solution[55] of the structure. The structure contains two molecules in the asymmetric unit. Both molecules have the same overall conformation but differ somewhat in the orientation of the phenyl group. Hydrogen atoms have been treated as riding atoms with fixed thermal parameters (B = 5.0 Å^2). The remaining atoms have been refined with anisotropic thermal parameters (no. of parameters 380). The final R factor was 4.1%.

(54) B. A. Frenz and Associates Inc. (1983), Structure Determination Package, College Station, Texas, and Enraf-Nonius, Delft.
(55) Germain, P.; Main, P.; Woolfson, M. M. *Acta Crystallogr., Sect. A* **1971**, *A27*, 368.

Acknowledgment. We are grateful for the financial support of this work by the Netherlands Cancer Foundation and by the Netherlands Foundation for Technical Research (STW), future Technical Science Branch/Division of the Netherlands Organization for the Advancement of Pure Research (ZWO). We also acknowledge J. M. Visser and J. L. M. Vrielink for recording the NMR and T. W. Stevens for recording the mass spectra.

Supplementary Material Available: Lists of positional and thermal parameters, bond lengths, and bond angles (8 pages). Ordering information is given on any current masthead page.

Electroreductive Cyclization. Ketones and Aldehydes Tethered to α,β-Unsaturated Esters (Nitriles). Fundamental Investigations

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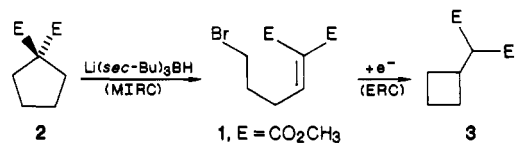
Received August 24, 1987

The intramolecular electrochemically initiated cyclization of a variety of α,β-unsaturated esters and one nitrile, each of which is tethered to an aldehyde or a ketone, has been investigated. Good yields (70–79%) of mono- and bicyclic products, resulting from closure between the β-carbon of the α,β-unsaturated unit and the aldehyde or ketone carbonyl carbon, were obtained. Cyclic voltammetry was used to determine that the α,β-unsaturated unit corresponded to the electrophore. In all but one instance, cyclization favored formation of the product wherein the hydroxy and (methoxycarbonyl)methyl units were trans to one another. The stereoselectivity was studied as a function of temperature, nature of the proton donor, proton availability, and percent conversion (i.e., as a function of time). Attempts to use the reaction to synthesize the marine natural product ambliol A were unsuccessful. A mechanistic scheme in which a reversible cyclization of the initially formed radical anion is followed by an irreversible proton transfer is suggested to account for the experimental observations.

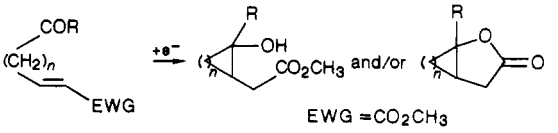
Introduction. Electroreductive Cyclization (ERC) Reactions. The conjugate addition of lithium *sec*-butylborohydride to the alkylidenemalonate **1**, leading to the formation of the cyclopentyl diester **2**, constitutes one example of what we have previously referred to as a MIRC (Michael-Initiated Ring Closure) reaction.[1-4] In contrast, an electrochemically initiated reduction of the same substrate afforded the cyclobutyl diester **3** in a reaction involving closure between the β (rather than the α) carbon of the starting material and the bromine-bearing carbon. Once reduced, an umpolung occurs and the formerly electrophilic β carbon becomes nucleophilic. In general, MIRC reactions and electroreductive cyclizations complement one another and allow the construction of rings of size n and $n - 1$, respectively.[5]



2 **1**, E = CO_2CH_3 **3**

(1) Little, R. D.; Dawson, J. R. *Tetrahedron Lett.* **1980**, *21*, 2609. Technically, the term Michael reaction refers to carbon-centered nucleophiles. See: Bergmann, E. D.; Ginsburg, D. *Organic Reactions*; Wiley: New York, 1959; Vol. 10, Chapter 3.
(2) For a discussion of the development of and application to total synthesis of the tandem Michael-Michael-Ring Closure (MIMIRC) reaction, refer to: Posner, G.; Mallamo, J. P.; Black, A. L. *Tetrahedron* **1981**, *37*, 3921.
(3) Little, R. D.; Dawson, J. R. *J. Am. Chem. Soc.* **1978**, *100*, 4607.
(4) Little, R. D.; Verhé, R.; Monte, W. T.; Nugent, S.; Dawson, J. R. *J. Org. Chem.* **1982**, *47*, 362.

Aldehydes and Ketones Tethered to α,β-Unsaturated Esters (Nitriles). Encouraged by these results, we elected to explore use of electroreductive cyclization (ERC) methodology for the construction of a variety of different ring systems and first decided to use substrates wherein a carbonyl unit was tethered to an α,β-unsaturated ester or nitrile. The successful implementation of the plan would lead to the formation of γ-hydroxy esters (nitriles) which could, either in situ or in a follow-up step, lead to the production of bi- or tricyclic lactones.[6]



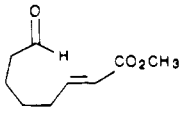
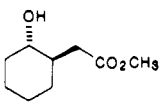
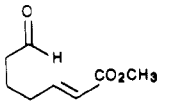
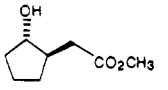
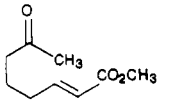
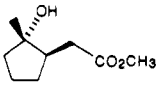
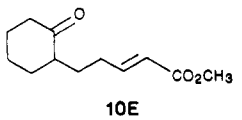
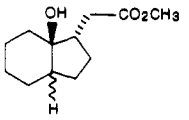
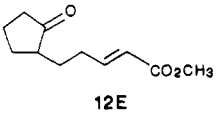
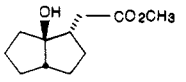
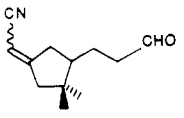
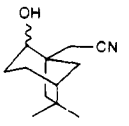
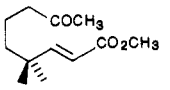
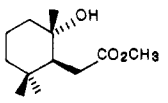
EWG = electron-withdrawing group

A variety of substrates was examined; the results are illustrated in Table I. In each case, the electroreductive cyclization reactions were carried out at controlled potential in 10% aqueous acetonitrile with Et_4NOTs as the supporting electrolyte. A standard H-cell, a mercury pool cathode, and a saturated calomel reference electrode (SCE) were used; the course of each reaction was monitored as a function of time by coulometry and thin layer chromatography. Each of the examples, except the last, illustrates that the reaction stereoselectively affords products wherein

(5) Nugent, S. T.; Baizer, M. M.; Little, R. D. *Tetrahedron Lett.* **1982**, *23*, 1339.
(6) Fox, D. P.; Little, R. D.; Baizer, M. M. *J. Org. Chem.* **1985**, *50*, 2202.

0022-3263/88/1953-2287$01.50/0

Table I.[a] Examples of Electroreductive Cyclization

substr	cyclized products	trans/cis ratio	yield (%)
 **4E**	 **5a**	1.8:1	72
 **6E**	 **7a**	1.4:1	70
 **8E**	 **9a**	5.1:1	76
 **10E**	 **11a**	2.5:1	74
 **12E**	 **13a**	11.4:1	79
 **14**	 **15**	1.7:1	73[b]
 **16**	 **17a**	1:2.9	70

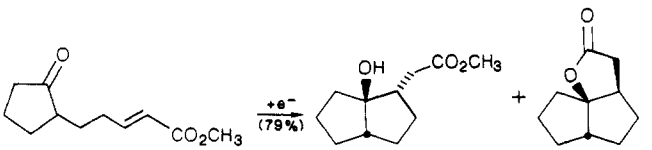
[a] Isolated yields of pure products. Only the trans isomer is illustrated. The **b** series of products refers to the cis isomer, either the open form hydroxy ester or the lactone. See Experimental Section. [b] In this case, diethyl malonate was used as the proton donor.

the ester and hydroxyl groups are trans to one another about the newly formed σ bond; the degree of stereoselectivity varies from being very poor (1.4:1) to being synthetically useful (11.4:1).

Cyclic Voltammetry; Nature of the Electrophore. Cyclic voltammetry (CV) established that the unsaturated ester unit was the electrophore involved in the reduction, not the aldehyde or ketone subunit. For reasons which will become apparent, each compound was examined separately in solutions containing Et_4NOTs as the supporting electrolyte dissolved in (a) dry acetonitrile, (b) a mixture consisting of 9:1 (by volume) acetonitrile/water, and (c) a mixture of 0.2 M diethyl malonate in a solution of acetonitrile.

