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Phosphine-catalyzed [4+2] cycloaddition of sulfamate-derived cyclic imines with allenoates: synthesis of sulfamate-fused tetrahydropyridines

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ABSTRACT

Using *n*-$PrPPh_2$ as the nucleophilic catalyst, the [4+2] cycloaddition reaction of the sulfamate-derived cyclic imines with allenoates works efficiently to yield various sulfamate-fused tetrahydropyridines in high yields with excellent diastereoselectivities. Using amino acid-based bifunctional phosphine as chiral catalyst, an asymmetric [4+2] cycloaddition reaction was achieved, giving chiral sulfamate-fused tetrahydropyridines in high yields with good enantiomeric excesses.

1. Introduction

The tetrahydropyridines are key units in or building blocks of many pharmaceuticals, agrochemicals, biologically active compounds, and natural products.[1] Therefore, the development of generally applicable synthetic tools toward tetrahydropyridine-fused compounds is highly desirable and has attracted much attention. Various efficient reactions have been reported for the preparation of the functionalized tetrahydropyridine.[2] Among these reactions, phosphine-catalyzed [4+2] cycloaddition of *N*-tosylaldimines with allenoates provided an expedient and efficient route.[3] In 2003, Kwon first reported this seminal work and demonstrated under phosphine catalysis conditions, a variety of allenoates carry out [4+2] cycloaddition with *N*-tosylaldimines to give the tetrahydropyridine derivatives in high yield.[4] In 2005, Fu developed asymmetric variant of this reaction by using binaphthyl-based C_2-symmetric monophosphine as chiral catalyst and achieved excellent enantioselectivity in the synthesis of functionalized tetrahydropyridines.[5] In 2011, Zhao described another impressive asymmetric version by employing a kind of simple and accessible bifunctional *N*-acyl-aminophosphine, providing facile accesses to optically active tetrahydropyridines.[6] In 2012, Ye extended the substrate scope of the reaction from aldimines to cyclic ketimines, and achieved phosphane-catalyzed [4+2] annulation of allenoates with cyclic ketimines to give sultam-fused tetrahydropyridines.[7] Although the *N*-tosylaldimines and cyclic ketimines in phosphine-catalyzed [4+2] cycloaddition with allenoates have been explored, the application of the sulfamate-derived cyclic aldimines in this reaction has never been reported. Since various sulfamate-containing compounds display the remarkable bioactivity,[8] the synthesis of sulfamate-fused tetrahydropyridines with two kinds of pharmacophores by phosphine-catalyzed [4+2] cycloaddition of the sulfamate-derived cyclic aldimines with allenoates will be very significant. As part of our research on the development of annulation reactions[9] for the synthesis of heterocycles, we herein describe phosphine-catalyzed [4+2] annulation of sulfamate-derived cyclic aldimines with α-substituted allenoates to afford the sulfamate-fused tetrahydropyridines.

2. Results and discussion

In initial attempt, we conducted a reaction of the benzol[*e*][1,2,3]oxathiazine 2,2-dioxide (**1a**) with ethyl 2-benzylbuta-2,3-dienoate (**2a**) in dichloromethane at room temperature for 24 h in the presence of 20 mol % PPh_3. To our delight, the target [4+2] cycloaddition product **3aa** was obtained in 83% yield with excellent diastereoselectivity (Table 1, entry 1). However, using more nucleophilic phosphines, such as PBu_3, PMe_3, and Me_2PPh as the catalyst, only trace of [4+2] cycloaddition product was obtained,

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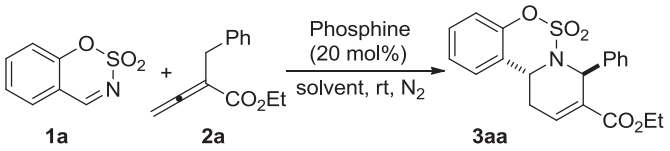
with most of the starting material **1a** left (entries 2–4). Therefore, we turned our attention to *n*-PrPPh$_2$, which has been identified to be the most effective catalyst in another [3+2] cycloaddition reaction of imine,[10] and an inspiring result, 88% yield with over 20:1 diastereoselectivity, was acquired within 12 h (Table 1, entry 5). Subsequently, a couple of solvents, such as THF, CH$_3$CN, MeOH, and toluene were screened. Except that methanol resulted in trace of the target product, other solvents are compatible for catalysis, providing the desired product in moderate to excellent yields with excellent diastereoselectivities (entries 6–9). In particular, when the reaction was carried out in toluene in the presence of the additive 3 Å MS, the best 97% yield and excellent diastereoselectivity was obtained within 12 h (Table 1, entry 10).

Table 1
Optimization of the reaction conditions for phosphine-catalyzed [4+2] cycloaddition of sulfamate-derived cyclic imine (**1a**) with allenoate (**2a**)[a]



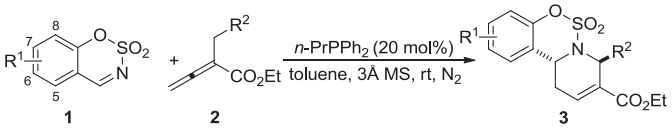
1a 2a 3aa

Entry	Phosphine	Solvent	Time (h)	Yield[b] (%)	dr[c]
1	PPh_3	CH_2Cl_2	24	83	>20:1
2	PBu_3	CH_2Cl_2	24	Trace	—
3	PMe_3	CH_2Cl_2	24	Trace	—
4	Me_2PPh	CH_2Cl_2	24	Trace	—
5	*n*-PrPPh$_2$	CH_2Cl_2	12	88	>20:1
6	*n*-PrPPh$_2$	THF	24	85	>20:1
7	*n*-PrPPh$_2$	CH_3CN	24	91	>20:1
8	*n*-PrPPh$_2$	CH_3OH	24	ND	—
9	*n*-PrPPh$_2$	Toluene	12	83	>20:1
10[d]	*n*-PrPPh$_2$	Toluene	12	97	>20:1

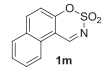
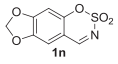
[a] 1.2 equiv of allenoate was used.
[b] Isolated yields.
[c] Determined by ^{1}H NMR analysis of the crude products. The relative configuration was determined by X-ray crystallographic analysis of the homologous sulfamate-fused tetrahydropyridine **3ai** (vide infra).[11]
[d] 50 mg of 3 Å MS was added.

After the optimized conditions were established, the reaction of a series of sulfamate-derived cyclic imines **1** and allenoates **2** was investigated (Table 2). With 20 mol % of *n*-PrPPh$_2$ as the catalyst and 3 Å MS as the additive, various sulfamate-derived cyclic imines **1** carried out [4+2] cycloaddition reaction with allenoates **2** in toluene at room temperature for 12–24 h, providing the ethyl 8-phenyl-11,11a-dihydro-8*H*-benzo[*e*]pyrido[1,2-*c*][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide derivatives (**3aa**–**an**) in moderate to excellent yields (45–98%) with excellent diastereoselectivities (>20:1) (Table 2, entries 1–27). The substituted sulfamate-derived cyclic imines **1** and substituted allenoates **2**, except for **1l** (Table 2, entries 12), regardless of whether electron-withdrawing or electron-donating groups were introduced to phenyl groups, generally afforded high yields (entries 1–24). The position of the substituents at the phenyl ring in the sulfamate-derived cyclic imines **1** or allenoates **2** seems to have negligible effect on the yields and diastereoselectivity. Unfortunately, under the above optimal conditions, α-methyl allenoate **2m** underwent the cycloaddition reaction to give lower 20% yield. Gratifyingly, when the reaction of α-methyl allenoate **2m** with cyclic imine **2a** was carried out in CH_2Cl_2 in the absence of additive 3 Å MS for 12 h, the corresponding product **3am** was obtained in 85% yield (entry 26). Interestingly, with the additive 3 Å MS, the product was produced in somewhat lower 77% yield. In contrast, the reaction of α-ethyl allenoate **2n** with **2a** was performed in CH_2Cl_2 without 3 Å MS for 60 h, only giving 45% yield (entry 27). The relative configuration of sulfamate-fused tetrahydropyridines was verified through single-crystal X-ray analyses of the annulation product **3ai** (Fig. 1).[11]

Table 2
Substrate scope for phosphine-catalyzed [4+2] cycloaddition of sulfamate-derived cyclic imines (**1**) with α-substituted allenoates (**2**)[a]



