Reactivity of Enol Carbonates with Ozone[†]

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Several dienes of varying steric bulk containing an enol carbonate have been synthesized and reacted selectively with ozone at the isolated double bonds. Rate measurements have been made for ozonolysis in a series of substituted cyclohexenes to demonstrate the unusually slow reactivity of the enol carbonate. Proton and carbon NMR chemical shifts have been presented to show that the enol carbonate is not particularly electron deficient in its double bond. Calculation of partial charges from the Mulliken population analysis shows good correlation with the NMR data. The results suggest a carbonate association with ozone that slows the rate of carbon−carbon bond cleavage.

Introduction

Substrate reactions with ozone have been of considerable interest[1] in environmental and atmospheric chemistry as well as in organic chemistry. The study of ozone's mechanism of action, from both experimental and quantum mechanical considerations, continues to be an area of attention.[2] The Criegee mechanism, with refinements,[3] and after numerous experimental and calculational treatments, continues to be widely accepted as the mode of reaction between alkenes and ozone. As demonstrated at low temperatures, many simple alkenes form an ozone−olefin charge-transfer complex,[4] prior to ozone's electrophilic or dipolar addition. In the case of electron-rich, oxygen-substituted double bonds, the formation of a σ complex[5] from electrophilic attachment of ozone at the center of highest electron density appears to then proceed directly to primary ozonide formation.

Whether the ozonolysis of an alkene proceeds directly to a primary ozonide or first forms a charge transfer or σ complex, the general reactivity and rates of reaction have been correlated with the electron density around the double bond as described by the inductive effects of the groups which are attached. The enol carbonate, as an example of a carbonate-substituted alkene, was implicated for its ability to inhibit ozonolysis at the double bond center to which it is attached.[6] As shown in oxygen-labeling experiments,[7] ozone does react reversibly with some carbonyl compounds; however, this reactivity largely goes unnoticed in the evaluation of reaction products. Whether the "enol carbonate effect" is a result of steric or electronic factors has until now remained unclear. The results reported here suggest that the enol carbonate substitution significantly inhibits the reactivity of the olefin toward ozone and that this may occur as a result of the formation of an unusual σ complex. In this instance, a simple analysis of the electron density about the double bond is not sufficient to explain the measured rates of reaction.

Discussion

It had been demonstrated by Danishefsky and co-workers[8] in the early 1980s that the enol carbonate functioned surprisingly well as a site-specific enolate equivalent for the storage and retrieval of the corresponding enolate. Advantage was taken of this in a selective ozonolysis procedure where reactivity was directed at an isolated double bond. At the time of that work, it was unclear whether the success enjoyed there was a result of steric factors in that particular molecule or whether electronics was the controlling factor. To test these factors, we have synthesized several regiospecific enolates with decreasing steric environments around the enol carbonate centers and have evaluated their reactivity with ozone, as shown in Table 1.

Enol carbonates **1**,[9] **3**, and **5** were prepared by the copper-catalyzed conjugate addition of butenyl Grignard,

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Table 1. Dienes and Their Corresponding Ozonolysis Products

dienes		aldehydes, isolated yields
1	2	94%
3	4	98%
5	6	86%
7	8	70%

Table 2. Second-Order Rate Constants ($k \times 10^4$) for the Reactions of Ozone with Olefins in CCl_4 Solution at 25 ± 1 °C[a]

	olefin	k (10^4), M^{-1} s^{-1}
9		2.0 ± 0.36
10		2.2 ± 0.15
11		5.2 ± 0.16
12		4.6 ± 0.37
13		39 ± 2.3
14		32 ± 1.9
15		11 ± 0.33
16		0.89 ± 0.09

[a] The rate constants were measured by competitive ozonolysis with 1-hexene. An absolute rate for 1-hexene of 7.6×10^4 M^{-1} s^{-1} was previously determined by Cvetanovic and Williamson.

followed by a trap with methyl chloroformate. Although this procedure was quite efficient for the preparation of enol carbonates **1** and **3**, the yields were quite low for the preparation of enol carbonate **5**, due to the inefficient direct methyl chloroformate trapping of the enolate. Enol acetate **7** was prepared by acetyl chloride trapping of the corresponding enolate, itself having been regenerated in the *n*-butyllithium reaction of enol carbonate **3**.

