Stereospecific Synthesis of Optically Active Benzobicyclic Ring Systems Coordinated to Tricarbonylchromium with Predetermined Absolute Configurations

André Meyer*[1] and Otmar Hofer[1b]

Contribution from the Laboratoire de Chimie des Organométalliques, ERA 477, Université de Rennes, 35042 Rennes Cedex, France, and the Organisch-Chemisches Institut der Universität Wien, Wien, Austria.
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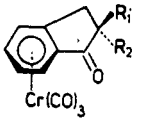
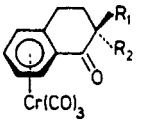
Abstract: A synthetic scheme for the preparation of new families of optically active benzobicyclic systems has been developed. A key step in the synthesis involved the use of arenetricarbonylchromium derivatives. Stereospecific base-catalyzed ring closure of 2-methyl 2-(3-oxobutyl)-1-indanone and 1-tetralonetricarbonylchromium led to optically active α-enones via classical annulation and to optically active benzobicyclic keto alcohols via an unusual cyclization at benzylic carbons. The assignment of the endo/exo stereochemistry was solved by a combination of ^{1}H NMR methods. Therefore, the complexed arenes, with a fully determined absolute configuration at every step of the reaction, are good precursors to known or previously inaccessible optically active benzobicyclic derivatives.

During the last decade the growing utilization of organometallic complexes in organic synthesis has achieved a remarkable level of success.[2] As part of our studies on novel stereocontrolled approaches to naturally occurring materials, one of our synthetic objectives was to test the efficacy of organic ligands, temporarily modified by complexation with transition metals, in the preparation of optically active substrates, with a known absolute configuration and which are not readily available. For the use of transition-metal complexes under stoichiometric reaction conditions, arenetricarbonylchromium derivatives offer several particular advantages. The easy fixation of the $Cr(CO)_3$ moiety, the introduction of known chemical and stereochemical modifications on the coordinated arene ring, and the facile removal of the organometallic group under mild conditions represent typical distinctive features of this class of compounds.[3]

In the course of our stereochemistry studies on molecules derived from "indanone" and "tetralone" skeletons complexed by the $Cr(CO)_3$ group, **1** and **4**, we have directed our efforts



1 $R_1 = R_2 = H$
2 $R_1 = CH_3$; $R_2 = H$
3 $R_1 = H$; $R_2 = CH_3$



4 $R_1 = R_2 = H$
5 $R_1 = CH_3$; $R_2 = H$
6 $R_1 = H$; $R_2 = CH_3$

toward the possibility of formation of additional rings, onto a preformed cyclic ketone, with a high degree of selectivity. The annulation reactions have indeed proved to be useful in the synthesis of racemic natural products[4] and it seemed worthwhile starting, in the early step, with optically active precursors in order to prepare directly the active compounds and thus eliminate the rather difficult problem of absolute configuration assignment.

We have previously described the utility of the $Cr(CO)_3$ moiety for the obtention of optically active ketones with a known absolute configuration where racemization through a keto-enol tautomerism, e.g., **2** ⇌ **3**, is overcome by handling diastereoisomers which possess a planar chirality (due to $Cr(CO)_3$) and a center of chirality.[3,5]

The first attempts, which were concerned with the Torgov synthesis of estrone derivatives[6] via novel chiral organometallic intermediates, e.g., 1-*exo*-vinyl-1-*endo*-tetraloltricarbonylchromium, failed and only a $Cr(CO)_3$ exchange between arenic ligands could be observed in the reaction conditions.[7]

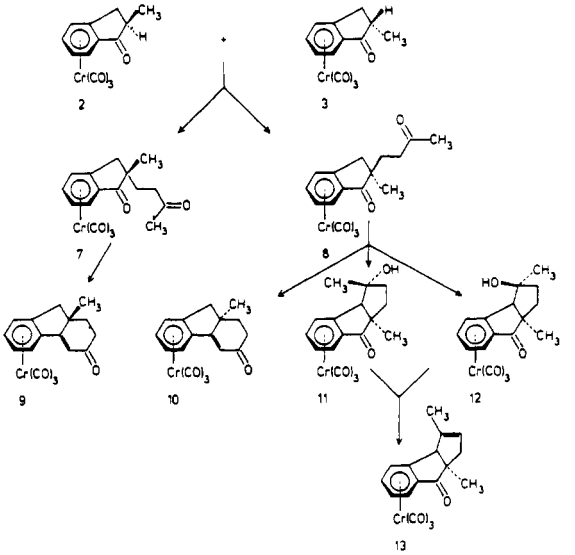
Another goal was the construction of CDE rings in derivatives of type **1** and **4** via a tricyclic enone by a "Robinson annulation", similar to the approach of Stork et al.[8] on the related 7-methoxy free ligand in the key step of pentacyclic triterpenes synthesis. We report here in detail the results obtained in this reaction using $Cr(CO)_3$-complexed precursors in racemic as well as in optically active forms, with special emphasis on the advantages offered by the use of the latter with total control of stereochemistry. A preliminary communication, concerning this problem, has been published.[9]

