 8.00 (4H, s), 8.08 (2H, d, *J*=9.2 Hz), 8.13–8.15 (6H, m), 8.21 (2H, d, *J*=8.0 Hz), 8.27 (2H, s), 8.33 (2H, d, *J*=9.2 Hz).

4.8.2. 1,3-Bis-[(*R*)-1-(1-pyrenyl)ethyl]imidazolium chloride. Following the general procedure given for **6**, glyoxal-bis-[(*R*)-1-(1-pyrenyl)ethyl]imine (492 mg, 0.96 mmol) was reacted with chloromethyl ethyl ether at room temperature for 1 h, and then for 16 h at 40 °C. The resulting precipitates were collected by filtration and dissolved in dichloromethane/methanol. The solution was treated by an activated carbon and evaporated to afford the chloride (351 mg, 65%). Slight yellow granules (methanol/ether); mp 240–245 °C (decomp); $[\alpha]_D^{24}$ −32.5 (*c* 0.16, EtOH, 23.3 °C); ^{1}H NMR ($CDCl_3$) *δ*: 2.29 (6H, d, *J*=6.7 Hz, C*H*$_3$CH), 7.10 (2H, q, *J*=6.7 Hz, CH_3C*H*), 6.65 (2H, s), 7.93 (2H, d, *J*=8.0 Hz), 7.96 (2H, d, *J*=9.2 Hz), 8.00 (2H, t, *J*=7.4 Hz), 8.05 (2H, d, *J*=8.6 Hz), 8.07 (2H, d, *J*=8.0 Hz), 8.13–8.19 (6H, m), 8.41 (2H, d, *J*=9.2 Hz), 11.76 (1H, s); ^{13}C NMR ($CDCl_3$) *δ*: 20.2, 47.5, 121.0, 122.1, 124.3, 124.7, 125.1, 125.4, 125.7, 126.3, 126.9, 127.9, 128.0, 128.6, 130.6, 131.3, 131.4, 131.6; HRMS (FAB) *m*/*z* calcd for $C_{39}H_{29}N_2$ (M^+): 525.2331, found: 525.2340.

4.8.3. 1,3-Bis-[(*R*)-1-(1-pyrenyl)ethyl]imidazolium tetrafluoroborate (*R*,*R*)-17. Following the procedure given for (*R*,*R*)-**12**, 1,3-bis-[(*R*)-1-(1-pyrenyl)ethyl]imidazolium chloride was treated with $AgBF_4$ to give (*R*,*R*)-**17** (60%) as a slight brown solid. This compound was used in the acylation reaction without further purification.

4.9. Preparation of 1,3-bis-[(*S*)-1-(9-phenanthryl)ethyl] imidazolium tetrafluoroborate (*S*,*S*)-18

4.9.1. Glyoxal-bis-[(*S*)-1-(9-phenanthryl)ethyl]imine. Following the general procedure given for glyoxal-bis-imine, (*S*)-(−)-1-(9-phenanthryl)ethylamine[23] (69 mg, 0.8 mmol) was reacted with glyoxal for 30 min at room temperature, and then for 2 h at 60 °C. The imine was quantitively obtained by extraction with dichloromethane and used in the subsequent reaction without further purification; ^{1}H NMR ($CDCl_3$) *δ*: 1.80 (6H, d, *J*=6.9 Hz, C*H*$_3$CH), 5.45 (2H, q, *J*=6.9 Hz, CH_3C*H*), 7.56–7.69 (8H, m), 7.88 (2H, d, *J*=8.0 Hz), 7.95 (2H, s), 8.17 (2H, d, *J*=9.2 Hz), 8.27 (2H,s), 8.64 (2H, d, *J*=8.0 Hz), 8.74 (2H, d, *J*=9.2 Hz).

