Stereoselectivity in Octahedral Complexes. II.[1] Cobalt(III) and Vanadium(III) Complexes of Carvone and Pulegone Derivatives

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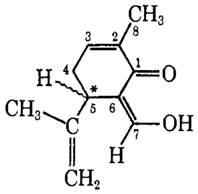
Abstract: Tris Co(III) complexes of (+)- and (−)-hydroxymethylenecarvone and (+)-hydroxymethylenepulegone have been synthesized in order to investigate the occurrence of stereoselectivity. The four diastereomers of each of the Co(III) complexes were separated by thin layer chromatography, and absolute configurations are assigned from CD and pmr studies. The relative abundances of diastereomers for the complex of (−)-hydroxymethylenecarvone are: Λ-*trans*, 48%; Δ-*trans*, 26%; Δ-*cis*, 18%; and Λ-*cis*, 8%. Well-resolved isotropic pmr shifts are observed for the V(III) complexes of (+)-hydroxymethylenecarvone and (+)-hydroxymethylenepulegone. Signal assignments are made with the aid of spin density calculations. The ratio of abundances of *trans* diastereomers for the V(III) complex of hydroxymethylenecarvone is found to be 0.62 from pmr signal integration. The stereoselectivity found for these Co(III) and V(III) complexes is considerably less than that found for complexes of camphor derivatives.

The phenomenon of stereoselectivity in coordination compounds has been a subject of increasing interest in recent years. A review of work through 1965 is available.[3] Interactions between substituents on asymmetric centers, which presumably are responsible for stereoselective effects in metal complexes, also occur in biological systems, and it is of interest and importance to investigate the relationship between these interactions and the degree of stereoselectivity. A great deal of work has involved complexes of optically active α-amino acids, 1,2-diamines, and other multidentate ligands.[3] It often has been observed that diastereomeric complexes of these chiral ligands do not occur in the expected statistical proportions, and the formation of diastereomers is said to be stereoselective. The stereoselectivity may have a kinetic or thermodynamic origin. The chelate rings in complexes of α-amino acids and 1,2-diamines are generally nonplanar, and ligand conformational effects are believed to be largely responsible for the observed stereoselectivity.[4] We are currently involved in an investigation of stereoselectivity in tris(bidentate) complexes having planar or nearly planar chelate rings. In these complexes stereoselectivity should be controlled by direct intramolecular interactions between asymmetric centers on adjacent chelate rings, and analysis of the interactions should be uncomplicated by chelate ring conformational preferences.

Earlier work has demonstrated the occurrence of stereoselectivity in formation of Cr(III), Co(III), and Rh(III) tris complexes of (+)-3-hydroxymethylenecamphor.[5] Recently we extended the work to include V(III) and Co(III) complexes of (−)-3-hydroxymethylenecamphor and (+)-3-acetylcamphor.[1] Signal assignments and integration of isotropically shifted proton resonance signals of the paramagnetic V(III) complexes allowed a quantitative measurement of the relative concentrations of Δ-*trans* and Λ-*trans* diastereomers.[6] Optical rotatory dispersion spectra of the mixture of Co(III) diastereomers indicated that for complexes having the (+)-camphor moiety, diastereomers having the Λ configuration predominate. The Δ configuration predominates for complexes derived from (−)-camphor. These conclusions have recently been corroborated by a chromatographic separation of the four diastereomers of tris[(+)-acetylcamphorato]cobalt(III).[7] Pmr analysis of the mixture of diastereomers reveals that the isomer having Λ-*trans* geometry is most abundant.[7]

The present paper describes the results of an investigation of Co(III) and V(III) complexes of hydroxymethylenecarvone (hmcar-H), I, and hydroxymethylenepulegone (hmpul-H), II. These ligands may be synthesized from commercially available (+)- and (−)-carvone and (+)-pulegone. Their absolute configurations have been assigned from a series of interconversions among terpene derivatives[8] including (+)-camphor and (+)-fenchone, the absolute configurations of which are established from X-ray studies.[9,10] In view of the distances between ligand asymmetric centers in tris complexes of I and II, it was anticipated at the outset that stereoselectivity would be less pronounced than in the tris complexes derived from camphor.[1,5]



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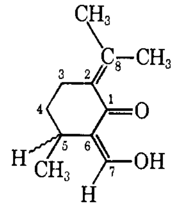

II

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[1] Part I: Y. T. Chen and G. W. Everett, Jr., *J. Amer. Chem. Soc.*, **90**, 6660 (1968).

[2] American Chemical Society Petroleum Research Fund Predoctoral Fellow, 1968–1969.

[3] J. H. Dunlop and R. D. Gillard, *Advan. Inorg. Chem. Radiochem.*, **9**, 185 (1966).

[4] E. J. Corey and J. C. Bailar, Jr., *J. Amer. Chem. Soc.*, **81**, 2620 (1959).

[5] (a) I. Lifschitz, *Rec. Trav. Chim. Pays-Bas*, **69**, 1495 (1950); (b) S. F. Mason, *Quart. Rev.* (London), **17**, 20 (1963); (c) J. H. Dunlop, R. D. Gillard, and R. Ugo, *J. Chem. Soc., A*, 1540 (1966).

[6] The nomenclature used throughout this paper is that proposed by T. S. Piper, *J. Amer. Chem. Soc.*, **83**, 3908 (1961), for tris complexes where Δ and Λ denote right- and left-hand helicity, respectively, about the C_3 or pseudo-C_3 axis of the complex.

[7] (a) C. S. Springer, Jr., R. E. Sievers, and B. Feibush, paper presented at the 157th National Meeting of the American Chemical Society, Minneapolis, Minn., April 1969; (b) C. S. Springer, Jr., private communication.

[8] A. J. Birch, *Ann. Rept. Progr. Chem.*, **47**, 177 (1950).

[9] F. H. Allen and D. Rogers, *Chem. Commun.*, 837 (1966).

