

Versatile methodology for the synthesis and α -functionalization of (2*R*,3*aS*,7*aS*)-octahydroindole-2-carboxylic acid

Francisco J. Sayago, M. Isabel Calaza, Ana I. Jiménez, Carlos Cativiela*

Departamento de Química Orgánica, Instituto de Ciencia de Materiales de Aragón, Universidad de Zaragoza-CSIC, 50009 Zaragoza, Spain

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Dedicated to Miguel Yus on the occasion of his 60th birthday

Abstract

An improved strategy for the effective synthesis of enantiomerically pure (2*R*,3*aS*,7*aS*)-octahydroindole-2-carboxylic acid (Oic), based on the formation of a trichloromethyloxazolidinone derivative, has been developed. Additionally, the completely diastereoselective α -alkylation of such oxazolidinone provides a very convenient and concise route to enantiopure α -tetrasubstituted derivatives of this Oic stereoisomer. © 2007 Elsevier Ltd. All rights reserved.

Keywords: Quaternary amino acid; Bicyclic proline analogue; Perhydroindole-2-carboxylic acid; Trichloromethyloxazolidinone; α -Alkylation; Self-reproduction of chirality; Crystal structure

1. Introduction

The development of practical synthetic routes to render enantiopure non-proteinogenic α -amino acids is receiving considerable attention due to their wide applicability in engineering peptide drugs.¹ The incorporation of non-coded α -amino acids into the sequence of bioactive peptides is considered a very useful approach to tailor their properties in order to make therapeutic applications feasible. Such applications are very limited due to poor metabolic stability, low bioavailability and lack of selectivity for a specific receptor. The incorporation of non-natural α -amino acids generates modifications in the secondary structure of these peptides and, as a result, improvements in selectivity and stability can often be achieved.²

Octahydroindole-2-carboxylic acid (Oic) is a non-coded α -amino acid with a bicyclic structure that is able to introduce certain backbone rigidity when incorporated into peptides, similar to that induced by proline,³ and, at the same time, is endowed with greater lipophilicity. This latter property is

very relevant for peptides and peptidomimetics because it is related to their rate of absorption and distribution through biological membranes and, hence, to their bioactivity.⁴ For this reason, the incorporation of residues of increased lipophilicity into bioactive peptides is a convenient way to improve their bioavailability.⁵

Interestingly, octahydroindole-2-carboxylic acid has been used as a surrogate of proline and phenylalanine in bradykinin, a linear nonapeptide hormone involved in pain and inflammation. In this way, Oic has contributed to improve the resistance to degrading enzymes of a family of orally available bradykinin B₂ receptor antagonists with attractive anti-cancer properties.⁶ It has also been used to stabilize a type-II' β -turn in small cyclic peptides in order to find a starting point for the design of alternative non-peptidic bradykinin B₂ antagonists.⁷ In addition, Oic is a key intermediate in the preparation of medically relevant drugs like potent ACE inhibitors for the treatment of hypertension (perindopril).⁸

Moreover, the octahydroindole-2-carboxylic acid motif with a diverse substitution profile has been found to be part of the structure of natural products like marine aeruginosins with potent antithrombotic properties.⁹ Besides, quaternary derivatives of Oic are the core structures of investigational

* Corresponding author. Tel./fax: +34 976 761210.

E-mail address: cativiela@unizar.es (C. Cativiela).

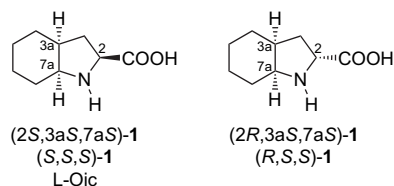


Figure 1. Structure of (2*S*,3*aS*,7*aS*)-octahydroindole-2-carboxylic acid and its epimer at the α carbon.

compounds with potential applications in diseases characterized by joint cartilage damage.¹⁰

All of the aforementioned applications involve octahydroindole-2-carboxylic acid with the absolute configuration (2*S*,3*aS*,7*aS*) (Fig. 1). This particular stereoisomer is usually denoted as L-Oic, and will be referred to as (S,S,S)-1 in the following text—a nomenclature without numerical locants is adopted for the sake of simplicity.

The significant occurrence of this bicyclic α -amino acid has stimulated our interest in developing efficient synthetic routes to access the different stereoisomers of octahydroindole-2-carboxylic acid in enantiomerically pure form. The so-called L-Oic, (S,S,S)-1, is the only commercially available stereoisomer and has therefore been the most widely used in peptidomimetic and medicinal chemistry research. Various strategies for the preparation of enantiopure (S,S,S)-1 have been reported in the literature and include stereoselective processes,¹¹ chemical resolutions¹² of diastereoisomeric salts of (S,S,S)-1 derivatives or their indoline precursors, and, more recently, enzymatic¹³ and chromatographic¹⁴ resolutions. In contrast, there is only one reported synthesis^{12a} of enantiomerically pure (R,S,S)-1 (Fig. 1), which involves an epimerization reaction of (S,S,S)-1 followed by laborious crystallizations, and suffers from a poor overall yield.

