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Nuclear Magnetic Resonance Spectroscopic Study on the Structure of Two Stereoisomeric Oxygenated Dimers of 3-Methylindole, 5aβ(*H*),11aα(*H*)-12-Hydroxy-10bβ,12-dimethyl-5a,10b,11a,12-tetrahydro-6*H*-oxazolo-[3,2-*a*:4,5-*b*′]diindole

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The oxygenated dimer (**2a**) of 3-methylindole, which was isolated from the reaction mixture obtained by oxygenation of 3-methylindole in the presence of *N,N*′-(*cis*-1,2-cyclohexylene)bis(3-*tert*-butylsalicylideneaminato)cobalt(II) in chloroform, was shown to be the stereoisomer of 5aβ(*H*),11aα(*H*)-12β-hydroxy-10bβ,12α-dimethyl-5a,10b,11a,12-tetrahydro-6*H*-oxazolo[3,2-*a*:4,5-*b*′]diindole (**1a**) with inverted configuration at the C_{12} atom, on the basis of ^{1}H- and ^{13}C-nuclear magnetic resonance (NMR) spectroscopic and chemical evidence. Kinetic parameters of restricted rotation about the amide bond in *N*-acetylated derivatives of **1a** and **2a** calculated from their dynamic NMR spectra were $\Delta H^{\neq}_{298} = 20.2 \pm 0.2$ and $\Delta S^{\neq}_{298} = +7.8 \pm 0.5$ for the former, and $\Delta H^{\neq}_{298} = 19.7 \pm 0.2$ kcal mol^{-1} and $\Delta S^{\neq}_{298} = +5.9 \pm 0.6$ cal K^{-1} mol^{-1} for the latter. Acid decomposition of both dimers, **1a** and **2a**, afforded 3,3′-dimethyl-1-(2′-indolyl)-oxindole, resulting from ring cleavage at the ether bond followed by dehydration.

Keywords——3-methylindole; oxygenation; dimerization; 6*H*-oxazolo[3,2-*a*:4,5-*b*′]diindole; 1-(2′-indolyl)oxindole; ^{1}H-NMR; ^{13}C-NMR; dynamic NMR

Oxygenation of 3-substituted indoles catalyzed by various transition metal complexes has been of interest in connection with the action of tryptophan-2,3-dioxygenase.[1] We have studied the catalytic oxygenation of 3-methylindole using derivatives of *N,N*′-ethylenebis(salicylideneaminato)cobalt(II), Co(salen), as catalysts.[2] In the previous paper,[3] the isolation and structure determination of an oxygenated dimer of 3-methylindole which was produced in the presence of a sterically crowded Co(salen) derivative, *N,N*′-(*cis*-1,2-cyclohexylene)bis(3-*tert*-butylsalicylideneaminato)cobalt(II), were reported. The dimer was determined to be 5aβ(*H*),11aα(*H*)-12β-hydroxy-10bβ,12α-dimethyl-5a,10b,11a,12-tetrahydro-6*H*-oxazolo[3,2-*a*:4,5-*b*′]diindole (**1a**), which has a novel ring system. We also isolated another dimeric product (**2a**) of 3-methylindole which showed spectral properties closely related to those of **1a**.

The present paper reports the structure of **2a**, the results of acid decomposition of both **1a** and **2a**, comparisons of their spectral properties, and the temperature dependency of ^{1}H-nuclear magnetic resonance (NMR) signals of their *N*-acetylated derivatives.

Results and Discussion

3-Methylindole was oxygenated in chloroform under oxygen in the presence of *N,N*′-(*cis*-1,2-cyclohexylene)bis(3-*tert*-butylsalicylideneaminato)cobalt(II) at 25 °C. The reaction mixture was chromatographed on a silica-gel column. Besides unreacted 3-methylindole and 2-formylaminoacetophenone as the main product, two oxygenated dimers of 3-methylindole

which showed similar spectral properties to each other were isolated in 5 and 6% yields. One of the dimers was eluted faster than the other on chromatography.[4] X-Ray crystal structure determination of the acetylated derivative of the former revealed it to be **1b**.[3] The latter was determined to be **2a** as described hereinafter.