1 2 3

Entry	R^1	R^2	Time (h)	3	Yield[b,c]/%
1	H (**1a**)	H (**2a**)	12	**3aa**	97
2	6-Me (**1b**)	H (**2a**)	24	**3ba**	98
3	8-Me (**1c**)	H (**2a**)	24	**3ca**	98
4	6-MeO (**1d**)	H (**2a**)	24	**3da**	94
5	7-MeO (**1e**)	H (**2a**)	24	**3ea**	95
6	8-MeO (**1f**)	H (**2a**)	24	**3fa**	93
7	6-*t*-Bu (**1g**)	H (**2a**)	24	**3ga**	82
8	8-*t*-Bu (**1h**)	H (**2a**)	24	**3ha**	79
9	6-F (**1i**)	H (**2a**)	24	**3ia**	96
10	6-Cl (**1j**)	H (**2a**)	24	**3ja**	92
11	6-Br (**1k**)	H (**2a**)	24	**3ka**	92
12	7-Br (**1l**)	H (**2a**)	24	**3la**	48
13	 1m	H (**2a**)	24	**3ma**	98
14	 1n	H (**2a**)	24	**3na**	88
15	H (**1a**)	3-MeC_6H_4 (**2b**)	12	**3ab**	90
16	H (**1a**)	4-MeC_6H_4 (**2c**)	12	**3ac**	94
17	H (**1a**)	3-FC_6H_4 (**2d**)	12	**3ad**	94
18	H (**1a**)	4-FC_6H_4 (**2e**)	12	**3ae**	95
19	H (**1a**)	3-ClC_6H_4 (**2f**)	12	**3af**	96
20	H (**1a**)	4-ClC_6H_4 (**2g**)	12	**3ag**	93
21	H (**1a**)	3-BrC_6H_4 (**2h**)	12	**3ah**	90
22	H (**1a**)	4-BrC_6H_4 (**2i**)	12	**3ai**	97
23	H (**1a**)	3-$CF_3C_6H_4$ (**2j**)	12	**3aj**	68
24	H (**1a**)	4-$CF_3C_6H_4$ (**2k**)	12	**3ak**	70
25	H (**1a**)	2-Naphthyl (**2l**)	12	**3al**	94
26[d]	H (**1a**)	H (**2m**)	12	**3am**	85
27[d]	H (**1a**)	Me (**2n**)	60	**3an**	45

[a] 1.2 equiv of allenoate was used.
[b] Isolated yields.
[c] All diastereomer ratios were >20:1, determined by ^{1}H NMR analysis of the crude products.
[d] The reactions were performed in CH_2Cl_2 in the absence of the additive 3 Å MS.

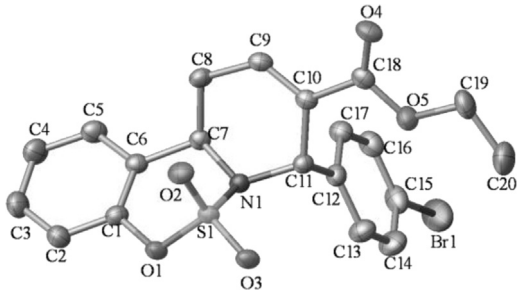
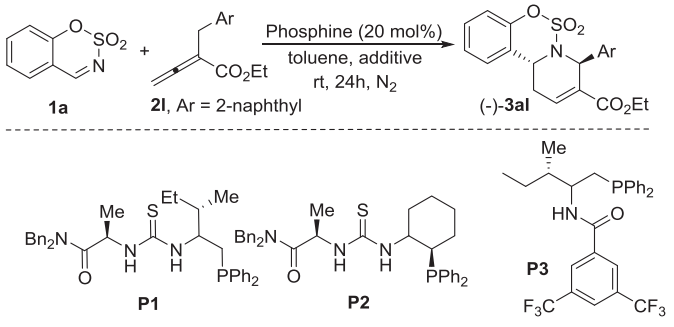


Fig. 1. The X-ray structure of **3ai**.

As mentioned in the Introduction, asymmetric [4+2] cycloaddition of electron-deficient imines with allenoates has been developed by using binaphthyl-based C_2-symmetric monophosphine[5] or bifunctional *N*-acyl-aminophosphine[6] as chiral

catalyst, and excellent enantioselectivity was achieved in the synthesis of functionalized tetrahydropyridines. On the basis of the outcomes, in order to synthesize enantiomerically enriched sulfamate-fused tetrahydropyridines, we investigated asymmetric variant of phosphine-catalyzed [4+2] cycloaddition of sulfamate-derived cyclic imines with allenoates. As a kind of simple and accessible chiral phosphines, which have displayed excellent enantioselectively catalytic capability, amino acid and thiourea-based bifunctional chiral phosphines (**P1**–**P3**) were chosen to be used in the target [4+2] cycloaddition reaction (Table 3). In the screening of chiral catalysts, the reaction of the cyclic imine **1a** and ethyl allenoate **2l** was explored as a model reaction (Table 3). Using 20 mol % of the thiourea-based bifunctional chiral phosphine **P1**, chiral sulfamate-fused tetrahydropyridine **3al** was obtained in 75% yield with 82% ee (entry 1). Very interestingly, the screening of the additives illustrated that the adding of molecular sieves into the reaction mixture could improve the enantioselectivity. In the presence of **P1** and 3 Å MS, the yield and the enantiomeric excess were increased to 85% and 87%, respectively (entry 2). In comparison, the adding of 4 Å MS resulted in a remarkable improvement of enantioselectivity, and the chiral product **3al** was obtained in 81% yield and 99% ee (entry 3). In the presence of 4 Å MS, another thiourea-based phosphine **P2** was quite inert and only afforded the product **3al** in 25% yield and −39% ee (entry 4). The amino acid-based phosphine **P3** could successfully catalyze the reaction in the presence of 4 Å MS to give the corresponding product in 70% yield and 90% ee (entry 5). Finally, the thiourea-based bifunctional chiral phosphine **P1**, which afforded the highest 99% ee at present, was chosen to be the best catalyst. The absolute configuration of **3al** as depicted was determined by X-ray analysis of the homologous chiral product **3af** (Fig. 2).[11]

Table 3
Screening of reaction conditions of asymmetric [4+2] cycloaddition of sulfamate-derived cyclic imine (**1a**) with allenoate (**2m**)[a]



Entry	Phosphine	Additive	Yield[b] (%)	ee[c] (%)	dr[d]
1	**P1**	—	75	82	4:1
2	**P1**	3 Å MS	85	87	4:1
3	**P1**	4 Å MS	81	99	4:1
4	**P2**	4 Å MS	25	−39[e]	>20:1
5	**P3**	4 Å MS	70	90	>20:1

[a] 1.2 equiv of allenoate was used.
[b] Isolated yields.
[c] The ee values of the major diastereoisomer were determined by chiral HPLC analysis.
[d] Determined by ^{1}H NMR analysis of the crude products.
[e] The minus means that the opposite configuration of the product was obtained.

Using the phosphine **P1** as the catalyst and in the presence of 4 Å MS, we investigated the substrate scope of enantioselective [4+2] cycloaddition of sulfamate-derived cyclic imines (**1**) with ethyl allenoates (**2**). As shown in Table 4, the sulfamate-fused tetrahydropyridines were obtained in good yields, and with moderate to excellent enantioselectivities. The sulfamate-derived cyclic imines

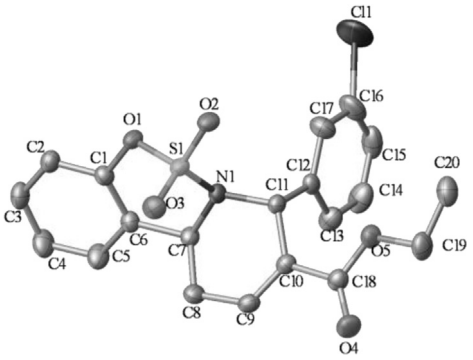
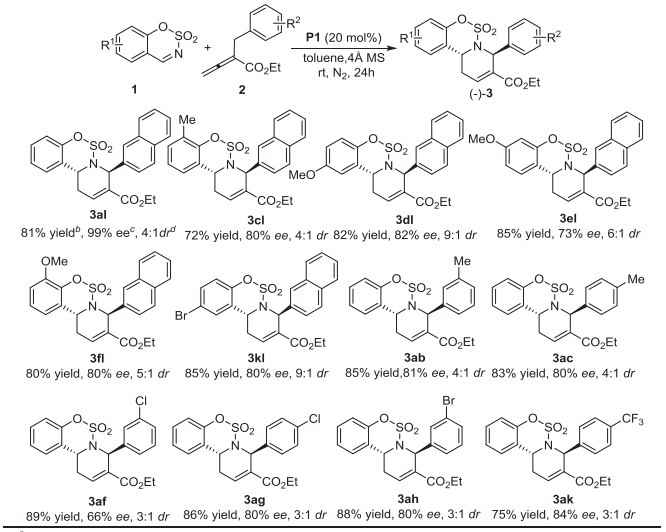


Fig. 2. The X-ray structure of chiral (−)-**3af**.