In this paper we report a more efficient method for the convenient synthesis of enantiomerically pure (R,S,S)-1, which will also allow access to α -alkyl derivatives in a concise manner.

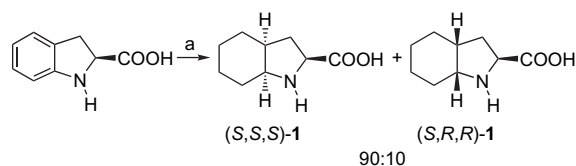
2. Results and discussion

The preparation of enantiomerically pure (R,S,S)-1 has only been described in the literature by Vincent et al.,^{12a} who used an epimerization reaction of enantiopure (S,S,S)-1 under acidic conditions, according to a general procedure reported by Yamada et al.¹⁵ This approach affords a 50:50 mixture of epimers from which the desired compound is isolated after consecutive preferential crystallizations. As a result, the synthesis becomes laborious and suffers from a low overall isolated yield. Previously, Henning and Urbach described¹⁶ a racemic synthesis of this compound through a base-promoted Favorskii-type ring contraction of an α -chlorinated lactam, a process that proceeds in a quite diastereoselective fashion. However, this approach involves more synthetic steps and details were not given concerning the isolation of the desired major stereoisomer (as a racemic mixture).

In principle, it seems that the easiest procedure for the synthesis of (R,S,S)-1 would be an epimerization reaction of

enantiopure (S,S,S)-1, obtained from commercial (S)-indoline-2-carboxylic acid, since other retrosynthetic possibilities from the disconnection approach do not seem to lead to more appropriate, or easily available, starting materials. Indeed, an improved epimerization reaction followed by a more competitive procedure for the separation of diastereoisomers other than preferential crystallizations, would be desirable for Vincent's strategy^{12a} to become efficient.

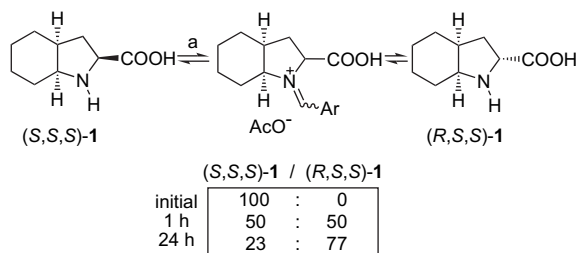
With this aim in mind, our synthesis began with the hydrogenation of commercially available (S)-indoline-2-carboxylic acid to afford diastereoisomeric (S,S,S)-1 and (S,R,R)-1 in a 90:10 ratio (Scheme 1), in a similar way to that described by Vincent et al.^{12a} In our case, the use of platinum oxide as a catalyst, instead of palladium on charcoal, allowed the hydrogenation to proceed at atmospheric pressure. The desired compound (S,S,S)-1 was isolated as a pure material, in 85% yield, after crystallization from ethanol.



Scheme 1. Synthesis of enantiomerically pure (S,S,S)-1. Reagents and conditions: (a) H₂, PtO₂, AcOH, 60 °C. Recrystallization of the mixture from EtOH furnishes pure (S,S,S)-1.

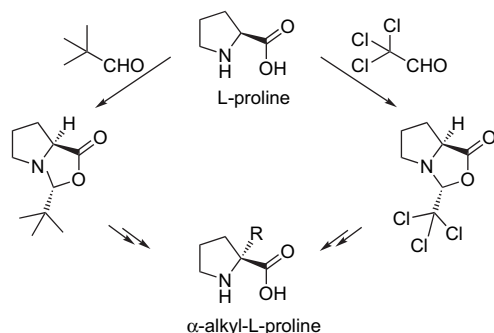
Enantiomerically pure (S,S,S)-1 was then submitted to Yamada's epimerization procedure,¹⁵ by heating in acetic acid in the presence of a catalytic amount of salicylaldehyde to promote the formation of a Schiff base (Scheme 2). According to the literature,^{12a} the epimerization progresses to give a 50:50 mixture of diastereoisomers after 1 h. However, we found that a prolonged reaction time leads to a considerable enrichment of the diastereoisomeric mixture in the desired epimer, with the final ratio (S,S,S)-1/(R,S,S)-1=23:77 after 24 h of reaction. Undoubtedly, this represents a substantial improvement and is expected to have a very positive effect on the overall efficiency of the method. In comparison, in the synthesis reported by Vincent et al.,^{12a} a 50:50 mixture of diastereoisomers was obtained and used for the isolation of (R,S,S)-1. This leads to a significant reduction in the final yield and also sets hurdles for its isolation by recrystallization techniques.

At this point, our efforts focused on finding a more competitive way to isolate the desired compound from the 23:77



Scheme 2. Epimerization of (S,S,S)-1. Reagents and conditions: (a) salicylaldehyde, AcOH, reflux.

mixture of epimers, other than laborious recrystallizations. In doing so, we turned our attention to reported investigations dealing with the highly stereoselective synthesis of bicyclic oxazolidinones derived from L-proline, such as those depicted in Scheme 3.¹⁷ This type of oxazolidinone, prepared by condensation of L-proline with a bulky alkyl aldehyde, has proven to be very valuable for the synthesis of α -tetrasubstituted prolines in enantiomerically pure form.^{17a,c}



Scheme 3. The most commonly used bicyclic oxazolidinones derived from L-proline.