As is indicated in Table 1, the selectivity in the ozonolysis reaction remains quite high at the isolated double bond as steric bulk is reduced. In comparing the *des*-methyl analogue **3** to enol carbonate **1**, the selectivity in the ozonolysis reaction remains largely unchanged. When enol carbonate **5** is reacted with ozone, selectivity begins to erode, with a net loss of about 10% in the isolated yield. These two reactions alone suggested that steric factors play a role, but perhaps only a small role in this selective ozonolysis. When enol acetate **7** was reacted with ozone, a substantial erosion in selectivity was observed, as evidenced by the loss of another 15% yield, as compared to that from enol carbonate **3**. In a comparative sense (**7** vs **3**), it was apparent that electronics played some role in a carbonate-inhibited ozonolysis. With the demonstration of its own selective behavior toward ozone in the enol acetate system, **7**, an estimation for the magnitude of the carbonate's electronic effect was not possible.

To define more clearly the role of electronic factors in the enol carbonate reactions, rate data were generated

for the reaction of ozone with a series of substituted cyclohexenes. With the exception of enol carbonate **16**, the substituted cyclohexenes in Table 2 were either commercially available or simply prepared as described in the literature.[10] Carbonate **16** was efficiently prepared by the methyl chloroformate trapping of the potassium hydride generated enolate of cyclohexanone. The second-order rate constants for the reaction of ozone with the molecules depicted in Table 2 were determined by competitive reaction with 1-hexene according to the procedure of Cvetanovic and Williamson.[11]

Most of the entries in Table 2 are unremarkable. As would be expected, the carbonyl and halogen substitutions (**9**, **10**) function to slow the rate of this electrophilic reaction, while the electron-donating oxygen substitution of entries **11**, **13**, **14**, and **15** leads to an acceleration in the reaction rate.[12] Quite remarkably, however, the enol carbonate **16** shows a greatly retarded rate of reaction in comparison to these entries, particularly in contrast

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Table 3. A Comparison of Relative Rates for the Reactions of Ozone with Olefins in CCl$_4$ (rt) and CH$_2$Cl$_2$ (−78 °C) Solution[a]

olefin	relative rate in CCl$_4$	relative rate in CH$_2$Cl$_2$
{11	1.13	1.0}
{12	1.0	2.7}
{15	12.4	3.0}
{16	1.0	1.0}

[a] The relative rate values that are listed above reflect comparisons within individual pairs (11:12 and 15:16).

to its enol acetate analogue, **15**. Perhaps more surprising is the fact that the reactivity of this enol carbonate is only about one-tenth that of the competitor compound, 1-hexene (7.6 × 10^4 M^{-1} s^{-1}).

Since the initial report of low reactivity for the enol carbonate-protected alkene was measured in dichloromethane at −78 °C, prudence suggested the measurement of rate constants under similar conditions. Carbon tetrachloride's relatively high melting point, −23 °C, unfortunately does not lend itself to a low-temperature study. Likewise, ozone's instability at room temperature in dichloromethane prohibits rate measurements under those conditions. A competitive measurement, conducted at low temperature in dichloromethane, between two pairs of cyclohexenes from Table 2, provided the results shown in Table 3. In comparing the enol acetate **15** and enol carbonate **16**, an erosion in selectivity is noted as evidenced by the change in rate constant ratios (12.4:1.0 → 3.0:1.0). While selectivity is often enhanced by decreasing reaction temperature, the increasing solvent polarity offset that effect in this instance.[13] This effect is observed more poignantly when entries **11** and **12** are compared. In this instance, not only is a significant ratio change observed, but a reversal in favor of **12** (1.13:1.0 → 1.0:2.7). While it is reasonable to argue that this reactivity results from the ground-state stabilization of **11**, through the use of a more polar solvent, for the more electronically similar enol acetate 15 and enol carbonate **16**, a transition-state effect is suggested.