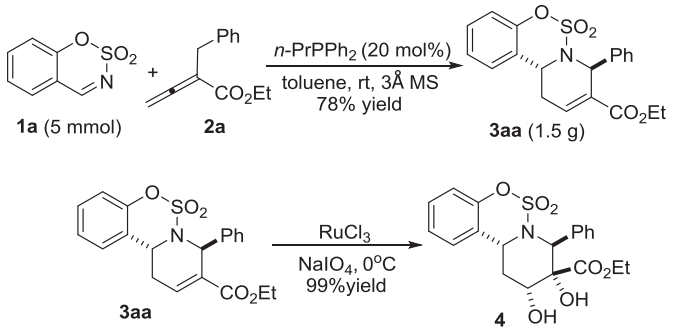
that bear a variety of functionalities on the aromatic ring underwent the reaction with allenoate **2l** to give the corresponding optically active tetrahydropyridine derivatives in good yields with good enantioselectivities that ranged from 73% to 99% (Table 4, **3al**–**kl**). Also various allenoates **2** carried out [4+2] cycloaddition with sulfamate-derived cyclic imine **1a** in the presence of chiral phosphine **P1** to give the tetrahydropyridine derivatives in good yields with good enantioselectivities (Table 4, **3ab**–**ak**).

Table 4
Substrate scope for asymmetric [4+2] cycloaddition of sulfamate-derived cyclic imines (**1**) with allenoates (**2**)[a]



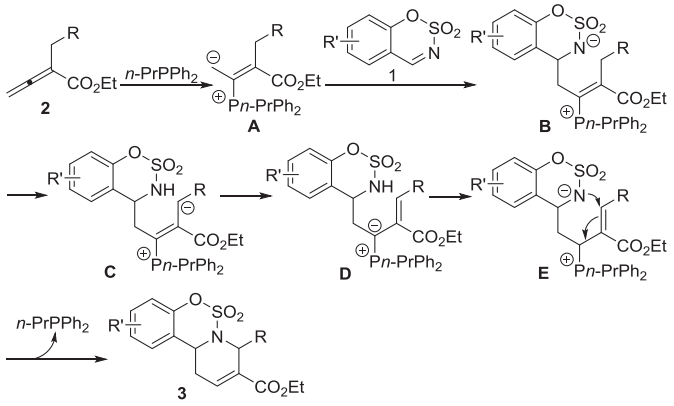
[a] 1.2 equivalents of allenoate was used.
[b] Isolated yields.
[c] The *ee* values of the major diastereoisomer were determined by chiral HPLC analysis.
[d] Determined by ^{1}H NMR analysis of the crude products.

As shown in Scheme 1, the present phosphine-catalyzed [4+2] cycloaddition of sulfamate-derived cyclic imines with allenoates could be a useful reaction in the synthesis of heterocyclic compounds. The reaction can be carried out on gram scale to provide the target product **3aa** in 78% yield. However, when the asymmetric variant of this reaction was scaled up to 5 mmol, the reaction was completely suppressed. The reason might be that the thiourea-based organocatalysts could form hydrogen-bonded aggregates.[12] In the further transformation of the product, the carbon–carbon double bond of the tetrahydropyridine part can easily be dihydroxylated in excellent yield.



Scheme 1. Gram-scale synthesis of tetrahydropyridine derivative and further transformation.

On the basis of Kwon's proposal[4] and Han's mechanistic studies,[13] a plausible mechanism for the reaction was outlined in Scheme 2. Phosphine catalyst undergoes conjugate addition to allenoates **2** to generate the intermediate **A**, which attacks the sulfamate-derived cyclic imines **1** to afford the intermediate **B**. Through consecutive proton transfer, the intermediate **E** is formed. Then the intermediate **E** undergoes 6-*endo* cyclization followed by expulsion of phosphine catalyst to give the sulfamate-fused tetrahydropyridine **3**.



Scheme 2. Proposed reaction mechanism.

3. Conclusion

In conclusion, an effective *n*-PrPPh$_2$-catalyzed [4+2] cycloaddition of various sulfamate-derived cyclic imines with allenoates has been developed for the synthesis of sulfamate-fused tetrahydropyridines. The reaction worked efficiently under mild reaction conditions to give the target products in high yields with excellent diastereoselectivities. With amino acid-based bifunctional phosphine as chiral catalyst, the sulfamate-derived cyclic imines underwent asymmetric [4+2] cycloaddition with allenoates, giving chiral sulfamate-fused tetrahydropyridines in high yields with good enantiomeric excesses.

4. Experimental

4.1. General

Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. Organic solutions were concentrated under reduced pressure using a rotary evaporator or oil pump. Reactions were monitored through thin-layer chromatography (TLC) on silica gel-precoated glass plates. Chromatograms were visualized by fluorescence quenching under UV light at 254 nm. Flash column chromatography was performed using Qingdao Haiyang flash silica gel (200–300 mesh). ^{1}H and ^{13}C NMR spectra were recorded using a Bruker-300 spectrometer. Accurate mass measurements were performed using an Agilent instrument with the EI-MS technique. X-ray crystallographic data were collected using a Bruker SMART CCD-based diffractometer equipped with a low-temperature apparatus operated at 100 K.

4.2. General procedure for the [4+2] cycloaddition reaction of sulfamate-derived cyclic imines with allenoates

Under a nitrogen atmosphere, to a stirred solution of cyclic imines **1** (0.125 mmol, 1.0 equiv) and 3 Å MS (50 mg) in toluene (2 mL) was successively added ethyl 2-benzylbuta-2,3-dienoate **2** (0.15 mmol, 1.2 equiv) and catalyst *n*-PrPPh$_2$ (0.025 mmol, 0.2 equiv) via a syringe in one portion. Then the reaction solution was stirred at room temperature and monitored by TLC. After the reaction was complete, the mixture was directly purified by column chromatography on silica gel (petroleum ether/EtOAc as the eluent) to furnish the corresponding product.

*4.2.1. Ethyl 8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3aa**).* Yield 97%, white solid, mp 142–144 °C. IR (film) ν_{max} 1712, 1367, 1251, 1172, 1056, 856, 799, 745, 705 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.42–7.24 (m, 7H), 7.22–7.06 (m, 2H), 7.01 (dd, *J*=1.1, 8.2 Hz, 1H), 6.11 (s, 1H), 4.72 (dd, *J*=5.2, 10.7 Hz, 1H), 4.25–3.96 (m, 2H), 3.13–2.98 (m, 1H), 2.86–2.69 (m, 1H), 1.14 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 165.2, 150.1, 138.8, 130.29, 130.28, 129.5, 129.4, 129.3, 127.7, 126.6, 123.6, 119.7, 61.9, 56.3, 52.6, 31.6, 14.9; HRMS (EI) calcd for $C_{20}H_{20}NO_5S^+$ [M+H]$^+$ 386.1057, found 386.1056.

*4.2.2. Ethyl 2-methyl-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ba**).* Yield 98%, white solid, mp 123–125 °C. IR (film) ν_{max} 1651, 1176, 874, 778, 714, 657, 637, 553, 490 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.42–7.28 (m, 6H), 7.06 (d, *J*=8.3 Hz, 1H), 6.94–6.85 (m, 2H), 6.10 (s, 1H), 4.66 (dd, *J*=5.2, 10.7 Hz, 1H), 4.23–4.02 (m, 2H), 3.12–2.96 (m, 1H), 2.83–2.67 (m, 1H), 2.28 (s, 3H), 1.14 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 164.3, 147.1, 138.0, 137.9, 135.4, 129.9, 129.3, 128.5, 128.4, 128.3, 127.0, 122.2, 118.4, 61.0, 55.3, 51.6, 30.7, 20.7, 13.9; HRMS (EI) calcd for $C_{21}H_{21}NO_5S^+$ [M+H]$^+$ 400.1213, found 400.1212.

*4.2.3. Ethyl 4-methyl-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ca**).* Yield 97%, white solid, mp 98–100 °C. IR (film) ν_{max} 1714, 1365, 1257, 1188, 889, 749 cm^{-1}; ^{11}H NMR (300 MHz, CDCl$_3$) δ 7.47–7.27 (m, 6H), 7.18–6.99 (m, 2H), 6.91 (d, *J*=7.6 Hz, 1H), 6.12 (s, 1H), 4.68 (dd, *J*=5.1, 10.7 Hz, 1H), 4.24–3.99 (m, 2H), 3.14–2.90 (m, 1H), 2.84–2.61 (m, 1H), 2.26 (s, 3H), 1.14 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 164.3, 147.7, 138.2, 137.9, 130.7, 129.2, 128.6, 128.4, 128.3, 128.2, 125.1, 124.2, 122.4, 61.0, 55.2, 51.5, 30.8, 15.4, 13.9; HRMS (EI) calcd for $C_{21}H_{21}NO_5S^+$ [M+H]$^+$ 400.1213, found 400.1210.