Properties of 2a

The high-resolution mass spectrum (MS) of **2a** showed a molecular ion at *m/e* 294.1364 which is in agreement with the molecular formula of $C_{18}H_{18}N_2O_2$ (M^+_{calcd}=294.1369). The chemical ionization (CI) MS of **2a** showed a quasimolecular ion (MH^+) at *m/e* 295 and confirmed that *m/e* 294 is the molecular ion for **2a**. Thus, **2a** was proved to be composed of two molecules of 3-methylindole and one molecule of oxygen, the same composition as that of **1a**. The infrared (IR) spectrum of **2a** showed the presence of O–H (3600 cm^{-1}) and N–H (3440 cm^{-1}). The ^1H- and ^{13}C-NMR spectral data for both **1a** and **2a** are summarized in Tables I through III, along with those of their acetylated derivatives. They had the same characteristic features, indicating that two molecules of the parent 3-methylindole were unsymmetrically combined. From these results, it is concluded that the dimers **2a** and **1a** have the same skeletal structure. Furthermore, the acid decomposition of both dimers yielded an identical product (*vide infra*).

Therefore, possible structures for the present dimer are limited to **2a** through **4** (Chart 1), all of which have *cis*-fused five-membered rings (either the BC or CD rings). *trans*-Fusion of two five-membered rings can be ruled out on the basis of internal strain energy.[5] Compound

TABLE I. ^1H-NMR Spectral Data for **1a**, **1b**, **2a**, and **2b** in $CDCl_3$[a]

Proton	**1a**	**1b**[b]	**2a**	**2b**[b]
CH_3	1.44 (s)	1.45 (s)	1.52 (s)	1.56[c] (s)
	1.55 (s)	1.59[c] (s)	1.64 (s)	1.67 (s)
CH_3–CO		2.57 (s)		2.54[c] (s)
O–H	3.08 (br s)	3.00 (br s)	2.16 (br s)	2.24 (br s)
N–H	4.42 (br s)		4.36 (br s)	
H-C_{11a}	4.69 (s)	4.61[c] (s)	4.68 (s)	4.70[c] (s)
H-C_{5a}	5.10 (s)	5.54, 5.71 (each br s, 1H (*ca.* 3:1))	4.87 (s)	5.43, 5.62 (each br s, 1H (*ca.* 7:4))
Arom. H	6.65—7.41 (m, 8H)	6.95—7.44 (m, 7H)	6.54—7.25 (m, 8H)	6.96—7.63 (m, 7H)
		8.31[d] (br d, *ca.* 1H)		8.25[d] (br d, *ca.* 1H)

a) The concentrations of samples were as follows: **1a**, 0.16; **1b**, 0.17; **2a**, 0.12; **2b**, 0.07 mol dm^{-3}. *b*) Measured at about 28 °C. *c*) These signals split into two signals on lowering the temperature. *d*) J=8 Hz. The signals are assigned to H-C_7.

TABLE II. ^{13}C-NMR Spectral Data for Non-aromatic Carbons in **1a**, **1b**, **2a**, and **2b** in $CDCl_3$

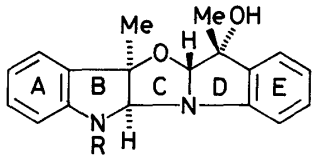
Carbon	**1a**	**1b**	**2a**	**2b**[a]	**2b**[b]
C_{5a}	88.5	89.1	86.5	87.3	86.4
C_{10b}	90.3	88.1	90.3	88.1	(86.5)
C_{11a}	100.3	100.0	103.0	102.4	102.9
C_{12}	77.2	77.3	78.8	78.3	78.9
$\underline{C}H_3$-C_{10b}	24.2	24.6[c]	24.1	24.7[c]	24.7[c]
$\underline{C}H_3$-C_{12}	26.0	25.4[c]	20.1	20.0	20.0
$\underline{C}H_3$–CO		24.9[c]		24.8[c]	24.8[c]
CH_3–$\underline{C}O$		169.7		169.8	169.8

a) Major conformer. *b*) Minor conformer. *c*) Assignments may be interchanged in each column.