What role electronic factors play in the enol carbonate effect is aided by focusing attention on the silyl enol ether **13**, enol acetate **15**, and enol carbonate **16**. As compared to 1-hexene, the electron-rich silyl enol ether would be expected to be much more nucleophilic toward ozone. This is consistent with its rate constant, $k = 39 × 10^4$ M^{-1} s^{-1}. Also as expected, the electron-rich enol acetate **15** is more reactive than 1-hexene but less reactive than the silyl enol ether **13**. Assuming that these two examples were behaving as expected, the enol carbonate's reactivity seemed unusual. The differences in electronegativity between the carbonate and acetate substituents were evaluated according to the method of Mullay[14] but found to be too small to account for such differences in reactivity.

An evaluation of the electronics about the alkene centers of **13**, **15**, and **16**, using ^{1}H and ^{13}C NMR chemical
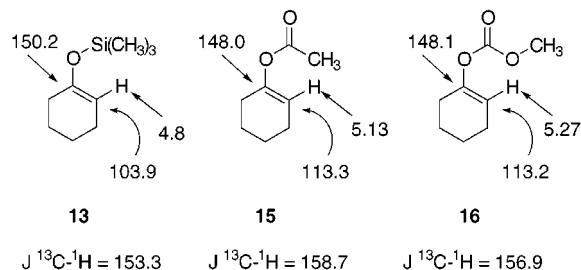
Figure 1. [13]C and ^{1}H chemical shifts are given in ppm and the J [13]C−[1]H coupling constants for the vinyl positions are given in Hz.

shifts,[15] and [13]C−[1]H coupling constants[16] for the vinyl proton, provides some clarification. As shown in Figure 1, electron densities suggest that there should be very little difference in reactivity between the enol acetate and enol carbonate. Chemical shifts and coupling constants for all important centers are nearly identical for the enol acetate and enol carbonate molecules. By contrast, the chemical shift and coupling constant information for carbon 2 (the H-substituted vinyl carbon) of the silyl enol ether shows that center to be more shielded ([1]H δ 4.8, [13]C δ 103.9, and [1]H−[13]C; $J = 153.3$ Hz) and likely more electron rich. This is in agreement with its high reactivity. If the NMR information for carbon 2 were to be a marker for unusual reactivity in the case of the enol carbonate, the chemical shift should have demonstrated greater shielding and a larger coupling would have been observed in comparison to the enol acetate. This result would have suggested less electron density in the carbon double bond and more s-character in the vinyl carbon hydrogen bond. That was clearly not the case.

When the silyl enol ether **13**, enol acetate **15**, and enol carbonate **16** were submitted for ab initio single-point energy calculations, at the HF 6-31G* level,[17] good agreement between partial charges obtained from the Mulliken population analysis and the NMR data was observed. A comparison is presented in Figure 2 between these three molecules along with cyclohexene, which has been reported[18] to have a rate constant for ozonolysis of 6.2 × 10^4 M^{-1} s^{-1}, a value that is quite similar to 1-hexene (7.6 × 10^4 M^{-1} s^{-1}). The relative trend can be followed for carbon 2 in comparing its chemical shift, calculated partial charge, and chemical reactivity. The intermediate reactivity of the enol acetate **15** is reflected in its intermediate value for the partial charge (−0.27) at carbon 2, as compared to the very reactive silyl enol ether (−0.34) and the less reactive cyclohexene (−0.18). If the enol carbonate's reactivity were to have been a result of an electronically depleted double bond, that factor would have been reflected in the relative trends of chemical shifts and coupling constants, along with a more electropositive value than that observed for the calculated partial charge (−0.24).