*4.2.4. Ethyl 2-methoxy-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3da**).* Yield 94%, pale yellow solid, mp 127–129 °C. IR (film) ν_{max} 1713, 1510, 1365, 1255, 1184, 1097, 1058, 1032, 824, 745 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.44–7.28 (m, 6H), 6.95 (d, *J*=9.0 Hz, 1H), 6.80 (dd, *J*=2.6, 9.0 Hz, 1H), 6.58 (d, *J*=2.6 Hz, 1H), 6.10 (s, 1H), 4.67 (dd, *J*=5.0, 10.7 Hz, 1H), 4.22–4.00 (m, 2H), 3.75 (s, 3H), 3.14–2.96 (m, 1H), 2.82–2.64 (m, 1H), 1.14 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 164.3, 157.0, 142.9, 137.9, 137.8, 129.4, 128.6, 128.4, 128.3, 123.4,

119.6, 114.6, 111.6, 61.0, 55.7, 55.3, 51.7, 30.7, 13.9; HRMS (EI) calcd for $C_{21}H_{22}NO_6S^+$ $[M+H]^+$ 416.1162, found 416.1162.

*4.2.5. Ethyl 3-methoxy-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ea**).* Yield 95%, pale yellow solid, mp 137–139 °C. IR (film) ν_{max} 1713, 1510, 1365, 1255, 1184, 1097, 1032, 824, 744 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.28 (m, 6H), 6.98 (d, J=8.7 Hz, 1H), 6.73 (dd, J=2.5, 8.7 Hz, 1H), 6.53 (d, J=2.5 Hz, 1H), 6.09 (s, 1H), 4.66 (dd, J=5.1, 10.5 Hz, 1H), 4.23–4.02 (m, 2H), 3.77 (s, 3H), 3.09–2.93 (m, 1H), 2.81–2.66 (m, 1H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3, 161.1, 150.8, 138.9, 138.8, 130.3, 129.5, 129.3, 128.2, 115.4, 113.6, 104.4, 61.9, 56.6, 56.3, 52.2, 31.7, 14.9; HRMS (EI) calcd for $C_{21}H_{22}NO_6S^+$ $[M+H]^+$ 416.1162, found 416.1162.

*4.2.6. Ethyl 4-methoxy-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3fa**).* Yield 93%, white solid, mp 167–169 °C. IR (film) ν_{max} 1712, 1483, 1366, 1255, 1192, 1162, 1053, 889, 740, 704 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.28 (m, 6H), 7.09 (t, J=8.0 Hz, 1H), 6.85 (d, J=8.0 Hz, 1H), 6.65 (d, J=8.0 Hz, 1H), 6.11 (s, 1H), 4.70 (dd, J=5.1, 10.7 Hz, 1H), 4.24–4.01 (m, 2H), 3.85 (s, 3H), 3.13–2.96 (m, 1H), 2.84–2.65 (m, 1H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3, 149.8, 139.9, 138.92, 138.86, 130.3, 129.5, 129.3, 126.6, 124.6, 118.6, 112.7, 61.9, 57.1, 56.2, 52.7, 31.6, 14.9; HRMS (EI) calcd for $C_{21}H_{22}NO_6S^+$ $[M+H]^+$ 416.1162, found 416.1162.

*4.2.7. Ethyl 2-(tert-butyl)-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ga**).* Yield 82%, white solid, mp 223–225 °C. IR (film) ν_{max} 1714, 1369, 1250, 1176, 1056, 873, 801, 708 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.44–7.27 (m, 7H), 7.06 (d, J=2.2 Hz, 1H), 6.94 (d, J=8.7 Hz, 1H), 6.13 (s, 1H), 4.68 (dd, J=5.1, 10.8 Hz, 1H), 4.25–4.02 (m, 2H), 3.16–2.98 (m, 1H), 2.85–2.68 (m, 1H), 1.26 (s, 9H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3, 149.8, 147.8, 139.1, 138.9, 130.2, 129.5, 129.33, 129.31, 127.5, 124.2, 122.7, 119.1, 61.9, 56.2, 52.7, 35.4, 32.2, 31.8, 14.9; HRMS (EI) calcd for $C_{24}H_{28}NO_5S^+$ $[M+H]^+$ 442.1683, found 442.1681.

*4.2.8. Ethyl 4-(tert-butyl)-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ha**).* Yield 79%, white solid, mp 140–142 °C. IR (film) ν_{max} 1713, 1365, 1258, 1188, 1168, 1065, 889, 802, 733, 702, 569 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.48–7.27 (m, 7H), 7.10 (t, J=7.6 Hz, 1H), 6.95 (d, J=7.6 Hz, 1H), 6.11 (s, 1H), 4.69 (dd, J=5.0, 10.8 Hz, 1H), 4.24–3.98 (m, 2H), 3.13–2.89 (m, 1H), 2.74 (dt, J=5.0, 19.3 Hz, 1H), 1.39 (s, 9H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 148.4, 140.1, 138.1, 137.7, 129.1, 128.6, 128.4, 126.8, 125.3, 124.8, 123.7, 60.9, 55.2, 51.5, 34.9, 31.5, 29.9, 13.9; HRMS (EI) calcd for $C_{24}H_{28}NO_5S^+$ $[M+H]^+$ 442.1683, found 442.1679.

*4.2.9. Ethyl 2-fluoro-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ia**).* Yield 96%, white solid, mp 110–112 °C. IR (film) ν_{max} 1713, 1493, 1383, 1262, 1195, 1168, 1057, 873, 741 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.43–7.27 (m, 3H), 7.24–6.93 (m, 6H), 6.07 (s, 1H), 4.72 (dd, J=5.0, 10.6 Hz, 1H), 4.26–4.01 (m, 2H), 3.17–2.99 (m, 1H), 2.78 (dt, J=5.0, 19.3 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 159.6 (d, $^1J_{C-F}$=245.9 Hz), 145.21, 145.17, 137.7, 137.4, 129.4, 128.6, 128.5, 128.3, 124.2 (d, $^3J_{C-F}$=7.7 Hz), 120.4 (d, $^3J_{C-F}$=8.6 Hz), 116.4 (d, $^2J_{C-F}$=23.8 Hz), 113.4 (d, $^2J_{C-F}$=25.0 Hz), 61.0, 55.4, 51.6 (d, $^4J_{C-F}$=1.8 Hz), 30.42, 13.90; HRMS (EI) calcd for $C_{20}H_{19}FNO_5S^+$ $[M+H]^+$ 426.0782, found 426.0784.

*4.2.10. Ethyl 2-chloro-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ja**).* Yield 92%, white solid, mp 214–215 °C. IR (film) ν_{max} 1714, 1488, 1384, 1249, 1176, 1079, 1057, 937, 864, 810, 743, 709 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.40–7.29 (m, 6H), 7.27–7.20 (m, 1H), 7.09 (d, J=2.1 Hz, 1H), 6.96 (d, J=8.8 Hz, 1H), 6.09 (s, 1H), 4.70 (dd, J=5.1, 10.5 Hz, 1H), 4.25–3.96 (m, 2H), 3.15–2.92 (m, 1H), 2.75 (dt, J=5.1, 19.3 Hz, 1H), 1.15 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 147.8, 137.6, 137.4, 131.0, 129.5, 129.4, 128.6, 128.5, 128.3, 126.7, 124.2, 120.2, 61.1, 55.5, 51.5, 30.4, 13.9; HRMS (EI) calcd for $C_{20}H_{19}ClNO_5S^+$ $[M+H]^+$ 420.0667, found 420.0664.

*4.2.11. Ethyl 2-bromo-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ka**).* Yield 92%, white solid, mp 156–157 °C. IR (film) ν_{max} 1713, 1478, 1383, 1251, 1188, 1170, 1117, 1055, 861, 802, 744, 707, 551 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.43–7.28 (m, 7H), 7.25–7.20 (m, 1H), 6.90 (d, J=8.8 Hz, 1H), 6.08 (s, 1H), 4.70 (dd, J=5.1, 10.5 Hz, 1H), 4.23–4.03 (m, 2H), 3.15–2.97 (m, 1H), 2.85–2.67 (m, 1H), 1.15 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.1, 149.3, 138.6, 138.4, 133.4, 130.6, 130.4, 129.6, 129.5, 129.3, 125.5, 121.4, 119.3, 62.0, 56.4, 52.4, 31.4, 14.9; HRMS (EI) calcd for $C_{20}H_{19}BrNO_5S^+$ $[M+H]^+$ 464.0162, found 464.0162.