[10] C. Rerat, *Acad. Sci. Paris, Ser. C*, **266**, 612 (1968).

Table I. Results of Elemental Analyses[a]

	Calcd, % C	Calcd, % H	Found, % C	Found, % H
Co(+hmcar)$_3$[b]	67.11	6.65	67.32	6.72
Δ-*cis*-Co(−hmcar)$_3$[c]			66.78	6.74
Λ-*trans*-Co(−hmcar)$_3$[c]			67.05	6.52
Δ-*trans*-Co(−hmcar)$_3$[c]			67.15	6.58
Λ-*cis*-Co(−hmcar)$_3$[c]			63.81	6.39
Co(+hmpul)$_3$[b]	66.43	7.60	67.07	8.00
Sample A[d]			65.72	7.72
Sample B[d]			66.78	8.05
Sample C[d]			65.90	7.97
Sample D[d]			66.07	7.97
V(+hmcar)$_3$[b,e]	68.03	6.74	67.68	7.07
V(+hmpul)$_3$[b,f]	67.33	7.70	67.16	8.03
V(hmdhcar)$_3$[b]	67.33	7.70	66.57	7.97
V(hmmenth)$_3$[b]	66.64	8.64	66.25	8.90

[a] Abbreviations used for ligand anions: hmcar = hydroxymethylenecarvone; hmpul = hydroxymethylenepulegone; hmdhcar = hydroxymethylenedihydrocarvone; hmmenth = hydroxymethylenementhone. [b] Mixture of diastereomers. [c] See text for assumptions made in assigning stereochemistry. [d] Samples from chromatographic separation of Co(+hmpul)$_3$. [e] μ_{eff} = 2.83 BM. [f] μ_{eff} = 2.99 BM.

Experimental Section

Preparation of Ligands. (+)-carvone, (−)-carvone, and (+)-pulegone were obtained from Aldrich Chemical Company and used without further purification. We found for (+)-carvone $[\alpha]^{25}\mathrm{D}$ +58.8° (neat), and for (+)-pulegone $[\alpha]^{29}\mathrm{D}$ +26.3° (neat). Reported rotations for these compounds vary somewhat, but most values are around +62° for (+)-carvone.[11a,b] The specific rotation reported for (+)-pulegone at 29° is +25.5°.[11c] The preparation of hydroxymethylenecarvone has been described previously.[12] We chose to use the procedure given by Hauser, *et al.*,[13] for the synthesis of 3-hydroxymethylenecamphor in the preparation of (+)- and (−)-hydroxymethylenecarvone and (+)-hydroxymethylenepulegone. The products were obtained as oils. After vacuum distillation the ligands were identified by their pmr spectra in chloroform solution.

2,3-Dihydrocarvone was prepared from (+)-carvone using zinc dust, according to the procedure of Wallach.[14] 2,8-Dihydro-(±)-pulegone, (±)-menthone, was obtained from Aldrich Chemical Company and used without further purification. These compounds were formylated in the same manner as carvone and pulegone.

Preparation of Cobalt(III) Complexes. The Co(III) complexes were prepared by a method similar to that described by Gillard, *et al.*, for the preparation of tris[(+)-hydroxymethylenecamphorato]cobalt(III).[6c] In a typical preparation stoichiometric amounts of ligand and $Na_3Co(CO_3)_3 \cdot 3H_2O$[15] were stirred vigorously for about 12 hr in a 1:1 mixture of benzene and water. The benzene layer containing the deep green complex was separated, and upon removal of solvent a green oil remained. This was taken up in ethanol and added to an aqueous solution of sodium carbonate. The precipitate which formed was filtered from the solution, washed well with water, and dried *in vacuo*. The dried product was extracted with *n*-pentane; the *n*-pentane was evaporated, leaving a solid which was then dissolved in a minimum amount of chloroform. The chloroform solution was passed through a short (∼5-cm) column of silica gel using chloroform as the eluent. Evaporation of chloroform from the product was followed by dissolution of the product in ethanol. The ethanol solution was added dropwise to an aqueous Na_2CO_3 solution. The resulting precipitate was washed thoroughly with water and dried over P_2O_5 *in vacuo*.

The samples prepared in this manner are mixtures of the four possible diastereomers. The results of elemental analyses are presented in Table I. All the Co(III) complexes are green.

Separation of Cobalt(III) Diastereomers. Attempts to separate the Co(III) diastereomers using column chromatography were not successful. However, the separation was achieved by thin layer chromatography with silica gel as the sorbent. Precoated preparative tlc plates with a 2-mm layer of Silica Gel F-254 were obtained from Brinkmann Instruments, Inc. The ascending technique was employed with multiple development using a 3:1 (by volume) *n*-pentane–diethyl ether solvent mixture. The separation required around 6 hr total development time.

For CD and pmr studies, the central portions of the four bands were carefully removed from the plate, and the samples were extracted from the silica gel with methanol. The individual diastereomers were precipitated by adding the methanol solutions to aqueous Na_2CO_3. The precipitates were washed well with water and dried over P_2O_5 *in vacuo*. Elemental analyses were carried out for the four separated diastereomers of the Co(III) complexes of (−)-hydroxymethylenecarvone, Co(−hmcar)$_3$, and (+)-hydroxymethylenepulegone, Co(+hmpul)$_3$ (see Table I).

In order to determine the relative amounts of diastereomers present for Co(−hmcar)$_3$, an effort was made to remove each band quantitatively. Corresponding bands from four plates were combined and extracted as described above. The solids remaining after evaporation of solvent were weighed. The results are given in Table II.

Table II. Diastereomers of Tris[(−)-hydroxymethylenecarvonato]cobalt(III)

Tlc band[a]	Stereochemistry[b]	CD, 580 mμ	Per cent of total
A	Δ-*cis*	−3.30	18
B	Λ-*trans*	+7.25	48
C	Δ-*trans*	−3.95	26
D[c]	Λ-*cis*	+0.35	8

[a] Bands A–D in order of increasing R_F value using *n*-pentane–diethyl ether. [b] See text for assumptions made. [c] This sample not obtained pure.