A possible explanation is proposed in Figure 3 for the anomalous behavior that has been observed for the enol

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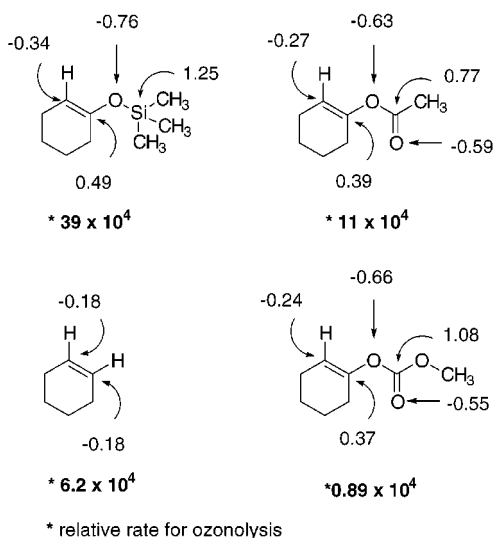
Figure 2. Partial charges were calculated at the HF 6-31G* level using the Mulliken method.
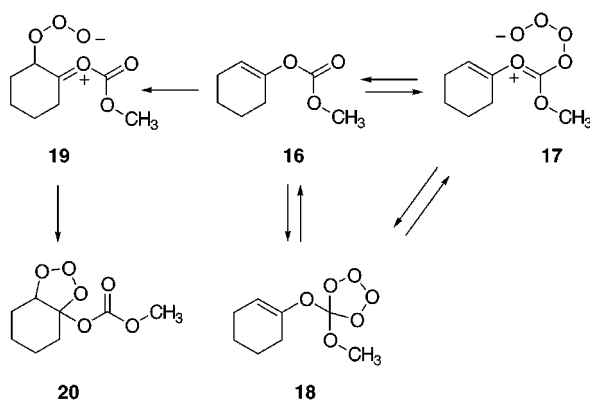
Figure 3. Reversible formation of a σ-complex is proposed to explain the unusual reactivity of the enol carbonate.

carbonates. By analogy with other oxygen-substituted alkenes, initial formation of a σ-complex **19**, followed by primary ozonide **20** formation, would have been expected.[5] This pathway is viable where an explanation of enhanced reactivity is required. In contrast, reaction with the electrophilic reagent occurring first at the molecule's center of highest electron density, the carbonyl, could reversibly produce either an unusual σ-complex **17** or a [3 + 2] addition product **18**.[7] These two are of course directly interconvertible. Of the two transients, **17** and **18**, we favor **17**, due to its especially stable cation, and the unlikelihood that complex **18** would appreciably alter the rate of turnover in the ozonolysis reaction. Calculated partial charges from the Mulliken population analysis for **18**, again at the HF 6-31G* level, show that carbon 2 is not particularly electropositive (C 2; −0.27, C 1; 0.38). These values are remarkably similar to those that were observed for the enol acetate, **15** (C 2; −0.27, C 1; 0.39), indicating a similar distribution in electron density. In contrast, the calculation for intermediate **17** shows carbon 2 to be more electropositive (C 2; −0.21, C 1; 0.30), further discounting intermediate **18**.

Summary

We have shown that the selectivity demonstrated for the ozonolysis of multiple olefin systems containing an enol carbonate is not greatly influenced by steric factors but instead is a result of an electronic effect, arising during the course of reaction. As in the Friedel−Crafts acylation or alkylation procedure, where an electron-rich aniline molecule is inhibited toward further reaction after its electron-rich nitrogen is tied up with the catalyst,[19] we speculate that the enol carbonate may be functioning similarly to inactivate the double bond toward further reaction with ozone.

The suggestion presented here that ozone may be reacting first at the molecule's center of highest electron density, prior to productive substrate consumption, could be general. It is probably not unreasonable that an enol acetate such as those described here (**7**, **15**) would attract itself first to the electrophilic ozone through its most electronegative center, the carbonyl oxygen. In this example, however, that complex is not well stabilized, and it would be expected to quickly reverse and release the substrate. Similarly, the enol carbonate has been implicated for helping to direct epoxidation away from the enol carbonate center, toward an apparently less electron-rich isolated double bond,[8] perhaps through a similar mechanism. Unlike ozonolysis reactions where π complexes[3,20] have long been used to explain certain types of reactivity, and unlike organometallic chemistry where the metal center is used as the coordinating sphere prior to productive substrate turnover,[21] little attention is focused on the role of prereaction substrate attraction and complexation. This type of analysis could prove to be worthwhile in considering other reactions.