The method which was used to establish the identity of the electrophore is best illustrated by referring to Table II and to compound **4E**, in particular. Notice first that the cyclic voltammogram for it in the presence of water displays one wave with E_{pc} -2.14 V vs SCE. When **4E** is reduced with hydrogen over palladium on charcoal, compound **4a** results. Its cyclic voltammogram is devoid of a reduction wave; only discharge of the supporting electrolyte is observed. Consequently, one can safely conclude that the aldehyde carbonyl unit does not correspond to the electrophore; the result illustrated for the THP ether **4b** corroborate the conclusion. In no case was a reversible electron transfer observed.

Stereoselectivity. The trans stereoselectivity is increased by operating at a reduced temperature. Thus, the trans/cis ratio for the conversion of keto ester **12** to the bicyclo[3.3.0] hydroxy esters **13a** and **13b** increases from 11.4:1 at room temperature to a respectable 26:1 at -20 °C.



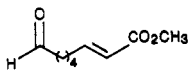
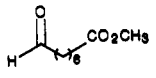
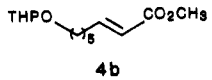
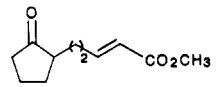
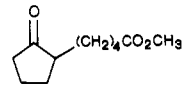
12 **13a** (*trans*) **13b** (*cis*)

temp (°C)	product ratio (**13a**:**13b**)
ambient	11.4:1
-20	26:1

If the reaction passed through an isokinetic point as the temperature was lowered, then the trans product, the major adduct at room temperature, would have become the minor product and the stereoselectivity would have been reversed.[7] The reaction was conducted in a solvent mixture consisting of 10% methanol in acetonitrile (v/v) to avoid saponification which occasionally accompanies the

(7) See, for example: Bunnett, J. F. In *Techniques in Organic Chemistry*; Weissberger, A., Ed.; Interscience: New York, 1961; Vol. VIII, pp 204–210. See also: Giese, B. *Acc. Chem. Res.* **1984**, *17*, 438. Stone, K. J.; Little, R. D. *J. Am. Chem. Soc.* **1985**, *107*, 2495.

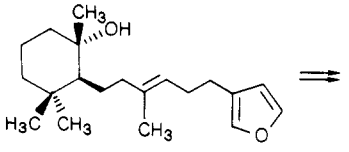
Table II. Cyclic Voltammetry; Nature of the Electrophore

substr	proton donor[a]	E_{pc} (V vs SCE)[b]	comments[c]
 4E	water	-2.14	
	$CH_2(CO_2C_2H_5)_2$	-2.22	note potential shift relative to 4b
 4a	water		no observable wave
	$CH_2(CO_2C_2H_5)_2$	-2.64	very close to electrolyte discharge
 4b	water	-2.20	
	$CH_2(CO_2C_2H_5)_2$	-2.34	peak height 1.5 times that observed in CH_3CN with no added proton donor
 12	water	-2.12	
	$CH_2(CO_2C_2H_5)_2$	-2.28	peak height 4.4 times that observed in CH_3CN with no added proton donor
 18	water		no observable wave
	$CH_2(CO_2C_2H_5)_2$		no observable wave

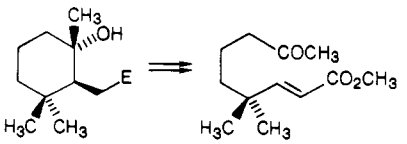
[a] Aqueous runs were carried out by using 0.74 M Et_4NOTs and a 9:1 ratio (by volume) of acetonitrile to water. The amount of substrate used in each case was ca. 0.05 mmol. Malonate runs used 2 equiv in each instance; the concentration of Et_4NOTs was 0.25 M. [b] 100 mV/s scan rate. [c] In no case was reversibility observed.

desired cyclization when 10% aqueous acetonitrile is used.

Attempted Application to Ambliol A (19). These results suggest that the methodology ought to be applicable to a total synthesis of the recently characterized marine natural product ambliol A (19).[8] A reasonable plan would call for construction of the six-membered ring by using an ERC reaction followed by creation of the remainder of the chain terminating in the furan unit.

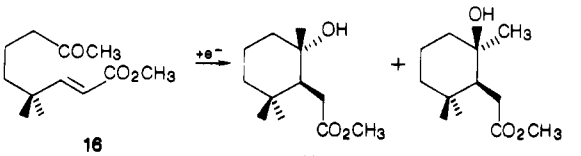


19, ambliol



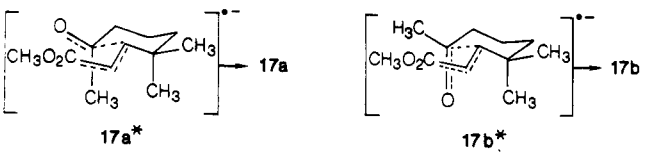
17a, E = CO_2CH_3 16

Unfortunately, electroreductive cyclization of keto enoate 16 leads to two products 17a and 17b in a yield of 70% and a ratio of 1:2.9 That is, the product wherein the ester and hydroxyl groups are cis rather than trans predominates.



16 17a 17b

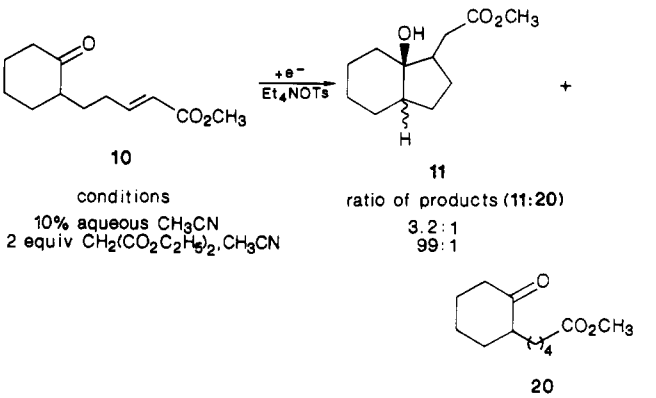
A simple and useful rationale can be provided from examination of the two transition-state formulations illustrated below. Notice that in the pseudo-chair representation **17a*** there exists an energy raising 1,3-diaxial methyl–methyl interaction which is absent in formulation **17b***, thereby suggesting a kinetic preference for the formation of **17b**. It is gratifying to us to note that one does



17a* 17b*

not have a resort to detailed considerations of difficult problems concerning how the substrate interacts with the electrode, the nature of the double layer, etc., to provide at least a qualitative rationale.

Avoidance of C_α–C_β π-Bond Saturation. While the reactions discussed thus far can be conducted simply and reliably, there remains a drawback. In particular, as the reaction progresses, the solution near the cathode becomes basic, thereby leading to the possibility of competing saponification, as indicated previously. This can be avoided by simply requiring that the pH of the medium be monitored and adjusted through the periodic addition of acetic acid. However, if it is added too rapidly, then reduction of the C_α–C_β π bond followed by proton abstraction and ultimately to saturation of that π unit occurs in competition with the desired cyclization. This problem can be overcome by switching to a dialkyl malonate as the proton source. The equation shown below dramatically illustrates this point.[9]



10 11

conditions

10% aqueous CH_3CN
2 equiv $CH_2(CO_2C_2H_5)_2$, CH_3CN

ratio of products (11:20)

3.2:1
99:1

20

Unfortunately, as illustrated in Table III, avoidance of π-bond reduction requires that one pay a price in terms of a corresponding decrease in trans stereoselectivity. Thus, for example, while closure of keto enoate 12 affords a trans/cis product ratio of 11.4:1 when the reaction is conducted in aqueous acetonitrile, that ratio drops dra-

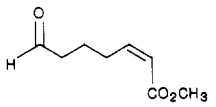
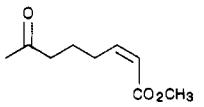
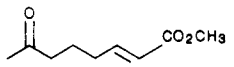
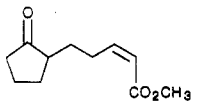
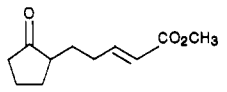
(8) Walker, R. P.; Faulkner, D. J. *J. Org. Chem.* **1981**, *46*, 1098. Walker, R. P.; Rosser, R. M.; Faulkner, D. J.; Bass, L. S.; Cunheng, C.; Clardy, J. *J. Org. Chem.* **1984**, *49*, 5160.