Preparation of Vanadium(III) Complexes. Solutions of the V(III) complexes must be protected from aerial oxidation, so preparations and recrystallizations were carried out under vacuum or nitrogen using apparatus similar to that described by Holm, *et al.*[16] Samples of complexes in the solid state appear to be stable for short periods in the presence of air.

The complexes were prepared by adding ligand to an aqueous Na_2CO_3 solution, followed by the stoichiometric amount of VCl_3 in aqueous solution. The mixture was stirred at room temperature for several hours, then the precipitate was removed and washed with water. The product was dried and extracted with *n*-pentane. The *n*-pentane was evaporated, leaving a solid which was dissolved in ethanol and reprecipitated by adding the ethanol solution dropwise to aqueous Na_2CO_3. The reprecipitation was repeated two more times, then the sample was washed thoroughly with water and dried *in vacuo* over P_2O_5. The purified products had brown or yellow-brown colors. Results of elemental analyses are given in Table I.

Physical Measurements. Electronic absorption spectra of the complexes in chloroform solution were recorded on a Cary Model 14 spectrophotometer. CD spectra were obtained from chloroform solutions of the complexes at 25° using a Cary Model 60 spectropolarimeter. Magnetic susceptibility measurements on solid samples of the V(III) complexes were made at room temperature by the Gouy method. Pmr spectra of the ligands and Co(III) complexes were obtained using a Varian Model A-60 spectrometer; spectra of the V(III) complexes in sealed tubes were recorded on a Varian Model HA-100 instrument operating in HR mode. Chemical shifts on the HA-100 instrument were measured by side banding. TMS was used as the internal reference in each case. All solution measurements on V(III) complexes were carried out under rigorously oxygen-free conditions.

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(11) (a) Y. R. Naves and P. Bachmann, *Helv. Chim. Acta*, **29**, 61 (1946); (b) J. L. Simonsen, "The Terpenes," Vol. I, Cambridge University Press, London, 1947; (c) M. Godchot, G. Cauquil, and R. Calas, *Bull. Soc. Chim. Fr.*, **6**, 1353 (1939).

(12) O. Wallach, *Ber.*, **28**, 31 (1895).

(13) C. R. Hauser, F. W. Swamer, and J. T. Adams, *Org. Reactions*, **8**, 59 (1954).

(14) O. Wallach, *Ann.*, **279**, 366 (1894).

(15) H. F. Bauer and W. C. Drinkard, *Inorg. Syn.*, **8**, 202 (1966).

(16) R. H. Holm, F. Röhrscheid, and G. W. Everett, Jr., *ibid.*, **11**, 72 (1968).

Results and Discussion

Cobalt(III) Complexes. Attempts to relate the signs of Cotton effects of metal complexes to absolute configuration using various theoretical approaches have not been very successful.[17] On a strictly empirical basis one can assign absolute configurations to Co(III) complexes of 1,2-diamines with some confidence, since the absolute configurations of (+)-[Co(en)$_3$]$^{3+}$ and (−)-[Co(−pn)$_3$]$^{3+}$ are known from Bijvoet X-ray structural determinations.[18,19] Also the absolute configuration of α-(+)-[Co(L-ala)$_3$] has been established by normal X-ray methods using the known absolute configuration of the ligand as a reference.[20] Tris (bidentate) Co(III) complexes have opposite helicities when viewed down the C_3 (or pseudo C_3) and C_2 axes, and Cotton effects of opposite sign are expected for the $^1A_1 \rightarrow {}^1E_a$ and $^1A_1 \rightarrow {}^1A_2$ electronic transitions in D_3 symmetry,[21] since they are polarized perpendicular to the C_3 and C_2 axes, respectively, of the complex. (+)-[Co(en)$_3$]$^{3+}$ and α-(+)-[Co(L-ala)$_3$], which have the Λ configuration, show positive Cotton effects for the low energy ($^1A_1 \rightarrow {}^1E_a$) absorption and much weaker negative Cotton effects for the $^1A_1 \rightarrow {}^1A_2$ transition at higher energy.[5b,17b,22] The low energy transition in (−)-[Co(−pn)$_3$], which has the Δ configuration,[19] shows a negative Cotton effect.[17c,23] A general rule has been formulated which states that if a dominant positive Cotton effect is found for the lowest energy, spin-allowed transition of a Co(III) complex having at least two five-membered rings, the complex has the Λ configuration.[17b,24] This relationship has been used to assign absolute configurations to a number of d^6 and d^3 tris complexes of diamines, amino acids, and dicarboxylic acids.[17,25,26] Relatively little effort has been directed toward establishing the absolute configurations of β-diketone complexes from ORD and CD spectra, and it is not definitely known whether the above general rule may be extended to these systems with six-membered chelate rings. The predominant isomer of tris[(+)-hydroxymethylenecamphorato]cobalt(III) has been assigned the Λ configuration on the basis of the sign of the Cotton effect for the 610-mμ absorption, which was attributed to the ^1E_a transition,[1,5c,26] A much weaker negative CD at 700 mμ was assigned to the $^1A_2$ transition.[26] It was assumed that the optical behavior of this β-ketoenol complex parallels that of 1,2-diamines and amino acids. Although this assumption has as yet no firm basis, it is used in this paper to assign tentative absolute configurations to Co(III) complexes of I and II.