4.9.2. 1,3-Bis-[(*S*)-1-(9-phenanthryl)ethyl]imidazolium chloride. Following the general procedure given for **6**, glyoxal-bis-[(*S*)-1-(9-phenanthryl)ethyl]imine (186 mg, 0.4 mmol) was reacted with chloromethyl ethyl ether at 40 °C for 20 h to afford the imidazolium chloride (104 mg, 60%) as a solid. Slight yellow powder (dichloromethane/ether); mp 177–180 °C; $[\alpha]_D^{24}$ −69.6 (*c* 1.0, $CHCl_3$, 23.0 °C); ^{1}H NMR ($CDCl_3$) *δ*: 2.09 (6H, d, *J*=6.8 Hz, C*H*$_3$CH), 6.72 (2H, q, *J*=6.8 Hz, CH_3C*H*), 6.87 (2H, s), 7.51–7.61 (8H, m), 7.63 (2H, s), 7.75 (2H, d, *J*=8.0 Hz), 8.01 (2H, d, *J*=7.9 Hz), 8.50 (2H, d, *J*=8.6 Hz), 8.58 (2H, d, *J*=8.0 Hz), 10.83 (1H, s); ^{13}C NMR ($CDCl_3$) *δ*: 21.5, 56.3, 120.7, 122.5, 123.3, 123.6, 126.1, 127.2, 127.2, 127.8, 128.0, 128.9, 129.3, 130.5, 130.7, 130.9, 131.4, 137.3.

4.9.3. 1,3-Bis-[(*S*)-1-(9-phenanthryl)ethyl]imidazolium tetrafluoroborate (*S*,*S*)-18. Following the procedure given for (*R*,*R*)-**12**, 1,3-bis-[(*S*)-1-(9-phenanthryl)ethyl]-imidazolium chloride was treated with $AgBF_4$ to give (*R*,*R*)-**18** (61%) as a slight brown solid. This compound was used in the acylation reaction without further purification.

4.10. General procedure for *N*-heterocyclic carbene-catalyzed asymmetric aclation of secondary alcohols

Potassium *tert*-butoxide (0.25 mmol) was added to a suspension of azolium salt (0.3 mmol) in ether (2 mL). The mixture was stirred at room temperature for 30 min. Vinyl acetate (1.2 mmol) and alcohol (1 mmol) were added at the indicated temperature to the mixture. The resulting mixture was stirred for the indicated time. The solvent was evaporated and the residue was purified by silica gel column chromatography by using ethyl acetate/hexane.

The results summarized in Table 3 were obtained by taking 5 μL of the sample from the reaction mixture, filtering it through a short silica gel column, and then subjecting to chiral HPLC analysis.

4.10.1. 1-(1-Naphthyl)ethanol 7. Analytical chiral HPLC: Chiralcel OD column, 0.46×25 cm, hexane/2-propanol 9:1, 0.5 mL min^{-1}; *S*, 19.8 min, *R*, 29.4 min. Chiralcel OD-H

column, 0.46×15 cm, hexane/2-propanol 9:1, 1 mL min^{-1}; *S*, 6.2 min, *R*, 9.7 min.

4.10.2. 1-(1-Naphthyl)ethyl acetate 8. Analytical chiral HPLC: Chiralcel OD column, 0.46×25 cm, hexane/2-propanol 9:1, 1 mL min^{-1}; *R*, 5.3 min, *S*, 6.4 min.

4.10.3. 1-(1-Phenyl)ethanol 19. Analytical chiral HPLC: Chiralcel OD column, 0.46×25 cm, hexane/2-propanol 95:5, 0.5 mL min^{-1}; *S*, 16.5 min, *R*, 19.7 min.

4.10.4. 1-(1-Phenyl)ethyl acetate 22. Analytical chiral HPLC: Chiralpac AS column, 0.46×25 cm, hexane/2-propanol 100:0.1, 0.5 mL min^{-1}; *R*, 15.8 min, *S*, 19.8 min.

4.10.5. 1-(2-Naphthyl)ethanol 20. Analytical chiral HPLC: Chiralpac AS column, 0.46×25 cm, hexane/2-propanol 97.5:2.5, 0.5 mL min^{-1}; *S*, 30.1 min, *R*, 35.1 min.

4.10.6. 1-(2-Naphthyl)ethyl acetate 23. Analytical chiral HPLC: Chiralpac AS column, 0.46×25 cm, hexane/2-propanol 99:1, 0.5 mL min^{-1}; *R*, 13.5 min, *S*, 16.3 min.

4.10.7. 1,2,3,4-Tetrahydro-1-naphtol 21. Analytical chiral HPLC: Chiralpac AS column, 0.46×25 cm, hexane/2-propanol 97.5:2.5, 0.5 mL min^{-1}; 20.6 min, 26.6 min.

4.10.8. 1,2,3,4-Tetrahydro-1-naphthyl acetate 24. Analytical chiral HPLC: Chiralpac AS column, 0.46×25 cm, hexane/2-propanol 97.5:2.5, 0.5 mL min^{-1}; 12.2 min, 15.7 min.

