EurJOC European Journal of Organic Chemistry

FULL PAPER

DOI: 10.1002/ejoc.201301281

A De Novo Stereocontrolled Approach to *syn*- and *anti*-Disubstituted Acyclic $\beta^{2,3}$-Amino Acid Enantiomers

Maria Cherepanova,[a] Loránd Kiss,[a] Enikő Forró,[a] and Ferenc Fülöp*[a,b]

Keywords: Synthetic methods / Amino acids / Kinetic resolution / Diastereoselectivity / Wittig reactions / Lactams

The stereocontrolled syntheses of functionalized acyclic $\beta^{2,3}$-amino acid derivatives in enantiomerically pure form were performed by starting from enantiopure *cis*- and *trans*-2-aminocyclopent-3-enecarboxylates, which were derived from a racemic bicyclic β-lactam. The synthetic strategy involves the stereoselective dihydroxylaton of the C–C double bond of the cyclopentene β-amino esters. The subsequent $NaIO_4$-mediated ring cleavage affords dialdehyde intermediates that undergo functionalization by a Wittig reaction.

Introduction

During the past 20 years, there has been an increasing interest in β-amino acids in view of the number of valuable biological properties that they possess. They exhibit noteworthy pharmacological activities and are components of many bioactive natural products such as the anticancer agent Taxol or Taxotere, the antitumoral agents cryptophycin, bestatin, microginin, and amastatin, and the antifungal agent jasplakinolide.[1a,1b] β-Amino acids are also structural building blocks of peptides and peptidomimetics.[1a–1d] Moreover, $\beta^{2,3}$-amino acids comprise a subclass of β-amino acids, and some are also elements of bioactive natural products. Dolastatins 11, 12, 16, and D, majusculamide C, and onchidin are natural products with activity against leukemia, whereas guineamides C and D, ulongapeptin, and malevamide C are natural antitumoral agents with structures that include a $\beta^{2,3}$-disubstituted amino acid moiety with different alkyl chains.[1a,1b]

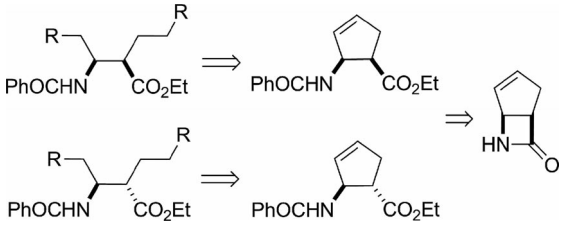
A number of synthetic methods are currently available for the preparation of racemic disubstituted $\beta^{2,3}$-amino acids. The general methods include a Curtius rearrangement of 2,3-disubstituted 1,4-dicarboxylic acid derivatives, a ring-opening of disubstituted β-lactams, and an oxidation of 2,3-disubstituted 1,3-amino alcohols,[1] yet more special routes involve the alkylation of β^3-amino acid derivatives at the α position,[2] the rearrangement of imides with hypervalent iodine reagents,[3] reactions of carboxylic acid esters with imidoyl chlorides,[4] the Ireland–Claisen [3,3]-sigmatropic rearrangement of enamino esters,[5] the oxidative ring cleavage of 2,3-dihydropyridones,[6] and the ring-opening of 4,5-disubstituted 1,3-oxazinanones.[7] Several other methods may be used to access these compounds in either racemic or enantiomerically pure form. For instance, the Michael conjugate addition of chiral amines to α,β-unsaturated esters followed by alkylation,[8] the dipolar cycloaddition of nitrones to olefins followed by an isoxazolidine ring-opening and oxidation,[9] the asymmetric hydrogenation of enamino esters,[10] the addition of carboxylic acid derivatives or aldehydes to aldimines under standard or organocatalytic conditions through a Mannich reaction followed by an oxidation,[11] the addition of ester enolates to chiral sulfinylimines,[12] and the diastereoselective intramolecular radical addition to oxime ethers[13] are important procedures that facilitate the syntheses of $\beta^{2,3}$-amino acids.

Although a wide range of synthetic methods offer efficient and practical approaches to different $\beta^{2,3}$-amino acid derivatives, most of them suffer from limitations that relate to the control of the stereochemistry of the transformations (e.g., *syn* vs. *anti* diastereoselectivity), the availability of appropriately substituted synthons, the large-scale applicability, and, in some cases, the cost of the reagents and materials.

Our present goal is to develop a new stereocontrolled synthetic approach to acyclic $\beta^{2,3}$-amino acid species that are derived from cyclopentene *cis*- and *trans*-disubstituted β-amino acids through dihydroxylation and oxidative ring-opening reactions followed by a Wittig transformation.[14] The stereochemistry of the acyclic target compounds was predetermined by the configuration of the cyclic starting material. The syntheses based on the *cis*- and *trans*-disubstituted unsaturated five-membered β-amino acid species from the racemic β-lactam are expected to give acyclic *anti*- and *syn*-disubstituted $\beta^{2,3}$-amino acid derivatives, respectively (see Scheme 1).

[a] Institute of Pharmaceutical Chemistry, University of Szeged, 6720 Szeged, Eötvös u. 6, Hungary
E-mail: fulop@pharm.u-szeged.hu
http://www2.pharm.u-szeged.hu/gyki/
[b] Stereochemistry Research Group of the Hungarian Academy of Sciences, University of Szeged, 6720 Szeged, Eötvös u. 6, Hungary

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.201301281.



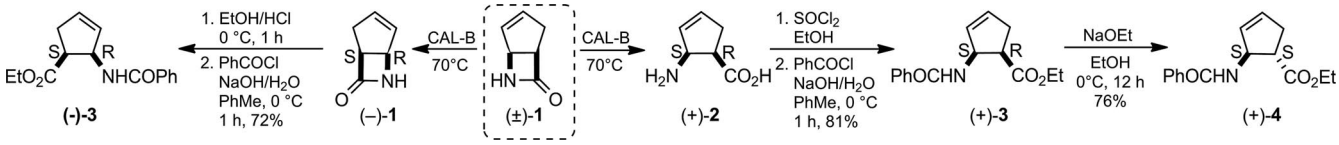
Scheme 1. Retrosynthetic scheme.