The condensation reaction gives a single diastereoisomer with the bulky alkyl group in a *cis* disposition with respect to the bridgehead hydrogen. A perspective view of the structure reveals a ‘roof’ shaped bicyclic framework, with the bulky alkyl moiety pointing towards the less crowded convex face (*exo*).^{17a,b}

According to this observation, it seems reasonable to consider that the ease of such a stereoselective condensation, when applied to octahydroindole-2-carboxylic acids, will be conditioned to the structural constraint of the resulting tricyclic system. Based on this premise, we envisaged the possibility of using this transformation as a tool for discrimination between (*R,S,S*)-**1** and (*S,S,S*)-**1**, where the two theoretical tricyclic systems, (*S,S,S,R*)-**2** and (*R,S,S,S*)-**2**, respectively,¹⁸ should show a priori remarkably different spatial constraints (Fig. 2). In fact, molecular models of these structures reflect a more sterically disfavoured situation for oxazolidinone (*R,S,S,S*)-**2**, due to partially overlapping hydrogens at the concave face defined by the tricyclic scaffold. To the best of our knowledge, the use of this reaction for selective discrimination between substituted epimeric prolines has not been explored, with all previous investigations focused on the reactivity of the oxazolidinones derived from L-proline.^{17,19}

To test our hypothesis, the 23:77 mixture of epimers (*S,S,S*)-**1** and (*R,S,S*)-**1** was treated with trichloroacetaldehyde in acetonitrile at room temperature.²⁰ We were delighted to observe that, while (*R,S,S*)-**1** reacted quantitatively with the aldehyde, (*S,S,S*)-**1** remained unreacted (Scheme 4). The condensation reaction, as in the case of L-proline, furnishes a single compound with a new chiral centre at C3 as a result of the trichloromethyl group being exclusively in a *cis* relationship with the hydrogen in the 9a position. This experimental result suggests that, indeed, the oxazolidinone derived from (*S,S,S*)-**1** (Fig. 2, right) is not formed because it would result in

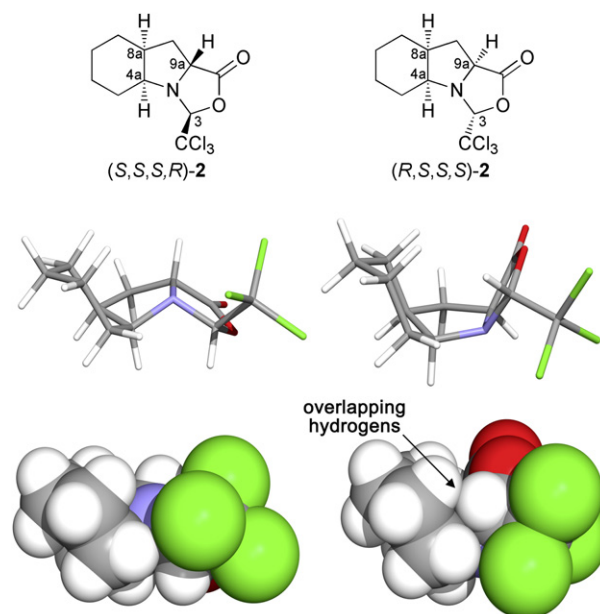
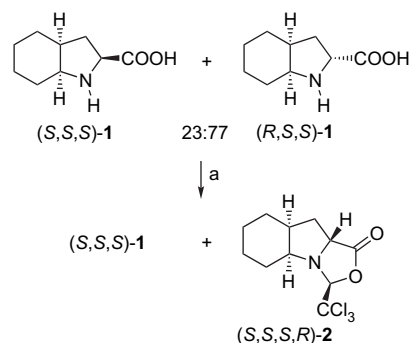


Figure 2. Stick and space filling models for the theoretical trichloromethyl-oxazolidinones derived from (*R,S,S*)-**1** (left) and (*S,S,S*)-**1** (right). The partially overlapping hydrogens in (*R,S,S,S*)-**2** are indicated.

a tricyclic system with substantial steric hindrance at the inner concave face defined by the rings. In particular, the hydrogen at C3 is oriented towards the cyclohexane ring and would therefore lie in close proximity to one of the hydrogens at C6, thus producing a steric clash.



Scheme 4. Synthesis of (*S,S,S,R*)-**2**. Reagents and conditions: (a) CCl_3CHO , CH_3CN , rt, 12 h.

The resulting oxazolidinone was easily isolated as a solid, after filtration through a short pad of silica eluting with dichloromethane.²¹ Single crystals were obtained from an ethyl acetate/hexanes solution and X-ray diffraction analysis corroborated the expected stereochemistry (Fig. 3). Also in this case, the two five-membered rings define a ‘roof’ shaped structure, with the bulky trichloromethyl group pointing towards the *exo* face. The pyrrolidine ring assumes an envelope conformation with carbon 8a deviating by 0.63 Å from the plane defined by the other four atoms, which corresponds to a $\text{C}^\gamma\text{-exo}$ conformation²² for the proline subunit. The junction to the chair of the six-membered ring is sitting at the flap of the envelope.

