Asymmetric Synthesis of All Stereoisomers of the Strigol Analogue GR24. Dependence of Absolute Configuration on Stimulatory Activity of *Striga hermonthica* and *Orobanche crenata* Seed Germination

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All four optically pure stereoisomers of the strigol analogue GR24 were prepared via two different routes. In the first approach enantiopure ABC-fragments **4** were used as the chiral source, whereas in the alternative route both antipodes of the latent D-ring **6** were employed. Bioassays revealed significant differences in activity between the four stereoisomers in the stimulation of germination of the parasitic weeds *Striga hermonthica* and *Orobanche crenata*.

Keywords: *Striga; Orobanche; germination, GR24*

INTRODUCTION

Parasitic weeds belonging to the genera *Striga*, *Orobanche*, and *Alectra* cause severe damage to several graminaceous and leguminous crops in tropical and semitropical areas of the eastern hemisphere (Musselman, 1987; Parker and Riches, 1993). Seeds of these parasitic weeds usually remain dormant in the soil, but after exposure to a specific germination stimulant, which is exuded by the roots of a suitable host, the seeds germinate and attach to the root system of the host (Press *et al*., 1990). The stimulation of germination, in particular the compounds by which this process is triggered, has received much attention. The most prominent naturally occurring germination stimulant, *viz*. (+)-strigol (**1**) (Figure 1), has been isolated from the root exudate of the false host cotton (*Gossypium hirsutum* L.) (Cook *et al*., 1966), and its structure was elucidated (Cook *et al*., 1972). The absolute configuration was unambiguously determined several years later (Brooks *et al*., 1985). Recently, it has been shown to be the major *Striga* germination stimulant produced by the true hosts maize (*Zea mays* L.) and proso millet (*Panicum miliaceum* L.) (Siame *et al*., 1993). It was demonstrated that the absolute stereochemistry of strigol **1** is of prime importance with respect to seed germination activity (Hauck and Schildknecht, 1990; Bergmann *et al*., 1993).

In a study to design simpler analogues of (+)-strigol (**1**) with optimal bioactivity, Johnson *et al*. (1976, 1981) have prepared the rather readily accessible synthetic analogue GR24 (**2**) (Figure 1). Its racemic preparation and the separation of its diastereomers was improved considerably (Mangnus *et al*., 1992a; Nefkens *et al*., 1996). The seed germination stimulatory activity toward several parasitic weed species is within the same order of magnitude as that of strigol (Pepperman *et al*., 1987; Hauck *et al*., 1992; Bergmann *et al*., 1993). For these reasons GR24 (**2**) has found widespread applications, including its use as a positive control in bioassays of *Orobanche* and *Striga* seed germination (Mangnus *et al*., 1992b). So far, only little attention has been paid to the influence of the absolute stereochemistry of synthetic strigol analogues on the biological activity. Recently, all four stereoisomers of GR7 (**3**), a strigol analogue lacking the A-ring, have been prepared and tested on seed germination activity (Mangnus and Zwanenburg, 1992). It was concluded that the correct absolute stereochemistry at C-2′ (*R*-configuration) is essential to exert maximal bioactivity.

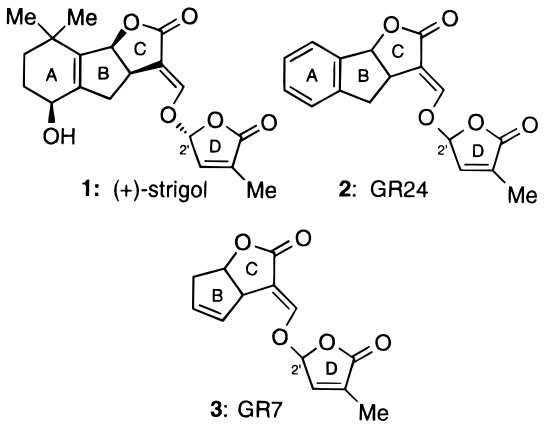

Figure 1. Structures of (+)-strigol (**1**) and synthetic strigol analogues **2** and **3**.

The present paper deals with the asymmetric syntheses of all four stereoisomers of GR24 (**2**) and their germination activities on seeds of *Striga hermonthica* (Del.) Benth and *Orobanche crenata* Forsk.

MATERIALS AND METHODS

Nomenclature. The AUTONOM 1.0 program, provided by the Beilstein Institute and Springer-Verlag (Weinheim, Germany) was used.