Four diastereomers are possible for tris complexes of ligands I and II. Since the donor oxygens are not equivalent, *cis* (1,2,3) and *trans* (1,2,6) geometrical isomers may occur, and each of these may exist in the Δ and Λ configurations. The situation is analogous to tris Co(III) complexes of optically active α-amino acids for which the four diastereomers have been isolated in some instances.[22,27–30]

The mixture of diastereomers obtained from the preparation of Co(−hmcar)$_3$ shows an overall positive Cotton effect in chloroform solution in the region of the 600-mμ absorption. This could mean that a Λ diastereomer is the most abundant or that the CD of one or more Λ isomers is greater than that of the Δ isomers. Preliminary thin layer chromatography on silica gel, using pentane–ether as the solvent, indicated that the diastereomers could be separated by this method, so 2-mm preparative layer plates (see Experimental Section) were employed. A reasonably good separation was achieved after several hours. Four green bands of varying intensities were readily observed. Band A, which had the smallest R_F value, was well separated from bands B, C, and D (in order of increasing R_F value). The latter three bands were closer together with a separation of about 2 cm. Corresponding bands from several plates were combined, and the samples were crystallized after extraction from silica gel with methanol. Results of elemental analyses are shown in Table I.

A combination of CD and pmr measurements was used to identify the separated diastereomers. The two *cis* isomers have C_3 symmetry, and the three ligands are related by symmetry, whereas the *trans* isomers have no symmetry. Thus, it was expected that pmr spectra of the *cis* isomers would be simpler than those of the *trans* isomers.[31] Pmr spectra of the samples from chromatographic bands B and C showed distinct splitting[32] of the 6.45-ppm resonance signal attributed to the aldehyde proton, but no splitting of this resonance was found for samples from bands A and D. Clearly the two diastereomers with *trans* geometry are from bands B and C, and samples from bands A and D have *cis* geometry.

The CD spectra of the four samples in chloroform solution are presented in Figure 1. Samples from bands A and C show negative Cotton effects near the wavelength of the low energy ligand field absorption maximum. The sample from band B shows a positive Cotton effect in this region. Using the assumptions outlined above and also assuming the effective ligand field symmetry is D_3 for both *cis* and *trans* species, we propose the following assignments of absolute configuration: sample A, Δ-*cis;* sample B, Λ-*trans;* and sample C, Δ-*trans*. Chromatographic band D was much less intense than the other three, and only a small amount of sample was obtained from several separations (less than 50 mg from four preparative plates). The elemental analysis for this sample was relatively poor

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(17) For summaries, see (a) ref 5b; (b) R. D. Gillard in "Physical Methods in Advanced Inorganic Chemistry," H. A. O. Hill and P. Day, Ed., Interscience Publishers, New York, N. Y., 1968; (c) J. Fujita and Y. Shimura in "Spectroscopy and Structure of Metal Chelate Compounds," K. Nakamoto and P. J. McCarthy, Ed., John Wiley and Sons, Inc., New York, N. Y., 1968.

(18) (a) Y. Saito, K. Nakatsu, M. Shiro, and H. Kuroya, *Bull. Chem. Soc. Jap.*, 30, 795 (1957); (b) K. Nakatsu, *ibid.*, **35**, 832 (1962).

(19) Y. Saito, H. Iwasaki, and H. Oto, *ibid.*, **36**, 1543 (1963).

(20) M. G. B. Drew, J. H. Dunlop, R. D. Gillard, and D. Rogers, *Chem. Commun.*, 42 (1966).

(21) These components arise from the magnetic dipole allowed $^1A_{1g} \rightarrow {}^1T_{1g}$ transition in O_h symmetry.

(22) R. G. Denning and T. S. Piper, *Inorg. Chem.*, **5**, 1056 (1966).

(23) A. P. Smirnoff, *Helv. Chim. Acta*, **3**, 177 (1920).

(24) R. D. Gillard, *Chem. Britain*, 205 (1967).

(25) R. D. Gillard, *Progr. Inorg. Chem.*, 7, 215 (1966).

(26) A. J. McCaffery, S. F. Mason, and R. E. Ballard, *J. Chem. Soc.*, 2883 (1965).

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(28) B. E. Douglas and S. Yamada, *Inorg. Chem.*, **4**, 1561 (1965).

(29) E. Larsen and S. F. Mason, *J. Chem. Soc., A*, 313 (1966).

(30) R. D. Gillard and N. C. Payne, *ibid.*, 1197 (1969).

(31) See footnote 1 and references therein for a more complete discussion.

(32) The sample from band C showed the expected[31] 1:1:1 triplet, but for the sample from band B a 2:1 doublet was found, indicating accidental degeneracy of two of the resonances. Slight splitting of other resonances was observed in both cases.

(Table I), and an unusual CD spectrum was obtained (Figure 1). The pmr spectrum of this sample indicates *cis* geometry, and we believe it to be the fourth diastereomer having Λ-*cis* symmetry. A positive Cotton effect is expected for this diastereomer. The unusual CD spectrum obtained could be a result of incomplete separation from the Δ-*trans* diastereomer (band C) which has a negative Cotton effect. The poor elemental analysis is likely a result of the difficulties in handling the small quantity of sample obtained.

The maxima of the CD bands in Figure 1 are seen to be at slightly shorter wavelength than the maxima of the absorption spectra. If the predominant CD band in each case corresponds to the $^1A_1 \rightarrow {}^1E_a$ transition, the transition to $^1A_2$, which is expected to have a Cotton effect of the opposite sign, lies at a longer wavelength, as in the case of tris[(+)-hydroxymethylenecamphorato]cobalt(III).[33] The latter transition is not apparent from the absorption spectra, nor is it observed in the CD spectra due to the wavelength limitations of our instrument.

A rough estimate of the relative amounts of the four diastereomers of Co(−hmcar)$_3$ present was obtained by weighing the total amounts of samples A–D from four chromatograms. The results are presented in Table II. The numbers are probably accurate only to within a few per cent. When the CD at 580 mμ of each of the four isomers is multiplied by its relative abundance and the products summed, the net calculated CD of the mixture, +1.89, compares favorably with the measured CD of the mixture before separation, +2.15. The overall CD of the mixture is determined by that of the Λ-*trans* diastereomer which is the most abundant and has the largest CD in absolute value.