Synthesis in the Series of Indanonetricarbonylchromium

The synthetic route is outlined in Scheme I. The ketones **2** and **3** were prepared either by complexation of methyl (2-methyl-3-phenyl)propanoate and cyclization of the corresponding carboxylic acid in polyphosphoric acid or by methylation of **1**.[3,10] The diastereoisomers **2** and **3** undergo equilibration in acidic or basic media via the enolic form.

The next step of the procedure involved the base-catalyzed Michael addition of methyl vinyl ketone (MVK) to the cyclic ketone. Problems concerned with this type of reaction have been thoroughly reviewed.[11] The choice of solvent and base can have an important influence on the stereochemistry of the products formed, but in general this addition has a low degree of stereoselectivity. In the case of **2** and **3**, the vapor phase in-

Scheme I



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troduction[12] of MVK into a benzene solution of the ketone, in the presence of a weak base (DBN),[12] proceeded with a high degree of stereoselectivity, giving rise to a mixture of the two Michael adducts (yield 90%) **7** and **8** (ratio **7**/**8** = 13/87). The exo position of the methyl group in **7** and the endo position in **8** were established by ^{1}H NMR ($\delta_{CH_3\ exo}$ 1.23, $\delta_{CH_3\ endo}$ 1.43) based on the known deshielding effect of the $Cr(CO)_3$ moiety on the endo methyl group.

The base-catalyzed ring closure is the key annulation step and occurs via an aldol condensation. This reaction has been discussed[13] and the intermediate ketol with a kinetically favored bridged structure can be transformed by choice of conditions into either a bridged ketone or a conjugated enone, which is the product of thermodynamic control.

From **7** and **8** only an enone type would be expected because of the absence of hydrogen on the second position α from the carbonyl. Thus, upon treatment with a strong base (methanolic solution of Triton B, benzene), ketone **7** afforded the diastereoisomeric α-enone **9** ($\delta_{CH_3\ exo}$ 1.33) in a high yield (90%). The outcome of this reaction corresponded to that of the noncomplexed series. Under the same conditions, the ketone **8** underwent two concurrent cyclizations. The first one led to the expected diastereoisomeric α-enone **10** ($\delta_{CH_3\ endo}$ 1.67), whereas the second ring formation, which is predominant (>90%), yielded two products **11** and **12** (ratio **11**/**12** = 45/55). Products **11** and **12** have same molecular weight as **8** (M^+ = 352) and both of them showed by spectroscopy (^{1}H NMR and IR) two methyl groups, a hydroxy function, a keto carbonyl, but only one benzylic hydrogen.

The assignment of the stereochemistry in **11** and **12** was not trivial and was elucidated on spectroscopic evidence (vide infra).

The unusual annulation in **8,** resulting from attack of the linear ketone in an exo fashion at the benzylic group rather than classical attack at the cyclic ketone, seemed at first surprising but could be easily explained by considering the activation effect of the methylene protons in the α position of an arene coordinated to $Cr(CO)_3$. Similar activations have been already reported as a consequence of the electron-withdrawing effect of the $Cr(CO)_3$ moiety. In side chains bonded to an aromatic complexed ring, carbanions could be created regiospecifically at the benzylic position and a further electrophilic attack could then be performed on the α carbon atom.[14,15] Moreover, in a rigid system, e.g., complexed indan, the exclusive exo substitution of hydrogens bonded to a carbon in the α position to the ring has been shown.[14] All this indicates that the acidity of the exo benzylic hydrogen is due to a combination of the electron-withdrawing effect of $Cr(CO)_3$ and the resonance stabilization of the carbanion formed by removal of the exo proton on treatment with an appropriate base.