(9) For other examples of the use of carbon acids, see: Thomas, H. G.; Lux, E. *Tetrahedron Lett.* **1972**, 965. Baizer, M. M.; Halcher, R. C. *J. Electrochem. Soc.* **1976**, *123*, 809. Powell, L. A.; Wightman, R. M. *J. Am. Chem. Soc.* **1979**, *101*, 4412.

Table III. Decreased Stereoselectivity with Malonate

substr	proton source	product ratio (trans:cis)	yield (%) of hydroxy ester
12	water	11.4:1	79
	$CH_2(CO_2C_2H_5)_2$	3.1:1	90
10	water	2.5:1	65–74
	$CH_2(CO_2C_2H_5)_2$	1.2:1	88

Table IV. Olefin Isomerization

substr	proton donor	Z/E at 50% conversn	trans/cis product ratio
 6Z	10% H_2O/CH_3CN	97:3	1.2:1
	$CH_2(CO_2C_2H_5)_2$	100:0	
 8Z	10% H_2O/CH_3CN	*a*	2.8:1
	$CH_2(CO_2C_2H_5)_2$	15:85	2.0:1
 8E	10% H_2O/CH_3CN	*a*	5.1:1
	$CH_2(CO_2C_2H_5)_2$	2:98	2.0:1
 12Z	10% H_2O/CH_3CN	*a*	6:1
	$CH_2(CO_2C_2H_5)_2$	15:85	3.1:1
 12E	10% H_2O/CH_3CN	*a*	11.4:1
	$CH_2(CO_2C_2H_5)_2$	2:98	3.1:1

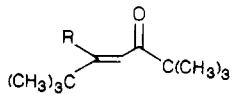
[a] No isomerization detected.

matically to 3.1:1 in acetonitrile containing 2 equiv of diethyl malonate.

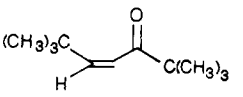
From the forgoing results, it is reasonable to conclude that the most efficient way to optimize trans stereoselectivity *and* avoid saturation of the C_α–C_β π bond is to operate at as low a temperature as is convenient and in the presence of a dialkyl malonate as the proton donor.

Olefin Isomerization. The stereochemical outcome of the ERC reaction is linked to the stereochemistry about the electrophore C–C π bond. Consider the examples illustrated in Table IV. In each instance, the reaction was carried to 50% conversion and the stereochemistry about the electrophore π bond of the recovered starting material was examined. No isomerization occurs when the reaction is conducted in 10% aqueous acetonitrile. Furthermore, while no isomerization is observed in the case of closure onto an aldehyde, substantial $Z \rightarrow E$ isomerization occurs when a ketone is utilized and the reaction is conducted in acetonitrile with diethyl malonate as the proton source. As illustrated in Table IV, when olefin isomerization occurs, both the *E* and *Z* geometric isomers of the starting material lead to the same cis/trans mixture of products. On the other hand, when isomerization is not observed, different product ratios are obtained.

An elegant series of experiments reported by House and co-workers in 1970 sheds light upon these issues.[10,11] In particular, it was found that the radical anions of the *E* and *Z* enones **21a** and **22** undergo rapid equilibrium at $T \geq -35$ °C but not at temperatures ≤ -78 °C. In addition,

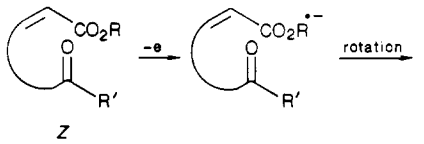


21a, R = H
21b, R = D

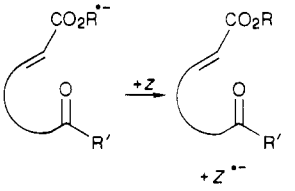


22

the existence of an electron-transfer pathway for isomerization was demonstrated. Thus, when the *Z* enone **22** was added to a solution of the radical anion derived from the *E* enone **21a**, equilibration of radical anions occurs within 15 min. Furthermore, addition of β-deuterio-substituted *E* enone **21b** to a solution containing the radical anion derived from **21a** affords an ESR spectrum which is a composite of that of the all-protio and the monodeuterio radical anions. Based upon this precedent, we suggest the scheme illustrated below to account for the observed



Z



isomerization of keto enoates **8Z** and **12Z**. To account for the difference in behavior between ketones and aldehydes, we simply propose that the rate of cyclization onto a ketone is slower than that of an aldehyde, thereby allowing sufficient time for isomerization to occur.

Reversible Cyclization.[10,12] **Proton Availability. Kinetic and/or Thermodynamic Control.** The reaction scheme illustrated below appears to account for all of the results which have been obtained as of this date. Basically, the pathway can be described as one which fits into the general category of an ECE process.[13] We suggest that the initial electron transfer is followed by a rapid and reversible cyclization to the closed form of the radical anion, then by an irreversible proton transfer to oxygen, finally by a second electron transfer to generate an enolate which undergoes rapid protonation.[12]

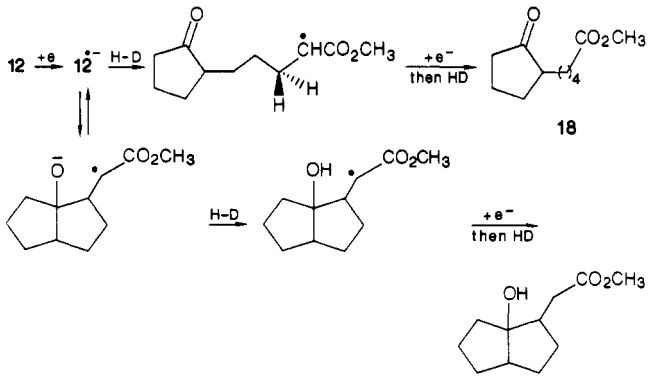
Additional support for this proposition comes from an examination of the cyclic voltammetry data illustrated in Table II. Notice particularly that the addition of a proton

(10) Parker, V. D. *Acta Chem. Scand., Ser. B* **1981**, *35*, 279 and references cited therein. See also: Baizer, M. M. In *Organic Electrochemistry*; Baizer, M. M., Ed.; Dekker: New York, 1973; p 679.

(11) Bowers, K. W.; Giese, R. W.; Grimshaw, J.; House, H. O.; Kolodny, N. H.; Kronberger, K.; Roe, D. K. *J. Am. Chem. Soc.* **1970**, *92*, 2783.

(12) The mechanism bears similarity to that proposed by Parker (ref 10 above) in conjunction with a study of the mechanism for the *intermolecular* electrohydrodimerization of diethyl fumarate. In particular, notice the suggestion of a reversible C–C bond formation in the linking of the radical anion to a molecule of unreduced substrate. In the present case, the strength of a C–C σ bond nearly matches that of the π portion of a carbonyl unit, thereby rendering the reversible process nearly thermoneutral. To lend credibility to the proposal of a reversible cyclization, the electroreductive cyclization of keto ester **12** was conducted at room temperature in acetonitrile containing 2 equiv of dimethyl malonate; the trans/cis product ratio (**13a**:**13b**) was determined at 50% and 100% conversion. At 50% conversion, the ratio was 3.2:1, while at reactions end, it dropped to 2.48:1. At the same time, only 2% $E \rightarrow Z$ olefin isomerization was detected (at 50% conversion).

(13) Testa, A. C.; Reinmuth, W. H. *Anal. Chem.* **1961**, *31*, 1320. Eberson, L.; Nyberg, K. *Adv. Phys. Org. Chem.* **1976**, *12*, 1. Parker, V. D. In *Topics in Organic Electrochemistry*; Fry, A. J., Britton, W. E., Eds.; Plenum Press: New York, 1986; p 35.



donor leads, in the case of compound **12**, to a marked increase in the intensity of the reduction wave. This suggests that the increased proton availability affords an increase in the rate of the proton-transfer step and that the electron-transfer–cyclization–protonation steps are closely linked to one another in time, certainly within the time-frame of the CV scan.

Based upon this scheme, one would predict that an increase in proton availability could manifest itself in one or both of two ways; that is, (1) either the rate of capture of the initially formed uncyclized radical anion could be accelerated, thereby leading, after the addition of a second electron and proton, to an increase in the amount of saturation of the C_α–C_β π bond or (2) assuming that radical anion cyclization is significantly faster than its interception by a proton donor, then an increase in proton availability should lead to an increase in the rate of irreversible proton capture by the cyclized radical anion, leading to a reduction in the time available for the attainment of equilibrium and to a modified distribution of cyclized products.