In the absence of stereoselective effects, the diastereomers should be present in the statistical ratio A:B:C:D = 1:3:3:1, since Δ and Λ configurations would be equally probable and the *trans* geometry has three times the probability of *cis*. The *trans* isomers are indeed found to be more abundant than *cis*, but in addition the Λ-*trans* isomer is definitely favored over the Δ-*trans*. Similarly, the Δ-*cis* configuration is favored over the Λ-*cis*. The observed stereoselectivity is believed to be thermodynamically controlled (*vide infra*) and must result from different interligand steric interactions involving substituents on the asymmetric carbons. In principle these interactions are different for each of the four diastereomers, and there is no reason why a particular helicity would necessarily be favored for both *cis* and *trans* geometries. Space-filling molecular models do not convincingly reveal appreciable differences in intramolecular steric interactions among the four diastereomers. The picture is complicated by the flexibility of the six-membered carvone ring at carbons 4 and 5; the bulky substituent on asymmetric carbon 5 can be axial or equatorial. Apparently rather subtle differences in steric interactions can lead to measurable differences in the thermodynamic stability of the diastereomers.

The mixture of diastereomers of Co(+hmcar)$_3$ shows a negative Cotton effect in the ~600-mμ region. Preparative layer chromatography of this complex reveals a pattern of bands which appears identical in relative R_F values and intensities with that of Co(−hmcar)$_3$. However, CD spectra of the samples show Cotton effects of opposite sign than those of corresponding samples from Co(−hmcar)$_3$ (see Figure 1). A trigonal complex is transformed into its enantiomer by inverting the configuration of the ligand asymmetric centers and reversing the overall helicity, *e.g.*, Λ-*cis*-Co(+hmcar)$_3$ is the enantiomer of Δ-*cis*-Co(−hmcar)$_3$. Enantiomers have the same R_F values on an achiral sorbent and also have identical intramolecular steric interactions. Thus, corresponding samples from the chromatograms of Co(−hmcar)$_3$ and Co(+hmcar)$_3$ are enantiomers and have the same relative abundances. Their CD curves should be mirror images if their optical purities are comparable. The CD curves in Figure 1 are very nearly enantiomeric except for those of the Δ-*cis*-Co(−hmcar)$_3$–Λ-*cis*-Co(+hmcar)$_3$ pair. We therefore assign the following absolute configurations to the samples of Co(+hmcar)$_3$: sample A, Λ-*cis;* sample B, Δ-*trans;* sample C, Λ-*trans;* and sample D, Δ-*cis*.

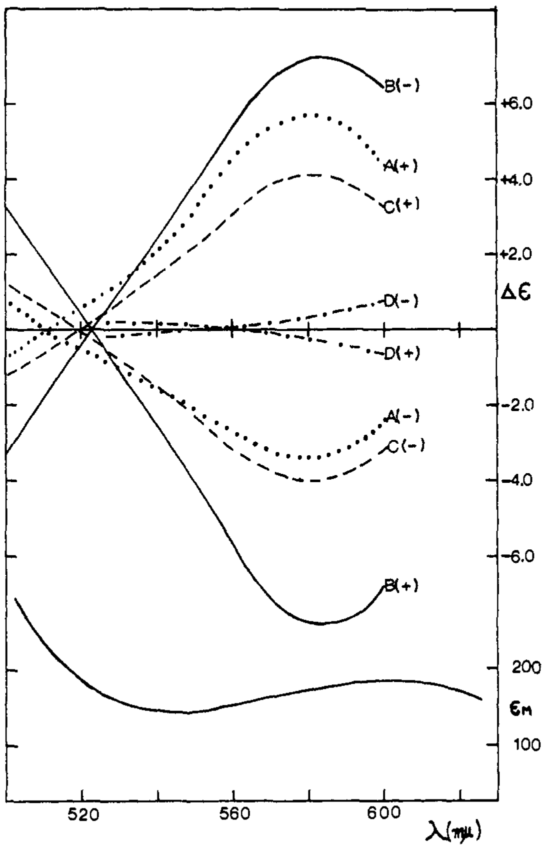

Figure 1. Spectra of Co(hmcar)$_3$ diastereomers in CHCl$_3$ solution at 25°. CD spectra: (·····), A(+) = Λ-*cis*-Co(+hmcar)$_3$, A(−) = Δ-*cis*-Co(−hmcar)$_3$; (—), B(+) = Δ-*trans*-Co(+hmcar)$_3$, B(−) = Λ-*trans*-Co(−hmcar)$_3$; (----), C(+) = Λ-*trans*-Co(+hmcar)$_3$, C(−) = Δ-*trans*-Co(−hmcar)$_3$; (-·-·-), D(+) = Δ-*cis*-Co(+hmcar)$_3$, D(−) = Λ-*cis*-Co(−hmcar)$_3$. Absorption spectrum: Λ-*trans*-Co(−hmcar)$_3$.

During the chromatographic separations of both Co(−hmcar)$_3$ and Co(+hmcar)$_3$ several very faint bands are visible in addition to the four relatively intense green bands described above. Two of these occur between bands A and B, and another is near band D. The greenish color of these weak bands indicates they are Co(III) complexes. The carvone used to synthesize the ligands is apparently not optically pure (see Experi-

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[33] The reverse order of $^1A_2$ and ^1E is found for 1,2-diamine complexes.