Results and Discussion

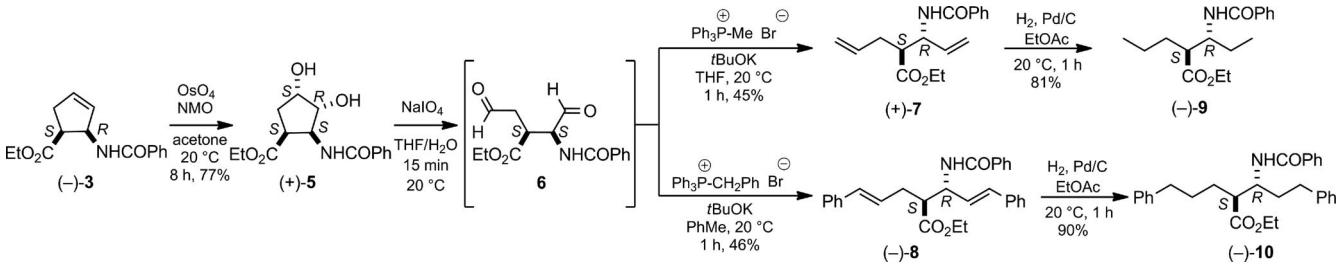
Racemic β-lactam (±)-**1** was first subjected to a kinetic resolution by employing an enzyme-catalyzed enantioselective β-lactam hydrolysis by using a slightly modified literature procedure.[15] Compound (±)-**1** was treated with CAL-B (*Candida antarctica* lipase B) in *t*BuOMe, and the resulting mixture was then shaken by an incubator shaker at 70 °C to give enantiomerically pure amino acid (+)-**2** (>99%*ee*) and unreacted β-lactam (–)-**1** (99%*ee*), which were separated. Next, (–)-**1** was treated with HCl/EtOH, which was followed by a benzoylation to afford the optically pure *N*-benzoyl-protected amino ester (–)-**3.** After (+)-**2** underwent group protection procedures, (+)-**3** was submitted to a base-induced epimerization to afford the *trans* diastereomer (1*S*,2*S*)-(+)-**4** in good yield (see Scheme 2). Preliminary experiments were first performed by employing racemic substances, and the well-established protocol was then extended to obtain enantiomerically pure compounds.

The stereoselective dihydroxylation of (1*R*,2*S*)-(–)-**3** in the presence of OsO_4 and *N*-methylmorpholine-*N*-oxide (NMO) yielded vicinal diol (+)-**5**, and the subsequent oxidative C–C bond cleavage with $NaIO_4$ gave access to dialdehyde intermediate **6** (for analogous transformations, see ref.[14]). It is noteworthy that intermediate **6** could not be isolated, and, therefore, further experiments were conducted with the diformyl derivative formed in situ. Dialdehyde **6** was then treated with Wittig reagents that were generated from either methyltriphenylphosphonium or benzyltriphenylphosphonium bromide with *t*BuOK in (tetrahydrofuran) THF to furnish the corresponding diolefinated *anti*-β-amino esters (+)-**7** and (–)-**8** in moderate yields. A subsequent catalytic hydrogenation of the C–C double bonds in the presence of Pd/C led to optically pure saturated acyclic dialkylated $\beta^{2,3}$-amino esters (–)-**9** and (–)-**10** (see Scheme 3).

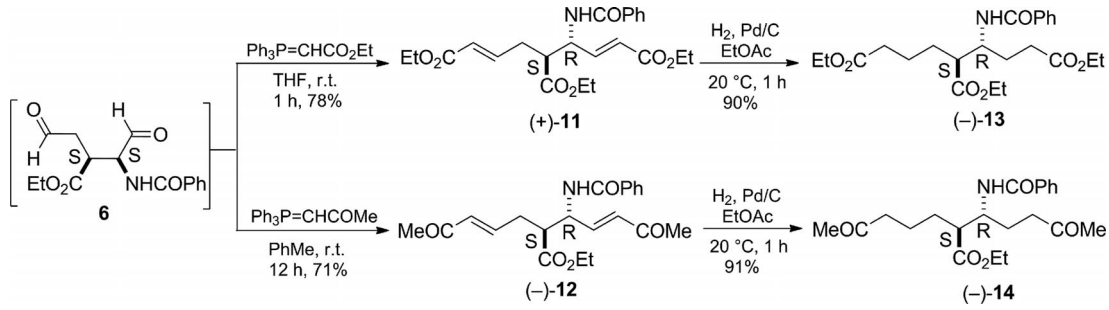
Further *anti*-β-amino acid derivatives were successfully synthesized by the treatment of the key diformyl intermediate **6** with commercially available phosphoranes. The reaction between dialdehyde **6** and either ethyl (triphenylphosphoranylidene)acetate or 1-(triphenylphosphoranylidene)-2-propanone resulted in disubstituted enantiomers (+)-**11**



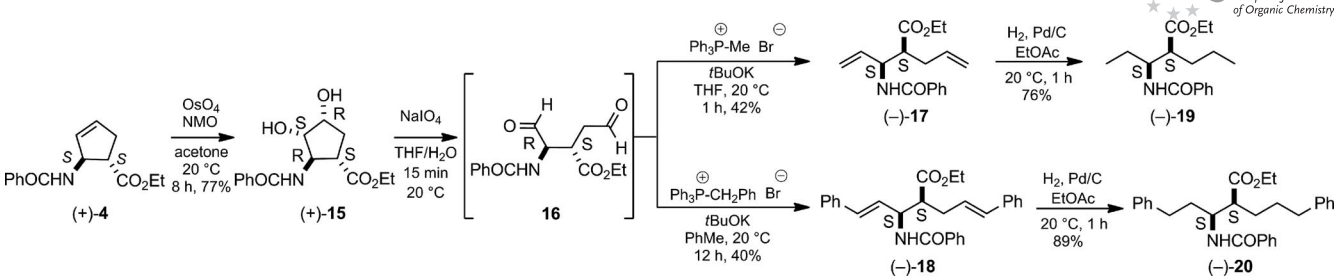
Scheme 2. Enzymatic resolution of racemic β-lactam **1** and preparation of *cis*- and *trans*-β-amino esters.



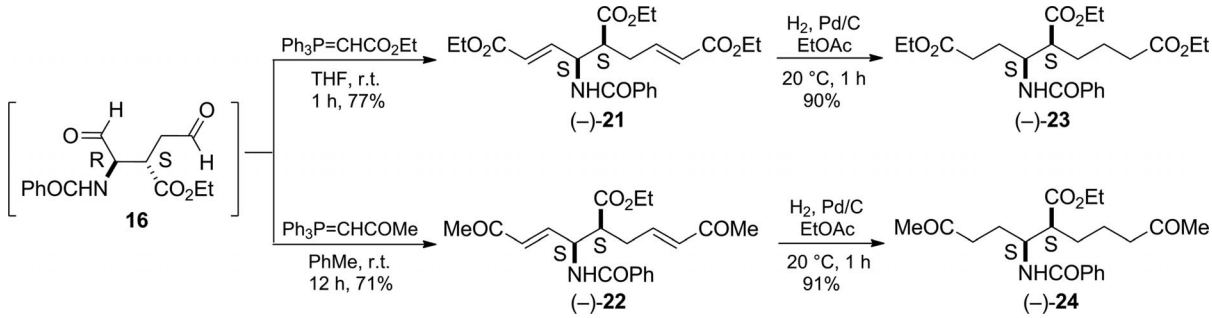
Scheme 3. Synthesis of disubstituted, open-chain β-amino acid derivatives (–)-**9** and (–)-**10** from *cis*-β-amino ester (–)-**3**.



Scheme 4. Synthesis of disubstituted, open-chain β-amino acid derivatives (–)-**13** and (–)-**14** from dialdehyde **6**.