Thus, the control of ring juncture in **7** and **8** is governed by stereoelectronic factors. In **7,** the oxobutyl group lies on the same side as the bulky $Cr(CO)_3$ group and as the endo benzylic hydrogen which is not activated; therefore, solely the normal aldol condensation leading to the conjugated α-enone takes place. In **8,** the oxobutyl group is free from the steric hindrance of $Cr(CO)_3$ and an attack on the activated exo benzylic hydrogen is now possible corresponding to transformation into a kinetically favored bridged structure which gives the two diastereoisomeric keto alcohols **11** and **12.**

Upon treatment with $SOCl_2$ in pyridine the keto alcohols **11** and **12** were converted by dehydration into the same nonconjugated enone **13** in 90% yield.

Synthesis in the Tetralonetricarbonylchromium Series

As a further extension of this procedure, we applied this annulation reaction to the tetralone derivatives, the skeleton of which appears in numerous examples and represents an important class of biosynthetic intermediates (Scheme II). The

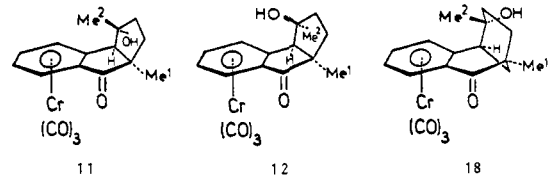
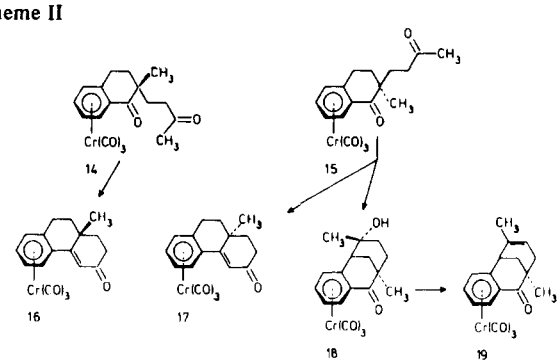


Figure 1. Relative configurations of cyclization products.

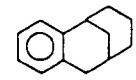
Scheme II



introduction of a 3-oxobutyl group onto a mixture of 2-*exo*-methyltetralonetricarbonylchromium (**5**), and 2-endo isomer **6,** gave rise to the two diastereoisomeric Michael adducts **14,** with an exo methyl group, and **15,** containing an endo methyl group with a similar degree of stereoselectivity as obtained with the indanone derivatives (ratio **14**/**15** = 13/87).

Cyclization of the exo methyl isomer **14,** under the same basic conditions as before, led to the normal formation of an α-enone complex **16** (yield 91%, $\delta_{CH_3\ endo}$ 1.23). Annulation of the major isomer **15** was in accord with the expectation that an alternate ring closure process could occur. Small amounts of the α-enone **17** ($\delta_{CH_3\ endo}$ 1.53) resulting from the classical aldol condensation were observed, whereas a keto alcohol **18** ($M^+_{15} = M^+_{18}$ = 366; two methyl groups, one hydroxyl group, one ketonic carbonyl) was constructed specifically by the unusual cyclization process. Spectrometric evidence for the structure, configuration, and conformation of **18** is presented below. In the cyclization product **18** a six-membered ring was produced and therefore the attack of the exo oxobutyl group took place solely at the activated benzylic C-4 and not at the adjacent methylene group C-3.

The above annulation process provided a new and convenient route to an aromatic system (particularly with optically active derivatives (vide infra)) which could be used later to reach the backbone of **20.** This type of structure has been already men-



tioned in the synthesis of polycyclic compounds by the ring closure of 3-phenylcyclopentanecarboxylic acid[16] and benzylcyclohexanols.[17,18]

Structure Determination. Results and Discussion

The spectrometric data provided evidence for the structure and the assignment of the relative stereochemistry of the unusual cyclization products **11, 12,** and **18,** as illustrated in Figure 1.

The first problem, which concerned the nature of the carbon atom involved in forming the new C–C bond, is solved immediately by observation of the chemical shifts (Table I). The ^{1}H NMR spectra of **11** and **12** exhibit only one benzylic proton as a singlet. For the benzylic hydrogen of **18** and **18a,**[32] a pseudotriplet which comes from the X part of an ABX system with vicinal couplings of 2.5 and 3.5 Hz (the geminal coupling is 12.5 Hz) is observed.