*4.2.12. Ethyl 3-bromo-8-phenyl-11,11a-dihydro-8H-benzo[e]pyrido [1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3la**).* Yield 48%, white solid, mp 179–181 °C. IR (film) ν_{max} 1638, 1384, 1249, 1174, 1125, 1056, 927, 569 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.40–7.27 (m, 7H), 7.20 (d, J=1.9 Hz, 1H), 6.98 (d, J=8.4 Hz, 1H), 6.08 (s, 1H), 4.68 (dd, J=5.2, 10.5 Hz, 1H), 4.24–4.02 (m, 2H), 3.10–2.96 (m, 1H), 2.83–2.65 (m, 1H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.1, 150.5, 138.6, 138.4, 130.4, 129.8, 129.6, 129.5, 129.3, 128.8, 123.0, 122.9, 122.6, 62.0, 56.4, 52.5, 31.4, 14.8; HRMS (EI) calcd for $C_{20}H_{19}BrNO_5S^+$ $[M+H]^+$ 464.0162, found 464.0158.

*4.2.13. Ethyl 4-phenyl-4,13c-dihydro-1H-naphtho[1,2-e]pyrido[1,2-c][1,2,3]oxathiazine-3-carboxylate 6,6-dioxide (**3ma**).* Yield 98%, white solid, mp 134–136 °C. IR (film) ν_{max} 1713, 1371, 1250, 1186, 1052, 948, 860, 812, 738, 703 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (t, J=8.7 Hz, 2H), 7.63–7.26 (m, 9H), 7.12 (d, J=8.7 Hz, 1H), 6.26 (s, 1H), 5.14 (dd, J=6.1, 10.2 Hz, 1H), 4.28–4.05 (m, 2H), 3.23–3.00 (m, 2H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 147.0, 139.2, 137.7, 131.1, 130.6, 129.4, 129.2, 128.8, 128.7, 128.5, 128.4, 127.6, 125.7, 122.3, 117.9, 115.4, 61.0, 55.2, 50.4, 29.5, 14.0; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 436.1213, found 436.1211.

*4.2.14. Ethyl 4-phenyl-1,4,4a,11b-tetrahydro-[1,3]dioxolo[4′,5′:4,5]benzo[1,2-e]benzo[c][1,2]oxathiazine-3-carboxylate 5,5-dioxide (**3na**).*- Yield 88%, white solid, mp 179–180 °C. IR (film) ν_{max} 1713, 1484, 1381, 1252, 1183, 1142, 1071, 887, 748 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ7.40–7.28 (m, 6H), 6.48 (d, J=7.5 Hz, 2H), 6.07 (s, 1H), 5.95 (s, 2H), 4.58 (dd, J=5.1, 10.6 Hz, 1H), 4.22–3.97 (m, 2H), 3.06–2.87 (m, 1H), 2.68 (dt, J=5.1, 19.3 Hz, 1H), 1.14 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 147.9, 145.6, 143.5, 137.9, 137.8, 129.3, 128.6, 128.4, 128.3, 114.8, 105.1, 102.1, 100.3, 61.0, 55.3, 51.6, 30.8, 13.9; HRMS (EI) calcd for $C_{21}H_{20}NO_7S^+$ $[M+H]^+$ 430.0955, found 430.0950.

*4.2.15. Ethyl 8-(m-tolyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ab**).* Yield 90%, white solid, mp 120–122 °C. IR (film) ν_{max} 1712, 1366, 1271, 1250, 1188, 1173, 1109, 1056, 858, 796, 760, 740 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.39–7.32 (m, 1H), 7.31–7.23 (m, 1H), 7.21–7.06 (m, 6H), 7.00 (d, J=8.2 Hz, 1H), 6.07 (s, 1H), 4.71 (dd, J=5.2, 10.8 Hz, 1H), 4.23–4.02 (m, 2H), 3.16–2.96 (m, 1H), 2.85–2.65 (m, 1H), 2.33 (s, 3H), 1.15 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 149.2, 138.4, 137.8, 137.7, 129.4, 129.3, 129.2, 129.1, 128.3, 126.7, 125.6,

125.3, 122.7, 118.7, 60.9, 55.2, 51.6, 30.6, 21.4, 13.9; HRMS (EI) calcd for $C_{21}H_{22}NO_5S^+$ $[M+H]^+$ 400.1213, found 400.1211.

*4.2.16. Ethyl 8-(p-tolyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ac**).* Yield 94%, white solid, mp 123–125 °C. IR (film) ν_{max} 1712, 1366, 1250, 1188, 1172, 1056, 857, 797, 759 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38–7.31 (m, 1H), 7.31–7.22 (m, 3H), 7.21–7.06 (m, 4H), 7.00 (dd, J=1.2, 8.2 Hz, 1H), 6.08 (s, 1H), 4.72 (dd, J=5.2, 10.7 Hz, 2H), 4.22–4.04 (m, 2H), 3.10–2.96 (m, 1H), 2.82–2.69 (m, 1H), 2.31 (s, 3H), 1.16 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3, 150.1, 139.2, 138.6, 135.8, 130.4, 130.2, 129.2, 127.7, 126.5, 123.7, 119.6, 61.9, 56.1, 52.5, 31.7, 22.0, 14.9; HRMS (EI) calcd for $C_{21}H_{22}NO_5S^+$ $[M+H]^+$ 420.1213, found 420.1215.

*4.2.17. Ethyl 8-(3-fluorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ad**).* Yield 94%, white solid, mp 104–106 °C. IR (film) ν_{max} 1711, 1639, 1255, 1188, 1172, 854, 798, 758, 670, 542 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.43–7.27 (m, 3H), 7.24–6.93 (m, 6H), 6.07 (s, 1H), 4.72 (dd, J=5.0, 10.6 Hz, 1H), 4.26–4.01 (m, 2H), 3.17–2.99 (m, 1H), 2.78 (dt, J=5.0, 19.3 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 162.8 (d, $^1J_{C-F}$=245 Hz), 161.1, 149.2, 140.5 (d, $^3J_{C-F}$=6.8 Hz), 138.3, 130.2 (d, $^3J_{C-F}$=8.1 Hz), 129.5, 128.9, 126.7, 125.8, 124.1 (d, $^4J_{C-F}$=3.0 Hz), 122.4, 118.8, 115.5 (d, $^2J_{C-F}$=28 Hz), 115.4 (d, $^2J_{C-F}$=30 Hz), 61.1, 54.8 (d, $^4J_{C-F}$=1.8 Hz), 51.8, 30.5, 13.9; HRMS (EI) calcd for $C_{20}H_{19}FNO_5S^+$ $[M+H]^+$ 404.0962, found 404.0964.

*4.2.18. Ethyl 8-(4-fluorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ae**).* Yield 95%, white solid, mp 98–100 °C. IR (film) ν_{max} 1634, 1508, 1366, 1250, 1172 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.26 (m, 4H), 7.23–7.09 (m, 2H), 7.07–6.98 (m, 3H), 6.07 (s, 1H), 4.71 (dd, J=5.0, 10.5 Hz, 1H), 4.26–3.98 (m, 2H), 3.16–2.93 (m, 1H), 2.78 (dt, J=5.0, 19.3 Hz, 1H), 1.16 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 162.2 (d, $^1J_{C-F}$=246.8 Hz), 149.2, 138.0, 133.8 (d, $^4J_{C-F}$=3.2 Hz), 130.2, 130.1, 129.4, 129.2, 126.7, 125.7, 122.5, 118.7, 115.7, 115.4, 66.4, 61.1, 54.7, 51.6, 30.6, 13.9; HRMS (EI) calcd for $C_{20}H_{19}FNO_5S^+$ $[M+H]^+$ 404.0962, found 404.0961.

*4.2.19. Ethyl 8-(3-chlorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3af**).* Yield 96%, white solid, mp 151–153 °C. IR (film) ν_{max} 1713, 1383, 1257, 1189, 1173, 1108, 1059, 863, 801, 758, 736 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.41–7.37 (m, 1H), 7.35–7.28 (m, 4H), 7.23–7.16 (m, 1H), 7.16–7.10 (m, 1H), 7.03 (dd, J=1.1, 7.8 Hz, 1H), 6.05 (s, 1H), 4.71 (dd, J=5.1, 10.5 Hz, 1H), 4.25–4.01 (m, 2H), 3.15–2.93 (m, 1H), 2.79 (dt, J=5.1, 19.3 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.0, 149.2, 140.1, 138.4, 134.5, 129.9, 129.5, 128.8, 128.7, 128.3, 126.73, 126.72, 125.8, 122.3, 118.8, 61.1, 54.9, 51.8, 30.5, 13.9; HRMS (EI) calcd for $C_{20}H_{19}ClNO_5S^+$ $[M+H]^+$ 420.0667, found 420.0662.