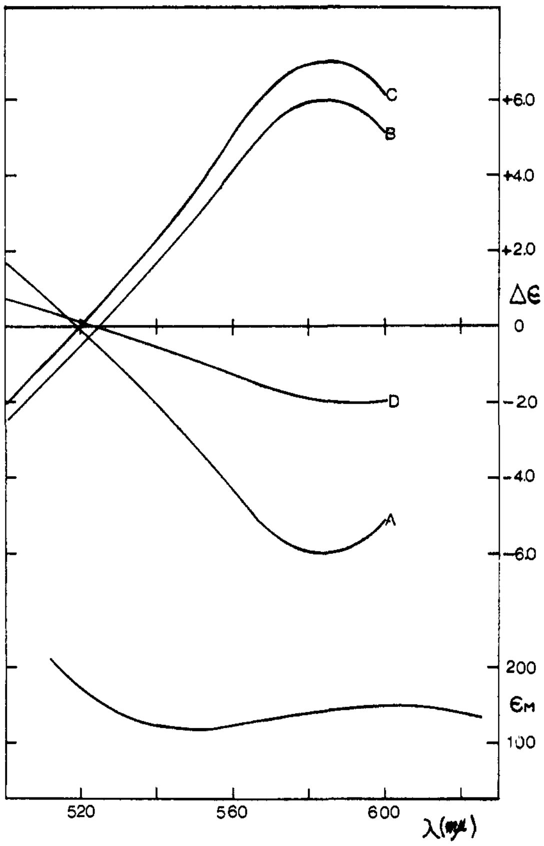

Figure 2. Spectra of Co(+hmpul)$_3$ diastereomers in $CHCl_3$ solution at 25°. CD spectra: A and D, Δ diastereomers; B and C, Λ diastereomers. Absorption spectrum: sample B.

mental Section), but the pmr spectrum of a neat sample at high gain shows little evidence of resonances not attributable to carvone.[34] It is likely that the impurity in (−)-carvone is (+)-carvone, and vice-versa, as a result of optically impure α-pinene used in synthesis of carvone. Thus small amounts[35a] of the mixed-ligand complex Co(−hmcar)$_2$(+hmcar) would be formed in the synthesis of Co(−hmcar)$_3$.[35b] In principle, the mixed ligand complex could exist in four diastereomeric forms, each of which could give a chromatographic band. We attribute the observed weak bands to these mixed-ligand species. As a result of their low abundances, no attempt was made to isolate and characterize these samples.

Chromatography of Co(+hmpul)$_3$ reveals a total of nine green bands of varying intensities. Four of these are considerably more intense than the others, and it is assumed that these contain the four diastereomers of Co(+hmpul)$_3$. Samples obtained from these bands are labeled A–D in order of increasing R_F values. They all gave acceptable elemental analyses (see Table I). In the 580-mμ region samples A and D show negative Cotton effects (Δ symmetry), whereas sample B and C show positive Cotton effects indicating Λ symmetry (see Figure 2). However, it was not possible to distinguish *cis* and *trans* species by pmr since there is extensive overlapping of resonances from different protons. Since specific stereochemistries could not be assigned to samples A–D, no attempt was made to obtain a quantitative measure of their relative abundances. It appears from the chromatograms that the order of abundances is B > C ≈ A > D. This is consistent with the positive Cotton effect found for the mixture of diastereomers. The origin of the weaker chromatographic bands is uncertain. They are probably due to Co(III) complexes formed from impurities in pulegone such as isopulegone,[11b] which can be formylated to give a β-ketoenol ligand.

Vanadium(III) Complexes. Symmetry considerations outlined earlier[1] for V(III) complexes of substituted camphors are applicable to the complexes of carvone and pulegone derivatives, since the latter are also unsymmetrical, chiral ligands. If the rate of diastereomer interconversion in solution is slow on the nmr time scale, up to eight pmr resonances may occur for each kind of ligand proton, depending upon which of the four possible diastereomers are present. The multiplicity of pmr signals expected from each diastereomer is given below

Diastereomer	Symmetry	No. signals per Proton type
Δ-*cis*	C_3	1
Δ-*trans*	C_1	3
Λ-*cis*	C_3	1
Λ-*trans*	C_1	3

If it can be shown that a set of signals arises from a single kind of proton, then the number of signals in the set and their relative areas can indicate which of the four diastereomers are present, and in what relative concentrations they occur. This provides a means of assessing stereoselectivity without separating the diastereomers, and is especially useful for labile complexes where diastereomer interconversion is more rapid than separation methods. Unfortunately the method is applicable for complexes of only a few transition metal ions. Chemical shift differences in diamagnetic complexes are generally not large enough to provide clear separation of corresponding resonances from several diastereomers. Most paramagnetic complexes have unfavorably long electron relaxation times, and nmr spectra are severely broadened. Vanadium(III) is one of the few paramagnetic ions for which well-resolved, isotropically shifted pmr signals of ligand protons may be observed.[1,36,37] The isotropic shift effect[38] amplifies chemical shift differences by at least an order of magnitude. This phenomenon was used previously to measure stereoselectivity in V(III) complexes of camphor derivatives.[1]

Assignment of Pmr Spectra. The isotropic pmr shift patterns observed in several different V(III) complexes of β-diketones and related ligands are all consistent with delocalization of α spin from vanadium to the lowest unfilled π molecular orbital (LUMO) of the ligand.[1,36,37] Apparently this mechanism is also predominant in the complexes of hydroxymethylenecarvone and hydroxymethylenepulegone. Positive spin density is expected in the pπ orbital of C(7), and the very broad pmr signal attributable to C(7)–H at high field in the spectra of both complexes is consistent with this. Assignments of the other resonance signals are made on the basis of their

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(34) "High Resolution Nmr Spectra Catalog," Vol. 1, Varian Associates, Palo Alto, Calif., 1962.

(35) (a) Note that the mole fraction of optical impurity is amplified by a factor of 3 upon complex formation. (b) Complexes having more than one *dextro* ligand would be formed in negligible quantities because of the overwhelming proportion of *levo* ligand present.

(36) (a) A. Forman, G. N. Murrell, and L. E. Orgel, *J. Chem. Phys.*, **31**, 1129 (1959); (b) D. R. Eaton, *J. Amer. Chem. Soc.*, **87**, 3097 (1965).

(37) F. Röhrscheid, R. E. Ernst, and R. H. Holm, *Inorg. Chem.*, **6**, 1315, 1607 (1967); *J. Amer. Chem. Soc.*, **89**, 6472 (1967).