Table I. Chemical Shifts (ppm)[a]

	11	11a	12	12a	18	18a
OH	1.86	1.84	1.40	1.20	1.68	1.70
Me^1	1.54	1.29	1.46	1.31	1.22	1.18
Me^2	1.40	1.37	1.54	1.54	1.32	1.22
H benzylic	3.14	3.22	2.97	2.97	2.63	2.92

[a] Varian XL 100, $CDCl_3$, δ.

Table II. LIS Data (Hz)[a]

	benzylic H	Me^1	Me^2	aromatic H
11	383	150	300	122, 54, 40, 75
12	315	124	416	9, −111, −19, 53
18	357	88	320	106, 53, 38, 85

[a] $CDCl_3$, $Eu(dpm)_3$/substrate concentration = 0.3.

Thus, with the carbon framework of these benzobicyclic keto alcohols well established, we may now focus on the assignment of configurations. The compounds **11** and **12** are diastereoisomers which differ only in the relative positions of the hydroxyl and methyl groups attached to the same carbon.

Examination of Dreiding models of **11** and **12** (Figure 1) shows that the methyl group Me^2 (directed toward the aromatic ring) in **11** should be shifted upfield by 15–20 Hz with respect to Me^2 in **12** (OH directed toward the aromatic ring and Me^2 turned away) as a result of the ring current effect. An upfield shift of 14 Hz (17 Hz for **11a**) relative to **12** (**12a**) is observed for **11** (Table I).

Strengthening of the above stereochemical assignment is based on a ^1H NMR double resonance experiment. Selective irradiation of the two methyl resonances (Me^1 and Me^2) in the spectra of **11a** and **12a** and measurement of the enhancement due to the benzylic proton gave results in good agreement with the former conclusions. For **11a,** on irradiation of Me^1 a 12% enhancement of the benzylic proton signal is found; on irradiation of Me^2 no effect is observed (i.e., Me^1 and H are in a cis position to each other, and Me^2 and H are in trans position). For **12a,** the irradiation of Me^1 led to a 15% enhancement for the benzylic H and the Me^2 irradiation gave a 15% enhancement (i.e., Me^1 and H and Me^2 and H are in cis position). In **18a,** the two methyl resonances are too close together (1.18, 1.22 ppm) to allow selective irradiation (XL 100, $CDCl_3$, argon).

Further proof was provided by LIS experiments. The relative configurations of Me^2 and OH in **11, 12,** and **18** are determined in a straightforward manner by $Eu(dpm)_3$-induced shifts. In addition, one must mention that, by these experiments, one gains some insight into the conformational behavior of the aliphatic five-membered ring in **11** and **12** and in particular of the cyclohexane ring in **18.**

The LIS values (Table II) for **11** and **12** allow a clear decision between the possible assignments. In **11,** the largest displacement is observed upon addition of shift reagent; therefore, the coordinating hydroxyl[19] group is cis to the benzylic hydrogen. The negative (upfield) shifts of the aromatic protons in **12** are in favor of a structure with the coordinating center directed toward the protons which become shielded.[20,21] This is only the case for structure **12.** A more quantitative treatment using the McConnell–Robertson equation (computer program PDIGM[22]) confirmed these results. *R* factors[23] of 9.5% for **11** and 10.7% for **12** were the best possible fit (13 and 17% for the wrong assignments). The newly formed aliphatic five-membered ring in **11** and **12** introduces some uncertainties in the torsional angles changing the position of the coordinating OH relative to the rest of the molecule. This can explain the relatively high *R* factors; a mixture of two or more particular conformations lowers the *R* factors to 5%. All this reflects the nonrigidity of the aliphatic five-ring partial system in **11** and **12.**

Table III. Configuration and Conformation of the Four Possible Structures for **18**

cyclohexane ring shape	subst directed toward the aromatic ring	computed *R* factors, %
boat	OH	36
boat	Me^2	12
chair	OH	27
chair	Me^2	5.7

For **18** the LIS data (Table II) allow a decisive choice between configurations and conformation as well. Comparison of the calculated shifts and the observed values for the four possible structures (Table III) indicates clearly that the stereochemical assignment shown in **18** is the correct one.

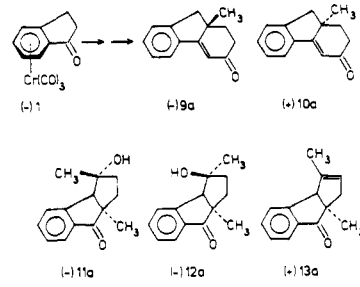
On applying the *R*-factor ratio significance test,[21,23,24] the structure with $R = 5.7\%$ appears as the actual one (confidence level > 99%).