Although we have not presented direct evidence for the formation of an unusual type of σ complex, we intend to gain valuable insight into its nature through the use of vibrational spectroscopy, and through the use of trajectory calculations to analyze pathways that may be followed during the course of the reaction. In addition, we will be evaluating the possible function of the carbonate group as a general protecting or directing group and be looking for its effect in altering the product outcome from substrate−ozone reactions.

Experimental Section

General Methods. Cyclohex-2-en-1-one (**10**), 3-ethoxycyclohex-2-en-1-one (**11**), 1-phenylcyclohexene (**12**), and 1-cyclohexenyloxytrimethylsilane (**13**) were purchased from Aldrich Chemical Co. and used without further purification. 2-Chlorocyclohex-2-en-1-one (**9**), 1-cyclohexenyloxy-*tert*-butyldimethylsilane (**14**), and cyclohex-1-enyl acetate (**15**) were prepared according to the published literature procedures.[10] Solvent red 19 was used as a 0.1% solution in methylene chloride. Dichloromethane was distilled from P_2O_5. Dimethyl sulfide (DMS) and HMPA were distilled from CaH_2. THF and diethyl ether were distilled from sodium metal and benzophenone. Ozone was generated with a Welsbach T-23 ozonator. Silica gel for flash chromatography was Merck type 60 (230−400 mesh). NMR spectra were recorded in $CDCl_3$ solution at 300 MHz. FTIR spectra were recorded neat. Analyses were performed by M−H−W Laboratories, Phoenix, AZ. CI and high-resolution mass spectra were recorded at the Mass Spectrometry Facility in the Department of Chemistry, University of

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California, Santa Barbara, CA. Gas chromatographic separations were made on a 30 m SPB-30 Supelco capillary column.

3-(3-Butenyl)-3-methylcyclohex-1-enyl Methyl Carbonate (3). A. Preparation of the Grignard reagent: Magnesium (0.40 g, 16.3 mmol) and several crystals of iodine were placed into a dry three-neck 50 mL round-bottom flask containing a reflux condenser and addition funnel. After the contents were flamed, the flask was cooled under argon. A mixture of dry ether (20 mL) and the bromide (1.38 mL, 1.84 g, 13.62 mmol) was added dropwise from the addition funnel over a 15 min period. The mixture was refluxed for an additional 15 min, then cooled.

B. Under a flow of argon, in a dried 125 mL round-bottom flask containing an addition funnel and reflux condenser, was added CuBr·DMS (0.19 g, 0.91 mmol), 3-methylcyclohex-2-en-1-one (1.03 mL, 1.0 g, 9.08 mmol), and 40 mL of dry DMS/Et$_2$O (50:50). The Grignard reagent was transferred via cannula to the addition funnel and added dropwise to the 0 °C cooled solution over a period of 1.5 h. After being warmed to room temperature for 1 h and then returned back to 0 °C, the mixture was treated with methyl chloroformate (3.51 mL, 4.29 g, 45.4 mmol) and then allowed to stir at room temperature overnight. The reaction mixture was quenched with 10 mL of NH$_4$Cl(satd) and the layers separated. The aqueous layer was washed once with 20 mL of ether. The combined ethers were washed four times with 20 mL portions of NH$_4$-Cl(satd) and then dried with MgSO$_4$. After concentration at the rotary evaporator, the 2.21 g of product, which contained carbon- and oxygen-acylated products, and the untrapped ketone, was purified on silica gel (85 g) (4% EtOAc/96% hexane eluent) to produce 0.91 g (45%) of the desired product, **3**, as a colorless liquid: IR (neat) 1759.5, 1689.5, 1640.2, 1256.3 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 5.79 (m 1H), 5.25 (s 1H), 4.03 (m 2H), 3.80 (s 3H), 2.15 (m 4H), 1.76 (m 2H), 1.43 (m 4H), 1.02 (s 3H); ^{13}C NMR (CDCl$_3$) δ 153.89, 147.61, 139.05, 122.63, 113.91, 54.65, 41.64, 34.64, 33.83, 28.38, 27.00, 26.27, 19.23; HRMS calcd for C$_{13}$H$_{21}$O$_3$ (M + H)$^+$ *m/e* 225.14907, measured 225.14831. Anal. Calcd for C$_{13}$H$_{20}$O$_3$: C, 69.61; H, 8.99. Found: C, 69.73; H, 8.77.