Syntheses. *General Remarks.* ^{1}H-NMR (100 MHz and 400 MHz) spectra were recorded on Bruker AC 100 and Bruker AM-400 spectrometers, respectively (Me_4Si as internal standard), both from Bruker (Wissembourg, France). All coupling constants are given as ^3J in hertz, unless indicated otherwise. For mass spectra a double-focusing VG7070E mass spectrometer from VG Analytical (Manchester, U.K.) was used. Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Elemental analyses were performed at the Department of Micro-analysis of this laboratory.

Solvents were dried using the following methods: Dichloromethane was distilled from P_2O_5. Diethyl ether was distilled

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from NaH. Hexane was distilled from CaH_2. Tetrahydrofuran was distilled from lithium aluminum hydride just before use. All other solvents were of analytical grade. Thin layer chromatography (TLC) was carried out on Merck precoated silica gel 60 F254 plates (0.25 mm) using the eluents indicated. Spots were visualized with UV or using a molybdate spray. "Flash" chromatography was carried out at a pressure of *ca.* 1.5 bar, using Merck Kieselgel 60H. Column chromatography at atmospheric pressure was carried out, using Merck Kieselgel 60.

Sodium hydride (60% in dispersion oil) was washed twice with hexane just before use. 3,3a,4,8b-Tetrahydroindeno[1,2-*b*]furan-2-one (*rac* **4**) and 5-bromo-3-methyl-2(5*H*)-furanone (**5**) were prepared following published methods (Mangnus *et al.*, 1992a). The synthesis of chlorolactones **6** and *ent* **6** was reported previously (Thuring *et al.*, 1995).

For the resolution of *rac* **4** microcrystalline cellulose triacetate (particle size 25−40 μm) from Fluka (Buchs, Switserland) was used. The enantiopurities of **4** and *ent* **4** were determined by HPLC analysis using an Spectra Physics SP8700 HPLC apparatus (Spectra Physics, Eindhoven, The Netherlands), a chiral Baker Chiralcel OD-H column [eluent hexane/ethanol 60:40 (v/v), flow rate 0.5 mL/min], and an LKB 2138 Uvicord S UV−vis detector (254 nm) (Pharmacia Biotech., Roozendaal, The Netherlands).

*Chromatographic Resolution of 3,3a,4,8b-Tetrahydroindeno-[1,2-b]furan-2-one (rac **4**).* The sorbent CTA (50 g) was swollen before use by heating in EtOH/H_2O 95:5 (150 mL) at *ca.* 75 °C for 20 min. A glass column (i.d. 2.5 cm) was slurry-packed with this material, and the stationary phase was eluted with 95% EtOH at a pressure of *ca.* 1.2 bar. The racemic lactone *rac* **4** (500 mg), dissolved in 95% EtOH (3 mL), was chromatographically resolved, using 95% EtOH as the eluent. Fractions of *ca.* 5 mL were collected, their optical rotations were recorded, and they were analyzed for enantiomeric excess (ee) by chiral HPLC: yield, 170 mg (34%) of pure fast-moving enantiomer **4** (t_R = 11.30 min) as a white solid; $[\alpha]_D$ −107.0° (*c* 0.4, $CHCl_3$), ee > 98%.

The slow-moving enantiomer, *ent* **4** (170 mg, 34%) (t_R = 12.18 min), was obtained as a white solid: $[\alpha]_D$ +102.5° (*c* 0.4, $CHCl_3$), ee > 98%.

*Formylation of 3a(R),8b(S)-**4** and Coupling with 5-Bromo-3-methyl-2(5H)-furanone **5** (General Procedure).* Potassium *tert*-butoxide (131 mg, 1.17 mmol) was added to a solution of lactone **4** (185 mg, 1.06 mmol) and methyl formate (1.6 mmol) in THF (5 mL) with stirring at 0 °C under nitrogen. Stirring was continued for 18 h at room temperature, followed by the addition of a solution of furanone **5** (207 mg, 1.17 mmol) in THF (10 mL) at 0 °C under nitrogen. After 18 h of stirring, precipitated potassium bromide was removed by filtration. The filtrate was concentrated *in vacuo*, and the residue was dissolved in a mixture of water (5 mL) and chloroform (10 mL). The aqueous phase was extracted with chloroform (three times). The combined organic layers were dried ($MgSO_4$) and concentrated *in vacuo*. The crude yellow oil was purified by flash chromatography (SiO_2, diisopropyl ether/ethyl acetate 4:1) to give two separated diastereomeric products, **2a** and *ent* **2b**, as white solids.