Facile Access to Optically Active Polycyclic Ketones with a Known Absolute Configuration by Total Control of the Reactivity and of the Stereochemistry

The optical resolution of carbonyl compounds is still an interesting problem but without a generally applicable solution and many methods have been investigated.[25,26] Furthermore, the assignment of the absolute configuration is not solved easily and the alternative process starting in an early key step with optically active compounds offers several advantages, particularly when the stereochemical course of the successive reactions is predictable with certainty.

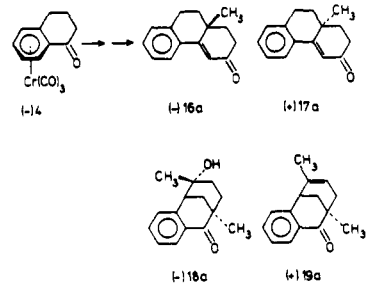
As mentioned elsewhere,[3] optically active metal complex precursors like (−)- or (+)-indanonetricarbonylchromium and (−)- or (+)-tetralonetricarbonylchromium provide a convenient route to enantiomeric ketones and alcohols with a known absolute configuration. Taking into account the regioselective activation of benzylic C–H bonds, the total control of the stereochemistry of the annulation reaction (vide supra), and the ease of disengagement of the arene ligand from its tricarbonylchromium complex, we have now a very useful method for the obtention of various optically active compounds.

Thus, starting from (−)-1-indanonetricarbonylchromium (**1**) and (−)-1-tetralonetricarbonylchromium (**4**) the same synthetic route was developed. The absolute configurations are fully known and are those given in Schemes I and II. A recent X-ray structure determination of a compound which possesses a planar chirality and a center of chirality on the metal atom confirmed the absolute configuration of the (−)-tetralone derivative **4.**[27] Alkylation of (−)-**1** led to the (−)-2-*exo*-methyl-1-indanonetricarbonylchromium (**2**). Michael addition of MVK converted (−)-**2** into the two diketones (−)-**7** (mp 75 °C, $[\alpha]_D$ −330°, exo Me) and (−)-**8** (mp 88 °C, $[\alpha]_D$ −353°, endo Me). Basic media annulation of (−)-**7** gave rise to the diastereoisomeric α-enone (−)-**9** (mp 170 °C, $[\alpha]_D$ −1040°, exo Me). Under the same basic conditions, (−)-**8** led to the



diastereoisomeric α-enone (−)-**10** (mp 192 °C, $[\alpha]_D$ −1088°, endo Me) and to the two active keto alcohols (−)-**11** (mp 139 °C, $[\alpha]_D$ −274°) and (−)-**12** (mp 70 °C, $[\alpha]_D$ −282°), which upon dehydration by $SOCl_2$ in pyridine were converted into the nonconjugated enone (−)-**13** (mp 111 °C, $[\alpha]_D$ −333°). Demetalation under mild conditions provided access to enantiomeric benzobicyclic compounds, of which the absolute configurations are, therefore, established unambiguously. Thus the diastereoisomeric α-enone (−)-**9** gave the free ligand (−)-**9a** ($[\alpha]_D$ −210°), while (−)-**10** led to (+)-**10a** ($[\alpha]_D$ +212°), (−)-**9a** and (+)-**10a** being enantiomers. Furthermore, the demetalated (+)-**13a** ($[\alpha]_D$ +27°) was obtained from the nonconjugated enone (−)-**13.** Finally, the two keto alcohols (−)-**11** and (−)-**12** gave on demetalation a pair of diastereoisomers, the *trans*-(−)-**11a** ($[\alpha]_D$ −31°) and the *cis*-(−)-**12a** ($[\alpha]_D$ −6°) compounds.