*4.2.20. Ethyl 8-(4-chlorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ag**).* Yield 93%, white solid, mp 146–148 °C. IR (film) ν_{max} 1638, 1490, 1366, 1257, 1189, 1171, 1093, 1057, 751, 559 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.26 (m, 6H), 7.23–7.06 (m, 2H), 7.02 (d, J=8.0 Hz, 1H), 6.05 (s, 1H), 4.69 (dd, J=4.9, 10.4 Hz, 1H), 4.26–4.00 (m, 2H), 3.17–2.90 (m, 1H), 2.78 (dt, J=4.9, 19.3 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 149.2, 138.2, 136.5, 134.5, 129.7, 129.5, 129.0, 128.8, 126.7, 125.8, 122.4, 118.8, 61.1, 54.7, 51.7, 30.6, 14.0; HRMS (EI) calcd for $C_{20}H_{19}ClNO_5S^+$ $[M+H]^+$ 420.0667, found 420.0661.

*4.2.21. Ethyl 8-(3-bromophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ah**).* Yield 90%, white solid, mp 162–164 °C. IR (film) ν_{max} 1711, 1383, 1371, 1253, 1188, 1172, 1058, 857, 800, 754, 734 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.52–7.47 (m, 1H), 7.47–7.25 (m, 4H), 7.24–7.10 (m, 3H), 7.03 (dd, J=1.2, 8.2 Hz, 1H), 6.04 (s, 1H), 4.71 (dd, J=5.2, 10.5 Hz, 1H), 4.27–4.03 (m, 2H), 3.19–2.95 (m, 1H), 2.88–2.69 (m, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.0, 149.2, 140.4, 138.5, 131.6, 131.2, 129.5, 128.7, 127.2, 126.7, 125.8, 122.7, 122.3, 118.8, 61.1, 54.7, 51.8, 30.4, 14.0; HRMS (EI) calcd for $C_{20}H_{19}BrNO_5S^+$ $[M+H]^+$ 464.0162, found 420.0158.

*4.2.22. Ethyl 8-(4-bromophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ai**).* Yield 97%, white solid, mp 146–148 °C. IR (film) ν_{max} 1711, 1488, 1382, 1253, 1171, 1108, 1059, 861, 759 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.53–7.43 (m, 2H), 7.41–7.23 (m, 4H), 7.22–7.07 (m, 2H), 7.06–6.98 (m, 1H), 6.03 (s, 1H), 4.69 (dd, J=5.1, 10.5 Hz, 1H), 4.25–4.01 (m, 2H), 3.14–2.96 (m, 1H), 2.78 (dt, J=5.1, 19.2 Hz, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.0, 149.2, 138.2, 137.1, 131.8, 130.0, 129.5, 129.0, 126.7, 125.7, 122.7, 122.4, 118.7, 61.1, 54.8, 51.7, 30.6, 14.0; HRMS (EI) calcd for $C_{20}H_{19}BrNO_5S^+$ $[M+H]^+$ 464.0162, found 420.0158.

*4.2.23. Ethyl 8-(3-(trifluoromethyl)phenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3aj**).* Yield 68%, white solid, mp 169–171 °C. IR (film) ν_{max} 1710, 1638, 1330, 1252, 1188, 1170, 1126, 855, 759, 702 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.66–7.55 (m, 3H), 7.53–7.38 (m, 2H), 7.35–7.27 (m, 1H), 7.24–7.10 (m, 2H), 7.04 (dd, J=1.1, 8.2 Hz, 1H), 6.11 (s, 1H), 4.70 (dd, J=5.1, 10.3 Hz, 1H), 4.26–4.03 (m, 2H), 3.18–3.00 (m, 1H), 2.82 (dt, J=5.1, 19.3 Hz, 1H), 1.15 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.9, 150.2, 140.2, 139.5, 132.9, 132.1, 131.7, 130.5, 130.2, 129.7, 127.6, 126.8, 126.3 (q, J_{C-F}=4.1 Hz), 125.8 (q, J_{C-F}=3.8 Hz), 123.1, 119.7, 62.1, 55.9, 52.9, 31.3, 14.8; HRMS (EI) calcd for $C_{21}H_{19}F_3NO_5S^+$ $[M+H]^+$ 454.0931, found 454.0928.

*4.2.24. Ethyl 8-(4-(trifluoromethyl)phenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ak**).* Yield 70%, white solid, mp 171–173 °C. IR (film) ν_{max} 1636, 1326, 1257, 1171, 1115, 1068 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.67–7.48 (m, 1H), 7.46–7.38 (m, 1H), 7.35–7.26 (m, 1H), 7.19 (td, J=1.2, 7.8 Hz, 1H), 7.14–7.09 (m, 1H), 7.03 (dd, J=1.2, 7.8 Hz, 1H), 6.11 (s, 1H), 4.70 (dd, J=5.1, 10.3 Hz, 1H), 4.24–4.03 (m, 2H), 3.19–2.99 (m, 1H), 2.91–2.71 (m, 1H), 1.17 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.0, 150.2, 143.0, 139.4, 131.8, 131.4, 130.5, 129.74, 129.69, 127.6, 126.8, 126.5 (q, J_{C-F}=3.8 Hz), 123.2, 123.0, 119.7, 62.2, 55.8, 52.9, 31.4, 14.9; HRMS (EI) calcd for $C_{21}H_{19}F_3NO_5S^+$ $[M+H]^+$ 454.0931, found 454.0930.

*4.2.25. Ethyl 8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3al**).* Yield 94%, white solid, mp 134–136 °C. IR (film) ν_{max} 1714, 1482, 1454, 1384, 1250, 1189, 1171, 1114, 1055, 862, 809 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.87–7.74 (m, 3H), 7.71–7.58 (m, 2H), 7.52–7.38 (m, 3H), 7.29–7.18 (m, 1H), 7.15–7.07 (m, 1H), 7.07–7.01 (m, 1H), 7.01–6.94 (m, 1H), 6.28 (s, 1H), 4.73 (dd, J=5.2, 10.7 Hz, 1H), 4.19–4.04 (m, 2H), 3.17–2.99 (m, 1H), 2.85–2.70 (m, 1H), 1.12 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 164.4, 149.2, 138.3, 135.4, 133.1, 132.8, 129.3, 129.2, 128.8, 128.0, 127.6, 127.0, 126.7, 126.51, 126.48, 126.3, 125.6, 122.4, 118.6, 61.0, 55.3, 51.5, 30.6, 13.9; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 436.1213, found 436.1211.

*4.2.26. Ethyl 11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3am**).* Yield 85%, white solid. ^1H NMR (300 MHz, $CDCl_3$) δ 7.39–7.31 (m, 1H), 7.25–7.15 (m, 2H), 7.11–7.03 (m, 2H), 5.08 (t, J=5.4 Hz, 1H), 4.20 (q, J=7.1 Hz, 2H), 4.13–4.02 (m, 1H), 4.00–3.87 (m, 1H), 3.05–2.89 (m, 2H), 1.28 (t,

J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 150.7, 134.1, 129.8, 126.4, 126.1, 125.6, 120.5, 118.4, 61.0, 54.5, 42.7, 28.5, 14.1. HRMS (EI) calcd for $C_{14}H_{16}NO_5S^+$ $[M+H]^+$ 309.0671, found 309.0669.

*4.2.27. Ethyl 8-methyl-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3an**).* Yield 45%, white solid. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38–7.29 (m, 1H), 7.25–7.17 (m, 2H), 7.09–6.98 (m, 2H), 5.06–4.91 (m, 2H), 4.35–4.15 (m, 2H), 2.96–2.81 (m, 1H), 2.80–2.67 (m, 1H), 1.51 (d, J=6.7 Hz, 3H), 1.31 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 149.5, 135.2, 132.6, 129.4, 126.6, 125.7, 122.9, 118.8, 61.0, 52.1, 49.3, 31.1, 19.8, 14.1. HRMS (EI) calcd for $C_{15}H_{18}NO_5S^+$ $[M+H]^+$ 323.0827, found 323.0829.

4.3. General procedure for asymmetric [4+2] cycloaddition reaction of sulfamate-derived cyclic imines with allenoates

Under a nitrogen atmosphere, to a stirred solution of cyclic imines **1** (0.1 mmol, 1.0 equiv), the catalyst **P1** (0.02 mmol, 0.2 equiv) and 4 Å MS (50 mg) in toluene (1 mL) was added allenoates **2** (0.12 mmol, 1.2 equiv) via a syringe in one portion. Then the reaction solution was stirred at room temperature and monitored by TLC. After the reaction was complete, the mixture was directly purified by column chromatography on silica gel (petroleum ether/EtOAc as the eluent) to furnish the corresponding product.