*3-[4-Methyl-5-oxo-2,5-dihydrofuran-2(R)-yloxymethylene]-3,3a(R),4,8b(S)-tetrahydroindeno[1,2-b]furan-2-one (**2a**) and Its 2′(S)-Epimer (ent **2b**).* These compounds were prepared according to the general procedure to give **2a**, 92 mg (yield 29%), and *ent* **2b**, 95 mg (yield 30%). Analytically pure samples were obtained by crystallization from hexane/ethyl acetate.

***2a**:* obtained as colorless crystals; mp 154−155 °C; $[\alpha]_D$ +436° (*c* 0.25, $CHCl_3$); R_f 0.32 (hexane/ethyl acetate 1:1); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.05 (m, 3H, CH_3), 3.11 (dd, 1H, ^2J = 16.8 Hz, J = 3.3 Hz, H_4), 3.44 (dd, 1H, ^2J = 16.8 Hz, J = 9.2 Hz, H_4), 3.95 (m, 1H, H_{3a}), 5.96 (d, 1H, J = 7.8 Hz, H_{8b}), 6.18 (m, 1H, OC*H*O D-ring), 6.97 (m, 1H, =C*H* D-ring), 7.23−7.36 (m, 3H, Ar *H*), 7.48 (d, 1H, ^4J = 2.5 Hz, =C*H*O), 7.51 (d, 1H, J = 7.1 Hz, Ar *H*); MS [EI, *m*/*z*, rel intensity (%)] 298 ([M]$^+$, 0.4), 201 ([$C_{12}H_9O_3$]$^+$, 39.3), 97 ([$C_5H_5O_2$]$^+$, 100). Anal. Calcd for $C_{17}H_{14}O_5$: C, 68.45; H, 4.73. Found: C, 68.22; H, 4.63.

*ent **2b**:* obtained as colorless crystals; mp 133.5−134.5 °C; $[\alpha]_D$ +273° (*c* 0.2, $CHCl_3$); R_f 0.24 (hexane/ethyl acetate 1:1); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.05 (m, 3H, CH_3), 3.10 (dd, 1H, ^2J = 16.9 Hz, J = 3.1 Hz, H_4), 3.42 (dd, 1H, ^2J = 16.9 Hz, J = 9.3 Hz, H_4), 3.94 (m, 1H, H_{3a}), 5.96 (d, 1H, J = 7.9 Hz, H_{8b}), 6.17 (m, 1H, OC*H*O D-ring), 6.96 (m, 1H, =C*H* D-ring), 7.23−7.36 (m, 3H, Ar *H*), 7.48 (d, 1H, ^4J = 2.5 Hz, =C*H*O), 7.50 (d, 1H, J = 7.5 Hz, Ar *H*); mass data were the same as for **2a**. Anal. Calcd for $C_{17}H_{14}O_5$: C, 68.45; H, 4.73. Found: C, 68.31; H, 4.68.

*3-[4-Methyl-5-oxo-2,5-dihydrofuran-2(R)-yloxymethylene]-3,3a(S),4,8b(R)-tetrahydroindeno[1,2-b]furan-2-one (**2b**) and Its 2′(S)-Epimer (ent **2a**).* These compounds were prepared according to the general procedure, starting from lacone *ent* **4** (186 mg, 1.07 mmol) to give **2b** (yield = 33%) and *ent* **2a** (yield = 27%). Analytically pure samples were obtained by crystallization from hexane/ethyl acetate.

***2b**:* obtained as colorless crystals; mp 133.5−134 °C; $[\alpha]_D$ −272° (*c* 0.2, $CHCl_3$). Anal. Calcd for $C_{17}H_{14}O_5$: C, 68.45; H, 4.73. Found: C, 68.26; H, 4.66. ^{1}H-NMR and mass data were the same as for compound *ent* **2b**.

*ent **2a**:* obtained as colorless crystals; mp 152.5−154.5 °C; $[\alpha]_D$ −446° (*c* 0.25, $CHCl_3$). Anal. Calcd for $C_{17}H_{14}O_5$: C, 68.45; H, 4.73. Found: C, 68.12; H, 4.67. ^{1}H-NMR and mass data were the same as for compound **2a**.