Scheme 5. Synthesis of disubstituted, open-chain β-amino acid derivatives (–)-**19** and (–)-**20** from *trans* β-amino ester (+)-**4**.



Scheme 6. Synthesis of disubstituted, open-chain β-amino acid derivatives (–)-**23** and (–)-**24** from dialdehyde **16**.

and (–)-**12**, respectively, in good yields. The catalytic reduction of the olefinic bonds then afforded the difunctionalized *anti*-β[2,3]-amino acid derivatives (–)-**13** and (–)-**14**, respectively, in high yields (see Scheme 4).

This well-established protocol was subsequently extended to the syntheses of *syn*-β-amino acid derivatives. The catalytic, 100% diastereoselective dihydroxylation of the C–C double bond of (+)-**4** by treatment with OsO_4 followed by the $NaIO_4$-mediated oxidative ring cleavage gave key intermediate dialdehyde **16**, which displayed the similar instability as that of its previously described analog **6**. Dialkenylated acyclic β-amino acid derivatives (–)-**17** and (–)-**18** were obtained in moderate yields through an in situ Wittig reaction by using either a methyltriphenylphosphonium or benzyltriphenylphosphonium salt and *t*BuOK. Further catalytic hydrogenations afforded access to the optically pure saturated *syn*-dialkylated products (–)-**19** and (–)-**20** in good yields (see Scheme 5).

Similar to the transformations depicted in Scheme 4, the reactions of dialdehyde **16** with either ethyl (triphenylphosphoranylidene)acetate or 1-(triphenylphosphoranylidene)-2-propanone resulted in Wittig products (–)-**21** and (–)-**22**, respectively, in good yields. The saturation of the olefinic bonds under catalytic hydrogenation conditions yielded the corresponding enantiopure *syn* derivatives, that is, difunctionalized β[2,3]-amino acid derivatives (–)-**23** and (–)-**24** (see Scheme 6).

Conclusions

In summary, a simple and efficient stereocontrolled procedure has been developed for the syntheses of enantiomeric acyclic β[2,3]-amino acid derivatives by starting from *cis*- ands *trans*-β-aminocyclopentenecarboxylate enantiomers, which were derived by an enzymatic resolution of a racemic bicyclic β-lactam. The syntheses involved the dihydroxylation of the C–C double bond of the cyclic starting materials followed by an oxidative ring cleavage and Wittig functionalization of the dialdehyde intermediates. As the stereogenic centers of the starting compounds were not affected during the transformations, their stereochemistry determined the configuration of the chiral centers in the final acylic β-amino acid derivatives.

Experimental Section

General Methods: The chemicals were purchased from Sigma–Aldrich. The NMR spectroscopic data were recorded at 400 MHz with either the solvents $CDCl_3$ or [D_6]dimethyl sulfoxide ([D_6]DMSO), and with tetramethylsilane as the internal standard. The solvents were used as received from the suppliers. Melting points were determined with a Kofler apparatus. Elemental analyses were recorded with a Perkin–Elmer CHNS-2400 Ser II elemental analyzer. Silica gel 60 F254 was purchased from Merck. All the experiments were first performed with the racemic substances. The ^1H and ^{13}C NMR spectra of the enantiomeric substances were the same as those of the corresponding racemic counterparts. The elemental analyses confirmed the results.

Gram-Scale Resolution of 7-Azabicyclo[4.2.0]oct-3-en-8-one [(±)-1]: Racemic **1** (6 g, 54.96 mmol) was dissolved in *t*BuOMe (80 mL), and CAL-B (4 g, 50 mg/mL) and water (0.96 mL, 54.96 mmol) were added. The resulting mixture was shaken in an incubator shaker at 80 °C for 4.5 h, and the reaction was stopped by filtration of the enzyme at 50% conversion. After evaporation of the solvent, the residue was crystallized to afford crystalline (1*S*,5*R*)-**1** (2.3 g, 47%); $[\alpha]_D^{25}$ = –33.6 (*c* = 0.32, $CHCl_3$), >98% *ee*. The enzyme that was removed by filtration was washed with distilled water (3 × 20 mL), and the water was evaporated to yield crystalline β-amino

acid (1*R*,2*S*)-**2** (3.2 g, 47%); $[\alpha]_D^{25}$ = +94.9 (*c* = 0.37, H_2O), >98% *ee*.

General Procedure for Dihydroxylation of *N*-Benzoyl-Protected Amino Esters: To a solution of *N*-benzoyl-protected β-amino ester **3** or **4** (see ref.[15]; 2 g, 7.7 mmol) and *N*-methylmorpholine *N*-oxide (3 mL, 29 mmol) in acetone (40 mL) was added OsO_4 (0.5 mL, 0.03 mmol) in *t*BuOH (0.06 M), and the resulting mixture was stirred at room temperature for 12 h. After completion of the reaction (monitored by TLC), a saturated aqueous Na_2SO_3 solution (120 mL) was added, and the reaction mixture was extracted with CH_2Cl_2 (3× 150 mL). The combined organic phases were dried with Na_2SO_4 and filtered, and the filtrate was concentrated in vacuo.

General Procedure for In Situ Dialdehyde Formation Followed by Wittig Reaction: To a solution of **5** or **15** (200 mg, 0.68 mmol) in THF/H_2O (10:1 v/v, 11 mL) was added $NaIO_4$ (291 mg, 1.36 mmol), and the reaction mixture was stirred at room temperature for 1 h under Ar to give diformyl derivative **6** or **16**. Water (20 mL) was then added, and the mixture was extracted with CH_2Cl_2 (2× 15 mL). The combined organic phases were dried with Na_2SO_4 and filtered. The filtrate was concentrated in vacuo to give the diformyl derivative **6** or **16**, which was then dissolved in dry THF (5 mL). The Wittig reagent (1.36 mmol) was then added to the solution. After stirring at room temperature for 1 h, the reaction mixture was concentrated in vacuo, and the residue was purified by column chromatography on silica gel (*n*-hexane/EtOAc).

General Procedure for In Situ Dialdehyde Formation Followed by the In Situ Wittig Reaction: To a solution of **5** or **15** (200 mg, 0.68 mmol) in THF/H_2O (10:1 v/v, 11 mL) was added $NaIO_4$ (291 mg, 1.36 mmol), and the reaction mixture was stirred at room temperature for 1 h under Ar to give diformyl derivative **6** or **16**. Water (20 mL) was then added, and the mixture was extracted with CH_2Cl_2 (2× 15 mL). The combined organic phases were dried with Na_2SO_4 and filtered. The filtrate was concentrated in vacuo to give the diformyl derivative **6** or **16**. The Wittig reagent was prepared separately by the addition of *t*BuOK (1.36 mmol) to a solution of the phosphonium salt (1.36 mmol) in dry THF (5 mL), and the resulting mixture was stirred for 10 min. The diformyl derivative **6** or **16** (200 mg, 0.68 mmol) was dissolved in dry THF (5 mL), and the resulting solution was added dropwise to the solution of the in situ generated Wittig reagent. After stirring at room temperature for 1 h, the reaction mixture was concentrated in vacuo, and the residue was purified by column chromatography on silica gel (*n*-hexane/EtOAc).