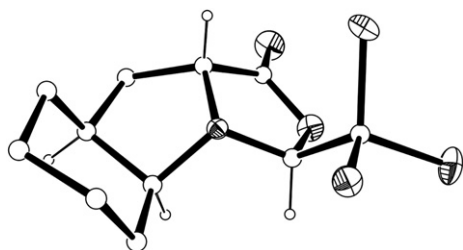
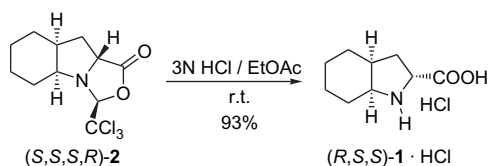


Figure 3. X-ray crystal structure of (S,S,S,R) -**2**. Heteroatoms are shown as thermal ellipsoids. Most hydrogens have been omitted for clarity.

The trichloromethyloxazolidinone obtained was then converted to the corresponding free amino acid through hydrolysis in acidic conditions (Scheme 5). Thus, treatment of (S,S,S,R) -**2** with a saturated solution of hydrogen chloride in ethyl acetate furnished (R,S,S) -**1** in enantiomerically pure form, as the hydrochloride salt. It is worth noting that the overall isolated yield of the final amino acid resulting from the epimerization–condensation–hydrolysis sequence was 56%, which represents a tremendous improvement when compared with the 30% described for direct crystallizations.^{12a}

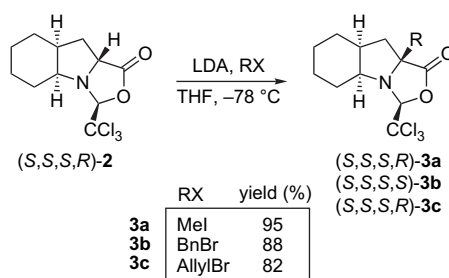


Scheme 5. Isolation of the enantiomerically pure amino acid (R,S,S) -**1**.

Thus, the trichloromethyloxazolidinone (S,S,S,R) -**2** has proven to be a key intermediate to allow a more efficient synthesis of (R,S,S) -**1**. At this point, we considered that this oxazolidinone could also be a valuable precursor to afford α -tetrasubstituted derivatives of this Oic stereoisomer. We decided to explore this possibility driven by the attractiveness of α -alkylated Oic derivatives for peptide-engineering purposes and the potential therapeutic value shown by structurally related compounds for the treatment of osteoarthritis.¹⁰

Treatment of oxazolidinone (S,S,S,R) -**2** with lithium diisopropylamide in THF at -78°C generated a lithium enolate that successfully reacted with several alkyl electrophiles in high yields (Scheme 6). As in the pioneering investigations by Seebach et al.,^{17a} we observed that both the trichloromethyl group and the newly introduced substituent are *cis* to each other on the *exo* side of the bicycle constituted by the two five-membered rings. This indicates that the enolate underwent alkylation exclusively at the *Si* face. The bridgehead nitrogen of (S,S,S,R) -**2** is strongly pyramidalised and its inversion does not take place, even when the enolate is generated, because of the high steric constraints that such a change would have on the system. For this reason, the enolate attacks the electrophile only from the face that was previously occupied by the α hydrogen, thus leading to the formation of a single stereoisomer with retention of configuration at C9a. This behaviour was named by Seebach as *self-*

reproduction of chirality.^{17a} The complete stereocontrol of this process becomes particularly remarkable in comparison with the only example of the α -alkylation of an L-Oic derivative reported to date.¹⁰ It has been shown that an *N*-protected methyl ester derivative of L-Oic undergoes methylation, upon treatment with LiHMDS, to afford the stereoisomer with retention of configuration as the major compound, together with a non-negligible percentage of the α -methylated epimer. In contrast, in our case, not even traces of the other possible stereoisomer could be detected. Single crystal X-ray diffraction analysis of the resulting α -tetrasubstituted compounds **3a–c** provided evidence for the alkylation reaction taking place with retention of configuration²³ (Fig. 4).



Scheme 6. Synthesis of α -quaternary derivatives.

In the three crystalline structures, the pyrrolidine ring assumes an envelope conformation and, as already observed for (S,S,S,R) -**2** (Fig. 3), it is the atom at the 8a position (C^γ considering the proline system) that deviates from planarity (0.58–0.61 Å). However, in contrast to (S,S,S,R) -**2**, in all three tetrasubstituted derivatives **3a–c** a C^γ -*endo* conformation²² is observed, i.e., the flap of the envelope points in the opposite direction. This probably helps to accommodate the newly introduced bridgehead substituent.

These α -tetrasubstituted oxazolidinones can be hydrolyzed in an acidic medium, although stronger conditions are required in comparison to the non-substituted analogue, as exemplified for the α -methyl derivative in Scheme 7. Thus, compound (S,S,S,R) -**3a** was heated under reflux in a mixture of hydrochloric acid and acetic acid to give the free α -methylated amino acid (R,S,S) -**4** as the hydrochloride salt in 92% yield.