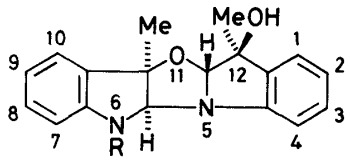
TABLE III. ^{13}C Chemical Shifts and Tentative Assignments for Aromatic Carbons in **1a**, **1b**, **2a**, and **2b** in $CDCl_3$

Carbon	**1a**	**1b**	**2a**	**2b**[a]	**2b**[b]
C_1	123.9[c]	123.9[c]	123.6[c]	123.8[c]	123.1[c]
C_2	122.2[d]	123.0[c]	121.8[d]	122.6[c]	122.2[c]
C_3	129.3[e]	129.5[d]	129.9[e]	130.3	—[h]
C_4	112.1[f]	111.0	112.3[f]	111.1	—[h]
C_{4a}	148.8[g]	147.8	151.0[g]	150.1	151.1
C_{6a}	149.5[g]	142.6	149.6[g]	142.7	141.0
C_7	109.5[f]	116.7	109.6[f]	116.7	113.8
C_8	130.1[e]	130.4[d]	130.1[e]	130.3	—[h]
C_9	119.5[d]	124.5[c]	119.5[d]	124.4[c]	125.2[c]
C_{10}	124.4[c]	124.4[c]	124.2[c]	124.2[c]	—[h]
C_{10a}	128.4	130.2	128.7	130.6	—[h]
C_{12a}	135.2	135.5	134.0	134.2	133.7

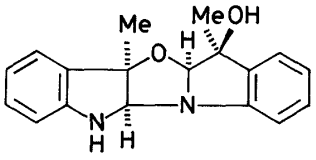
a) Major conformer. *b*) Minor conformer. *c*—*g*) Assignments may be interchanged in each column. *h*) Signal not observed.



1a : R=H
1b : R=Ac



2a : R=H
2b : R=Ac



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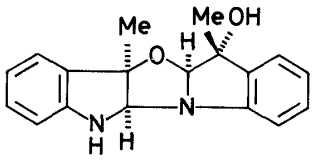

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Chart 1

2a has a structure in which the configuration at C_{12} is inverted from that of **1a**. Compounds **3** and **4** have a *cis–syn–cis* structure for the three consecutive five-membered rings and they differ from each other in the configuration at C_{12}.

Acetylation of 2a

Dimer **2a** was acetylated with acetic anhydride in pyridine at 50 °C. The formation of the *N*-acetylated derivative (**2b**) was confirmed by high-resolution MS, ^1H- and ^{13}C-NMR spectra, the absorptions of O–H stretching (3600 cm^{-1}) and C=O stretching (1670 cm^{-1}), and disappearance of the N–H stretching absorption of **2a**. The ^1H-NMR spectrum of **2b** showed temperature dependency as described later.

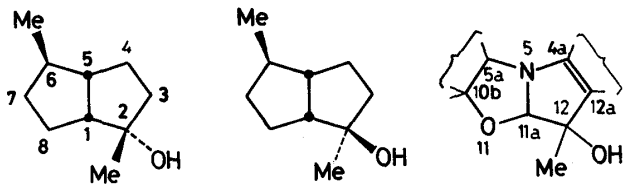
^1H- and ^{13}C-NMR Spectra of 2a and 2b

The assignments of ^1H- and ^{13}C-NMR signals of **1a** and **1b** have been described in the previous paper.[3] The same treatment for **2a** and **2b** leads to the assignments shown in Tables I, II, and III.

In the ^{13}C-NMR spectra, the differences in chemical shifts for the corresponding nuclei between **1a** and **2a**, and those between **1b** and **2b** ($\Delta\delta$(**2a**−**1a**), $\Delta\delta$(**2b**−**1b**)) are large at the