To test these ideas, we have examined the electroreductive cyclization of keto ester **12** in the presence of two proton donors of differing pK_a's. Assuming a reasonable correlation between thermodynamic and kinetic acidities, one would expect that upon changing from diethyl malonate whose pK_a (DMSO) is 15, to malononitrile whose pK_a (DMSO) is 11,[14] there should occur changes in accord with one or both of the suggestions put forth above. Indeed, when the reaction was conducted in the presence of malononitrile, *both* an increase in the rate of capture of the initially formed radical anion *as well as the* cyclized form was observed. Thus, there *was a desirable effect* upon the stereoselectivity; it rose from a trans/cis ratio of 3.3:1 by using diethyl malonate to a value of 9:1 when malononitrile was used. Unfortunately, however, the amount of C_α–C_β π bond saturated product **18** (note Table II) increased dramatically to the point where it comprised 82% of the product mixture. Thus, these results support the mechanistic scheme put forth above but do not provide one with a practical means for increasing the stereoselectivity.

proton donor	pK_a (DMSO)	trans/cis (**13a**:**13b**)	% satd product (**18**)
$CH_2(CO_2C_2H_5)_2$	15	3.3:1	1.3
$CH_2(CN)_2$	11	9:1	82

Concluding Remarks. We hope to find a set of conditions which will lead to products selectively (stereo, regio), efficiently, and in a predictable manner. If one could accomplish this objective, then the results may have exciting and useful consequences in their application to organic synthesis. Additional studies directed toward this end are in progress.

(14) Bordwell, F. G.; Fried, H. E. *J. Org. Chem.* **1981**, *46*, 4327.

Experimental Section

All yields reported are isolated yields of material judged to be homogeneous by TLC, GC, and NMR spectroscopy unless otherwise specified. Glassware was oven-dried, and for air-sensitive reactions, solvents, reagents, etc., were introduced into the reaction vessels via syringe through serum caps under an atmosphere of nitrogen or argon. All temperatures are recorded in °C. All solvents were distilled and/or dried prior to use by using standard methods. Diethyl ether and tetrahydrofuran (THF) were distilled from sodium benzophenone kethyl and toluene from sodium, all under nitrogen. Infrard spectra were obtained by using thin films deposited on NaCl plates with a Perkin-Elmer 1330 Infracord or a Biorad FTS-60 spectrometer. Thin layer chromatography (TLC) was performed on silica gel precoated glass plates (E. Merck 60F-254); visualization was accomplished by using an ultraviolet handlamp, or with iodine, *p*-anisaldehyde, and/or phosphomolybdic acid stain. Gravity-flow liquid chromatography was carried out on E. Merck silica gel 60 (230–400 mesh, ASTM); solvent mixtures were prepared by volume.

^{1}H NMR spectra were recorded on a Nicolet NT 300 (300 MHz) spectrometer in $CDCl_3$ containing Me_4Si as an internal reference (coupling constants are in hertz). Low and high resolution mass spectral data were obtained with the assistance of Dr. H. M. Webb of UCSB by using either a ZAB 2-F spectrometer or a VG 70-250 HF spectrometer in the electron impact (EI) or chemical ionization (CI; methane) modes. Combustion analyses were performed by Galbraith Laboratories, Knoxville, TN.

Analytical gas chromatography (GC) was carried out on either a Hewlett-Packard 5830 A or a 5890 A gas chromatograph equipped with a Hewlett-Packard 18850 or a 3392 A integrator and a flame ionization detector. An Ultra II (5% phenylmethylsilicone, Hewlett-Packard; 25 m × 0.200 mm) capillary column was utilized with helium as the carrier gas.

Methyl (*E*)- and (*Z*)-8-Oxo-2-octenoate (4E and 4Z). The compounds were prepared from the known[15] methyl 8-hydroxy-2-octenoate by using a Swern oxidation[16] [procedure was exactly the same as that described below for compounds **6E** and **6Z** except that the following quantities of materials were used: 1.0 mL (11.51 mmol) of oxalyl chloride in 25 mL of dichloromethane; 1.63 mL (23 mmol) of DMSO in 5 mL of dichloromethane; 1.63 g (9.48 mmol) of alcohol in 10 mL of dichloromethane; 6.7 mL (47.9 mmol) of triethylamine. Workup consisted of the addition of 30 mL of water, extraction with dichloromethane (2 × 15 mL), and successive single washes with 7 mL each of 1% HCl, water, 10% $NaHCO_3$, and again with water prior to chromatography on silica gel eluting with 10–20% ethyl acetate in Skellysolve F to afford a 92% combined yield (1.48 g) of compounds **4E** and **4Z**].

Spectral data for compound **4E**: IR (neat) 2945, 2870, 2730, 1728, 1660, 1438, 1272, 1200, 1180, 1155, 1040, 985 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.77 (t, 1, J = 1.3, CHO), 6.94 (dt, 1, J = 7.0, 15.7, HC=CCO_2), 5.84 (dt, J = 15.7, 1.4, C=$CHCO_2$), 3.73 (s, 3, OCH_3), 2.46 (td, 2, J = 7.1, 1.3, CH_2CHO), 2.24 (m, 2, CH_2C=C), 1.65 (m, 2, CH_2), 1.51 (m, 2, CH_2). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.24; H, 8.05. For the *Z*-isomer **4Z**: IR (neat) 2955, 2865, 2820, 1727, 1647, 1442, 1410, 1200, 1180, 820 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.77 (t, 1, J = 1.5, CHO), 6.21 (dt, 1, J = 7.6, 11.5, HC=CCO_2), 5.80 (dt, 1, J = 11.5, 1.5, C=$CHCO_2$), 3.71 (s, 3, OCH_3), 2.70 (m, 2, CH_2C=C), 2.47 (td, 2, J = 1.5, 7.2, CH_2CHO), 1.68 (m, 2, CH_2), 1.50 (m, 2, CH_2). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.19; H, 8.03.

Methyl (*E*)- and (*Z*)-7-Oxo-2-heptenoate (6E and 6Z). To a three-necked 100-mL round-bottomed flask equipped with two pressure-equalizing dropping funnels and an overhead mechanical stirrer was added a solution of 0.93 mL (10.6 mmol) of oxalyl chloride in 22.5 mL of methylene chloride. One addition funnel contained 1.51 mL (21.3 mmol) of DMSO in 4.5 mL of methylene chloride while the other contained a solution of 1.4 g (8.86 mmol) of methyl 7-hydroxyhept-2-enoate[17] in 9 mL of methylene chloride. The flask was cooled to −60 °C with a dry ice–acetone bath and the DMSO solution was added dropwise over 5 min; gas evolution was observed. After 10 min, the alcohol solution was added over about 5 min; some white solid formed. Stirring was continued

(15) Yokoi, K.; Matsubara, Y. *Nippon Kagaku Kaishi* **1978**, 1415.
(16) Mancuso, A. J.; Swern, D. *Synthesis* **1981**, 165.
(17) Tufariello, J. J.; Trybulski, E. J. *J. Org. Chem.* **1974**, *39*, 3378.

for 15 min at −60 °C and then 6.17 mL (44.3 mmol) of triethylamine was added dropwise over 5 min; a large amount of precipitate formed. The reaction mixture was allowed to warm to room temperature and 30 mL of water was added. After 10 min of stirring, the organic layer was separated. The aqueous layer was extracted with methylene chloride (1 × 20 mL) and the organic layer was washed successively with 1% HCl (1 × 6 mL), water (1 × 6 mL), 10% sodium bicarbonate (1 × 6 mL), and water (1 × 6 mL). The organic layer was dried over $MgSO_4$ and concentrated in vacuo to afford 1.41 g of a yellow oil which was chromatographed on silica gel by using 15% ethyl acetate in Skellysolve F to afford 147 mg (11%) of **6Z** along with 1.078 g (78%) of **6E**.