3. Conclusion

We have established an improved methodology for the efficient synthesis of enantiomerically pure $(2R,3aS,7aS)$ -octahydroindole-2-carboxylic acid. This stereoisomer can be efficiently separated from its epimer by means of a selective condensation reaction with trichloroacetaldehyde. In addition, the resulting oxazolidinone constitutes a versatile intermediate that undergoes completely diastereoselective α -alkylation reactions, thus providing a very convenient and concise route to access enantiomerically pure α -alkyl derivatives of $(2R,3aS,7aS)$ -octahydroindole-2-carboxylic acid.

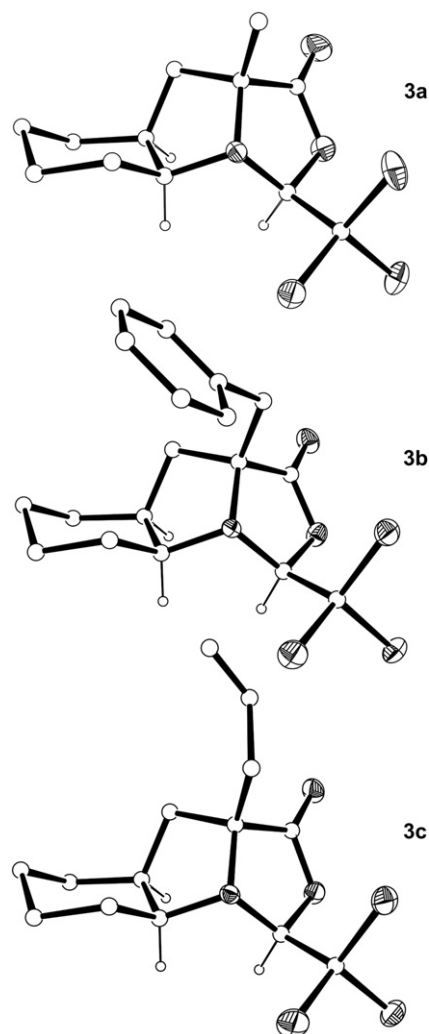


Figure 4. X-ray crystal structures of the α -tetrasubstituted oxazolidinones (*S,S,S,R*)-**3a**, (*S,S,S,S*)-**3b** and (*S,S,S,R*)-**3c**. Heteroatoms are shown as thermal ellipsoids. Most hydrogens have been omitted for clarity.

4. Experimental

4.1. General

All reagents were used as received from commercial suppliers without further purification. Thin-layer chromatography (TLC) was performed on Macherey-Nagel Polygram syl G/UV precoated silica gel polyester plates. The products were visualized by exposure to UV light (254 nm), iodine vapour or submersion in cerium molybdate stain [aqueous solution of

phosphomolybdic acid (2%), $\text{CeSO}_4 \cdot 4\text{H}_2\text{O}$ (1%) and H_2SO_4 (6%)]. Column chromatography was performed using 60 Å silica gel purchased from SDS. Melting points were determined on a Gallenkamp apparatus and are uncorrected. IR spectra were registered on a Mattson Genesis or a Nicolet Avatar 360/370 FTIR spectrophotometer; ν_{max} is given for the main absorption bands. ^1H and ^{13}C NMR spectra were recorded on a Bruker AV-400 instrument at room temperature using the residual solvent signal as the internal standard; chemical shifts (δ) are expressed in parts per million and coupling constants (J) in hertz. Optical rotations were measured at room temperature using a JASCO P-1020 polarimeter. High-resolution mass spectra were obtained on a Bruker Microtof-Q spectrometer.

4.2. X-ray diffraction

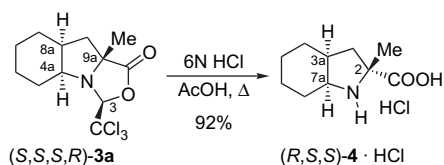
Colourless single crystals of (*S,S,S,R*)-**2** and (*S,S,S,R*)-**3a** were obtained by slow evaporation from ethyl acetate solutions. Compounds (*S,S,S,S*)-**3b** and (*S,S,S,R*)-**3c**, which are oils, furnished single crystals upon standing. The X-ray diffraction data were collected at room temperature on an Oxford Diffraction Xcalibur diffractometer provided with a Sapphire CCD detector, using graphite-monochromated Mo K α radiation ($\lambda=0.71073$ Å). The structures were solved by direct methods using SHELXS-97^{24a} and refinement was performed using SHELXL-97^{24b} by the full-matrix least-squares technique with anisotropic thermal factors for heavy atoms. Hydrogen atoms were located by calculation and affected by an isotropic thermal factor fixed to 1.2 times the U_{eq} of the carrier atom (1.5 for the methyl protons). Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 658042–658045. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

4.2.1. Crystallographic data for (*S,S,S,R*)-**2**

Orthorhombic, space group $P2_12_12_1$; $a=8.6296(2)$ Å, $b=9.9887(3)$ Å, $c=15.4787(4)$ Å; $Z=4$; $d_{\text{calcd}}=1.486$ g cm $^{-3}$; 7764 reflections collected, 2570 unique ($R_{\text{int}}=0.024$); data/parameters: 2570/155; final R indices ($I>2\sigma I$): $R_1=0.028$, $wR_2=0.062$; final R indices (all data): $R_1=0.042$, $wR_2=0.065$. Highest residual electron density: 0.18 e Å $^{-3}$.