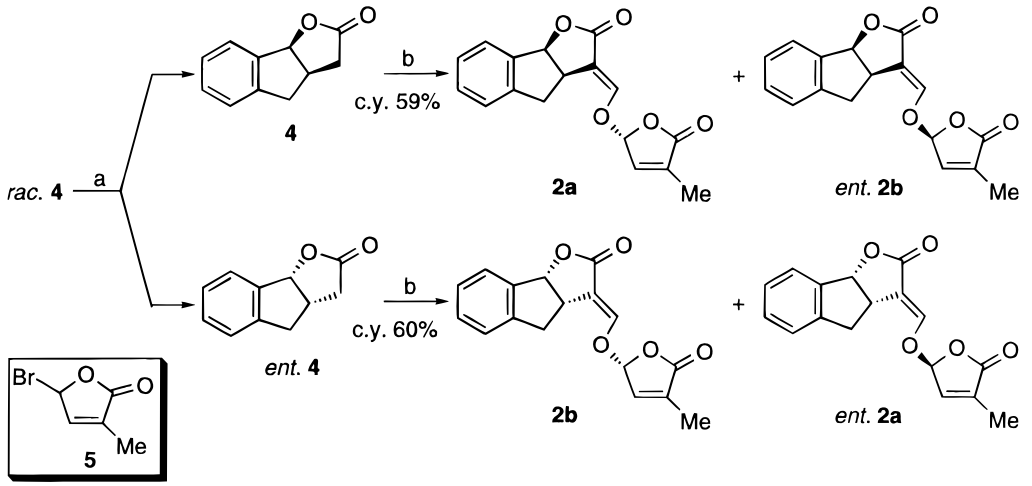
Determination of Enantiopurities. ^{1}H-NMR (400 MHz) analysis of racemic mixtures of diastereomers **2a** and **2b** with optical shift reagent Eu(hfc)$_3$ (0.5 equiv) revealed a downfield shift for all resonances, with a prominent 1:1 splitting of the signal for the enol ether proton (=C*H*−O), amounting to 0.35 ppm. ^{1}H-NMR (400 MHz) spectra of pure compounds **2a,b** and *ent* **2a,b** displayed comparable shifts on treatment with Eu(hfc)$_3$, but in contrast to the racemates, no splitting of signals was observed, indicating an enantiopurity of at least 98%.

*3-[6(S)-Methyl-5-oxo-4-oxatricyclo[5.2.1.0^{2,6}]dec-8-en-3(R)-yloxymethylene]-3,3a(R),4,8b(S)-tetrahydroindeno[1,2-b]furan-2-one (**7a**) and Its 3a(S),8b(R) Diastereomer (**7b**).* To a stirred suspension of NaH (139 mg, 3.48 mmol) in diethyl ether (10 mL) was gradually added a solution of *rac* **4** (300 mg, 1.72 mmol) in diethyl ether (5 mL) at room temperature under nitrogen. Ethyl formate (1.7 mL, 21 mmol) was added, and stirring was continued for 15 h. The solvent was removed *in vacuo*. The thus obtained sodium salt was dissolved in DMF (10 mL). A solution of chlorolactone **6** (372 mg, 1.87 mmol) in DMF (3 mL) was gradually added at room temperature under nitrogen. After 17 h of stirring, the mixture was quenched with acetic acid (0.5 mL) and the solvent was removed *in vacuo*. The residue was dissolved in a mixture of water and ethyl acetate. The aqueous phase was extracted with ethyl acetate (two times), and the combined organic layers were washed with water (two times), dried ($MgSO_4$), and concentrated *in vacuo*. The crude product was purified using flash chromatography (SiO_2, hexane/ethyl acetate 2:1) to afford two diastereomeric products. The fast-moving diastereomer **7a** (222 mg, 35%) was obtained as a white solid, and crystallization from diisopropyl ether/ethyl acetate afforded analytically pure **7a**. The slow-moving diastereomer **7b** (211 mg, 34%) was obtained as a white solid, which gave an analytically pure sample after crystallization from hexane/ethyl acetate.