Spectra data for compound **6Z**: IR (neat) 2957, 2837, 2725, 1727, 1647, 1442, 1411, 1201, 1183, 1171, 822 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.78 (t, 1, J = 1.3, CHO), 6.19 (dt, 1, J = 7.7, 11.4, HC=CCO_2), 5.83 (dt, 1, J = 11.4, 1.5, =$CHCO_2$), 3.71 (s, 3, OCH_3), 2.70 (m, 2, CH_2CH=C), 2.49 (td, 2, J = 1.3, 7.2, CH_2CHO), 1.8 (m, 2, CH_2). For the E isomer **6E**: IR (neat) 2955, 2840, 2727, 1727, 1661, 1441, 1320, 1276, 1202, 1160, 1043, 984 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.77 (t, 1, J = 1.3, CHO), 6.92 (dt, 1, J = 6.9, 15.6, CH=CCO_2), 5.84 (dt, 1, 15.6, 1.5, =CHCO), 3.73 (s, 3, OCH_3), 2.48 (td, 2, J = 1.3, 7.2, CH_2CHO), 2.25 (m, 2, CH_2CH=), 1.81 (m, 2, CH_2). Anal. Calcd for $C_8H_{12}O_3$: C, 61.52; H, 7.74. Found: C, 61.24; H, 7.65.

Methyl (*E*)- and (*Z*)-7-Oxo-2-octenoate (8E and 8Z). Each isomer was prepared by using the same procedure; the E isomer of aldehyde **6E** served as the precursor of **8E** while **6Z** served as the precursor for **8Z**. The detailed procedure for only the E isomer is presented.

To a 50-mL round-bottomed flask equipped with a pressure-equalizing dropping funnel and a magnetic stirring bar was added a solution of 0.500 g (3.21 mmol) of aldehyde **6E** disolved in 11 mL of ether. The stirred solution was cooled to −25 °C and 1.21 mL of 3.17 M MeMgBr (Alfa) was added dropwise; a white solid formed rapidly. After 45 min at −25 °C, a 50-μL aliquot was withdrawn, added to ether, and quenched with 30 mL of saturated ammonium chloride. TLC analysis indicated the need to add additional Grignard reagent (0.6 mL, 1.9 mmol). After 4.25 h, the reaction was quenched by the addition of 6 mL of saturated ammonium chloride at −25 °C. The aqueous layer was extracted with ether, and the etheral solutions were dried over $MgSO_4$ and concentrated in vacuo to afford 0.50 g of a light yellow liquid. Chromatography over silica gel using 25% ethyl acetate in Skellysolve F led to 86 mg of recovered starting material and 282 mg (51%) of the known[18] hydroxy ester as a clear colorless oil displaying the following spectral data: IR (neat) 3700–3100, 2940, 2875, 1725, 1661, 1440, 1312, 1275, 1203, 1168, 1132, 1038, 992 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.96 (dt, 1, J = 15.6, 7, HC=CCO_2), 5.83 (dt, J = 15.6, 1.3, C=$CHCO_2$), 3.82 (m, 1), 3.73 (s, 3, OMe), 2.22 (m, 2, CH_2COH), 1.4–1.8 (m, 5, CH_2CH_2 and OH), 1.20 (d, 3, J = 6.2, CH_3); exact mass (CI, CH_4) calcd for $C_9H_{17}O_3$ (M + 1) 173.1178, obsd 173.1163.

This material (270 mg, 1.57 mmol) was converted directly to 230 mg (86%) of the keto ester **8E** by using the Swern oxidation procedure described above.

Spectral data for **8E**: IR (neat) 3005, 2957, 1726, 1717, 1660, 1438, 1360, 1319, 1273, 1200, 1177, 1155, 1040, 983 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.92 (dt, 1, J = 15.6, 7.0, CH=CCO_2), 5.83 (dt, 1, J = 15.6, 1.4, C=$CHCO_2$), 3.73 (s, 3, OMe), 2.46 (t, 2, J = 7.3, $COCH_2$), 2.73 (m, 2, CH_2C=C), 2.14 (s, 3, $COCH_3$), 1.75 (m, 2, CH_2). For isomer **8Z**: IR (neat) 3000, 2955, 1725, 1712, 1645, 1440, 1408, 1368, 1290, 1200, 1175, 1010, 823 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.20 (dt, 1, J = 11.5, 7.6, CH=CCO_2), 5.80 (dt, 1, J = 11.5, 1.6, C=$CCHCO_2$), 3.705 (s, 3, OMe), 2.67 (m, 2, CH_2C=C), 2.48 (t, 2, J = 7.4, $COCH_2$), 2.14 (s, 3, CH_3), 1.74 (m, 2, CH_2); exact mass (CI, CH_4) calcd for $C_8H_{13}O_3$ (M + 1) 157.0864, obsd 157.0833.

Preparation of Keto Esters 10E and 10Z. To a 5-mL round-bottomed flask topped with a serum cap was added 33.4 mg (0.10 mmol) of (carbomethoxytriphenylphosphoranylidene)-acetate in 0.75 mL of acetonitrile at room temperature. 2-(3-Oxopropyl)cyclohexanone[19] (15.4 mg, 0.1 mmol) in 85 μL of acetonitrile was added and stirring was continued. The reaction was monitored by TLC. The solvent was removed in vacuo and the solid was repeatedly washed with ether. The etheral layer was concentrated in vacuo to afford 25 mg of a yellow oil which was chromatographed over silica gel by using 10% ethyl acetate in Skellysolve F to afford an 85% yield of a ca. 6:94 mixture of **10Z** and **10E**, respectively.

Spectral data for compound **10Z**: IR (neat) 2945, 2870, 1725, 1717, 1647, 1450, 1442, 1202, 1170, 819 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.22 (dt, 1, J = 7.6, 11.5, CHC=CCO_2), 5.78 (dt, 1, J = 1.3, 11.5, C=$CCHCO_2$), 3.70 (s, 3, OMe), 2.66 (m, 2), 2.1–2.5 (m, 4), 1.8–2.1 (m, 3), 1.65 (m, 2), 1.25–1.45 (m, 2); exact mass (CI, CH_4) calcd for $C_{12}H_{19}O_3$ (M + 1) 211.1335, obsd 211.1314. Spectral data for compound **10E**: IR (neat) 2943, 2870, 1728, 1712, 1660, 1451, 1437, 1327, 1315, 1278, 1215, 1197; ^1H NMR (300 MHz, $CDCl_3$) δ 6.94 (dt, 1 H, J = 6.9, J = 15.6, CHC=CCO_2), 5.82 (dt, 1 H, J = 15.6, J = 1.4, $CHCO_2CH_3$), 3.72 (s, 3 H, CO_2CH_3), 2.2–2.5 (m, 5 H), 1.8–2.2 (m, 4 H), 1.66 (m, 2 H), 1.37 (m, 2 H). Anal. Calcd for $C_{12}H_{20}O_3$: C, 68.55; H, 8.63. Found: C 68.29; H, 8.70.

Preparation of Keto Esters 12E and 12Z. To a 50-mL round-bottomed flask topped with a serum cap and under a nitrogen atmosphere was added 1.17 g (3.5 mmol) of (carbomethoxytriphenylphosphoranylidene)acetate in 25 mL of acetonitrile (the ylide was incompletely dissolved) and 0.49 g (3.5 mmol) of 2-(3-oxopropyl)cyclopentanone[19] in 1.6 mL of acetonitrile. The course of the reaction was monitored by TLC. After 20 h at room temperature, the reaction was stopped, the solvent was removed in vacuo, 6.5 mL of ether was added, and the resulting solution was filtered after first being stirred for 0.5 h. The solution was concentrated in vacuo and the sequence was repeated several times to afford 0.826 g of oily residue. Chromatography on silica gel by using 15% ethyl acetate in Skellysolve F as the eluant provided 613 mg (89%) of the E isomer **12E** together with 36 mg (5%) of the Z isomer **12Z**.

Spectral data for compound **12Z**: IR (neat) 2965, 1742 (C=O), 1729 (C=O), 1647 (C=C), 1442, 1412, 1200, 1178, 822 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$, **12Z**) δ 6.22 (dt, 1, ^3J = 7.5, J = 11.5, CH=CCO_2), 5.80 (dt, 1, J = 1.6, J = 11.5, C=$CCHCO_2$), 3.71 (s, 3, $COOCH_3$), 2.72 (m, 2), 2.27 (m, 2), 1.35–2.15 (m, 7); MS (70 eV), m/z (rel intensity) 196 (M^+, 3), 164 (M^+ − MeOH, 39), 113 (54), 100 (22), 97 (26), 84 (100), 83 (27), 81 (59), 68 (20), 55 (31), 53 (22); exact mass calcd for $C_{11}H_{16}O_3$ (M^+) 196.1099, obsd 196.1098. Spectral data for compound **12E**: IR (neat) 2960, 1742, 1729, 1660, 1438, 1320, 1278, 1204, 1178, 1042 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.94 (dt, 1 H, J = 6.9, J = 15.6, CHC=CCO_2), 5.85 (dt, 1 H, J = 15.6, J = 1.5, $CHCO_2CH_3$), 3.72 (s, 3 H, CO_2CH_3), 2.28 (m, 3 H), 1.7–2.15 (m, 6 H), 1.35–1.6 (m, 2 H). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.47; H, 8.34.