4.2.2. Crystallographic data for (*S,S,S,R*)-**3a**

Orthorhombic, space group $P2_12_12_1$; $a=8.0709(4)$ Å, $b=10.0848(5)$ Å, $c=17.7838(8)$ Å; $Z=4$; $d_{\text{calcd}}=1.434$ g cm $^{-3}$; 8697 reflections collected, 2868 unique ($R_{\text{int}}=0.026$); data/parameters: 2868/165; final R indices ($I>2\sigma I$): $R_1=0.030$, $wR_2=0.061$; final R indices (all data): $R_1=0.048$, $wR_2=0.065$. Highest residual electron density: 0.16 e Å $^{-3}$.



Scheme 7. Isolation of the (*R,S,S*) isomer of (α Me)Oic in enantiomerically pure form.

4.2.3. Crystallographic data for (S,S,S,S)-**3b**

Orthorhombic, space group $P2_12_12_1$; $a=8.6469(1)$ Å, $b=9.5584(1)$ Å, $c=22.3424(4)$ Å; $Z=4$; $d_{\text{calcd}}=1.398$ g cm $^{-3}$; 24,447 reflections collected, 4017 unique ($R_{\text{int}}=0.038$); data/parameters: 4017/218; final R indices ($I>2\sigma I$): $R_1=0.027$, $wR_2=0.050$; final R indices (all data): $R_1=0.052$, $wR_2=0.053$. Highest residual electron density: 0.15 e Å $^{-3}$.

4.2.4. Crystallographic data for (S,S,S,R)-**3c**

Orthorhombic, space group $P2_12_12_1$; $a=8.7355(4)$ Å, $b=13.1329(5)$ Å, $c=14.1367(5)$ Å; $Z=4$; $d_{\text{calcd}}=1.387$ g cm $^{-3}$; 8804 reflections collected, 2851 unique ($R_{\text{int}}=0.031$); data/parameters: 2851/181; final R indices ($I>2\sigma I$): $R_1=0.030$, $wR_2=0.058$; final R indices (all data): $R_1=0.058$, $wR_2=0.063$. Highest residual electron density: 0.17 e Å $^{-3}$.

4.3. Synthesis of (2S,3aS,7aS)-octahydroindole-2-carboxylic acid, (S,S,S)-**1**

A solution of (S)-indoline-2-carboxylic acid (3.0 g, 18.38 mmol) in acetic acid (60 mL) was hydrogenated at 60 °C in the presence of PtO $_2$ (300 mg). After 24 h, the catalyst was filtered off and washed with acetic acid. The solvent was evaporated to dryness and the resulting residue was crystallized from ethanol to afford pure (S,S,S)-**1** as a white solid (2.64 g, 15.60 mmol, 85% yield). Mp 267–269 °C. $[\alpha]_D^{25} -45.6$ (c 0.46, MeOH). IR (KBr) ν 3600–2200, 1623 cm $^{-1}$. ^1H NMR (D $_2$ O, 400 MHz) δ 1.23–1.64 (m, 7H), 1.73–1.82 (m, 1H), 1.91–2.01 (m, 1H), 2.25–2.36 (m, 2H), 3.65 (m, 1H), 4.06 (m, 1H). ^{13}C NMR (D $_2$ O, 100 MHz) δ 20.88, 21.36, 24.38, 25.06, 32.36, 36.91, 59.34, 59.70, 175.42. HRMS (ESI) C $_9$ H $_{16}$ NO $_2$ [M+H] $^+$: calcd 170.1176, found 170.1174.

4.4. Synthesis of (3S,4aS,8aS,9aR)-3-trichloromethyloctahydrooxazolo[3,4-a]indol-1-one, (S,S,S,R)-**2**

A solution of (S,S,S)-**1** (2.0 g, 11.82 mmol) in acetic acid (20 mL) was treated with salicylaldehyde (75 μ L, 0.71 mmol) and heated under reflux for 24 h. The solvent was evaporated and the residue lyophilized to furnish a 23:77 mixture of epimers (S,S,S)-**1** and (R,S,S)-**1**. This mixture was suspended in dry acetonitrile (40 mL) and treated with anhydrous trichloroacetaldehyde (2.0 mL, 20.50 mmol). The resulting suspension was stirred under an argon atmosphere at room temperature for 24 h. The mixture was filtered through a pad of Celite $^{\text{®}}$ and the filtrate was concentrated. The residue was purified through a short pad of silica gel eluting with dichloromethane to afford pure (S,S,S,R)-**2** as a white solid (2.11 g, 7.07 mmol, 60% yield). Mp 144–146 °C (dec). $[\alpha]_D^{25} +59.4$ (c 0.47, CHCl $_3$). IR (Nujol) ν 1739 cm $^{-1}$. ^1H NMR (CDCl $_3$, 400 MHz) δ 1.20–1.48 (m, 3H), 1.54–1.71 (m, 4H), 1.87 (m, 1H), 1.96–2.20 (m, 3H), 3.18 (m, 1H), 4.27 (dd, 1H, $J=8.8$, 7.2 Hz), 5.18 (s, 1H). ^{13}C NMR (CDCl $_3$, 100 MHz) δ 20.26, 23.62, 26.80, 27.67, 34.46, 38.49, 61.27,

66.42, 100.48, 102.14, 176.88. HRMS (ESI) C $_{11}$ H $_{15}$ Cl $_3$ NO $_2$ [M+H] $^+$: calcd 298.0163, found 298.0157.