(38) D. R. Eaton and W. D. Phillips, *Advan. Magn. Resonance*, **1**, 103 (1965).

relative areas and the direction of shifts predicted from spin density calculations. The theoretical π spin densities for the 7-atom system representative of both hydroxymethylenecarvone and hydroxymethylenepulegone anions are given in Table III. The McLachlan method[39] is of greater utility in assigning the resonances, since sites of negative spin density are indicated. Due to uncertainty in the choice of parameters for the calculations, only the relative spin densities are significant. We are assuming that the observed isotropic pmr shifts arise primarily from the contact interaction and that the pseudo-contact mechanism is relatively unimportant in these complexes.[36b] Contributions to the shifts from spin delocalization through σ orbitals are likely, since the spin-containing metal orbitals are of suitable symmetry for σ or π bonding in trigonal V(III) chelates.

Table III. Results of Spin Density Calculations[a]

	C_7	C_6	C_1	C_2	$C_{3,8}$	
Hückel	0.106	0.026	0.177	0.138	0.406	LUMO[b]
McLachlan	0.114	−0.041	0.212	−0.002	0.604	
Hückel	0.059	0.544	0.035	0.028	0.081	HFMO[c]
McLachlan	−0.025	0.763	−0.042	0.009	0.069	

[a] Parameters used: $\alpha_0 = \alpha + 1.5\beta$, $\beta_{CO} = 1.5\beta$, $\lambda = 1.2$. [b] Energy = -0.58β. [c] Energy = $+0.58\beta$.

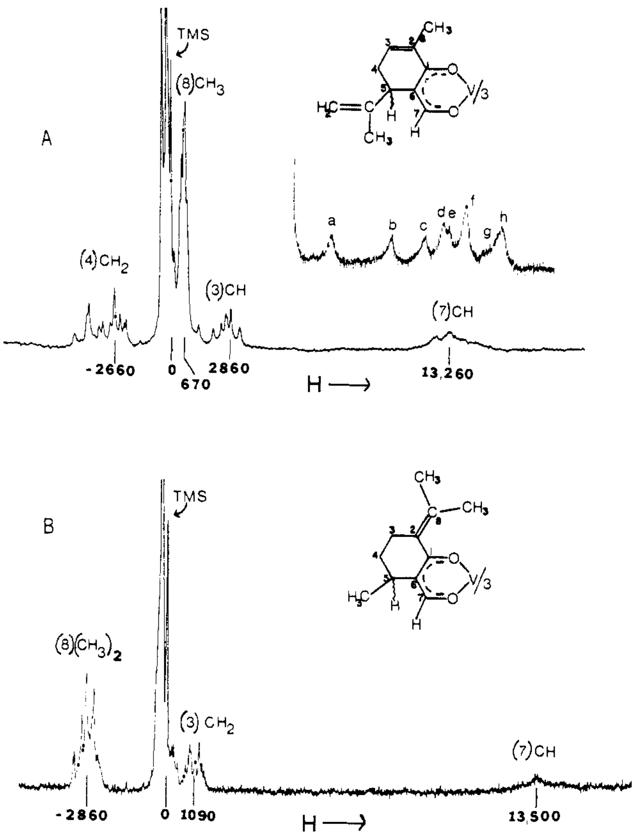

Figure 3. Proton resonance spectra (100 MHz) in CCl_4 solution at ~30°. A, V(+hmcar)$_3$; B, V(+hmpul)$_3$. Frequencies shown are chemical shifts relative to tetramethylsilane.

The pmr spectrum of V(+hmcar)$_3$ in carbon tetrachloride solution is shown in Figure 3(A). If the unpaired spin is in LUMO, upfield resonances are expected for C(7)-H, C(2)-CH_3, C(3)-H, and C(5)-H, whereas C(4)-H_2 should appear at low field (see Table III). The set of signals centered around 3000 Hz downfield of TMS having an overall area of two is assigned to the two protons on C(4). The intense multiple signal ~650 Hz upfield of TMS has an area of approximately three and is assigned to C(2)-CH_3. The very broad signal around +13,000 Hz is assigned to C(7)-H, and the remaining set of signals in the upfield region, 1300–3200 Hz, having an overall area of one is assigned to C(3)-H. Spin delocalization in HFMO, which is expected to result in upfield shifts for C(3)-H only (see Table III), is not compatible with the observed spectrum. As an aid in confirming the above assignments, the V(III) complex of 2,3-dihydrohydroxymethylenecarvone, V(hmdhcar)$_3$, was prepared. The π conjugation which allows unpaired spin to reach C(2)-CH_3, C(3)-H, and C(4)-H_2 in V(+hmcar)$_3$ is absent in V(+hmdhcar)$_3$, and in accord with this, the resonances at ~ 650 and 1300–3200 Hz upfield and 2100–4600 Hz downfield are absent in the pmr spectrum of the latter. The C(5) and C(7) protons should receive unpaired spin in V(+hmdhcar)$_3$, however, and signals at +300 Hz and +13,500 Hz are assigned to these protons, respectively.

The pmr spectrum of V(+hmpul)$_3$ is shown in Figure 3(B). The broad signal at ~+13,500 Hz is assigned to C(7)-H; additional upfield resonances are expected for C(3)-H_2 and C(5)-H. The group of resonances of area two centered around +1100 Hz are assigned to C(3)-H_2. Signals at ~300 Hz upfield of TMS and partially obscured by TMS are assigned to C(5)-H. The rather intense signals at low field (2400–3300 Hz) have an area of six and are assigned to the C(8) methyls. The pmr spectrum of the V(III) complex of dihydrohydroxymethylenepulegone (hydroxymethylenementhone) shows no resonances in the regions ~1100 Hz upfield and 2400–3300 Hz downfield, thus supporting the assignments for C(3)-H_2 and the C(8) methyls. The signal of C(5)-H appears around +450 Hz in the dihydro complex.