General Procedure for Catalytic Hydrogenation: A solution of **7**, **8**, **11**, **12**, **17**, **18**, **21**, or **22** (200 mg, 0.68 mmol) and 10 mol-% Pd/C (20 mg) in EtOAc (20 mL) was stirred under H_2 atmosphere for 1 h. The reaction mixture was then filtered through silica gel and Celite. The filtrate was concentrated under reduced pressure, and the residue was purified by column chromatography on silica gel (*n*-hexane/EtOAc). The *ee* values were determined by HPLC analysis.

Ethyl (1*S*,2*R*)-2-Benzamidocyclopent-3-enecarboxylate [(–)-3]: White solid (72% yield); m.p. 83–85 °C. $[\alpha]_D^{25}$ = –99 (*c* = 0.28, EtOH).[15] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.16 (t, *J* = 7.15 Hz, 3 H), 2.57–5.66 (m, 1 H, CH_2), 2.84–2.91 (m, 1 H, CH_2), 3.44–3.50 (m, 1 H, 1-H), 4.01–4.11 (m, 2 H, OCH_2), 5.55–5.62 (m, 1 H, 2-H), 5.70–5.73 (m, 1 H, 4-H), 5.96–5.99 (m, 1 H, 3-H), 6.51 (br. s, 1 H, NH), 7.38–7.51 (m, 3 H, Ar), 7.71–7.75 (m, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.8, 34.5, 47.0, 56.7, 60.6, 128.2, 128.9, 130.1, 131.9, 134.2, 135.4, 166.8, 172.8 ppm.

Ethyl (1*S*,2*S*)-2-Benzamidocyclopent-3-enecarboxylate [(+)-4]: White solid (76% yield); m.p. 94–96 °C. $[\alpha]_D^{25}$ = +104 (*c* = 0.275, EtOH).[15] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.26 (t, *J* = 7.15 Hz, 3 H), 2.62–2.73 (m, 1 H, CH_2), 2.79–2.86 (m, 1 H, CH_2), 2.97–3.05 (m, 1 H, 1-H), 4.12–4.20 (m, 2 H, OCH_2), 5.47–5.55 (m, 1 H, 2-H), 5.72–5.77 (m, 1 H, 4-H), 5.95–6.01 (m, 1 H, 3-H), 6.18 (br. s, 1 H, NH), 7.43–4.55 (m, 3 H, Ar), 7.78–7.75 (m, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 36.3, 49.7, 60.2, 61.0, 128.2, 129.0, 131.8, 131.9, 132.1, 135.1, 166.7, 175.1 ppm.

Ethyl (1*S*,2*S*,3*R*,4*S*)-2-Benzamido-3,4-dihydroxycyclopentanecarboxylate [(+)-5]: White solid (77% yield); m.p. 125–126 °C. R_f = 0.3 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = +102 (*c* = 0.3, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.29 (t, *J* = 7.18 Hz, 3 H, CH_3), 2.15–2.33 (m, 2 H, 4-H), 3.48 (q, *J* = 8.9 Hz, 1 H, 5-H), 4.05–4.12 (m, 2 H, 2-H, 3-H), 4.18–4.25 (m, 2 H, OCH_2), 4.51–4.58 (m, 1 H, 1-H), 7.41–7.83 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.7, 33.7, 43.9, 55.6, 60.7, 70.6, 76.4, 128.2, 128.9, 131.9, 135.5, 167.5, 174.0 ppm. $C_{15}H_{19}NO_5$ (293.32): calcd. C 61.42, H 6.53, N 4.78; found C 61.19, H 6.32, N 4.48.

Ethyl (1*S*,2*R*,3*S*,4*R*)-2-Benzamido-3,4-dihydroxycyclopentanecarboxylate [(+)-15]: White solid (77% yield); m.p. 74–77 °C. R_f = 0.3 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = +40.5 (*c* = 0.415, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.20 (t, *J* = 7.06 Hz, 3 H, CH_3), 2.03–2.22 (m, 2 H, 4-H), 3.06 (q, *J* = 7.43 Hz, 1 H, 5-H), 3.72–3.76 (m, 1 H, 2-H), 4.09–4.20 (m, 2 H, OCH_2), 4.27–4.33 (m, 1 H, 3-H), 4.57–4.65 (m, 1 H, 1-H), 6.98 (d, *J* = 8.52 Hz, 1 H, NH), 7.35–7.79 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 34.3, 46.2, 55.4, 60.9, 72.2, 73.6, 128.2, 129.0, 132.0, 135.3, 167.0, 175.7 ppm. $C_{15}H_{19}NO_5$ (293.32): calcd. C 61.42, H 6.53, N 4.78; found C 61.19, H 6.32, N 4.48.

Triethyl (1*E*,3*R*,4*S*,6*E*)-3-Benzamidohepta-1,6-diene-1,4,7-tricarboxylate [(+)-11]: White solid (78% yield); m.p. 28–30 °C. R_f = 0.4 (*n*-hexane/EtOAc, 1:1). $[\alpha]_D^{25}$ = +15.3 (*c* = 0.32, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.24–1.33 (m, 9 H, 3 CH_3 overlapping), 2.40–2.49 (m, 1 H, 3-H), 2.70–2.79 (m, 1 H, 5-H), 2.92–2.99 (m, 1 H, 4-H), 4.10–4.25 (m, 6 H, OCH_2), 5.06–5.17 (m, 1 H, 5-H), 5.82–6.06 (m, 2 H, 2-H, 6-H), 6.85–6.95 (m, 2 H, 1-H, 7-H), 7.39–7.89 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 31.9, 48.7, 52.2, 60.7, 61.0, 61.4, 123.2, 123.7, 128.3, 129.2, 132.4, 134.8, 145.9, 146.2, 166.1, 167.1, 172.6 ppm. $C_{23}H_{29}NO_7$ (431.48): calcd. C 64.02, H 6.77, N 3.25; found C 63.79, H 6.52, N 3.53.

Ethyl (2*S*,3*R*,*E*)-3-Benzamido-6-oxo-2-[(*E*)-4-oxopent-2-enyl]hept-4-enoate [(–)-12]: Colorless oil (71% yield); R_f = 0.5 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = –3 (*c* = 0.255, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.25–1.33 (m, 3 H, CH_3), 2.26 (s, 3 H, CH_3), 2.28 (s, 3 H, CH_3), 2.47–2.55 (m, 1 H, 1′-H), 2.72–2.83 (m, 1 H, 1′-H), 3.01–3.07 (m, 1 H, 2-H), 4.18–4.26 (m, 2 H, OCH_2), 5.10–5.17 (m, 1 H, 3-H), 6.17 (d, *J* = 15.7 Hz, 1 H, 2-H), 6.30 (d, *J* = 15.9 Hz, 1 H, 4-H), 6.73–6.82 (m, 2 H, 3′-H, 5-H), 7.08 (d, *J* = 8.84 Hz, 1 H, NH), 7.37–7.85 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]-DMSO): δ = 14.9, 27.9, 28.1, 32.0, 48.8, 52.5, 61.8, 128.3, 129.1, 131.9, 132.5, 133.1, 134.9, 144.5, 145.2, 167.1, 172.8, 198.4, 198.6 ppm. $C_{21}H_{25}NO_5$ (371.43): calcd. C 67.91, H 6.78, N 3.77; found C 67.66, H 6.33, N 4.08.