3-(3-Butenyl)cyclohex-1-enyl Methyl Carbonate (5).[22] As in the preparation of enol carbonate (**3**), the Grignard reagent was prepared from 4-bromo-1-butene (10.1 g, 74.8 mmol) and magnesium (3.6 g, 148.1 mmol) in dry ether (30 mL). Under argon and with cooling (0 °C), the Grignard reagent was added dropwise over a period of 1.5 h to cyclohex-2-en-1-one (4.42 g, 46.0 mmol) and copper bromide (0.76 g, 5.30 mmol) in dry ether (20 mL). After an additional 1 h of stirring at 0 °C, dry HMPA (40 mL) was added, followed by the dropwise addition of methyl chloroformate (48.0 g, 508 mmol) at such a rate that the exotherm of the reaction was controlled. After being stirred to room temperature overnight, the mixture was poured into saturated NH$_4$Cl (100 mL) and extracted three times with 50 mL of ether. The ether extract was washed four times with 30 mL water and once with 30 mL of brine and then dried with MgSO$_4$. After concentration at the rotary evaporator, the 6.71 g of product was impregnated on silica gel (20 g) and loaded onto and purified from silica gel (100 g) (4% EtOAc/96% hexane eluent) to produce 0.66 g (7%) of the desired product, **5**, as a colorless liquid: IR (neat) 1759.5, 1686.9, 1654.3, 1265.6 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 5.79 (m 1H), 5.40 (m 1H), 4.97 (m 2H), 3.79 (m 3H), 2.16 (m 5H), 1.75 (m 3H), 1.44 (m 2H), 1.18 (m 1H); ^{13}C NMR (CDCl$_3$) δ 153.97, 148.62, 138.49, 118.30, 114.51, 54.77, 34.97, 33.75, 31.00, 27.96, 26.42, 21.27; mass spectrum (M + H)$^+$ *m/e* 211; HRMS calcd for C$_{12}$H$_{17}$O$_3$ (M − H)$^+$ *m/e* 209.11777, measured 209.11834. Anal. Calcd for C$_{12}$H$_{18}$O$_3$: C, 68.54; H, 8.63. Found: C, 68.32; H, 8.43.

3-(3-Butenyl)-3-methylcyclohex-1-enol Acetate (7). Under argon, into a dry three-neck round-bottom flask was added