following nuclei: $\underline{C}H_3$-C_{12}, (−5.9, −5.4); C_{11a}, (+2.7, +2.4); C_{12}, (+1.6, +1.0); C_{12a}, (−1.2, −1.3); C_{4a}, (+2.2, +2.3); and C_{5a}, (−2.0 ppm, −1.8 ppm). These sites are next to N_5 for C_{4a}, C_{5a}, and C_{11a}, or in the D ring for the rest. Whitesell and Matthews have reported the substituent effects on ^{13}C chemical shifts of bicyclo[3.3.0]octane derivatives,[6] and two geometrical isomers of 2-hydroxy-2,6-dimethyl-*cis*-bicyclo[3.3.0]octane, **5** and **6**, have analogous arrangements to those of the CD rings in **1a** and **2a**, respectively (Chart 2). The differences in ^{13}C chemical shifts between **5** and **6**, $\Delta\delta$(**6**−**5**), are −4.9, +2.8, +2.5, −2.4, and +2.1 ppm for $\underline{C}H_3$-C_2, C_1, C_2, C_3, and C_4, respectively. These values are in fairly good agreement with the differences in the ^{13}C chemical shifts between **1** and **2** described above. Thus, the configuration at C_{12} of **2a** should be inverted from that of **1a**.

A remarkable difference in chemical shift was observed for the hydroxyl proton of HO-C_{12}. The signals for **2a** and **2b** resonate at higher field by 0.92 and 0.76 ppm than those for **1a** and **1b**, respectively. Though an intermolecular hydrogen bonding between the acetyl C=O and HO-C_{12} was observed in the crystal of **1b**,[3] an intramolecular hydrogen bonding between HO-C_{12} and O_{11} plays some role in $CDCl_3$ solution, because a hydrogen-bonding proton shows a downfield shift.[7] This also accounts for the difference in adsorption of **1a** and **2a** on silica-gel in column chromatography.