Triethyl (3*S*,4*S*,6*E*)-3-Benzamidohepta-(1*E*)-1,6-diene-1,4,7-tricarboxylate [(–)-21]: White solid (77% yield); m.p. 39–41 °C. R_f = 0.6 (*n*-hexane/EtOAc, 1:1). $[\alpha]_D^{25}$ = –43 (*c* = 0.265, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.22–1.28 (m, 9 H, 3 CH_3 overlapping), 2.53–2.68 (m, 2 H, 5-H), 2.93–3.06 (m, 1 H, 4-H), 4.12–4.22 (m, 6 H, OCH_2), 5.09–5.15 (m, 1 H, 3-H), 5.87 (d, *J* = 15.5 Hz, 1 H, 1-H), 5.97 (dd, ^1J = 15.6 Hz, ^2J = 1.52 Hz, 1 H, 7-H), 6.82–6.94 (m, 2 H, 2-H, 6-H), 7.41–7.91 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 31.9, 48.7, 52.4, 60.6, 60.9.0, 61.2, 123.5, 123.7, 128.2, 129.2, 132.4, 134.8, 145.8, 146.5, 166.2, 167.1, 172.5,

179.1 ppm. $C_{23}H_{29}NO_7$ (431.48): calcd. C 64.02, H 6.77, N 3.25; found C 64.36, H 6.47, N 2.96.

Ethyl (2*S*,3*S*,*E*)-3-Benzamido-6-oxo-2-[(*E*)-4-oxopent-2-enyl]hept-4-enoate [(–)-22]: Yellow oil (71% yield); R_f = 0.5 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = –17.7 (*c* = 0.31, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.26–1.34 (m, 3 H, CH_3), 2.23 (s, 3 H, CH_3), 2.28 (s, 3 H, CH_3), 2.60–2.74 (m, 2 H, 1′-H), 2.99–3.05 (m, 1 H, 2-H), 4.17–4.27 (m, 2 H, OCH_2), 5.15–5.22 (m, 1 H, 3-H), 6.15 (d, *J* = 15.9 Hz, 1 H, 2′-H), 6.25 (dd, ^1J = 15.8 Hz, ^2J = 1.85 Hz, 1 H, 4-H), 6.70–6.82 (m, 2 H, 3′-H, 5-H), 7.40–7.93 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 27.6, 28.0, 29.9, 32.1, 48.8, 52.7, 61.3, 128.2, 129.0, 129.2, 132.4, 133.3, 134.9, 144.5, 145.3, 166.9, 172.9, 198.4 ppm. $C_{21}H_{25}NO_5$ (371.43): calcd. C 67.91, H 6.78, N 3.77; found C 67.63, H 7.06, N 3.42.

Ethyl (2*S*,3*R*)-2-Allyl-3-benzamidopent-4-enoate [(+)-7]: Colorless oil (45% yield); R_f = 0.3 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = +9.1 (*c* = 0.31, EtOH). ^{1}H NMR (400 MHz, [D$_6$]DMSO): δ = 1.13 (t, *J* = 6.99 Hz, 3 H, CH_3), 2.20–2.30 (m, 2 H, 1′-H), 2.70–2.80 (m, 1 H, 2-H), 4.03 (q, *J* = 7.07 Hz, 2 H, OCH_2), 4.68 (q, *J* = 8.74 Hz, 1 H, 3-H), 4.92–5.17 (m, 4 H, 5-H, 3′-H), 5.61–5.88 (m, 2 H, 3-H, 2′-H), 7.41–7.84 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 15.2, 31.4, 50.2, 54.1, 60.9, 117.3, 117.7, 128.2, 129.2, 132.1, 135.3, 136.0, 137.1, 167.1, 173.6 ppm. $C_{17}H_{21}NO_3$ (287.36): calcd. C 71.06, H 7.37, N 4.87; found C 70.73, H 6.99, N 4.58.

Ethyl (2*S*,3*R*)-3-Benzamido-(*E*)-2-cinnamyl-5-phenylpent-4-enoate [(–)-8]: White solid (46% yield); m.p. 85–88 °C. R_f = 0.4 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = –6.4 (*c* = 0.31, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.26–1.32 (m, 3 H, CH_3), 2.51–2.61 (m, 1 H, 4-H), 2.75–2.87 (m, 1 H, 1′-H), 2.96–3.11 (m, 1 H, 2-H), 4.24 (q, *J* = 7.19 Hz, 2 H, OCH_2), 5.15–5.23 (m, 1 H, 3-H), 6.22–6.35 (m, 2 H, 2′-H, 4-H), 6.52 (d, *J* = 16.1 Hz, 1 H, 3′-H), 6.72 (d, *J* = 15.8 Hz, 1 H, 5-H), 6.97–7.04 (m, 1 H, NH), 7.13–7.87 (m, 15 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 15.0, 33.4, 50.9, 53.9, 60.9, 126.8, 127.1, 127.7, 128.3, 128.6, 129.2, 129.4, 129.6, 131.3, 132.0, 132.2, 132.4, 135.3, 137.2, 137.8, 166.7, 173.4 ppm. $C_{29}H_{29}NO_3$ (439.55): calcd. C 79.24, H 6.65, N 3.19; found C 79.52, H 6.30, N 2.80.

Ethyl (2*S*,3*S*)-2-Allyl-3-benzamidopent-4-enoate [(–)-17]: Colorless oil (42% yield); R_f = 0.2 (*n*-hexane/EtOAc, 5:1). $[\alpha]_D^{25}$ = –43 (*c* = 0.215, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.28–1.33 (m, 3 H, CH_3), 2.32–2.56 (m, 2 H, 1-H), 2.83–2.99 (m, 1 H, 2-H), 4.20 (q, *J* = 7.01 Hz, 2 H, OCH_2), 4.95–5.02 (m, 1 H, 3-H), 5.05–5.38 (m, 4 H, 5-H, 3′-H), 5.72–5.98 (m, 2 H, 3-H, 2′-H), 7.44–7.44 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 34.0, 50.0, 54.4, 60.8, 117.8, 118.1, 128.1, 129.2, 132.1, 136.2, 137.0, 137.1, 166.3, 173.5 ppm. $C_{17}H_{21}NO_3$ (287.36): calcd. C 71.06, H 7.37, N 4.87; found C 70.74, H 7.02, N 5.03.