the enol carbonate (**3**) (0.50 g, 2.232 mmol) and dry Et$_2$O (10 mL). After the mixture was cooled in a methanol/ice bath, the resultant was treated dropwise with *n*-BuLi (4.32 mL, 1.6M, 6.91 mmol) over a period of 5 min. The resultant was stirred for 1 h at −10 °C. After the addition of HMPA (1.55 mL, 8.93 mmol), the reaction mixture was treated by the dropwise addition of AcCl (0.56 g, 0.51 mL, 0.713 mmol) over a 5 min period. After being stirred at room temperature overnight, the mixture was diluted with 25 mL of petroleum ether (30−60) and washed five times with water and once with brine. After drying with Na$_2$SO$_4$, filtration, and concentration in a rotary evaporator, 0.53 g of material was obtained. The crude was chromatographed on 24 g of silica gel (5% EtOAc/95% 30−60 petroleum ether eluent) to give 0.34 g (74%) of the desired product, **7**, as a colorless liquid: IR (neat) 3076.6, 1757.7, 1686.7, 1640.1, 1220.0 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 5.80 (m 1H), 5.13 (s 1H), 4.93 (m 2H), 2.10 (s 3H), 2.06 (m 4H), 1.75 (m 2H), 1.42 (m 4H), 1.02 (s 3H); ^{13}C NMR (CDCl$_3$) δ 169.18, 147.44, 139.20, 122.67, 113.91, 41.76, 34.64, 33.98, 28.45, 27.15, 26.77, 21.00, 19.31; HRMS calcd for C$_{13}$H$_{21}$O$_2$ (M + H)$^+$ *m/e* 209.15416, measured 209.15407. Anal. Calcd for C$_{13}$H$_{20}$O$_2$: C, 74.96; H, 9.68. Found: C, 75.06; H, 9.71.

Cyclohex-1-enyl Methyl Carbonate (16). Into a 100 mL round-bottom flask under argon was added KH (2.68 g of 35% = 0.94 g, 23.43 mmol) as a 35% suspension in oil.[23] The hydride was washed three times with hexane and then blown dry with argon. Dry THF (55 mL) was added with stirring. Cyclohexanone (2.0 g, 20.38 mmol) was added dropwise via syringe over a 10 min period. After 15 min, the resulting gel-like material was treated by the dropwise addition of a solution of methyl chloroformate (2.5 g, 26.5 mmol) in THF (10 mL). After this addition, the gel dispersed to give a light yellow solution that was stirred at room temperature overnight. The reaction mixture was quenched with 35 mL of Na$_2$CO$_3$ (satd) and then extracted three times with 25 mL of Et$_2$O. The combined ether layers were washed twice with 25 mL of Na$_2$CO$_3$ (satd) and once with brine and dried with MgSO$_4$. Concentration gave 2.66 g of crude product that was chromatographed on silica gel (130 g) using a gradient elution (2%, 3%, then 4% ethyl acetate with 30−60 petroleum ether) to give 1.0 g (32%) of the desired product, **16**, as a colorless liquid: IR (neat) 1757.2, 1692.6, 1441.5, 1259.6 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 5.42 (m 1H), 3.80 (s 3H), 2.18 (m 2H), 2.11 (m 2H), 1.75 (m 2H), 1.58 (m 2H); ^{13}C NMR (CDCl$_3$) δ 153.90, 148.41, 113.84, 54.62, 26.15, 23.33, 22.38, 21.38; mass spectrum *m/e* 156 (M$^+$); HRMS calcd for C$_8$H$_{12}$O$_3$ (M$^+$) 156.07864, measured 156.07819 Anal. Calcd for C$_8$H$_{12}$O$_3$: C, 61.52; H, 7.74. Found: C, 61.70; H, 7.87.

General Procedure for the Ozonolysis of Dienes 3, 5, and 7 and the Characterization of Aldehydes 4, 6, and 8. Into a 100 mL round-bottom flask containing a gas dispersion tube were added the diene (1.0 mmol) and CH$_2$Cl$_2$ (30 mL), followed by a trace of Sudan Red 7B dye (sufficient to impart a pale burgundy color).[24] Nitrogen was bubbled through the solution, which was then cooled to −78 °C. The nitrogen line was replaced with a line from the ozone generator, and a stream was delivered over a 5 min period until the burgundy color began to change toward that of a white zinfandel. The ozone line was quickly removed and the nitrogen stream replaced. After 20 min under a stream of nitrogen, the gas dispersion tube was removed and replaced by a magnetic stirring bar. Zinc dust (1.0 g, 15.3 mmol) was added, followed by 2 mL of glacial acetic acid. The cooling bath was removed and the flask allowed to warm to room temperature. The solution was filtered through diatomaceous earth and concentrated at the rotary evaporator. The residue was flashed through a plug of silica gel with CH$_2$Cl$_2$ and concentrated to give the pure aldehyde product. The structure of these compounds was consistent with their infrared, ^{1}H NMR, and mass spectra. In addition, they corresponded to those reported by Danishefsky[9] and were interconvertible with their dienes