4.5. Synthesis of (2R,3aS,7aS)-octahydroindole-2-carboxylic acid hydrochloride, (R,S,S)-**1**·HCl

A 3 N solution of HCl in anhydrous ethyl acetate (8 mL) was added to (S,S,S,R)-**2** (300 mg, 1.01 mmol) and the resulting mixture was stirred at room temperature for 24 h. The solvent was concentrated in vacuo and the resulting solid was washed with small portions of ethyl acetate to afford pure (R,S,S)-**1** as the hydrochloride salt (193 mg, 0.94 mmol, 93% yield). Mp 176–178 °C. $[\alpha]_D^{25} +29.6$ (c 0.47, MeOH). IR (KBr) ν 3507, 3200–2300, 1732, 1578 cm $^{-1}$. ^1H NMR (D $_2$ O, 400 MHz) δ 1.20–1.51 (m, 5H), 1.54–1.70 (m, 2H), 1.72–1.82 (m, 1H), 2.02–2.15 (m, 1H), 2.23–2.36 (m, 2H), 3.72 (m, 1H), 4.38 (m, 1H). ^{13}C NMR (D $_2$ O, 100 MHz) δ 20.51, 21.01, 23.95, 24.72, 32.44, 36.33, 57.61, 59.94, 172.76. HRMS (ESI) C $_9$ H $_{16}$ NO $_2$ [M–Cl] $^+$: calcd 170.1176, found 170.1177.

4.6. Synthesis of (3S,4aS,8aS,9aR)-9a-methyl-3-trichloromethyloctahydrooxazolo[3,4-a]indol-1-one, (S,S,S,R)-**3a**

A 1.8 M solution of LDA in hexanes (720 μ L, 1.29 mmol) was added dropwise by syringe to a stirred solution of (S,S,S,R)-**2** (200 mg, 0.67 mmol) in anhydrous THF (3.5 mL) at –78 °C. After stirring at this temperature for 30 min, methyl iodide (169 μ L, 2.71 mmol) was added dropwise. The resulting solution was then warmed to –50 °C and stirred at this temperature overnight. The reaction mixture was treated with water (4 mL) and extracted with dichloromethane several times. The combined organic layers were dried over anhydrous MgSO $_4$ and filtered. The solvent was concentrated in vacuo and the residue was purified by column chromatography (eluent: hexanes/ethyl acetate 10:1) to afford pure (S,S,S,R)-**3a** as a white solid (200 mg, 0.64 mmol, 95% yield). Mp 134–136 °C. $[\alpha]_D^{25} +9.4$ (c 0.45, CHCl $_3$). IR (Nujol) ν 1787 cm $^{-1}$. ^1H NMR (CDCl $_3$, 400 MHz) δ 1.09–1.22 (m, 1H), 1.23–1.39 (m, 2H), 1.47–1.66 (m, 2H) overlapped with 1.62 (s, 3H), 1.68–1.85 (m, 2H), 1.88–1.97 (m, 1H), 2.02 (m, 1H), 2.15–2.30 (m, 2H), 3.15 (m, 1H), 5.05 (s, 1H). ^{13}C NMR (CDCl $_3$, 100 MHz) δ 19.95, 24.50, 24.96, 27.43, 28.79, 36.98, 40.88, 68.77, 70.45, 100.41, 102.35, 177.84. HRMS (ESI) C $_{12}$ H $_{17}$ Cl $_3$ NO $_2$ [M+H] $^+$: calcd 312.0319, found 312.0320.

4.7. Synthesis of (3S,4aS,8aS,9aR)-9a-benzyl-3-trichloromethyloctahydrooxazolo[3,4-a]indol-1-one, (S,S,S,S)-**3b**

Using benzyl bromide (326 μ L, 2.74 mmol) as the alkylating agent, an identical procedure to that described above was applied to the transformation of (S,S,S,R)-**2** (200 mg, 0.67 mmol) into (S,S,S,S)-**3b** (230 mg, 0.59 mmol, 88% yield). The product was isolated as an oil that crystallized

upon standing. Mp 150–151 °C. $[\alpha]_D -26.6$ (c 0.48, CHCl_3). IR (Nujol) ν 1794 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz) δ 0.80–0.97 (m, 2H), 1.23–1.59 (m, 5H), 1.71 (m, 1H), 1.97–2.22 (m, 3H), 2.91–3.09 (m, 2H), 3.29 (d, 1H, $J=13.8$ Hz), 5.12 (s, 1H), 7.21–7.36 (m, 5H). ^{13}C NMR (CDCl_3 , 100 MHz) δ 19.91, 24.43, 25.00, 27.67, 35.84, 36.26, 42.32, 71.45, 72.58, 100.04, 103.48, 127.13, 127.93, 131.63, 135.28, 177.42. HRMS (ESI) $\text{C}_{18}\text{H}_{20}\text{Cl}_3\text{NNaO}_2$ $[\text{M}+\text{Na}]^+$: calcd 410.0452, found 410.0443.