4,4-Dimethyl-3-[2-(1,3-dioxacyclohex-2-yl)ethyl]cyclopentan-1-one.[20] To a 10-mL round-bottomed flask fitted with a reflux condenser and containing 198 mg (8.14 mmol) of magnesium turnings was added at room temperature 2 mL of THF. A self-sustained reflux commenced upon the dropwise addition of a neat solution of 1.43 g (7.33 mmol) of 2-(3-bromopropyl)-1,3-dioxane. Following completion of the addition of the acetal, 3 mL of THF was added and the resulting solution was refluxed for 30 min. After cooling to 0 °C and adding 2 mL of THF, cuprous iodide (170 mg, 892 mmol) was added, and the resulting mixture was stirred at 0 °C for 1 h. A solution of 550 mg (5.0 mmol) of 4,4-dimethylcyclopentenone dissolved in 2 mL of THF was added via syringe pump over a period of 1 h. The resulting grey solution was stirred for 1 h at 0 °C at which time TLC analysis (silica gel, 40% ethyl acetate in Skellysolve F) indicated complete disappearance of the enone. After the mixture was quenched by the addition of 50 mL of a cold (ice–water) solution of saturated ammonium chloride adjusted to pH 8 with ammonium hydroxide, it was extracted with ether (3 × 50 mL), washed with brine, dried

(18) Wada, K.; Ishida, T. *J. Chem. Soc., Perkin Trans. 1* **1979**, 1154.

(19) Cope, A. C.; Nealy, D. L.; Scheiner, P.; Wood, G. *J. Am. Chem. Soc.* **1965**, *87*, 3130. Allan, R. D.; Gordiner, B. G.; Wells, R. J. *Tetrahedron Lett.* **1968**, 6055. Epsztajn, J.; Bieniek, A.; Brzezinski, J. Z. *Pol. J. Chem.* **1980**, *54*, 341. Stork, G.; Landsman, H. K. *J. Am. Chem. Soc.* **1956**, *78*, 5129.

(20) This compound was prepared by following a procedure adapted from Brattesani and Heathcock (Brattesani, D. N.; Heathcock, C. H. *J. Org. Chem.* **1975**, *40*, 2165) and described in detail in Bal et al. (Bal, S. A.; Marfat, A.; Helquist, P. *J. Org. Chem.* **1982**, *47*, 5045.

over $MgSO_4$, filtered, and concentrated in vacuo to afford 1.59 g of a crude oil. Chromatography using 50 g of silica gel and 40% ether in Skellysolve F afforded 1.022 g (90%) of 4,4-dimethyl-3-[2-(1,3-dioxacyclohex-2-yl)ethyl]cyclopentan-1-one.

Spectral data were the following: FTIR (neat) 2953, 2655, 1740, 1651, 1405, 1378, 1243, 1144, 1001 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 4.32 (t, 1 H, J = 5, CHO_2), 3.81 (apparent dd, 2 H, J = 11, 4.5), 3.33 (t, 2 H, J = 12), 2.11 (dd, 1 H, J = 8, 18.5), 1.83 (m, 1 H, J = 17.5), 1.69 (d, 1 H, J = 17.5), 1.53–1.65 (m, 4 H), 1.35 (m, 1 H), 1.08 (m, 1 H), 0.75 (s, 3 H, CH_3), 0.65 (apparent br d, 1 H), 0.52 (s, 3 H, CH_3); exact mass (CI, CH_4) calcd for $C_{13}H_{23}O_3$ (M + 1) 227.1648, obsd 227.1637.

[4,4-Dimethyl-3-(2-formylethyl)cyclopentylidene]acetonitrile (14). To a suspension of hexane-washed sodium hydride (15 mg, 60% in oil) in 500 μL of tetrahydrofuran (THF) at room temperature was added dropwise diethyl (cyanomethyl)-phosphonate (50 mg, 0.31 mmol). Following gas evolution, the clear solution was stirred at room temperature for 30 min and 4,4-dimethyl-3-[2-(1,3-dioxacyclohex-2-yl)ethyl]cyclopentan-1-one (41 mg, 0.18 mmol) was added in 500 μL of THF. The reaction, judged to be complete by TLC after 4 h, was quenched with water and the aqueous solution was extracted with ether (3 × 30 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, and concentrated in vacuo to afford 54 mg of a clear oil as a mixture of E and Z isomers. TLC (1:1 ether/SSF) R_f 0.30 and 0.34. The crude product mixture was diluted with 2 mL of methanol, 5 mg of p-TsOH was added, and the solution was heated to reflux for 1.5 h, then diluted with water, and extracted with ether (3 × 35 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, and concentrated in vacuo to give 41 mg of a clear oil, which was chromatographed on silica gel (5 g, 230–400 mesh, 50/50 ether/SSF) affording 32 mg (74%) of the desired product as a mixture of geometric isomers. TLC (1:1 ether/SSF) R_f 0.36 and 0.40.

Spectral data were the following: FTIR (neat) 2954–2831, 2215, 1641, 1612, 1464, 1386, 1369, 1128, 1074, 959 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.18 (br s, 1 H, vinyl), 4.36 (m, 1 H, $CH(OMe)_2$), 3.31–3.33 (overlapping singlets, 6 H), 2.9 (dd, 1 H, J = 7.2, 18.5, one isomer), 2.7 (dd, 1 H, J = 7.8, 18.5, other isomer), 2.61 (br s, 1 H), 2.55 (br s, 1 H), 2.1–2.4 (m, 2 H, one isomer), 1.45–1.7 (m, 4 H, other isomer), 1.09 and 0.794 (s, 3 H), 1.06 and 0.772 (s, 3 H). To the dimethoxy acetal (30 mg, 0.13 mmol) disolved in 2 mL of 9:1 (v/v) acetone/water was added 5 mg of p-TsOH. The solution was stirred at room temperature for 4 h, the solvent was removed under reduced pressure, and the residue was diluted with water and extracted with ether. The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, and concentrated in vacuo to give 27 mg of a clear oil, which was chromatographed on silica gel (5 g, 230–400 mesh, 50/50 ether/SSF) providing 24 mg (96%) of pure aldehyde.

Spectral data were the following: IR (neat) 2958–2837, 2735, 2719, 2214, 1725, 1640, 1612, 1464, 1419, 1388, 1370, cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.80 and 9.78 (t, 1 H, both isomers), 5.20 (br s, 1 H, both isomers), 2.1–3.0 (m, 6 H), 1.8–2.0 (m, 1 H), 1.6–1.8 (m, 1 H), 1.3–1.4 (m, 1 H), 1.11 and 1.09 (s, 3 H, both isomers), 0.827 and 0.804 (s, 3 H, both isomers); exact mass calcd for $C_{12}H_{17}NO$ (CI, M + 1) 192.1388, obsd (mixture of E/Z isomers) 192.1378.

Methyl 4,4-Dimethyl-8-oxo-2-nonenoate (16). The known[21] 1-hydroxy-2,2-dimethylhepten-6-one (1.35 g, 8.54 mmol) was added to a stirred solution of pyridinium chlorochromate (PCC, 2.61 g, 12.8 mmol, Aldrich) and Celite (3.0 g) in 25.6 mL of methylene chloride at room temperature. After being stirred for 2 h, the reaction mixture was diluted with ether (25 mL), stirred for an additional hour, filtered through Florisil, and concentrated in vacuo. The solvents were replaced by chloroform (31.3 mL), and (triphenylphosphoranylidene)acetate (3.14 g, 9.4 mmol, Lancaster) was added in one portion. The resulting Wittig reaction was complete after stirring the mixture for 1.5 h at room temperature. Concentration in vacuo afforded a semisolid which was chromatographed on silica gel by using 1:1 ether/petroleum ether to yield 1.24 g (69%) of methyl 4,4-dimethyl-8-oxo-2-nonenoate (16).

(21) Sneen, R. A.; Matheny, N. P. *J. Am. Chem. Soc.* **1964**, *86*, 3905, 5503. Kropf, H.; Bernert, C.-L. *Liebigs Ann. Chem.* **1971**, *751*, 121.