Ethyl (2*S*,3*S*)-3-Benzamido-(*E*)-2-cinnamyl-5-phenylpent-4-enoate [(–)-18]: Yellow solid (40% yield); m.p. 69–73 °C. R_f = 0.4 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = –43 (*c* = 0.27, EtOH). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.22–1.26 (m, 3 H, CH_3), 2.60–2.79 (m, 2 H, 1′-H), 2,98–3.05 (m, 1 H, 2-H), 4.16–4.26 (m, 2 H, OCH_2), 5.14–5.26 (m, 1 H, 3-H), 6.19–6.31 (m, 2 H, 3-H, 2′-H), 6.47–6.71 (m, 2 H, 5-H, 3′-H), 7.22–7.97 (m, 15 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]-DMSO): δ = 15.0, 33.4, 50.8, 54.2, 60.8, 126.8, 127.2, 127.8, 128.1, 128.6, 129.2, 129.4, 129.6, 131.3, 132.0, 132.2, 132.4, 135.4, 137.2, 137.8, 166.3, 173.6 ppm. $C_{29}H_{29}NO_3$ (439.55): calcd. C 79.24, H 6.65, N 3.19; found C 78.89, H 6.30, N 3.41.

Ethyl (2*S*,3*R*)-3-Benzamido-2-propylpentanoate [(–)-9]: Colorless oil (81% yield); R_f = 0.3 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = –7 (*c* = 0.285, EtOH); 98%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (isopropyl alcohol, 80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (retention time, min) = 17.25 (antipode 19.83). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90–1.04 (m, 3 H, CH_3), 1.27–1.87 (m, 12 H, 3 CH_2 and 2 CH_3), 2.64–2.70 (m, 1 H, 2-H), 4.21 (q, *J* = 7.31 Hz, 2 H, OCH_2), 4.29–4.38 (m, 1 H, 3-H), 7.43–7.87 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 11.4, 14.7, 14.9, 20.9, 26.3, 31.9, 50.7, 53.1, 60.8, 128.2, 129.1, 132.0, 135.6, 167.5, 174.9 ppm. $C_{17}H_{25}NO_3$ (291.39): calcd. C 70.07, H 8.65, N 4.81; found C 69.77, H 8.91, N 4.53.

Ethyl (2*S*,3*R*)-3-Benzamido-5-phenyl-2-(3-phenylpropyl)pentanoate [(–)-10]: White solid (90% yield); m.p. 106–108 °C. R_f = 0.5 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = –2 (*c* = 0.3, EtOH), 99%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 17.86 (antipode 22.20). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.28 (t, *J* = 7.12 Hz, 3 H, CH_3), 1.48–2.01 (m, 6 H, 3 CH_2 overlapping 2.61–2.82 (m, 5 H, 2-H, 2 $PhCH_2$ overlapping), 4.15–4.25 (m, 2 H, OCH_2), 4.43–4.52 (m, 1 H, 3-H), 6.45 (d, *J* = 9.29 Hz, 1 H, NH), 7.14–7.78 (m, 15 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 28.9, 29.5, 32.8, 35.0, 35.6, 50.9, 51.0, 60.8, 126.5, 128.1, 129.1, 132.0, 135.7, 142.5, 142.6, 167.7, 174.6 ppm. $C_{29}H_{33}NO_3$ (443.58): calcd. C 78.52, H 7.50, N 3.16; found C 78.19, H 7.21, N 2.82.

Triethyl (3*R*,4*S*)-3-Benzamidoheptane-1,4,7-tricarboxylate [(–)-13]: White solid (90% yield); m.p. 41–42 °C. R_f = 0.3 (*n*-hexane/EtOAc, 1:1). $[\alpha]_D^{25}$ = –3.3 (*c* = 0.37, EtOH), 98%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 29.83 (antipode 33.05). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.12–1.31 (m, 9 H, 3 CH_3 overlapping), 1.54–2.08 (m, 6 H, 5-H, 2-H, 6-H), 2.29–2.50 (m, 4 H, 1-H, 7-H), 2.64–2.70 (m, 1 H, 4-H), 3.95–4.26 (m, 6 H, OCH_2), 4.33–4.42 (m, 1 H, 3-H), 6.67 (d, *J* = 9.23 Hz, 1 H, NH), 7.40–7.80 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 23.2, 28.1, 28.9, 31.4, 34.1, 50.6, 50.8, 60.5, 60.6, 60.9, 128.1, 129.0, 132.1, 135.3, 167.3, 173.2, 174.2 ppm. $C_{23}H_{33}NO_7$ (435.52): calcd. C 63.43, H 7.64, N 3.22; found C 63.11, H 7.32, N 2.89.

Ethyl (2*S*,3*R*)-3-Benzamido-6-oxo-2-(4-oxopentyl)heptanoate [(–)-14]: Colorless oil (91% yield); R_f = 0.4 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = –27.2 (*c* = 0.33, EtOH), 99%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 18.22 (antipode 24.52). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.32 (t, *J* = 6.94 Hz, 3 H, CH_3), 1.53–3.27 (m, 18 H, 2-H, 3-H, 3 CH_2, 2 $COCH_2$, 2 $COCH_3$ overlapping), 4.17–4.28 (m, 2 H, OCH_2), 7.41–7.64 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 22.1, 27.2, 29.1, 30.7, 43.4, 46.4, 50.9, 59.5, 61.0, 61.4, 128.1, 131.2, 132.0, 135.3, 167.4, 169.9, 174.1, 174.4 ppm. $C_{21}H_{29}NO_5$ (375.46): calcd. C 67.18, H 7.79, N 3.73; found C 66.85, H 8.00, N 3.99.

Ethyl (2*S*,3*S*)-3-Benzamido-2-propylpentanoate [(–)-19]: Colorless oil (76% yield); R_f = 0.4 (*n*-hexane/EtOAc, 5:1). $[\alpha]_D^{25}$ = –26.4 (*c* = 0.33, EtOH), 99%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 11.71 (antipode 12.53). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90–1.04 (m, 3 H, CH_3), 1.25–1.88 (m, 12 H, 2 CH_3, 3 CH_2 overlapping 2.64–2.75 (m, 1 H, 2-H), 4.17–4.27 (m, 2 H, OCH_2), 4.28–4.37 (m, 1 H, 3-H), 7.43–7.89 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]-DMSO): δ = 11.4, 14.7, 15.0, 21.2, 25.4, 31.3, 50.2, 52.9, 60.7, 127.9, 129.1, 132.0, 135.8, 166.9, 174.6 ppm. $C_{17}H_{25}NO_3$ (291.39): calcd. C 70.07, H 8.65, N 4.81; found C 69.74, H 8.30, N 4.51.