5 6 1,2

Chart 2

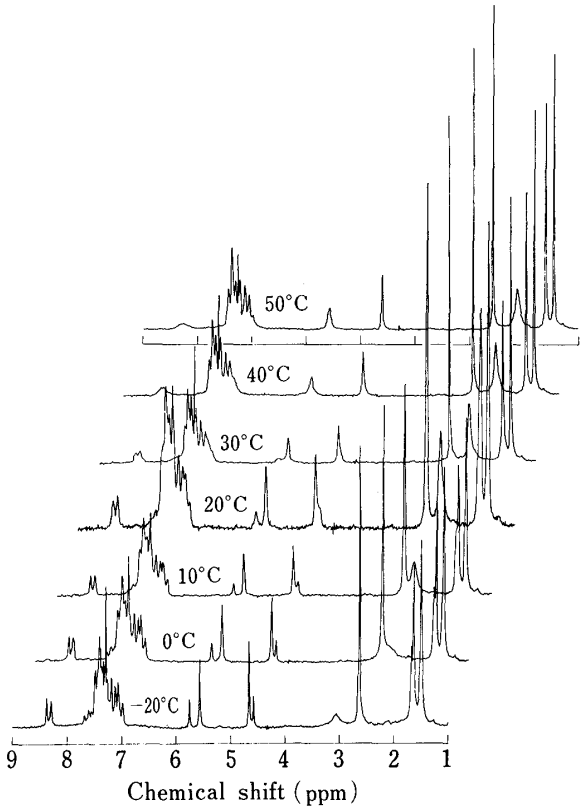


Fig. 1. Temperature-Dependent ^1H-NMR Spectra of **1b** in $CDCl_3$

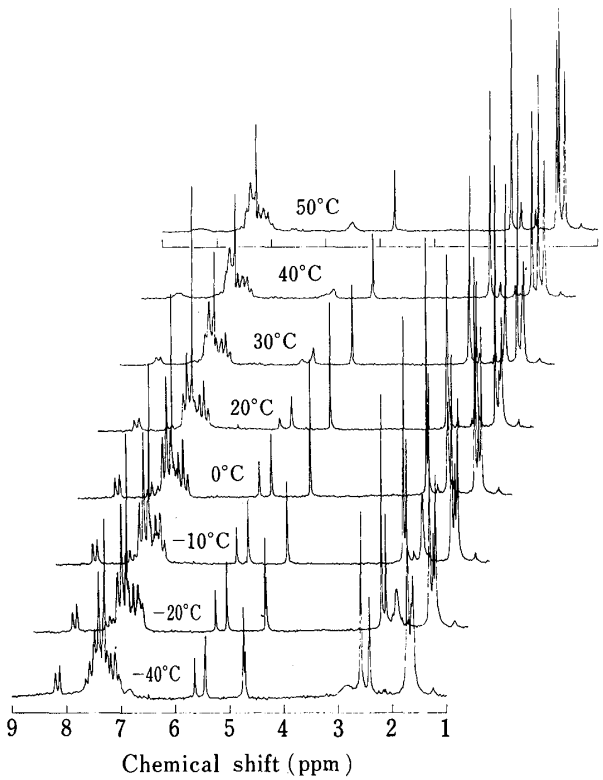


Fig. 2. Temperature-Dependent ^1H-NMR Spectra of **2b** in $CDCl_3$

However, the above-mentioned NMR data as well as other spectral data are equivocal as regards whether **2a** has a *cis–anti–cis* or a *cis–syn–cis* structure about the three successive five-membered rings. The *cis–syn–cis* structure would result in severe stereochemical congestion and the rotation barrier about the CH_3CO–N bond would be large in contrast to the observed result described below.

Temperature-Dependent NMR Spectra of 1b and 2b

The ^{1}H-NMR spectra of **1b** and **2b** in $CDCl_3$ at various temperatures are shown in Figs. 1 and 2, respectively. The temperature-dependent ^{1}H-NMR spectrum of **1b** has been reported previously.[3] The characteristics of the change in the ^{1}H-NMR spectrum of **2b** with change in temperature are described below compared to those at 28 °C (shown in Table I).

Two broad singlets due to H-C_{5a} at 5.43 and 5.62 ppm coalesced at 50 °C giving a broad singlet at 5.48 ppm. The singlet due to H-C_{11a} at 4.70 ppm split into two singlets at 4.70 and 4.72 ppm at −20 °C. One of the methyl singlets at 1.56 ppm split into two singlets at 1.57 and 1.62 ppm at 0 °C. This signal is assignable to CH_3-C_{10b}. The acetyl methyl singlet at 2.54 ppm split into two singlets at 2.54 and 2.58 ppm at 0 °C and the high-field side signal moved upfield on lowering the temperature, while **1b** showed no temperature dependency for the corresponding acetyl group. The doublet due to H-C_7 at 8.25 ppm showed line broadening on raising the temperature.

The temperature dependency described above is concluded to arise from restricted rotation of the acetyl group, as observed for **1b**,[3] because (a), no broadening of the signals due to H-C_{5a} and H-C_{11a} was observed even at −50 °C in the ^{1}H-NMR spectrum of **2a**; and (b), the activation parameters for the rotation obtained by line-shape analysis were values typical of those for various amide systems.[8] The predominant conformer is expected to have the C=O group oriented toward the A ring.[9] From the separated signals for H-C_{5a}, the ratios of the minor conformer to the major one were determined to be 0.26 : 0.74 and 0.35 : 0.65 for **1b** and **2b**, respectively. These values were almost constant between 20 and −40 °C.

In the ^{13}C-NMR spectrum of **2b**, several signals were accompanied by a small signal due to the minor conformer (Tables II and III), whereas we could detect only one signal of the minor conformer which could be assigned to C_7 in the ^{13}C-NMR spectrum of **1b**.[3] This

TABLE IV. Kinetic Parameters of Restricted Rotation about the Amide Bond in **1b** and **2b**[a]

	1b	**2b**
E_a/kcal mol^{-1}	20.8±0.2	20.3±0.2
log A	14.9±0.1	14.5±0.1
$\Delta H^{\neq}_{298}$/kcal mol^{-1}	20.2±0.2	19.7±0.2
$\Delta S^{\neq}_{298}$/cal K^{-1} mol^{-1}	+7.8±0.5	+5.9±0.6
$\Delta G^{\neq}_{298}$/kcal mol^{-1}	17.9±0.3	17.9±0.3

a) Determined by ^{1}H-dynamic NMR in $CDCl_3$.