4.10.9. 1-(1-Naphthyl)ethyl propionate. Analytical chiral HPLC: Chiralcel OD column, 0.46×25 cm, hexane/2-propanol 9:1, 0.5 mL min^{-1}; *R*, 9.7 min, *S*, 11.3 min.

4.10.10. 1-(1-Naphthyl)ethyl butyrate. Analytical chiral HPLC: Chiralcel OD–H column, 0.46×15 cm, hexane/2-propanol 98:2, 1 mL min^{-1}; *R*, 3.4 min, *S*, 4.2 min.

4.10.11. 1-(1-Naphthyl)ethyl benzoate. Analytical chiral HPLC: Chiralpac AD-H column, 0.46×15 cm, hexane/2-propanol 98:2, 1 mL min^{-1}; *R*, 5.6 min, *S*, 7.0 min.

References and notes

1. (a) Ukai, T.; Tanaka, R.; Dokawa, T. *J. Pharm. Soc. Jpn.* **1943**, *63*, 296–300. (b) Ukai, T.; Dokawa, T.; Tsubokawa, S. *J. Pharm. Soc. Jpn.* **1944**, 3–4.
2. Breslow, R. *J. Am. Chem. Soc.* **1958**, *80*, 3719–3726.
3. (a) Stetter, H. *Angew. Chem., Int. Ed.* **1976**, *88*, 695–704. (b) Stetter, H.; Kuhlmann, H. *Chem. Ber.* **1976**, *109*, 2890–2896. (c) Stetter, H.; Kuhlmann, H. *Org. React.* **1991**, *40*, 407–496.
4. Berkessel, A.; Gröger, H. *Asymmetric organocatalysis*; Wiley-VCH: Weinheim, 2005.
5. Enders, D.; Balensiefer, T. *Acc. Chem. Res.* **2004**, *37*, 534–541.
6. (a) Sheehan, J. C.; Hunneman, D. H. *J. Am. Chem. Soc.* **1966**, *88*, 3666–3667. (b) Sheehan, J. C.; Hara, T. *J. Org. Chem.* **1974**, *39*, 1196–1199. (c) Takagi, W.; Tamura, Y.; Yano, Y. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 478–480. (d) Zhao, C.; Chen, S.; Wu, P.; Wen, Z. *Huaxue Xuebao* **1988**, *46*, 784–790. (e) Marti, J.; Castells, J.; Lopez-Calahorra, F. *Tetrahedron Lett.* **1993**, *34*, 521–524. (f) Enders, D.; Breuer, K. *Helv. Chim. Acta* **1996**, *79*, 1217–1221. (g) Knight, R. L.; Leeper, F. J. *Tetrahedron Lett.* **1997**, *38*, 3611–3614. (h) Gerhards, A. U.; Leeper, F. J. *Tetrahedron Lett.* **1997**, *38*, 3615–3618. (i) Dvorak, C. A.; Rawal, V. H. *Tetrahedron Lett.* **1998**, *39*, 2925–2928. (j) Knight, R. L.; Leeper, F. J. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1891–1893. (k) Enders, D.; Kallfass, U. *Angew. Chem., Int. Ed.* **2002**, *41*, 1743–1745.
7. (a) Enders, D.; Breuer, K.; Runsink, J.; Teles, J. H. *Helv. Chim. Acta* **1996**, *79*, 1899–1902. (b) Kerr, M. S.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2002**, *124*, 10298–10299. (c) Kerr, M. S.; Rovis, T. *Synlett* **2003**, 1934–1936.
8. (a) Inoue, H.; Higashiura, K. *J. Chem. Soc., Chem. Commun.* **1980**, 549–550. (b) Castells, J.; Pujol, F.; Llitjós, H.; Moreno-Mañas, M. *Tetrahedron* **1982**, *38*, 337–346.
9. (a) Grasa, G. A.; Kissling, R. M.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 3583–3586. (b) Nyce, G. W.; Lamboy, J. A.; Connor, E. F.; Waymouth, R. M.; Hedrick, J. L. *Org. Lett.* **2002**, *4*, 3587–3590. (c) Grasa, G. A.; Güveli, T.; Singh, R.; Nolan, S. P. *J. Org. Chem.* **2003**, *68*, 2812–2819. (d) Singh, R.; Kissling, R. M.; Letellier, M.-A.; Nolan, S. P. *J. Org. Chem.* **2004**, *69*, 209–212.