Ethyl (2*S*,3*S*)-3-Benzamido-5-phenyl-2-(3-phenylpropyl)pentanoate [(–)-20]: Colorless oil (89% yield); R_f = 0.5 (*n*-hexane/EtOAc, 3:1). $[\alpha]_D^{25}$ = –26.5 (*c* = 0.32, EtOH), 99%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at

250 nm]: R_t (min) = 13.51 (antipode 16.49). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.32 (t, J = 7.19 Hz, 3 H, CH_3), 1.56–1.98 (m, 6 H, 2 CH_2 overlapping), 2.59–2.81 (m, 5 H, 2-H, PhCH_2 overlapping), 4.22 (q, J = 6.96 Hz, 2 H, OCH_2), 4.45–4.52 (m, 1 H, 3-H), 7.13–7.87 (m, 15 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 15.0, 28.3, 29.8, 32.7, 34.1, 35.6, 50.2, 51.0, 60.7, 126.6, 128.1, 129.1, 131.9, 135.7, 142.6, 167.1, 174.4 ppm. $C_{29}H_{33}NO_3$ (443.58): calcd. C 78.52, H 7.50, N 3.16; found C 78.20, H 7.23, N 3.35.

Triethyl (3*S*,4*S*)-3-Benzamidoheptane-1,4,7-tricarboxylate [(–)-23]: Colorless oil (90% yield); R_f = 0.5 (*n*-hexane/EtOAc, 1:1). $[\alpha]_D^{25}$ = –32 (c = 0.41, EtOH), 99%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 19.79 (antipode 21.25). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.22–1.40 (m, 9 H, 3 CH_3 overlapping), 1.51–2.71 (m, 11 H, 2-H, 5 CH_2 overlapping), 4.18–4.28 (m, 6 H, OCH_2), 4.31–4.39 (m, 1 H, 3-H), 7.41–7.87 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]-DMSO): δ = 14.9, 23.4, 27.4, 28.5, 31.0, 33.9, 50.3, 50.7, 52.1, 60.9, 128.0, 129.1, 132.1, 135.4, 167.1, 173.8, 174.0 ppm. $C_{23}H_{33}NO_7$ (435.52): calcd. C 63.43, H 7.64, N 3.22; found C 63.16, H 7.29, N 3.56.

Ethyl (2*S*,3*S*)-3-Benzamido-6-oxo-2-(4-oxopentyl)heptanoate [(–)-24]: Yellow oil (91% yield); R_f = 0.4 (*n*-hexane/EtOAc, 1:4). $[\alpha]_D^{25}$ = –14.5 (c = 0.32, EtOH), 98%*ee*. HPLC [Chiralpack IA column, *n*-hexane/IPA (80:20), flow rate: 0.5 mL/min, detection at 250 nm]: R_t (min) = 22.42 (antipode 26.31). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.34 (t, J = 7.10 Hz, 3 H, CH_3), 1.61–2.00 (m, 6 H, 3 CH_2), 2.28–2.54 (m, 7 H, 1-H, $COCH_3$ overlapping), 2.66–2.72 (m, 1 H, 2-H), 3.64 (m, 4 H, $COCH_2$), 4.24 (q, J = 7.18 Hz, 2 H, OCH_2), 4.39–4.47 (m, 1 H, 3-H), 7.43–7.87 (m, 5 H, Ar) ppm. ^{13}C NMR (100 MHz, [D$_6$]DMSO): δ = 14.9, 22.2, 26.4, 28.6, 30.4, 30.7, 43.3, 46.3, 50.9, 60.9, 128.0, 129.1, 132.1, 135.4, 167.0, 170.0, 174.4, 208.9 ppm. $C_{21}H_{29}NO_5$ (375.46): calcd. C 67.18, H 7.79, N 3.73; found C 67.44, H 8.09, N 3.49.

Ethyl 2-benzamidocyclopent-3-enecarboxylate (3): White solid (74% yield); m.p. 82–85 °C.

Ethyl 2-benzamidocyclopent-3-enecarboxylate (4): White solid (76% yield); m.p. 93–96 °C.

Ethyl 2-benzamido-3,4-dihydroxycyclopentanecarboxylate (5): White solid (77% yield); m.p. 125–126 °C.

Ethyl 2-benzamido-3,4-dihydroxycyclopentanecarboxylate (15): White solid (77% yield); m.p. 75–77 °C.

Triethyl 3-benzamidohepta-(1*E*)-1,6-diene-1,4,7-tricarboxylate (11): White solid (78% yield); m.p. 29–30 °C.

Ethyl 3-benzamido-6-oxo-2-(4-oxopent-2-enyl)hept-4-enoate (12): Colorless oil (68% yield).

Triethyl 3-benzamidohepta-1,6-diene-1,4,7-tricarboxylate (21): White solid (75% yield); m.p. 37–39 °C.

Ethyl 3-benzamido-6-oxo-2-(4-oxopent-2-enyl)hept-4-enoate (22): Yellow oil (69% yield).

Ethyl 2-allyl-3-benzamidopent-4-enoate (7): Colorless oil (50% yield).

Ethyl 3-benzamido-2-cinnamyl-5-phenylpent-4-enoate (8): White solid (43% yield); m.p. 85–88 °C.

Ethyl 2-allyl-3-benzamidopent-4-enoate (17): Colorless oil (44% yield).

Ethyl 3-benzamido-2-cinnamyl-5-phenylpent-4-enoate (18): Yellow solid (39% yield); m.p. 70–72 °C.

Ethyl 3-benzamido-2-propylpentanoate (9): Colorless oil (81% yield).

Ethyl 3-benzamido-5-phenyl-2-(3-phenylpropyl)pentanoate (10): White solid (90% yield); m.p. 105–106 °C.

Triethyl 3-benzamidoheptane-1,4,7-tricarboxylate (13): White solid (90% yield); m.p. 41–42 °C.

Ethyl 3-benzamido-6-oxo-2-(4-oxopentyl)heptanoate (14): Colorless oil (89% yield).

Ethyl 3-benzamido-2-propylpentanoate (19): Colorless oil (79% yield).

Ethyl 3-benzamido-5-phenyl-2-(3-phenylpropyl)pentanoate (20): Colorless oil (87% yield).

Triethyl 3-benzamidoheptane-1,4,7-tricarboxylate (23): Colorless oil (90% yield).

Ethyl 3-benzamido-6-oxo-2-(4-oxopentyl)heptanoate (24): Yellow oil (91% yield).

Supporting Information (see footnote on the first page of this article): Copies of the ^{1}H and ^{13}C NMR spectra.

Acknowledgments

The authors are grateful to the Hungarian Research Foundation (OTKA Nos. NK81371 and K100530) and TAMOP-4.2.2.A-II/1/KONV-2012-0035 for the financial support. This paper was supported by the Hungarian Academy of Sciences (János Bolyai Research Scholarship to L. K.).