*4.3.1. (8S,11aR)-Ethyl 8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3al**).* Yield 81%, white solid. $[\alpha]_D^{20}$ −171.1 (c 0.65, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87–7.74 (m, 3H), 7.71–7.58 (m, 2H), 7.52–7.38 (m, 3H), 7.29–7.18 (m, 1H), 7.15–7.07 (m, 1H), 7.03 (dd, J=1.4, 7.8 Hz, 1H), 6.99 (d, J=8.2 Hz, 1H), 6.28 (s, 1H), 4.73 (dd, J=5.2, 10.7 Hz, 1H), 4.19–4.04 (m, 2H), 3.17–2.99 (m, 1H), 2.85–2.70 (m, 1H), 1.12 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 149.2, 138.3, 135.4, 133.1, 132.8, 129.3, 129.2, 128.8, 128.0, 127.6, 127.0, 126.7, 126.51, 126.48, 126.3, 125.6, 122.4, 118.6, 61.0, 55.3, 51.5, 30.6, 13.9; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 436.1213, found 436.1211; HPLC analysis: 99% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=14.790 min, t_{R2}=19.218 min).

*4.3.2. (8S,11aR)-Ethyl 4-methyl-8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3cl**).* Yield 72%, white solid. $[\alpha]_D^{20}$ −127.7 (c 0.39, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.90–7.77 (m, 3H), 7.69–7.59 (m, 2H), 7.53–7.41 (m, 3H), 7.14–7.06 (m, 1H), 7.02 (t, J=7.6 Hz, 1H), 6.92–6.83 (m, 1H), 6.29 (s, 1H), 4.70 (dd, J=5.2, 10.9 Hz, 1H), 4.13 (q, J=7.1 Hz, 2H), 3.19–2.98 (m, 1H), 2.84–2.69 (m, 1H), 2.26 (s, 3H), 1.13 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.5, 147.7, 138.6, 135.5, 133.2, 132.8, 130.7, 129.2, 128.8, 128.1, 128.1, 127.6, 127.0, 126.6, 126.5, 126.3, 125.1, 124.2, 122.3, 61.0, 55.3, 51.5, 30.8, 15.4, 14.0; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 450.1370, found 450.1372; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=18.160 min, t_{R2}=23.305 min).

*4.3.3. (8S,11aR)-Ethyl 2-methoxy-8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3dl**).* Yield 82%, pale yellow solid. $[\alpha]_D^{20}$ −98.0 (c 0.52, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.88–7.78 (m, 3H), 7.70–7.58 (m, 2H), 7.53–7.41 (m, 3H), 6.94 (d, J=9.0 Hz, 1H), 6.78 (dd, J=2.8, 9.0 Hz, 1H), 6.54 (d, J=2.8 Hz, 1H), 6.26 (s, 1H), 4.68 (dd, J=5.2, 10.8 Hz, 1H), 4.12 (q, J=7.1 Hz, 2H), 3.72 (s, 3H), 3.18–3.00 (m, 1H), 2.85–2.69 (m, 1H), 1.13 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 157.0, 142.9, 138.3, 135.5, 133.1, 132.8, 129.3, 128.7, 128.0, 127.6, 127.0, 126.6, 126.5, 126.3, 123.3, 119.6, 114.7, 111.6, 61.0, 55.7, 55.3, 51.6, 30.7, 13.9; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 466.1319, found 466.1318; HPLC analysis: 82% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=13.686 min, t_{R2}=18.379 min).

*4.3.4. (8S,11aR)-Ethyl 3-methoxy-8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3el**).* Yield 85%, pale yellow solid. $[\alpha]_D^{20}$ −141.7 (c 0.65, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89–7.77 (m, 3H), 7.71–7.58 (m, 2H), 7.54–7.39 (m, 3H), 6.93 (d, J=8.8 Hz, 1H), 6.69 (dd, J=2.5, 8.8 Hz, 1H), 6.52 (d, J=2.5 Hz, 1H), 6.25 (s, 1H), 4.67 (dd, J=5.2, 10.6 Hz, 1H), 4.12 (q, J=7.1 Hz, 2H), 3.74 (s, 3H), 3.13–2.95 (m, 1H), 2.81–2.64 (m, 1H), 1.13 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 160.1, 149.8, 138.3, 135.5, 133.1, 132.8, 129.2, 128.7, 128.1, 127.6, 127.2, 127.0, 126.54, 126.46, 126.3, 114.3, 112.6, 103.4, 61.0, 55.6, 55.4, 51.2, 30.7, 13.9; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 466.1319, found 466.1320; HPLC analysis: 73% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=21.287 min, t_{R2}=26.078 min).

*4.3.5. (8S,11aR)-Ethyl 4-methoxy-8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3fl**).* Yield 80%, white solid. $[\alpha]_D^{20}$ −80.3 (c 0.46, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87–7.77 (m, 3H), 7.69–7.59 (m, 2H), 7.51–7.42 (m, 3H), 7.06 (t, J=8.1 Hz, 1H), 6.85–6.78 (m, 1H), 6.63–6.57 (m, 1H), 6.28 (s, 1H), 4.71 (dd, J=5.2, 10.8 Hz, 1H), 4.12 (q, J=7.1 Hz, 2H), 3.84 (s, 1H), 3.18–3.02 (m, 1H), 2.84–2.69 (m, 1H), 1.13 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4, 148.8, 138.9, 138.4, 135.5, 133.1, 132.8, 129.3, 128.7, 128.1, 127.6, 127.1, 126.6, 126.5, 126.3, 125.6, 123.5, 117.7, 111.7, 61.0, 56.2, 55.3, 51.7, 30.6, 14.0; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 466.1319, found 466.1321; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=27.116 min, t_{R2}=31.021 min).

*4.3.6. (8S,11aR)-Ethyl 2-bromo-8-(naphthalen-2-yl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3kl**).* Yield 85%, white solid. $[\alpha]_D^{20}$ −79.6 (c 0.61, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.88–7.76 (m, 3H), 7.69–7.55 (m, 2H), 7.54–7.40 (m, 3H), 7.35 (dd, J=8.8, 2.0 Hz, 1H), 7.20 (d, J=2.0 Hz, 1H), 6.88 (d, J=8.8 Hz, 1H), 6.25 (s, 1H), 4.72 (dd, J=5.2, 10.6 Hz, 1H), 4.12 (q, J=7.1 Hz, 2H), 3.18–3.00 (m, 1H), 2.85–2.68 (m, 1H), 1.13 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.2, 148.3, 137.8, 135.1, 133.2, 132.8, 132.4, 129.6, 129.3, 128.9, 128.1, 127.6, 127.1, 126.6, 126.40, 126.39, 124.4, 120.4, 118.3, 61.1, 55.5, 51.4, 30.3, 13.9; HRMS (EI) calcd for $C_{24}H_{22}NO_5S^+$ $[M+H]^+$ 514.0318, found 514.0320; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=21.970 min, t_{R2}=25.996 min).

*4.3.7. (8S,11aR)-Ethyl 8-(m-tolyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ab**).* Yield 85%, white solid. $[\alpha]_D^{20}$ −83.0 (c 0.51, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.39–7.32 (m, 1H), 7.31–7.23 (m, 1H), 7.21–7.06 (m, 6H), 7.00 (d, J=8.2 Hz, 1H), 6.07 (s, 1H), 4.71 (dd, J=5.2, 10.8 Hz, 1H), 4.23–4.02 (m, 2H), 3.16–2.96 (m, 1H), 2.85–2.65 (m, 1H), 2.33 (s, 3H), 1.15 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 149.2, 138.4, 137.8, 137.7, 129.4, 129.3, 129.2, 129.1, 128.3, 126.7, 125.6, 125.3, 122.7, 118.7, 60.9, 55.2, 51.6, 30.6, 21.4, 13.9; HRMS (EI) calcd for $C_{21}H_{22}NO_5S^+$ $[M+H]^+$ 400.1213, found 400.1211; HPLC analysis: 81% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=10.477 min, t_{R2}=13.549 min).