***7a**:* mp 174−177 °C; $[\alpha]_D$ +276° (*c* 0.1, $CHCl_3$); R_f 0.48 (hexane/ethyl acetate 1:1); ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.61 (s, 3H, CH_3), 1.74 (m, 2H, H_{10}), 2.74 (dd, 1H, J = 4.2 Hz, J < 1 Hz, H_2), 2.91 (m, 1H, H_7), 3.09 (dd, 1H, ^2J = 16.8 Hz, J = 3.8 Hz, CH_2 B-ring), 3.24 (m, 1H, H_1), 3.46 (dd, 1H, ^2J = 16.8 Hz, J = 8.9 Hz, CH_2 B-ring), 3.93 (m, 1H, H_{3a}), 5.23 (d, 1H, J < 1 Hz, H_3), 5.94 (d, 1H, J = 7.8 Hz, H_{8b}), 6.25 (m, 2H, H_8 and H_9), 7.27−7.55 (m, 4H, Ar *H*), 7.40 (d, 1H, ^4J = 2.5 Hz, =C*H*O); MS [EI, *m*/*z*, rel intensity (%)] 364 ([M]$^+$, 0.3), 299 ([$C_{17}H_{15}O_5$]$^+$, 0.3), 203 ([$C_{12}H_{11}O_3$]$^+$, 27.1), 163 ([$C_{10}H_{11}O_2$]$^+$, 93.2), 97 ([$C_5H_5O_2$]$^+$, 100), 66 ([C_5H_6]$^+$, 15.6). Anal. Calcd for $C_{22}H_{20}O_5$: C, 72.52; H, 5.53. Found: C, 72.11; H, 5.46.

***7b**:* mp 192.5−194.5 °C; $[\alpha]_D$ −334° (*c* 0.1, $CHCl_3$); R_f 0.36 (hexane/ethyl acetate 1:1); ^{1}H NMR ($CDCl_3$, 100 MHz) δ 1.63 (s, 3H, CH_3), 1.73 (m, 2H, H_{10}), 2.78 (dd, 1H, J = 3.7 Hz, J < 1 Hz, H_2), 2.91 (m, 1H, H_7), 3.05 (dd, 1H, ^2J = 16.8 Hz, J = 3.5 Hz, CH_2 B-ring), 3.24 (m, 1H, H_1), 3.42 (dd, 1H, ^2J = 16.8 Hz, J = 8.8 Hz, CH_2 B-ring), 3.93 (m, 1H, H_{3a}), 5.24 (d, 1H, J < 1 Hz, H_3), 5.95 (d, 1H, J = 7.9 Hz, H_{8b}), 6.26 (m, 2H, H_8 and

Scheme 1. Resolution of *rac* 4 and Coupling with 5



a) cellulose triacetate chromatography, b) 1. KO*t*Bu, HCO_2Me 2. **5**

H_9), 7.21−7.53 (m, 4H, Ar *H*), 7.39 (d, 1H, $^4J = 2.8$ Hz, =C*H*O); mass data were the same as for **7a**. Anal. Calcd for $C_{22}H_{20}O_5$: C, 72.52; H, 5.53. Found: C, 71.91; H, 5.47.

*3-[6(R)-Methyl-5-oxo-4-oxatricyclo[5.2.1.0^{2,6}]dec-8-en-3(S)-yloxymethylene]-3,3a(R),4,8b(S)-tetrahydroindeno[1,2-b]furan-2-one (ent **7b**) and Its 3a(S),8b(R) Diastereomer (ent **7a**).* These compounds were prepared in the same way as described for **7a** and **7b**, starting from *rac* **4** (302 mg, 1.73 mmol) and chlorolactone *ent* **6** (379 mg, 1.91 mmol). The fast-moving diastereomer *ent* **7a** (202 mg, 32%) was obtained as a white solid, and crystallization from diisopropyl ether/ethyl acetate afforded analytically pure *ent* **7a**. The slow-moving diastereomer *ent* **7b** (215 mg, 34%) was obtained as a white solid, which gave an analytically pure sample after crystallization from hexane/ethyl acetate.

*ent **7a**:* mp 171−173.5 °C; $[\alpha]_D$ −278° (*c* 0.1, $CHCl_3$). Anal. Calcd for $C_{22}H_{20}O_5$: C, 72.52; H, 5.53. Found: C, 72.58; H, 5.45. ^{1}H-NMR and mass data were the same as for compound **7a**.

*ent **7b**:* mp 193−193.5 °C; $[\alpha]_D$ +340° (*c* 0.1, $CHCl_3$). Anal. Calcd for $C_{22}H_{20}O_5$: C, 72.52; H, 5.53. Found: C, 72.17; H, 5.53. ^{1}H-NMR and mass data were the same as for compound **7b**.

*Cycloreversion of Adducts **7a,b** and ent **7a,b**.* A solution of the enantiopure cycloadduct **7** (93 mg, 0.26 mmol) in *o*-dichlorobenzene (40 mL) was heated at 180 °C for 14 h. The solvent was removed *in vacuo*. The residue was purified by flash chromatography (SiO_2, hexane/ethyl acetate 2:1) to give the corresponding enantiomer of **2** (44 mg, 58%) as a solid. All enantiomers of **2** prepared via this procedure showed identical physical and chiroptical properties as described above.