Spectral data were the following: IR (neat) 2970, 1728, 1656, 1438, 1367, 1318, 1280, 1204, 1175 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.90 (d, 1, J = 16.2, $HC{=}CCO_2$), 5.74 (d, 1, J = 16.2, $C{=}CHCO_2$), 3.73 (s, 3, OMe), 2.39 (t, 2, J = 7.1, $CH_2C{=}O$), 2.12 (s, 3, $CH_3C{=}O$), 1.2–1.6 (m, 4, 2 CH_2), 1.06 (s, 6, *gem*-CH_3). Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 66.80; H, 9.51.

Cyclic Voltammetry. Cyclic voltammetry were carried out on a BAS Model CV-1B unit at a scan rate of 100 mV/s. The data were recorded on a Houston Instrument Omnigraphic 100 recorder; cathodic peak potentials were recorded unless indicated otherwise. In no case was a reversible wave observed. Aqueous runs were carried out by using 0.74 M Et_4NOTs and a 9:1 ratio (by volume) of acetonitrile to water. The amount of substrate used in each case was ca. 0.05 mmol. Runs involving the use of diethyl malonate as the proton source used 2 equiv of the latter in each instance; the concentration of Et_4NOTs was 0.25 M. The results are illustrated in Table II.

General Procedure; Preparative Runs. An Electrosynthesis Company Model 410 potentiostatic controller, Model 640 digital coulometer, and Model 8460 potentiostat power supply were used for preparative runs. The current was monitored by using a Fluke 8022 B multimeter. A saturated calomel electrode (SCE) with an agar plug and luggin capillary was used as the reference electrode. In general, a degassed (nitrogen) solution of 0.74 M Et_4NOTs in a 9:1 (v/v) mixture of acetonitrile and water was introduced into anodic (15 mL) and cathodic (10 mL) chambers of an H-cell equipped with a platinum foil anode, a mercury pool cathode, and a medium porosity sintered glass frit. The cathodic chamber also contained a reference electrode (SCE with agar junction) and a pH electrode. The substrate (0.2 mmol) was added to the catholyte and reduced at a controlled potential of −2.1 to −2.2 V. The pH of the catholyte was maintained between the starting value and 0.6 unit higher, through the periodic addition (syringe) of glacial acetic acid. In most instances, reactions were allowed to proceed until at least 2 F/mol of electricity had passed and TLC analysis indicated the disappearance of the starting material. The colorless catholyte was withdrawn, 1.7 mL of water was added to it, and the solution was concentrated in vacuo. The aqueous residue was extracted with four 10-mL portions of ether. After back-extraction with water and 10% sodium bicarbonate, the etheral solution was dried over $MgSO_4$. GC analysis gave the product ratios reported in Table I. Column chromatography over silica gel using mixtures of ether or ethyl acetate in Skellysolve F was utilized to isolate products.

Reactions employing diethyl malonate as the proton source were conducted in a similar fashion with the following differences. Both catholyte and anolyte contained a 0.74 M solution of Et_4NOTs dissolved in acetonitrile. Diethyl malonate (0.8 mmol) and the substrate (0.2 mmol) were added to the catholyte and reduction was carried out at −2.25 V. No control of pH during the reaction was required. The reaction was complete after the passage of at least 2 F/mol of electricity. The catholyte was then treated with 0.4 mmol of glacial acetic acid prior to performing a standard water workup as described above. Cis hydroxy esters tended to lactonize, both upon GC analysis and upon column chromatography over silica gel. Extended treatment with silica gel or treatment with pyridinium p-toluenesulfonate (PPTS) cleanly converted the cis isomers into the corresponding lactones. The lactones were normally not formed in the reactions using acetonitrile/water.

Low Temperature Runs (e.g. 12 → 13a + 13b). A dry ice/acetone bath was used to maintain temperatures of −25 to −30 °C. Again, the reaction was conducted by using 0.2 mmol of keto ester 12 and 0.74 M Et_4NOTs dissolved in a 9:1 (v/v) mixture of acetonitrile/methanol and containing 2.0 equiv of dimethyl malonate as the proton donor. The workup was identical with that reported above, except that the glacial acetic acid was added directly to the cold catholyte solution.

Spectral Data for Products Produced Electrochemically. Spectral data for each product formed from the reactions described above are listed in the remaining portions of the Experimental Section. Spectral data for the known[22] compound **5a**: IR (neat)

(22) Takeda, T.; Hoshiko, T.; Mukaiyama, T. *Chem. Lett.* **1981**, 797. The cis lactone and open form cis hydroxy acid methyl ester are also known: Chiche, L.; Christol, H.; Coste, J.; Pietrasanta, F.; Plenat, F. *Can. J. Chem.* **1981**, *59*, 164.

3660–3100, 2935, 2860, 1740, 1451, 1440, 1358, 1282, 1241, 1166, 1110, 1060, 1040 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.680 (s, 3 H, CO_2CH_3), 3.233 (m, 1 H, C*H*OH), 2.66 (dd, 1 H, J = 15.3, J = 5.7, C*H*$_2CO_2CH_3$), 2.21 (dd, 1 H, J = 15.3, J = 6.6, C*H*$_2CO_2CH_3$), 2.00 (m, 1 H, C*H*$CH_2CO_2CH_3$), 1.83 (d, 1 H, J = 6.3, OH), 1.75 (m, 3 H), 1.64 (m, 1 H), 1.26 (m, 3 H), 1.07 (m, 1 H); MS (70 eV), m/z (rel intensity) 154 ($M^+ - H_2O$, 4), 141 ($M^+ - CH_3O$, 5), 140 ($M^+ - CH_3OH$, 7), 99 (45), 98 (56), 97 (23), 94 (20), 87 (29), 83 (24), 81 (50), 80 (22), 79 (31), 74 (26), 70 (23), 68 (41), 67 (100), 59 (37), 57 (31), 55 (83), 54 (26), 43 (51), 42 (26), 41 (100), 39 (70). Spectral data for the cis hydroxy ester **5b** and its corresponding lactone were consistent with those reported in the literature.[22]

Spectral data for compound **7a**: IR (neat) 3440 (br, OH), 2960, 2880, 1742 (C=O), 1442, 1345, 1258, 1197, 1178, 1138, 1095 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.87 (m, 1, CHOH), 3.693 (s, 3, OMe), 2.84 (br s, 1, OH), 2.43 (m, 1, AB of ABX), 2.10 (m, 1, ring), 1.98 (m, 2, ring), 1.67 (m, 3, ring), 1.25 (m, 1, ring); MS (CI, CH_4), m/z (rel intensity) 159 (MH^+, 12), 141 ($MH^+ - H_2O$, 100), 127 (MH^+ - MeOH, 15), 109 (63), 81 (43); exact mass (CI, CH_4) calcd for $C_8H_{15}O_3$ (M + 1) 159.1021, obsd 159.1022.

For the corresponding cis lactone **7b**: IR (neat) 2965, 2875, 1772, 1359, 1180, 1100, 1028, 985 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.00 (m, 1 H, CHO), 2.81 (m, 2 H, $CHCO_2$), 2.29 (d, 1 H, J_{app} = 15.7, $CHCO_2$), 2.02 (m, 1 H), 1.71 (m, 4 H), 1.57 (m, 1 H); MS (70 eV), m/z (rel intensity) 126 (M^+, 8), 98 ($M^+ - CO$, 18), 97 (31), 83 (21), 82 ($M^+ - CO_2$, 11) 80 (32), 70 (21), 69 (24), 67 (100), 55 (81), 54 (80), 42 (40), 41 (86), 39 (90).

Spectral data for compound **9a**: IR (neat) 3700–3100 (OH), 2965, 2883, 1729 (C=O), 1442, 1378, 1332, 1298, 1208, 1160, 1067, 1015, 996, 955, 920 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.689 (s, 3, OMe), 2.64 (br s, 1, OH, exchanges with D_2O), 2.39 (m, 1, AB of ABX, CH_2CO_2), 2.25 (m, 1, ring), 1.98 (m, 1, ring), 1.72 (br m, 4, ring), 1.24 (m, 1, ring), 1.15 (s, 3, CH_3); MS (CI, CH_4), m/z (rel intensity) 155 ($MH^+ - H_2O$, 83), 123 (100); MS (70 eV), m/z (rel intensity) 157 (M^+ - Me, 8), 154 ($M^+ - H_2O$, 12), 140 (M^+ - MeOH, 45), 129 (70), 25 (42), 112 (75), 111 (40), 98 (90), 97 (85), 81 (90), 74 (45), 71 (100), 69 (42), 59 (65), 58 (75), 55 (75). Anal. Calcd for $C_9H_{16}O_3$: C, 62.77; H, 9.36. Found: C, 62.73; H, 8.90.