Stereoselectivity in V(III) Complexes. Although in principle one could deduce the degree of stereoselectivity in both V(+hmpul)$_3$ and V(+hmcar)$_3$ from their pmr spectra, we were able to do so with confidence only for V(+hmcar)$_3$. Figure 3(A) shows that the set of signals assigned to C(3)-H is well separated from all other resonances, and the overlap among individual components is not severe. The insert in Figure 3(A) is an expansion of this set of signals. Eight components may be seen in the expanded spectrum, indicating that all four diastereomers are present. Overlapping resonances were analyzed by a Du Pont Model 310 curve resolver. Resonances a, b, and c proved to have the same area within the limits of error, and are thus assigned to one of the *trans* diastereomers. Although signals d, f, and h differ in height, they are of nearly equal area and are attributed to the other *trans* diastereomer. Signals e and g must arise from the two *cis* diastereomers. The latter signals have much smaller areas than the other six, indicating that the *cis* diastereomers are not present in their statistical proportions.

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(39) A. D. McLachlan, *Mol. Phys.*, 3, 233 (1960).

Table IV. Isotropic Shifts in Tris Complexes of Vanadium (III)[a]

V(+hmcar)$_3$	C(2)–CH$_3$	600, 690, 790, 850, 960
	C(3)–H	1980 (a), 2670 (b), 3050 (c), 3260 (d), 3320 (e), 3500 (f), 3750 (g), 3930 (h)
	C(4)–H$_2$	−1860, −1960, −2150, −2420, −2620, −2950, −3130, −3620, −3700, −4300
	C(7)–H	13,350 14,000
V(+hmpul)$_3$	C(8)–(CH$_3$)$_2$	−3190, −3160, −2910, −2740, −2540, −2490, −2310
	C(3)–H$_2$	890, 980, 1040, 1240, 1370, 1460, 1560
	C(7)–H	14,000

[a] Measured in Hz at 100 MHz relative to free ligand resonances; all measurements at 29°; frequencies are for well-resolved signals only.

The ratio of the average area of signals a, b, and c to the average area of signals d, f, and h was determined. The average of this ratio from four spectra was found to be 0.62 with a standard deviation of 0.05. This ratio is a measure of the relative concentrations of the two *trans* diastereomers in solution. These diastereomers differ only in the chirality of coordination about V(III) and are expected to occur in equal concentrations in the absence of stereoselective effects. The ratio of *cis* diastereomers cannot be determined without appreciable error. However it appears that one *cis* isomer is about twice as abundant as the other. It is clear that a stereoselective effect is operative in V(+hmcar)$_3$. Complexes of V(III) are generally labile, and the proportions of diastereomers present in an equilibrium mixture reflect their relative thermodynamic stabilities. Assuming the same intramolecular interactions occur in V(+hmcar)$_3$ and Co(+hmcar)$_3$, we propose the Δ-*trans* configuration for the most abundant isomer of V(+hmcar)$_3$ and Λ-*trans* for the second most abundant isomer.

The set of resonances assigned to the C(4) protons of V(+hmcar)$_3$ should consist of sixteen components: six from each *trans* diastereomer and two from each *cis* diastereomer. An expansion of this region of the spectrum reveals ten well-defined signals; others undoubtedly lie under these ten. No definite assignments of these signals could be made due to overlap which renders integration difficult.

The resonances of the C(8)–methyl and C(3)–methylene protons of V(+hmpul)$_3$ should each contain up to sixteen components. Seven signals are clearly visible in each set (see Table IV); however, severe overlapping makes it impossible to assign the signals and measure stereoselectivity for this complex.

Summary

Thin layer chromatography of Co(+hmcar)$_3$ and Co(−hmcar)$_3$ gives four principal bands. The relative abundances of samples obtained form the chromatogram of Co(−hmcar)$_3$ are given in Table II. Samples from the chromatogram of Co(+hmcar)$_3$ are the enantiomers of corresponding samples of Co(−hmcar)$_3$ and must have the same relative abundances. Absolute configurations are assigned to the four diastereomers of Co(−hmcar)$_3$ and of Co(+hmcar)$_3$ on the basis of pmr and CD studies. Using the data from Table II, the ratio of Δ-*trans*-Co(−hmcar)$_3$ to Λ-*trans*-Co(−hmcar)$_3$ is 0.54. This ratio is expected to be 1.0 in the absence of stereoselective effects. Intramolecular steric interactions responsible for the observed stereoselectivity are not readily apparent from space-filling models.

The ratio of the two *trans* diastereomers of V(+hmcar)$_3$ was obtained from the pmr spectrum of the isomeric mixture. Assuming the most abundant diastereomer of V(+hmcar)$_3$ has the same absolute configuration as the most abundant diastereomer of Co(+hmcar)$_3$, the ratio of Λ-*trans*-V(+hmcar)$_3$ to Δ-*trans*-V(+hmcar)$_3$ is 0.62. This ratio compares favorably with that found for the Co(III) complexes and strongly indicates that diastereomer population in the Co(III) complexes is thermodynamically controlled. The very rough estimate of 0.5 for the ratio of *cis* isomers of V(+hmcar)$_3$ is close to the corresponding ratio (0.44) for Co(−hmcar)$_3$.

The stereoselectivity in V(+hmcar)$_3$ is considerably less than that found for tris[(+)-3-acetylcamphorato]vanadium(III) where the ratio of Δ-*trans* to Λ-*trans* is 0.31.[1] This difference was anticipated in view of the greater interligand steric interactions possible for the complex of acetylcamphor. The most abundant diastereomers of tris[(+)-acetylcamphorato]vanadium(III) and -cobalt(III)are believed to have Λ-*trans* symmetry.[1,7] The Λ-*trans* isomers are also most abundant for V(−hmcar)$_3$ and Co(−hmcar)$_3$. It is perhaps significant that the reported[8,9] absolute configurations of (+)-camphor and (−)-carvone are closely related.

Thin layer chromatography of Co(+hmpul)$_3$ allows separation of the four diastereomers, but *cis* and *trans* species could not be clearly distinguished by pmr. Estimates of stereoselectivity are qualitative only. Severe signal overlap in the pmr spectrum of V(+hmpul)$_3$ prevents measurement of stereoselectivity.

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