[1] a) E. Juaristi, V. A. Soloshonok, *Enantioselective Synthesis of β-Amino Acids*, 2nd ed., Wiley-VCH, New York, **2005**; b) M. Liu, M. P. Sibi, *Tetrahedron* **2002**, *58*, 7991–8035; c) R. P. Cheng, S. H. Gellman, W. F. Degrade, *Chem. Rev.* **2001**, *101*, 3219–3232; d) D. Seebach, J. Gardiner, *Acc. Chem. Res.* **2008**, *41*, 1366–1375; e) D. Seebach, A. K. Beck, S. Capone, G. Deniau, U. Grošelj, E. Zass, *Synthesis* **2009**, 1–32; f) A. Liljeblad, L. T. Kanerva, *Tetrahedron* **2006**, *62*, 5831–5854; g) T. L. March, M. R. Johnston, P. J. Duggan, J. Gardiner, *Chem. Biodivers.* **2012**, *9*, 2410–2441; h) B. E. Sleebs, T. T. Van Nguyen, A. B. Hughes, *Org. Prep. Proced. Int.* **2009**, *41*, 429–478; i) B. Weiner, W. Szymanski, D. B. Janssen, A. J. Minnaard, B. L. Feringa, *Chem. Soc. Rev.* **2010**, *39*, 1656–1691; j) E. Juaristi, J. Escalante, B. Lamatsch, D. Seebach, *J. Org. Chem.* **1992**, *57*, 2396–2398.

[2] a) J. Gardiner, K. H. Anderson, A. Downard, A. D. Abell, *J. Org. Chem.* **2004**, *69*, 3375–3382; b) S. Capone, S. Pedatella, A. Guaragna, M. De Nisco, G. Palumbo, *Tetrahedron* **2007**, *63*, 12202–12206.

[3] a) K. Moriyama, K. Ishida, H. Togo, *Chem. Commun.* **2012**, *48*, 8574–8576; b) K. Moriyama, K. Ishida, H. Togo, *Org. Lett.* **2012**, *14*, 946–949.

[4] S. Fustero, J.-F. Sanz-Cervera, J. Piera, M. Sanchez-Rosello, G. Chiva, A. Simon-Fuentes, *J. Fluorine Chem.* **2004**, *125*, 621–627.

[5] P. M. Ylioja, A. D. Mosley, C. E. Charlot, D. R. Carbery, *Tetrahedron Lett.* **2008**, *49*, 1111–1114.

[6] M. Ege, K. T. Wanner, *Tetrahedron* **2008**, *64*, 7273–7282.

[7] B. E. Sleebs, A. B. Hughes, *J. Org. Chem.* **2007**, *72*, 3340–3352.

[8] a) A. M. Chippindale, S. G. Davies, K. Iwamoto, R. M. Parkin, C. A. P. Smethurst, A. D. Smith, H. Rodriguez-Solla, *Tetrahedron* **2003**, *59*, 3253–3265; b) S. G. Davies, A. M. Fletcher, P. M. Roberts, J. E. Thomson, *Tetrahedron: Asymmetry* **2012**, *23*, 1111–1153.

[9] a) A. R. Minter, A. A. Fuller, A. K. Mapp, *J. Am. Chem. Soc.* **2003**, *125*, 6846–6847; b) A. A. Fuller, B. Chen, A. R. Minter,

A. K. Mapp, *J. Am. Chem. Soc.* **2005**, *127*, 5376–5383; c) N. Sewald, *Angew. Chem.* **2003**, *115*, 5972; *Angew. Chem. Int. Ed.* **2003**, *42*, 5794–5795.

[10] a) C. Bruneau, J.-L. Renaud, T. Jerphagnon, *Coord. Chem. Rev.* **2008**, *252*, 532–544; b) J.-H. Xie, S.-F. Zhu, Q.-L. Zhou, *Chem. Soc. Rev.* **2012**, *41*, 4126–4139.

[11] a) F. A. Davis, N. Theddu, *J. Org. Chem.* **2010**, *75*, 3814–3820; b) J. W. Yang, M. Stadler, B. List, *Angew. Chem.* **2007**, *119*, 615; *Angew. Chem. Int. Ed.* **2007**, *46*, 609–611; c) P. Dziedzic, J. Vesely, A. Cordova, *Tetrahedron Lett.* **2008**, *49*, 6631–6634; d) M. Yamanaka, J. Itoh, K. Fuchibe, T. Akiyama, *J. Am. Chem. Soc.* **2007**, *129*, 6756–6764; e) F. A. Davis, M. Song, *Org. Lett.* **2007**, *9*, 2413–2416.

[12] a) F. A. Davis, J. M. Szewczyk, R. E. Reddy, *J. Org. Chem.* **1996**, *61*, 2222–2225; b) T. P. Tang, J. A. Ellman, *J. Org. Chem.* **2002**, *67*, 7819–7832.

[13] H. Miyabe, K. Fujii, T. Goto, T. Naito, *Org. Lett.* **2000**, *2*, 4071–4074.

[14] a) B. Kazi, L. Kiss, E. Forró, I. Mándity, F. Fülöp, *ARKIVOC* **2010**, *9*, 31–39; b) B. Kazi, L. Kiss, E. Forró, F. Fülöp, *Tetrahedron Lett.* **2010**, *51*, 82–85; c) L. Kiss, B. Kazi, E. Forró, F. Fülöp, *Tetrahedron Lett.* **2008**, *49*, 339–342; d) L. Kiss, M. Cherepanova, E. Forró, F. Fülöp, *Chem. Eur. J.* **2013**, *19*, 2102–2107; for several other analogous reactions involving vicinal diol transformation through dialdehydes, see also: F. Caputo, C. Cattaneo, F. Clerici, M. L. Gelmi, S. Pellegrino, *J. Org. Chem.* **2006**, *71*, 8467–8472; A. Robinson, G. L. Thomas, R. J. Spandl, M. Welch, D. R. Spring, *Org. Biomol. Chem.* **2008**, *6*, 2978–2981; M. Lee, S. S. Stahl, S. H. Gellman, *Org. Lett.* **2008**, *10*, 5317–5319; Y. Fricke, N. Kopp, B. Wünsch, *Synthesis* **2010**, 791–796; G. Malik, X. Guinchard, D. Crich, *Org. Lett.* **2012**, *14*, 596–599; C. A. D. Sousa, F. Rizzo-Aguiar, M. L. C. Vale, X. García-Mera, O. Caamaño, J. E. Rodríguez-Borges, *Tetrahedron Lett.* **2012**, *53*, 1029–1032; J. A. Perez-Bautista, M. Sosa-Rivadeneyra, L. Quintero, H. Hopfl, F. A. Tejeda-Dominguez, F. Sartillo-Piscil, *Tetrahedron Lett.* **2009**, *50*, 5572–5574.

[15] a) E. Forró, F. Fülöp, *Tetrahedron: Asymmetry* **2004**, *15*, 2875–2880; b) L. Kiss, M. Nonn, E. Forró, R. Sillanpää, F. Fülöp, *Tetrahedron Lett.* **2009**, *50*, 2605–2608; c) M. Nonn, L. Kiss, E. Forró, Z. Mucsi, F. Fülöp, *Tetrahedron* **2011**, *67*, 4079–4085; d) I. Coldham, K. N. Price, R. E. Rathmell, *Org. Biomol. Chem.* **2003**, *1*, 2111–2119.

Received: August 26, 2013
Published Online: November 13, 2013