4.8. Synthesis of (3*S*,4*aS*,8*aS*,9*aR*)-9*a*-allyl-3-trichloromethyloctahydrooxazolof[3,4-*a*]indol-1-one, (*S,S,S,R*)-**3c**

Using allyl bromide (237 μL , 2.74 mmol) as the alkylating agent, an analogous procedure to that described above, allowed the transformation of (*S,S,S,R*)-**2** (200 mg, 0.67 mmol) into (*S,S,S,R*)-**3c** (185 mg, 0.55 mmol, 82% yield), which was isolated as an oil that crystallized upon standing. Mp 114–115 °C. $[\alpha]_D -3.3$ (c 0.48, CHCl_3). IR (Nujol) ν 1791 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz) δ 1.04–1.18 (m, 1H), 1.19–1.39 (m, 2H), 1.43–1.64 (m, 2H), 1.65–1.75 (m, 1H), 1.76–1.90 (m, 2H), 1.98–2.23 (m, 3H), 2.54 (ddd, 1H, $J=14.0$, 7.1, 0.9 Hz), 2.72 (dd, 1H, $J=14.0$, 7.6 Hz), 3.12 (m, 1H), 5.08 (s, 1H), 5.11–5.23 (m, 2H), 5.97 (m, 1H). ^{13}C NMR (CDCl_3 , 100 MHz) δ 20.09, 24.57, 25.07, 28.57, 36.46, 36.79, 43.56, 70.75, 71.17, 100.08, 102.88, 119.24, 132.67, 176.86. HRMS (ESI) $\text{C}_{14}\text{H}_{19}\text{Cl}_3\text{NO}_2$ $[\text{M}+\text{H}]^+$: calcd 338.0476, found 338.0463.

4.9. Synthesis of (2*R*,3*aS*,7*aS*)-2-methyloctahydroindole-2-carboxylic acid hydrochloride, (*R,S,S*)-**4-HCl**

Acetic acid (4 mL) and 6 N HCl (4 mL) were added to (*S,S,S,R*)-**3a** (200 mg, 0.64 mmol) and the reaction mixture was heated under reflux for 12 h. The solvent was concentrated in vacuo and the resulting solid was washed with small portions of ethyl acetate to afford pure (*R,S,S*)-**4** as the hydrochloride salt (130 mg, 0.59 mmol, 92% yield). Mp 206–208 °C. $[\alpha]_D +28.2$ (c 0.47, MeOH). IR (KBr) ν 3434, 3200–2200, 1731, 1591 cm^{-1} . ^1H NMR (D_2O , 400 MHz) δ 1.18–1.71 (m, 7H) overlapped with 1.65 (s, 3H), 1.78–1.89 (m, 1H), 2.07 (dd, 1H, $J=17.1$, 12.9 Hz), 2.29 (m, 1H), 2.39 (dd, 1H, $J=17.1$, 8.9 Hz), 3.74 (m, 1H). ^{13}C NMR (D_2O , 100 MHz) δ 20.19, 21.73, 23.37, 24.85, 24.93, 36.09, 39.02, 59.85, 68.59, 175.45. HRMS (ESI) $\text{C}_{10}\text{H}_{18}\text{NO}_2$ $[\text{M}-\text{Cl}]^+$: calcd 184.1332, found 184.1341.

Acknowledgements

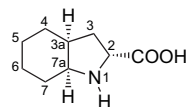
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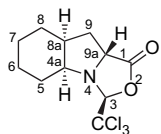
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- Note that the order of stereochemical descriptors *R/S* obey different numeration profiles in compounds **1** and **2**. In particular, the α carbon occupies

position 2 in the former and position 9a in the latter. Abbreviated names, with and without numerical locants, are exemplified below for clarity.



(2*R*,3*aS*,7*aS*)-**1**
(*R,S,S*)-**1**



(3*S*,4*aS*,8*aS*,9*aR*)-**2**
(*S,S,S,R*)-**2**

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20. The preparation of trichloromethyloxazolidinones was preferred to *tert*-butyloxazolidinones because of their greater stability. In the case of proline, the corresponding trichloromethyloxazolidinone is a crystalline solid,

while the *tert*-butyl derivative is highly sensitive to hydrolysis and unstable in air.

21. Unreacted (*S,S,S*)-**1** can be isolated, if desired, by washing the silica pad with MeOH.
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23. Although the relative spatial disposition of substituents at carbon 9a is identical for all three tetrasubstituted compounds **3a–c**, the stereochemical descriptors *R/S* giving the absolute configuration of the carbon centre differ. Thus, the compound with a benzyl substituent (**3b**) has an *S* configuration at position 9a due to the different priority of the substituents in comparison with the methyl or allyl derivatives.
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