A similar reaction sequence was carried out on (−)-tetralonetricarbonylchromium (**4**) ($[\alpha]_D$ −860°). After methylation by the previously described method or by lithium diisopropylamide/CH_3I and further reaction with MVK the two Michael adducts (−)-**14** (minor mp 87 °C, $[\alpha]_D$ −664°, exo Me) and (−)-**15** (mp 98 °C, $[\alpha]_D$ −640°, endo Me) were ob-



tained. Cyclization of (−)-**14** led to the diastereoisomeric α-enone (−)-**16** (mp 174 °C, $[\alpha]_D$ −2250°, exo Me). Cyclization of (−)-**15** led to the α-enone (−)-**17** (mp 160 °C, $[\alpha]_D$ −1890°, endo Me) and to the predominant keto alcohol (−)-**18** (mp 122 °C, $[\alpha]_D$ −752°) as well. Demetalation of the two diastereoisomers (−)-**16** and (−)-**17** gave enantiomers with a known absolute configuration; (−)-**16** led to (−)-**16a** ($[\alpha]_D$ −436°) and (−)-**17** gave (+)-**17a** ($[\alpha]_D$ +440°). This optically active unsaturated ketone (+)-**17a** has recently been resolved via its carboxymethoxine.[18] Further dehydration converted the keto alcohol (−)-**18** into the nonconjugated enone (−)-**19** (mp 158 °C, $[\alpha]_D$ −726°). Finally, after demetalation, the benzobicyclic keto alcohol (−)-**18a** ($[\alpha]_D$ −200°) was obtained from (−)-**18,** and (−)-**19** led to the benzobicyclic enone (+)-**19a** (mp 67 °C, $[\alpha]_D$ +24°) with a known absolute configuration.

The above results indicate that the methods presented in this communication could also serve to overcome the difficulties encountered by previous authors who could not determine the enantiomeric or diastereoisomeric purity of their products in the Michael addition reaction.[29]

Experimental Section[30]

Mixture of Racemic 2-*exo*-Methyl-1-indanonetricarbonylchromium (2) and 2-*endo*-Methyl-1-indanonetricarbonylchromium (3). The mixture of these two isomers was obtained either by cyclization of 2-methyl-3-(phenyltricarbonylchromium)propanoic acid in polyphosphoric acid[10] or by methylation of 1-indanonetricarbonylchromium[3] (with NaH/CH_3I or with lithium diisopropylamide/CH_3I at low temperature) and further equilibration of the exo isomer.[31]

Michael Addition of MVK to Produce the δ-Diketones 7 and 8. A mixture of the ketones **2** and **3** (2.256 g, 8 mmol) was dissolved in 50 mL of benzene. To this was added at once 0.7 mL of DBN.[12] The solution was stirred at room temperature and a stream of nitrogen bubbling through methyl vinyl ketone (MVK) was allowed to pass through the solution. The reaction evolution was followed by TLC (eluent benzene–ether, 3:1) until the starting ketones had disappeared. The solution was poured into 100 mL of 10% hydrochloric acid and the aqueous phase was extracted with ether. The ether extracts were washed with water, dried ($MgSO_4$), and evaporated in vacuo. Preparative TLC was executed on the crude product. The fastest moving zone gave 0.34 g of **7:** mp 94–95 °C (from ether–petroleum ether); NMR δ 1.23 (s, 3, exo CH_3), 2.22 (s, 3, $COCH_3$); IR 1991, 1934, and 1916 ($Cr(CO)_3$), 1725 (5-ring CO), 1716 cm^{-1} ($COCH_3$). Anal. ($C_{17}H_{16}CrO_5$) C, H.

The second zone (the R_f of the two products are very close to each other) gave 2.28 g of **8:** mp 107–109 °C (from ether–petroleum ether); NMR δ 1.43 (s, 3, endo CH_3), 2.21 (s, 3, $COCH_3$); IR 1994, 1936, and 1918 ($Cr(CO)_3$), 1724 (5-ring CO), and 1716 cm^{-1} ($COCH_3$). Anal. ($C_{17}H_{16}CrO_5$) C, H.

Conversion of 7 into the α-Enone 9. The following cyclization procedure was used. To 171 mg (0.5 mmol) of the diketone **7** in 20 mL of benzene was added 0.2 g of 40% methanolic solution of Triton B. The reaction mixture was stirred at 20 °C and followed by TLC. After 1 h the solution was quenched into 50 mL of 5% hydrochloric acid and extracted with ether. Final purification by preparative TLC gave 145 mg of a dark red solid **9:** mp 157–158 °C (from ether–petroleum ether); NMR δ 1.33 (s, 3, exo CH_3), 6.20 (s, 1, CH=C); IR 1982, 1923, and 1913 ($Cr(CO)_3$), 1675 (6-ring CO), 1639 cm^{-1} (C=C); UV 276 nm (ε 19 400), 319–327 (7750), 455 (4800). Anal. ($C_{17}H_{14}CrO_4$) C, H.