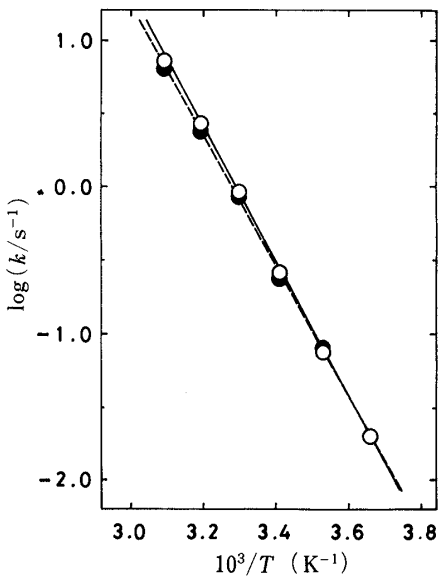


Fig. 3. Arrhenius Plots for the Rates of Restricted Rotation about the Amide Bond in **1b** and **2b** in $CDCl_3$

1b, ○; **2b**, ●

difference in the ^{13}C-NMR spectra of **1b** and **2b** is ascribed to the higher abundance of the minor conformer of **2b** than that of **1b**, and partly to poorer resolution of the spectrum for **1b**.

The rate constants of the restricted rotation were obtained by the application of curve-fitting analysis assuming a two-site exchange for the signal(s) of H-C_{5a}, and the Arrhenius plots (Fig. 3) showed that the $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values were similar in **1b** and **2b**, as listed in Table IV. These kinetic parameters are in agreement with those for the restricted rotation of an amide group: the values for *N*,*N*-dimethylbenzamide (in $CDCl_3$)[10a] and *N*,*N*-dimethylacetamide (in acetone-d_6)[10b] have been reported as $\Delta H^{\neq}_{298} = 16.8$ and 19.0 kcal mol^{-1}, and $\Delta S^{\neq} = 3.7 \pm 0.2$ and 3.1 ± 2 cal K^{-1} mol^{-1}, respectively.

Reaction Path Leading to the Formation of 1a and 2a

We have proposed that the formation of **1a** occurs by dimerization of 3-hydroxy-3-methyl-3*H*-indole,[3] which can lead to bond formation between the nitrogen center of one 3-methylindole molecule and the 2-position of the other. In this route, four isomers, **1a**, **2a**, **3**, and **4**, are expected to form, but the *cis–syn–cis* structure (**3** and **4**) should be thermodynamically more unstable than the *cis–anti–cis* one (**1a** and **2a**), so that **3** and **4** are unlikely to form. Two possible paths for the dimerization of the 3-hydroxyindolenine, previously proposed,[3] are consistent with the structures of the two isomeric dimers **1a** and **2a**.

Acid Decomposition of the Oxygenated Dimers

Both **1a** and **2a** yielded 3,3′-dimethyl-1-(2′-indolyl)oxindole (**7**) on treatment with dilute hydrochloric acid in ethanol at room temperature. The structure of **7** was determined based on the following findings. (i) The molecular ion at *m/e* 276.1266 (high-resolution MS) is in agreement with the value of 276.1263 for $C_{18}H_{16}N_2O$. (ii) The presence of N–H (3480 cm^{-1}) and C=O (1725 cm^{-1}) was detected in the IR spectrum, and the latter absorption is close to that of 3-methyloxindole (1715 cm^{-1}). (iii) Two methyl resonances, a doublet (1.59 ppm, J = 7 Hz) and a singlet (2.17 ppm), were observed in the ^{1}H-NMR spectrum, and the latter can be assigned to the methyl group attached to the indole heterocyclic ring. (iv) Two singlet signals of sp^2 carbons, assigned to $C_{3'}$ and $C_{2'}$, were observed at 107.6 and 130.0 ppm in the ^{13}C-NMR spectrum.

The dimer **2a** was also found to form **7** on treatment with acid, although in poor yield. A possible reaction path for the formation of **7**, which involves cleavage of the central five-membered ring at the ether bond followed by dehydration from the generated 1,2-diol, is shown in Chart 3. This reaction sequence involves two *E*2 reactions and will be favored by the