Biological Activity. *Seeds.* Seeds of *Striga hermonthica* [from *Sorghum bicolor* (L.) Moench] and *Orobanche crenata* (from *Vicia faba* L.) were harvested in Burkina Faso in 1994 and in Egypt in 1991, respectively, and were stored in the dark at room temperature until use in germination tests. Bioassays were carried out essentially following the procedure of Mangnus *et al.* (1992b) with minor modifications. Only analytically pure samples as judged from correct elemental analyses were used in these experiments.

Preparation of Test Solutions. A compound to be tested was weighed out very accurately to the amount of 2.5 mg, dissolved in 5 mL of acetone p.a., and diluted with demineralized water to 25 mL. Aliquots of this stock solution were further diluted with water to obtain test solutions containing 1, 0.5, 0.1, 0.05, and 0.001 mg/L test compound and 0.2, 0.1, 0.02, 0.01, and 0.0002% (v/v) acetone, respectively.

Bioassays. For surface sterilization seeds of *S. hermonthica* were subsequently exposed to 70% (v/v) ethanol for 5 min and sodium hypochlorite (2% active chlorine) for 2 min with agitation. Seeds of *O. crenata* were exposed to an aqueous solution of sodium hypochlorite (2% active chlorine) for 5 min with agitation. The seeds were then thoroughly rinsed with water and dried.

For conditioning the sterilized seeds were spread on glass fiber filter paper disks (8-mm diameter; approximately 30−70 seeds per disk) in Petri dishes, each containing two disks (*Striga*) or four disks (*Orobanche*), wetted with water, and stored in the dark for 14 days at 20 °C for *Orobanche* seeds and at 30 °C for *Striga* seeds. Then the conditioning water was removed and replaced by 100 μL of test solution per disk (*Orobanche*) or 3 mL per Petri dish (*Striga*). After incubation for 24 h (*Striga*) and 5 days (*Orobanche*) in the dark at the indicated temperatures, the germination percentage was determined under a microscope. Seeds were considered to be germinated if the radical protruded through the seed coat.

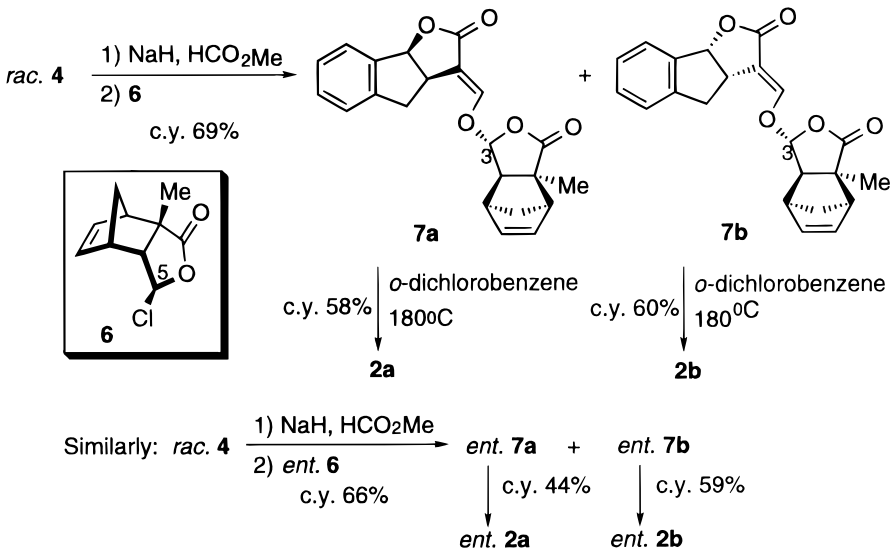
In each test series aqueous solutions with 0.2% (v/v) acetone were used as negative control. Test solutions of a 1:1 diastereomeric mixture of GR24 at the same concentrations were used as positive controls. All tests were performed in duplicate, and in each test the germination percentages were determined on 6 disks (*Striga*) or 12 disks (*Orobanche*) per treatment.

RESULTS AND DISCUSSION

Synthesis. To achieve the resolution of GR24 (**2**), two synthetic approaches were considered. The first approach (Scheme 1) involves the separation of tricyclic lactone *rac* **4** into its enantiomers, followed by formylation and coupling of the individual enantiomers with racemic 5-bromofuranone (**5**) in an analogous manner as described previously for the racemic preparation of GR24 (Mangnus *et al.*, 1992a).