10. A preliminary communication of this work was published: Suzuki, Y.; Yamauchi, K.; Muramatsu, K.; Sato, M. *Chem. Commun.* **2004**, 2770–2771.
11. Related reactions using chiral NHCs were recently reported: (a) Reynolds, N. T.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2004**, *126*, 9518–9519. (b) Chan, A.; Scheidt, K. A. *Org. Lett.* **2005**, *5*, 905–908.
12. (a) Miyashita, A.; Matsuda, H.; Suzuki, Y.; Iwamoto, K.; Higashino, T. *Chem. Pharm. Bull.* **1994**, *42*, 2017–2022. (b) Miyashita, A.; Suzuki, Y.; Iwamoto, K.; Higashino, T. *Chem. Pharm. Bull.* **1994**, *42*, 2633–2635. (c) Miyashita, A.; Suzuki, Y.; Okumura, Y.; Higashino, T. *Chem. Pharm. Bull.* **1996**, *44*, 252–254. (d) Miyashita, A.; Suzuki, Y.; Kobayashi, M.; Kuriyama, N.; Higashino, T. *Heterocycles* **1996**, *43*, 509–512. (e) Miyashita, A.; Suzuki, Y.; Nagasaki, I.; Ishiguro, C.; Iwamoto, K.; Higashino, T. *Chem. Pharm. Bull.* **1997**, *45*, 1254–1258. (f) Miyashita, A.; Obae, K.; Suzuki, Y.; Iwamoto, K.; Oishi, E.; Higashino, T. *Hetrocycles* **1997**, *45*, 2159–2173. (g) Miyashita, A.; Suzuki, Y.; Okumura, Y.; Iwamoto, K.; Higashino, T. *Chem. Pharm. Bull.* **1998**, *46*, 6–11. (h) Miyashita, A.; Suzuki, Y.; Iwamoto, K.; Higashino, T. *Chem. Pharm. Bull.* **1998**, *46*, 390–399. (i) Miyashita, A.; Suzuki, Y.; Iwamoto, K.; Oishi, E.; Higashino, T. *Hetrocycles* **1998**, *49*, 405–413. (j) Suzuki, Y.; Toyota, T.; Imada, F.; Sato, M.; Miyashita, A. *Chem. Commun.* **2003**, 1314–1315.
13. For general reviews, see: (a) Spivey, A. C.; Maddaford, A.; Redgrave, A. J. *Org. Prep. Proced. Int.* **2000**, *331*, 333–365. (b) Robinson, D. E. J. E.; Bull, S. D. *Tetrahedron: Asymmetry* **2003**, *14*, 1407–1446.
14. Herrmann, W. A.; Goossen, L. J.; Köcher, C.; Artus, G. R. J. *Angew. Chem., Int. Ed.* **1996**, *35*, 2805–2807.
15. Arduengo, A. J., III,; Krafczyk, R.; Schmutzler, R. *Tetrahedron* **1999**, *55*, 14523–14534.
16. Kano, T.; Sasaki, K.; Maruoka, K. *Org. Lett.* **2005**, *7*, 1347–1349.
17. Roje, M.; Hamersak, Z.; Sunjic, V. *Synth. Commun.* **2002**, *32*, 3413–3417.

18. Goto, J.; Ito, M.; Katsuki, S.; Saito, N.; Nanbara, T. *J. Liq. Chromatogr.* **1986**, *9*, 683–694.
19. For chiral cyclophane, (*R*)-16-hydroxy-14-oxabicyclo[11.2.2] heptadecane-1(16),13(17)-diene-2,15-dione, see: Sato, M.; Uehara, F.; Sato, K.; Yamaguchi, M.; Kabuto, C. *J. Am. Chem. Soc.* **1999**, *121*, 8270–8276.
20. Resolution of racemic amines using a chiral cyclophane will be published later.
21. Noji, M.; Ohno, T.; Fuji, K.; Futaba, N.; Tajima, H.; Ishii, K. *J. Org. Chem.* **2003**, *68*, 9340–9347.
22. Shoji, O.; Nakajima, D.; Ohkawa, M. *Mocromolecules* **2003**, *36*, 4557–4566.
23. Li, Y.; Ng, K.-H.; Selvaratnam, S.; Tan, G.-K.; Vittal, J. J.; Leung, P.-H. *Organometallics* **2003**, *22*, 834–842.