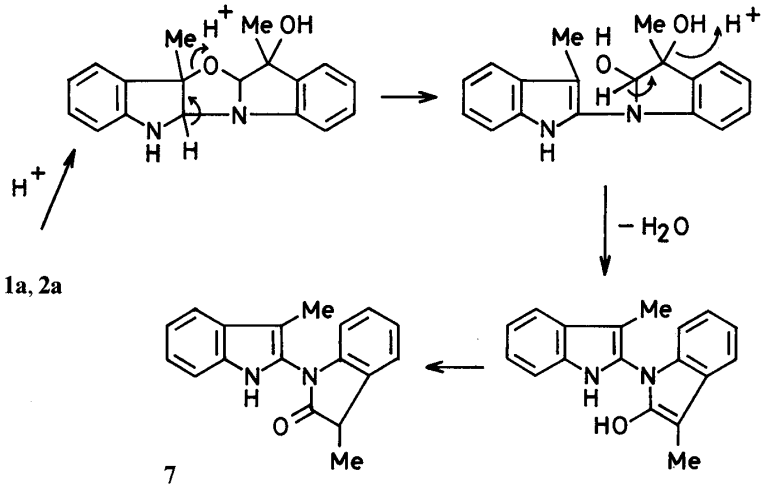


Chart 3

structural features of **1a**: the relative positions of H-C_{5a} and O_{11}, and H-C_{11a} and OH-C_{12} are both *trans*. On the other hand, the relative position of H-C_{5a} and O_{11} is *trans* but that of H-C_{11a} and OH-C_{12} is *cis* in **2a**. This difference in stereochemistry between **1a** and **2a** is correlated to the lower yield of **7** from **2a** (20%) than from **1a** (50%).

Experimental

All the reagents were used as received without further purification. MS were measured on a JEOL JMS-DX300 or a Hitachi M-80A mass spectrometer both operating at 70 eV. IR spectra were obtained with a JASCO IRA-1 spectrophotometer. ^{1}H-NMR spectra were recorded on a JEOL MH-100 or a JEOL FX-100 spectrometer. ^{13}C-NMR spectra were recorded on the JEOL FX-100 spectrometer operated at 25.05 MHz. Typical acquisition parameters were as follows: spectral width 5000 Hz, flip angle 26°, and pulse delay 3—4 s with 8192 data points. All the chemical shifts are reported in δ values relative to internal tetramethylsilane.

Oxygenation of 3-Methylindole and Isolation of 2a——Oxygen was passed through a chloroform solution (220 cm^3) of 3-methylindole (2.5 g, 19 mmol) in the presence of *N,N'*-(*cis*-1,2-cyclohexylene)bis(3-*tert*-butylsalicylideneaminato)cobalt(II) (0.13 g, 0.27 mmol) for 3 h at 25 °C. The reaction products were chromatographed on a silica-gel column with a mixture of hexane and ethyl acetate as the eluent. Yields: 2-formylaminoacetophenone, 0.41 g (14%); **1a**, 0.14 g (5%); **2a**, 0.15 g (6%).[3] This crude product (**2a**) was chromatographed again on a silica-gel column (Wakogel C-200, 3 × 35 cm) using a mixture of hexane and ethyl acetate (3 : 1) to give **2a** as a pale brown solid (96 mg). Attempts to recrystallize the resulting compound were unsuccessful. High-resolution MS *m/e*: 294.1364 (M^+, Calcd for $C_{18}H_{18}N_2O_2$: 294.1369). MS *m/e* (rel. intensity): 294 (M^+, 14), 233 (13), 132 (47), 131 (99), 130 (100). CIMS (isobutane) *m/e* (rel. intensity): 295 (MH^+, 51), 277 (MH^+–H_2O, 43), 208 (17), 148 (46), 132 (48), 131 (100), 130 (60). ^{1}H- and ^{13}C-NMR: Tables I—III. IR ($CHCl_3$): 3600 (ν_{OH}) and 3440 (ν_{NH}) cm^{-1}.

Acetylation of 2a——A mixture of **2a** (34 mg), pyridine (0.40 cm^3), and acetic anhydride (0.20 cm^3) was stirred for 30 min at 50 °C. The mixture was diluted with 9 cm^3 of chloroform, washed three times with water (each in 6 cm^3), dried over sodium sulfate, and concentrated under reduced pressure to give a pale yellow viscous oil (33 mg). This was crystallized from a mixture of chloroform and hexane to afford **2b** as white needles (11 mg). mp 216—218 °C (dec. uncorrected). High-resolution MS *m/e*: 336.1476 (M^+, Calcd for $C_{20}H_{20}N_2O_3$: 336.1475) and 173.0832 (Calcd for $C_{11}H_{11}NO$: 173.0841). MS *m/e* (rel. intensity): 336 (M^+, 3), 173 (66), 131 (100), 130 (33). ^{1}H- and ^{13}C-NMR: Tables I—III. IR ($CHCl_3$): 3590 (ν_{OH}) and 1670 ($\nu_{C=O}$, amide) cm^{-1}.