Tricyclic lactone *rac* **4** was chromatographically resolved using cellulose triacetate (CTA) as the chiral stationary phase. It has been demonstrated that a wide variety of racemic γ- and δ-lactones can be separated by column chromatography on the chiral phase CTA, on both analytic and preparative scales (Francotte and Lohmann, 1987). In the present case 500 mg of *rac* **4** was resolved by "flash" chromatography at a pressure of *ca.* 1.2 bar, using 50 g of CTA and 95% ethanol as the eluent, in a total recovery of enantiopure tricyclic lactones **4** and *ent* **4** of 68%. The enantiopurity of **4** and *ent* **4** was assessed by HPLC, using cellulose carbamate as the chiral stationary phase. The diastereomeric mixtures obtained after formylation and coupling of **4** and *ent* **4** with **5** (Scheme 1) were both separated by flash chromatography (SiO_2) to give **2a**, *ent* **2b** and **2b**, and *ent* **2a** (ee values > 98%) in total isolated yields of 59% and 60%, respectively. The ee values were determined by ^{1}H NMR using the chiral shift reagent $Eu(hfc)_3$.

Scheme 2. Coupling Reactions of *rac* 4 with 6 and *ent* 6 and Cycloreversion



In the second approach the complete resolution of GR24 (**2**) was accomplished by formylation of *rac* **4**, followed by coupling with the homochiral latent D-rings **6** and *ent* **6**, respectively (Scheme 2).

The asymmetric syntheses of **6** and *ent* **6**, together with their application in the preparation of all four homochiral diastereomers of GR7 (**3**), have recently been described (Thuring *et al.*, 1995). The sequence as outlined in Scheme 2 gave the cycloadducts **7a** and **7b** and their corresponding enantiomers in diastereomeric ratios of approximately 1:1. These reactions proceeded with complete stereocontrol as no signals arising from the respective C_3-epimers could be detected in the NMR spectra. Cycloreversion by heating the homochiral adducts of **7** in *o*-dichlorobenzene at 180 °C afforded the corresponding enantiopure stereoisomers of GR24 (**2**), which have the same $[\alpha]_D$ values as those prepared by the route depicted in Scheme 1. It was essential to control the reaction temperature and time carefully to avoid concomitant epimerization at $C_{2'}$ of **2**.

Determination of Absolute Configuration. It was attempted to establish the absolute configuration of the GR24 (**2**) stereoisomers by comparison of their circular dichroism (CD) spectra with those of the corresponding stereoisomers of strigol **1**, which have been reported (Heather *et al.*, 1976; Frischmuth *et al.*, 1993). However, such a correlation is not reliable, because GR24 (**2**) has a different ABC-chromophore. Therefore, an X-ray diffraction analysis of **2a** was undertaken (Moers *et al.*, 1995) to establish its absolute configuration. A stereoview of **2a** is depicted in Figure 2. With the absolute configuration of **2a** known, the configuration of the remaining stereoisomers could be assigned on the basis of the synthetic sequence.

Biological Activity. The germination stimulatory activity of all stereoisomers of GR24 **2a,b** and *ent* **2a,b** was assayed using seeds of *S. hermonthica* and *O. crenata*. In each bioassay a diastereomeric mixture of GR24 was included as a positive control. In preliminary experiments the concentration-dependent activity range (GR24) of seeds of *S. hermonthica* has been established. Maximal germination percentages were obtained within the concentration range 0.01−1 mg/L. Half-maximal activity was observed at approximately 0.001 mg/L (data not shown). The relative bioactivity of the individual stereoisomers of GR24 was therefore assayed at an optimal concentration (0.1 mg/L) and at a sensitive concentration (0.001 mg/L). It was anticipated that the latter should exhibit more profound differences. Relevant data are collected in Table 1.

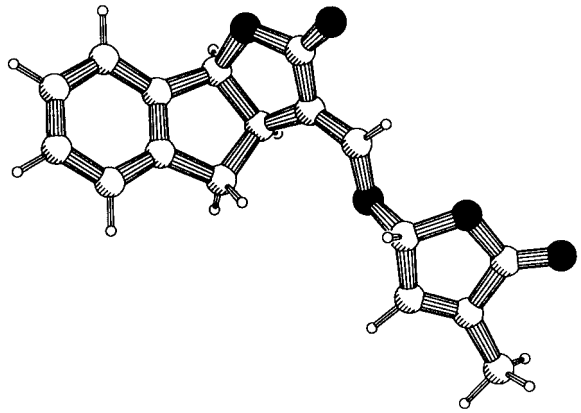


Figure 2. PLUTON-generated drawing of X-ray crystal structure of **2a**.