*4.3.8. (8S,11aR)-Ethyl 8-(p-tolyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ac**).* Yield 83%, white solid. $[\alpha]_D^{20}$ −79.5 (c 0.27, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38–7.31 (m, 1H), 7.31–7.22 (m, 3H), 7.21–7.06 (m, 4H), 7.00 (dd, J=1.2, 8.2 Hz, 1H), 6.08 (s, 1H), 4.72 (dd, J=5.2, 10.7 Hz, 2H), 4.12 (qd, J=3.6, 7.1 Hz, 1H), 3.10–2.96 (m, 1H), 2.82–2.69 (m, 1H), 2.31 (s, 3H), 1.16 (t, J=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.3, 150.1, 139.2,

138.6, 135.8, 130.4, 130.2, 129.2, 127.7, 126.5, 123.7, 119.6, 61.9, 56.1, 52.5, 31.7, 22.0, 14.9; HRMS (EI) calcd for $C_{21}H_{22}NO_5S^+$ $[M+H]^+$ 420.1213, found 420.1215; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=10.816 min, t_{R2}=13.808 min).

*4.3.9. (8S,11aR)-Ethyl 8-(3-chlorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3af**).* Yield 89%, white solid. $[\alpha]_D^{20}$ −87.3 (*c* 0.62, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 7.41–7.37 (m, 1H), 7.35–7.28 (m, 4H), 7.20 (td, *J*=1.2, 7.5 Hz, 1H), 7.13 (dd, *J*=1.5, 7.8 Hz, 1H), 7.03 (dd, *J*=1.1, 8.2 Hz, 1H), 6.05 (s, 1H), 4.71 (dd, *J*=5.1, 10.5 Hz, 1H), 4.25–4.01 (m, 2H), 3.15–2.93 (m, 1H), 2.79 (dt, *J*=5.1, 19.3 Hz, 1H), 1.17 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.0, 149.2, 140.1, 138.4, 134.5, 129.9, 129.5, 128.8, 128.7, 128.3, 126.73, 126.72, 125.8, 122.3, 118.8, 61.1, 54.9, 51.8, 30.5, 13.9; HRMS (EI) calcd for $C_{20}H_{19}ClNO_5S^+$ $[M+H]^+$ 420.0667, found 420.0662; HPLC analysis: 66% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=12.195 min, t_{R2}=18.201 min).

*4.3.10. (8S,11aR)-Ethyl 8-(4-chlorophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ag**).* Yield 86%, white solid. $[\alpha]_D^{20}$ −89.3 (*c* 0.65, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.26 (m, 6H), 7.23–7.06 (m, 2H), 7.02 (d, *J*=8.0 Hz, 1H), 6.05 (s, 1H), 4.69 (dd, *J*=4.9, 10.4 Hz, 1H), 4.26–4.00 (m, 2H), 3.05 (dd, *J*=10.7, 19.0 Hz, 1H), 2.78 (dt, *J*=4.9, 19.3 Hz, 1H), 1.17 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.1, 149.2, 138.2, 136.5, 134.5, 129.7, 129.5, 129.0, 128.8, 126.7, 125.8, 122.4, 118.8, 61.1, 54.7, 51.7, 30.6, 14.0; HRMS (EI) calcd for $C_{20}H_{19}ClNO_5S^+$ $[M+H]^+$ 420.0667, found 420.0661; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=12.355 min, t_{R2}=17.901 min).

*4.3.11. (8S,11aR)-Ethyl 8-(3-bromophenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ah**).* Yield 88%, white solid. $[\alpha]_D^{20}$ −92.7 (*c* 0.33, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 7.49 (t, *J*=1.8 Hz, 1H), 7.47–7.25 (m, 4H), 7.24–7.10 (m, 3H), 7.03 (dd, *J*=1.2, 8.2 Hz, 1H), 6.04 (s, 1H), 4.71 (dd, *J*=5.2, 10.5 Hz, 1H), 4.27–4.03 (m, 2H), 3.19–2.95 (m, 1H), 2.88–2.69 (m, 1H), 1.17 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.0, 149.2, 140.4, 138.5, 131.6, 131.2, 129.5, 128.7, 127.2, 126.7, 125.8, 122.7, 122.3, 118.8, 61.1, 54.7, 51.8, 30.4, 14.0; HRMS (EI) calcd for $C_{20}H_{19}BrNO_5S^+$ $[M+H]^+$ 464.0162, found 420.0158; HPLC analysis: 80% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=13.599 min, t_{R2}=21.568 min).

*4.3.12. (8S,11aR)-Ethyl 8-(4-(trifluoromethyl)phenyl)-11,11a-dihydro-8H-benzo[e]pyrido[1,2-c][1,2,3]oxathiazine-9-carboxylate 6,6-dioxide (**3ak**).* Yield 75%, white solid. $[\alpha]_D^{20}$ −62.5 (*c* 0.51, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 7.57 (dd, *J*=8.4, 27.8 Hz, 4H), 7.41 (t, *J*=3.6 Hz, 1H), 7.35–7.26 (m, 1H), 7.23–7.08 (m, 2H), 7.03 (dd, *J*=8.2, 1.2 Hz, 1H), 6.11 (s, 1H), 4.70 (dd, *J*=5.1, 10.3 Hz, 1H), 4.24–4.03 (m, 2H), 3.19–2.99 (m, 1H), 2.91–2.71 (m, 1H), 1.17 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.0, 150.2, 143.0, 139.4, 131.8, 131.4, 130.5, 129.74, 129.69, 127.6, 126.8, 126.5 (q, J_{C-F}=3.8 Hz), 123.2, 123.0, 119.7, 62.2, 55.8, 52.9, 31.4, 14.9; HRMS (EI) calcd for $C_{21}H_{19}F_3NO_5S^+$ $[M+H]^+$ 454.0931, found 454.0930; HPLC analysis: 84% ee (Chiralcel OD-H: 5:95 isopropanol/hexane, 1 mL/min, 254 nm, t_{R1}=10.558 min, t_{R2}=14.311 min).

4.4. General procedure for the scale-up reaction

Under a nitrogen atmosphere, to a stirred solution of cyclic imines **1a** (5 mmol, 1.0 equiv) and 3 Å MS in toluene (50 mL) was successively added ethyl 2-benzylbuta-2,3-dienoate **2a** (6 mmol, 1.2 equiv) and catalyst *n*-$PrPPh_2$ (1 mmol, 0.2 equiv) via a syringe in one portion. Then the reaction solution was vigorously stirred at room temperature and monitored by TLC. After the reaction was complete, the mixture was filtered and concentrated under reduced pressure before purified by column chromatography on silica gel (petroleum ether/EtOAc) to furnish the corresponding product **3a** (1.5 g) as a white solid (78% yield).

4.5. General procedure for the synthesis of 4

$NaIO_4$ (88 mg, 0.41 mmol, 1.5 equiv) and then distilled water (0.22 mL) were added to a 50-mL flask. After the $NaIO_4$ had dissolved, the solution was cooled in an ice bath, and H_2SO_4 (6 drops of a 2 N solution) and then $RuCl_3 \cdot nH_2O$ (2 or 3 small crystals) were added. The solution was stirred for 5 min, and then EtOAc (0.4 mL) was added. The solution was stirred for an additional 5 min, and then CH_3CN (0.8 mL) was added. The solution was stirred for five more minutes, and then a solution of **3aa** (110 mg, 0.28 mmol) in EtOAc (0.6 mL) was added in one portion. The solution was stirred for 6 min at 0 °C, and then it was transferred by pipette into a solution of 10% $NaHCO_3$ (2.0 mL) and saturated Na_2SO_3 (4.6 mL). The solution was stirred for 30 min, and then it was extracted with EtOAc (3×25 mL). The combined organic extracts were dried over Na_2SO_4, filtered, and concentrated. Purification of the residue by column chromatography (2:1 petroleum ether/EtOAc) gave **4** (99% yield) as a white solid. Mp 182–184 °C; ^1H NMR (300 MHz, DMSO-d_6) δ 7.54–7.28 (m, 8H), 7.11 (dd, *J*=1.5, 7.9 Hz, 1H), 5.91 (s, 1H), 5.46 (dd, *J*=3.2, 12.0 Hz, 1H), 5.10–5.03 (m, 2H), 4.81–4.69 (m, 1H), 3.77–3.50 (m, 2H), 0.72 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 172.4, 149.8, 137.4, 130.6, 130.5, 129.9, 129.7, 128.5, 127.2, 125.8, 119.6, 79.2, 68.9, 65.8, 61.8, 57.3, 14.6; IR (film) ν_{max} 3436, 1636, 1173 cm^{-1}; HRMS (ESI) calcd for $C_{20}H_{22}NO_7S^+$ $[M+H]^+$ 420.1111, found 420.1113.

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Supplementary data

Copies of ^1H and ^{13}C NMR spectra of all products and X-ray data of **3ai** and (−)-**3af** are available. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.11.063.

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11. Crystallographic data for **3ai** and (−)-**3af** have been deposited with the Cambridge Crystallographic Data Centre as deposition number CCDC 949997 and 966308, respectively. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.
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