(22) Attempts to directly trap the potassium enolate, itself prepared by the potassium/ammonia reduction of the corresponding α,β-unsaturated enone, also produced very low yields of the enol carbonate product, with the untrapped saturated ketone predominating. We are currently investigating the potassium/ammonia reduction of α,β-unsaturated ketones and will report on that in the future.

(23) The use of KH to generate enolates is described: Brown, C. A. *J. Org. Chem.* **1974**, *39*, 3913−3918.

(24) The use of the Sudan dyes in ozonolysis is described: Veysoglu, T.; Mitscher, L. A.; Swayze, J. K. *Synthesis* **1980**, 807−810.

by Wittig reaction. The IR absorptions corresponding to acetate or carbonate persisted along with a new absorption corresponding to the aldehyde at 1724 cm^{-1}. In the ^{1}H NMR the vinyl proton (1H) corresponding to the cyclohexene persisted with no evidence of vinyl absorptions corresponding to the terminal olefin. The adehyde's presence was clearly demonstrated by the presence of an absorption at 9.80 (t, 1H, $J \approx$ 0.5 Hz).

General Procedure for the Ozonolysis of Cyclohexenes 9−16 and Derivation of the Rate Constants. Preparation of Clean CCl$_4$. HPLC-grade CCl$_4$ was first distilled and then saturated with ozone and additionally treated for 1 h. The CCl$_4$ was purged free of ozone with a stream of nitrogen for a period of 2 h. After this time the CCl$_4$ showed an absence of a pink color when treated with aqueous potassium iodide (1 M).

Gas Chromatography Measurements. Samples were analyzed on a 30 m SPB-30 Supelco capillary column with a semipolar phase. The helium flow through the GC was set at 80 cm s^{-1}. For each run the GC was set at 50 °C for 2 min followed by a 25 °C min^{-1} ramp up to 200 °C.

Preparation of the Calibration Graphs. To build each calibration graph, three samples were prepared quantitatively in the range of 2×10^{-2} to 5×10^{-3} M for both 1-hexene and the olefin, while an internal standard of decane (0.1 M) was used. For each ozonolysis measurement two plots were prepared; the first placed (area 1-hexene/area decane) on the y-axis and [hexene]/[decane] on the x-axis; the second placed (area olefin/area decane) on the y-axis and [olefin]/[decane] on the x-axis. The R values for these graphs were generally better than 0.98.

Preparation and Reaction of Samples with Ozone. Samples were prepared at a concentration of [olefin] $\approx 4.2 \times 10^{-3}$ M and [1-hexene] $\approx 4.2 \times 10^{-3}$ M in clean CCl$_4$ with decane as an internal standard [decane] ≈ 0.1 M. At room temperature, in a stoppered round-bottom flask containing a 1 mL iquot of the reactant solution was injected a 1 mL aliquot of ozone saturated CCl$_4$ and the resultant allowed to react for 4 min. One microliter samples of this reaction mixture were analyzed by gas chromatography.

Determination of the Rate Ratios. The competitive rate constant for each alkene was determined from the (GC measured change in area) change in concentration of each component, using the equation shown here.[11] This equation is derived from the individual second-order rate equations

$$\frac{k_2}{k_1} = \ln\frac{[R_2(\text{f})]}{[R_2(\text{o})]} \Big/ \ln\frac{[R_1(\text{f})]}{[R_1(\text{o})]}$$

where $R_2(\text{f})$ and $R_1(\text{f})$ are the concentrations after ozonolysis for each olefin pair (olefin/1-hexene) and $R_2(\text{o})$ and $R_1(\text{o})$ are the concentrations before ozonolysis for each olefin pair (olefin/1-hexene), measured in mol L^{-1}.