Acid Decomposition of 1a and 2a——A solution of **1a** (20 mg) in ethanol (5 cm^3) was treated with 0.1 N aqueous hydrochloric acid (1 cm^3), and the mixture was stirred for 21 h at room temperature.[11] Ethanol (10 cm^3) was added to the solution and the whole was concentrated at low temperature. The residue was chromatographed on a silica-gel column (Wakogel C-200, 1.5 × 10 cm) with a mixture of hexane and 2-propanol (25 : 1) to give 9 mg of **7**. High-resolution MS *m/e*: 276.1266 (M^+, Calcd for $C_{18}H_{16}N_2O$: 276.1263) and 233.1062 (Calcd for $C_{16}H_{13}N_2$: 233.1079). MS *m/e* (rel. intensity): 276 (M^+, 100), 249 (46), 233 (77), 147 (64), 130 (65). ^{1}H-NMR ($CDCl_3$) δ: 1.59 (d, 3H, J = 7 Hz, CH_3-C_3), 2.17 (s, 3H, CH_3-$C_{3'}$), 3.64 (q, 1H, J = 7 Hz, CH_3–CH), 6.70 (d, 1H, J = 6 Hz, arom. H), 7.00—7.32 (m, 6H, arom. H). 7.58 (d, 1H, J = 7 Hz, arom. H), 8.15 (br, 1H, NH). ^{13}C-NMR ($CDCl_3$) δ: those assignments marked with * or ** may be interchangeable, 8.6 (q, CH_3-$C_{3'}$), 15.8 (q, CH_3-C_3), 40.7 (d, C_3), 107.6 (s, $C_{3'}$), 109.8 (d, C_7), 111.2 (d, $C_{7'}$), 119.2 (d, $C_{4'}$)*, 119.7 (d, $C_{6'}$)*, 122.9 (d, $C_{5'}$)**, 123.3 (d, C_5)**, 123.9 (d, C_4)**, 124.3 (s, C_{3a}), 128.1 (d, C_6), 128.1 (s, $C_{3a'}$), 130.0 (s, $C_{2'}$), 134.4 (s, $C_{7a'}$), 143.2 (s, C_{7a}), 178.9 (s, C_2). IR ($CHCl_3$): 3480 (ν_{NH}) and 1725 ($\nu_{C=O}$, lactam) cm^{-1}.

Compound **2a** was also decomposed and the product was isolated by a similar method, except for the reaction period (11 h).[11] Yield, 4 mg. The ^{1}H-NMR spectrum of this compound was identical to that of **7** from **1a**.

Temperature-Dependent NMR Measurement——Samples were dissolved in $CDCl_3$ to about 5×10^{-2} mol dm^{-3}. ^{1}H-NMR spectra were recorded on a JEOL FX-100 spectrometer operated at 99.6 MHz. Typical acquisition parameters were as follows: spectral width 2000 Hz and flip angle 23° with 8192 data points, and data were accumulated 40 times. The temperature was controlled by a JEOL NM-5471 controller attached to the spectrometer; the accuracy was ± 1 °C. The line-shape analysis was performed by means of a modified Gutowsky and Holm method.[12] Calculations were carried out on an NEC PC-9801E personal computer. From the observed signal for H-C_{5a}, 30—40 data were taken within the range of 80 Hz. With variation of base line and the exchange rate, the fitting was done by the method of trial and error: the calculated curve was compared with the experimental data on a cathode ray tube display. The calculation was repeated with various values of the rate constant until a visual best fit was obtained. The best fitting rate constants (s^{-1}) were as follows (temperatures are given in parentheses in °C). **1b**: 7.2 (50), 2.7 (40), 0.92 (30), 0.26 (20), 0.07_5 (10), 0.02 (0); **2b**: 6.5 (50), 2.4 (40), 0.86 (30), 0.25 (20), 0.08 (10), 0.02 (0). These values were used for the calculation of the activation parameters.

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References and Notes

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