Table 1. Germination Percentages for Seeds of *S. hermonthica* after Exposure to Solutions (0.1 and 0.001 mg/L) of GR24 Enantiomers 2 and the Corresponding Racemic Mixture of Diastereomers *rac* 2[a]

entry	compound	configuration at C-2′	at 10^{-1} mg/L	at 10^{-3} mg/L
1	**2a**	*R*	56.2 ± 4.6	32.5 ± 4.5
2	*ent* **2b**	*S*	40.8 ± 2.5	0.7 ± 0.4[b]
3	*ent* **2a**	*S*	4.0 ± 0.6	0.5 ± 0.5[b]
4	**2b**	*R*	54.0 ± 2.6	0.4 ± 0.4[b]
5	*rac* **2**[c]	*R*/*S*	47.1 ± 3.9	33.2 ± 2.2

[a] The data presented ± SE are from one representative experiment. [b] Not significantly different from aqueous control (without stimulant). [c] Equimolar mixture of two racemic diastereomers.

The same stereoisomers were also tested for stimulant activity on seeds of *O. crenata*, using four concentrations. The results are shown in Figure 3.

These data (Table 1; Figure 3) reveal that there is a significant difference in stimulatory activity among the four stereoisomers. For both parasitic species, the enantiomer of GR24 possessing the "natural" absolute stereochemistry, *viz.* **2a**, is considerably more active than its optical antipode *ent* **2a**. The difference in activity amounts to at least a factor of 100. The relative importance of the different stereogenic centers can be addressed by comparison of the bioactivities of the

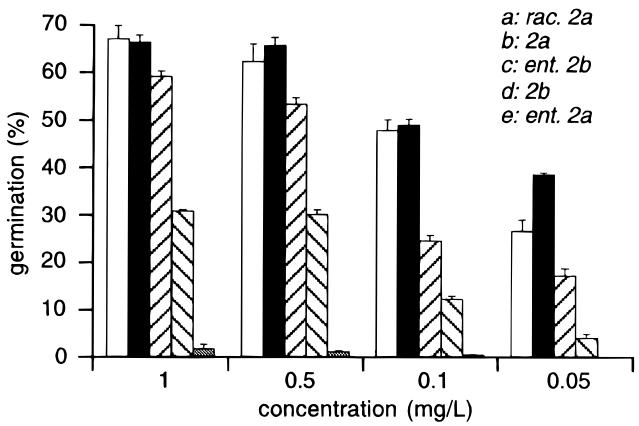


Figure 3. Germination percentages for seeds of *O. crenata* after exposure to different concentrations of GR24 enantiomers **2**. The data presented ± SE are from one single representative experiment.

$C_{3a}C_{8b}$-epimer **2b** and the $C_{2'}$-epimer *ent* **2b**. The data in Table 1 (entries 2 and 4) reveal in the case of *S. hermonthica* a slight preference for the correct stereochemistry at $C_{2'}$. In contrast, the data obtained for *O. crenata* (Figure 3) suggest that for this species the absolute configuration at $C_{3a}C_{8b}$ is more important for the stimulatory activity than the configuration at $C_{2'}$. This result is in contrast with data obtained from a comparative study of GR7 stereoisomers, which revealed a more profound role of the $C_{2'}$-configuration (Mangnus and Zwanenburg, 1992). This discrepancy indicates that one cannot attribute the configuration of a particular stereogenic center as solely relevant for the biological activity by disregarding the entire three-dimensional structure. Because GR7 lacks the A-ring, its smaller BC-part is apparently more flexible with respect to interactions within the receptor cavity. This implies a less critical requirement for its absolute configuration in comparison with the ABC-fragment of GR24.

Concluding Remarks. Two routes for the asymmetric synthesis of all four stereoisomers of GR24 have been presented. The route that requires the homochiral latent D-rings **6** and *ent* **6** is generally applicable in the enantioselective synthesis of strigol analogues. The relative importance of the absolute configuration at the different stereogenic centers in GR24 for the germination stimulatory activity has been assessed, indicating that the molecular shape is determined by the combination of all stereocenters.

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