For the corresponding cis lactone **9b**: IR (neat) 2975, 2880, 1771, 1273, 1227, 1195, 1152, 950 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.89 (dd, 1 H, J = 9.1 and 18.3, CHC=O), 2.46 (m, 1 H), 2.33 (dd, 1 H, J = 2.6 and 18.3, CHC=O), 2.08 (m, 1 H), 1.94 (m, 1 H), 1.55–1.8 (m, 4 H), 1.49 (s, 3 H, CH_3); MS (70 eV), m/z (rel intensity) 140 (M^+, 9), 125 ($M^+ - CH_3$, 6), 112 (14), 111 (13), 98 (41), 97 (100), 81 (28), 69 (22), 68 (12), 67 (10), 58 (37), 55 (43).

Spectral data for **11a**: IR (neat) 3700–3200, 2940, 2880, 2865, 1730, 1441, 1317, 1277, 1204, 1158, 1028, 1000 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.67 (s, 3, OMe), 2.62 (br s, 1, OH), 2.46 (m, 1), 2.26 (m, 2), 1.96 (m, 2), 1.1–1.8 (m, 11 H). Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 67.65; H, 9.64. Spectral data for the bridgehead isomer of **11a**: IR (neat, minor isomer) 3520 (br OH), 2940, 2865, 1740 (C=O), 1441, 1309, 1282, 1202, 1160, 960; ^1H NMR (300 MHz, $CDCl_3$, minor isomer) δ 3.67 (s, 3, OMe), 2.37 (m, 2), 2.08 (m, 2), 1.1–1.8 (m, 13 H); MS (70 eV), m/z (rel intensity, minor isomer) EI 212 (M^+, 9), 181 (10), 180 (M^+ - MeOH, 38), 152 (65), 137 (33), 111 (64), 98 (100), 97 (27), 83 (29), 67 (25), 55 (62); exact mass calcd for $C_{12}H_{20}O_3$ (M^+) 212.1413, obsd 212.1437. For the cis lactone **11b**: IR (neat) 2935, 2865, 1774, 1235, 1200, 1182, 1169, 1052 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.83 (A of ABX, 1), 2.62 (m, 1), 2.34 (m, app d, 1), 2.32 (m, 1), 2.11 (m, 1), 1.98 (m, 1), 1–1.9 (m, 10). Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.08; H, 9.02.

Spectral data for compound **13a**: IR (neat) 3450, 2955, 2870, 1727, 1440, 1317, 1278, 1212, 1170, 1008 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.69 (s, 3 H, OMe), 3.42 (br s, 1 H, OH), 2.47 (m, 2 H, AB of ABX, CH_2CO_2), 2.05–2.3 (m, 3 H), 1.5–1.95 (m, 5 H), 1.15–1.45 (m, 3 H), 0.95–1.1 (m, 1 H). Anal. Calcd for $C_{11}H_{18}O_3$: C, 66.64; H, 9.15. Found: C, 66.74; H, 9.15. For isomer **13b**: IR (neat) 2958, 2870, 1775, 1387, 1225, 1174, 1167, 1033, 986, 957 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.74 (m, 1 H), 2.49 (m, 1 H), 2.36 (m, 2 H), 1.7–2.1 (m, 6 H), 1.2–1.7 (m, 4 H). Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.26; H, 8.47.

Spectral data for nitrile **15**: IR (neat, mixture of E/Z isomers) 3440–3495, 2927–2950, 2869, 2251, 1464, 1455, 1121, 1103, 1064 cm^{-1}; ^1H NMR (300 MHz, C_6D_6) δ 3.23 (br s, 1 H, CH α to OH, cis product), 3.15 (apparent t, 1 H, CH α to OH, trans product), 2.04 and 1.87 (dd, 2 H, J = 16.8 Hz, CH_2 α to CN, trans product), 2.08 and 1.74 (dd, 2 H, J = 16.5 Hz, CH_2 α to CN, cis product), 1.8 (m, ca. 0.5 H under dd), 1.66 (apparent d, ca. 0.5 H), 0.960–1.50 (m, 8 H), 0.892 and 0.899 (overlapping singlets, 6 H, trans product), 0.838 and 0.821 (overlapping singlets, 6 H, cis product); ^1H NMR (300 MHz, $CDCl_3$) δ 3.69 (apparent d, 1 H, CH α to OH, cis product), 3.61 (apparent t, 1 H, CH α to OH, trans product), 2.4–2.6 (m, 2 H), 2.1–2.17 (m, 1 H), 1.9–2.05 (m, 1 H), 1.17–1.82 (m, 8 H), 1.09 (s, 6 H, trans product), 1.07 (s, 6 H, cis product); exact mass calcd for $C_{12}H_{20}NO$ (CI, CH_4, M + 1) 194.1544, obsd (mixture of cis/trans isomers) 194.15609.

Spectral data for compound **17a**: IR (neat) 3470, 2957, 2880, 2860, 1734, 1466, 1440, 1373, 1290, 1205, 1178, 1155 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.68 (s, 3, OMe), 2.51 (dd, 1, J = 15.8, 7.1, $CHCO_2$), 2.32 (dd, 1, J = 4.7, 15.8, $CHCO_2$), 1.91 (dd, 1, J = 4.7, 7.1, C*H*CH_2CO_2), 1.82 (m, 1), 1.2–1.65 (m, 6), 1.16 (s, 3, OH), 0.92 (s, 3, *gem*-CH_3), 0.82 (s, 3, *gem*-CH_3); exact mass calcd for $C_{11}H_{18}O_2$ (lactone corresponding to **17a**) 182.1306, obsd 182.1306. For the known[23] cis lactone **17b**: IR (neat) 2950, 2880, 1775, 1455, 1385, 1264, 1231, 1205, 1175, 1157, 1100, 1017, 948 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.46 (m, 2, AB of ABX, CH_2C=O), 2.06 (dd, 1, X of ABX, C*H*CH_2CO), 1.84 (m, 1), 1.3–1.65 (m, 5), 1.53 (s, 3, CH_3CO), 1.05 (s, 3, *gem*-CH_3), 0.91 (s, 3, *gem*-CH_3).

Spectral data for compound **18**: IR (neat) 2950, 2865, 1740 (C=O), 1453, 1440, 1435, 1270, 1202, 1160 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.66 (s, 3, OMe), 2.32 (t, 3, J = 7.4 Hz, CH_2CO_2), 1.9–2.3 (m, 4), 1.2–1.9 (m, 9); MS (70 eV), m/z (rel intensity) 198 (M^+, 5), 167 (5), 166 (M^+ - MeOH, 3), 138 (8), 121 (10), 84 (100), 83 (17), 74 (18); exact mass calcd for $C_{11}H_{18}O_3$ 198.1256, obsd 198.1264.

Acknowledgment. We are grateful to the National Science Foundation for their support of this research.

Registry No. **4a**, 3884-92-2; **4b**, 113705-03-6; **4E**, 96293-27-5; **4Z**, 113704-92-0; **5a**, 78844-18-5; **5b**, 78002-67-2; **6E**, 2018-86-2; **6Z**, 110302-07-3; **7a**, 96293-31-1; **7b**, 10082-36-7; **8E**, 96293-28-6; **8Z**, 113704-93-1; **9a**, 96293-33-3; **9b**, 24871-13-4; **10E**, 96293-26-4; **10Z**, 113704-94-2; **11a**, 96293-30-0; **11b**, 113704-98-6; **12E**, 96293-29-7; **12Z**, 113704-95-3; **13a**, 113704-99-7; **13b**, 41894-88-6; **14**, 113725-92-1; **15** (isomer I), 113705-00-3; **15** (isomer II), 113705-01-4; **16**, 113704-97-5; **17a**, 113705-02-5; **17b**, 37531-06-9; **18**, 13672-63-4; **19**, 76215-30-0; $CH_2(CO_2C_2H_5)_2$, 105-53-3; $CH_2(CN)_2$, 109-77-3; CH_3CN, 75-05-8; Et_4NOTs, 733-44-8.

(23) Hoye, T. R.; Kurth, M. J. *J. Org. Chem.* **1978**, *43*, 3693.