Cyclization of 8. α-Enone 10, and Keto Alcohols 11 and 12. In a similar manner to that described above, 700 mg of **8** in 40 mL of benzene was treated with 0.6 g of methanolic solution of Triton B. After workup, the crude material was submitted to preparative TLC (eluent benzene–ether, 3:1). The fastest moving zone contained 50 mg of the diastereomeric α-enone **10:** mp 225 °C dec (from ether–petroleum ether); NMR δ 1.67 (s, 3, endo CH_3), 6.20 (s, 1, CH=C); IR 1982, 1923, and 1912 ($Cr(CO)_3$), 1671 (6-ring CO), 1635 cm^{-1} (C=C); UV 275 nm (ε 14 200), 321 (7000), 450 (2800). Anal. ($C_{17}H_{14}CrO_4$) C, H.

The second zone gave 260 mg of red crystals of **11:** mp 108–110 °C (from ether–petroleum ether); NMR (100 MHz) δ 1.54 (s, 3, endo CH_3), 1.40 (s, 3, CH_3), 1.86 (s, 1, D_2O exchange, OH), 3.14 (s, 1, benzylic H); IR 3614, 3587 (OH), 1994, 1938, 1920 ($Cr(CO)_3$), 1724 cm^{-1} (5-ring CO). Anal. ($C_{17}H_{16}CrO_5$) C, H.

Then 300 mg of orange-red needles of **12** were obtained: mp 169–170 °C (ether–petroleum ether); NMR (100 MHz) δ 1.54 (s, 3, endo CH_3), 1.46 (s, 3, CH_3), 1.42 (s, 1, D_2O exchange, OH), 2.97 (s, 1, benzylic H); IR 3612, 3589 (OH), 1991, 1934, and 1917 ($Cr(CO)_3$), 1725 cm^{-1} (5-ring CO). Anal. ($C_{17}H_{16}CrO_5$) C, H.

Dehydration of 11. Nonconjugated Enone 13. The keto alcohol **11** (95 mg) was dissolved in 3 mL of freshly distilled pyridine. A stream of nitrogen was passed through the solution and a few drops of thionyl chloride were added. Immediately the solution turned from an orange-red to a deep red color and TLC showed completion of the reaction. The solution was poured into 50 mL of 10% hydrochloric acid and extracted with ether. Purification by preparative TLC gave 75 mg of **13:** mp 189–191 °C (ether–petroleum ether); NMR δ 1.57 (s, 3, endo CH_3), 1.88 (s, 3, $C(CH_3)$=C), 5.30 (s, 1, CH=C); IR 1993, 1937, and 1919 ($Cr(CO)_3$), 1724 (5-ring CO), 1520 cm^{-1} (C=C); UV 325 nm (ε 9600), 420 (3020). Anal. ($C_{17}H_{14}CrO_4$) C, H.

Dehydration of 12. Enone 13. Under the same conditions as above, 200 mg of **12** gave 150 mg of a red solid, mp 190 °C. The compound was identical with **13** by TLC and NMR spectroscopy.

Syntheses in the Tetralone Series. The synthetic procedures are similar to those described above.

Methylation of 1-Tetralonetricarbonylchromium (4). A solution of 0.5 g of **4** in 10 mL of THF was added rapidly under N_2 at −70 °C to freshly prepared lithium diisopropylamide (from 1.6 mL of a 1.6 M solution of butyllithium in hexane and 0.4 mL of diisopropylamine in 10 mL of THF at −78 °C). The mixture was allowed to warm up to 0 °C and 2 g of methyl iodide was then added. The reaction was followed by TLC (ether–petroleum ether) and showed a rapid reaction giving rise to the 2-*exo*-methyl derivative and small quantities of the 2,2-dimethyl compound. After 1 h the mixture was poured into dilute hydrochloric acid and extracted with ether. After chromatographic separation, 0.41 g of **5** and 0.060 g of the 2,2-dimethyl compound were obtained.[3]

Michael Addition of MVK to Produce the δ-Diketones 14 and 15. Using the procedure described above and starting from 2.37 g (8 mmol) of **5** or of the mixture of **5** and **6** (obtained by direct complexation of 2-methyl-1-tetralone), the following compounds were isolated:

2-*exo*-methyl-2-*endo*-(3-oxobutyl)-1-tetralonetricarbonylchromium [**14,** 0.35 g; mp 146–148 °C (from dichloromethane–pentane); NMR δ 1.19 (s, 3, exo CH_3), 2.17 (s, 3, $COCH_3$); IR 1987, 1930, and 1915 ($Cr(CO)_3$), 1726 (6-ring CO), 1686 cm^{-1} ($COCH_3$). Anal. ($C_{18}H_{18}CrO_5$) C, H] and 2-*exo*-(3-oxobutyl)-2-*endo*-methyl-1-tetralonetricarbonylchromium [**15,** 2.32 g; big, red crystals; mp 113–114 °C (from ether–petroleum ether); NMR δ 1.22 (s, 3, endo CH_3), 2.16 (s, 3, $COCH_3$); IR 1989, 1931, and 1913 ($Cr(CO)_3$, 1725 (6-ring CO), and 1684 cm^{-1} ($COCH_3$). Anal. ($C_{18}H_{18}CrO_5$) C, H].

Conversion of 14 into the α-Enone 16. Following the procedure given for the indanone derivative and starting from 0.183 g of **14,** 0.151 g of dark red crystals were obtained: mp 164–166 °C (from ether–petroleum ether); NMR δ 1.23 (s, 3, exo CH_3), 6.40 (s, 1, CH=C); IR 1984, 1926, and 1915 ($Cr(CO)_3$), 1673 (6-ring CO), 1602 cm^{-1} (C=C); UV 275 nm (ϵ 15 000), 319–329 (5600), 455 (2900). Anal. ($C_{18}H_{16}CrO_4$) C, H.

Cyclization of 15. α-Enone 17 and Keto Alcohol 18. Under the same basic conditions as before the following compounds were isolated by chromatography starting from 0.4 g of **14.** The first zone contained 0.030 g of the α-enone **17,** dark red crystals: mp 152–153 °C (from ether–petroleum ether); NMR δ 1.53 (s, 3, endo CH_3), 6.43 (s, 1, CH=C); IR 1981, 1922, and 1908 ($Cr(CO)_3$), 1765 (6-ring CO), 1600 cm^{-1} (C=C); UV 270 nm (ϵ 15 900), 332 (6800), 455 (3600). Anal. ($C_{18}H_{16}CrO_4$) C, H.

The second eluate was the keto alcohol **18** (0.32 g): mp 140–141 °C (long, orange-red crystals from dichloromethane–hexane); NMR (100 MHz) δ 1.22 (s, 3, endo CH_3), 1.32 (s, 3, CH_3), 1.68 (s, 1, D_2O exchange, OH), 2.63 (pseudotriplet, 1, benzylic H); IR 3618, 3587 (OH), 1990, 1933, and 1916 ($Cr(CO)_3$), 1690 cm^{-1} (6-ring CO); mass spectrum M^+ calcd 366.0559, found 366.056. Anal. ($C_{18}H_{18}CrO_5$) C, H.

Dehydration of 18. Nonconjugated Enone 19. The keto alcohol **18** (0.3 g) was converted by $SOCl_2$ in pyridine, as described above, into **19** (0.24 g): mp 144–145 °C (red crystals from ether–petroleum ether); NMR δ 1.30 (s, 3, endo CH_3), 1.77 (s, 3, $C(CH_3)$=C), 5.26 (s, 1, CH=C); IR 1987, 1930, and 1912 ($Cr(CO)_3$), 1688 (6-ring CO), 1520 cm^{-1} (C=C); UV 325 nm (ϵ 7450), 425 (2500). Anal. ($C_{18}H_{16}CrO_4$) C, H.

General Procedure for Decomplexation. As described elsewhere,[3] a solution of 0.105 g of **11** in 50 mL of ether was exposed to sunlight. After filtration, the organic solution was dried and evaporated to dryness under reduced pressure. Thus 0.056 g of the free ligand **11a** was obtained.

Access to Optically Active Compounds with Fully Known Absolute Configurations. The synthetic procedures were the same as those described above, starting from optically active indanonetricarbonylchromium and tetralonetricarbonylchromium obtained by a previous method.[3] The compounds were identical with the racemic derivatives by TLC, IR, and NMR spectroscopy. Melting points, optical rotations, and absolute configurations are given in the first part.

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(31) Taking a pure endo or exo isomer, the addition even of a weak base like DBN gave a mixture of fast equal amounts of the two isomers.
(32) a stands for the corresponding demetalated compound.