Approaches to Stereoselective Dioxygenation of Alkenes: Chiral Phosphite Ozonides

Patrick H. Dussault* and Kevin R. Woller

Department of Chemistry, University of Nebraska−Lincoln, Lincoln, Nebraska 68588-0304

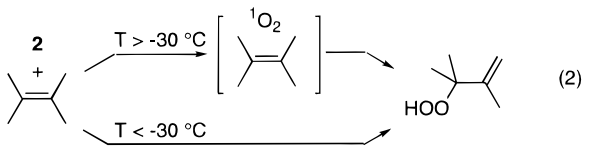
Received August 12, 1996 (Revised Manuscript Received January 8, 1997)

As a part of a continuing program targeting the synthesis of peroxide-containing natural products, we have been interested in the use of singlet oxygen ($^1O_2$) for stereoselective introduction of carbon−oxygen bonds. Addition of $^1O_2$ to prochiral alkenes, although a versatile method for synthesis of allylic hydroperoxides, is limited to the formation of racemic products.[1] Previous approaches to controlling oxygenation stereochemistry have included auxiliary-directed dioxygenation of dienes and enoates with $^1O_2$,[2,3] dioxygenation of chiral allylstannanes,[4] hydroxyl-directed dioxygenation of allylic alcohols,[5] and reaction within chiral inclusion complexes.[6−8] These methods, while often effective within a given class of substrates, are limited in scope. We became interested in a broadly applicable approach to stereoselective dioxygenation based upon a chiral $^1O_2$ equivalent, and we now report our efforts involving chiral phosphite ozonides.

Readily prepared by low-temperature reaction of a phosphite with excess ozone (eq 1), phosphite ozonides are unstable, releasing $^1O_2$ at a rate dependent upon both temperature and structure.[9,10] The best-known member of the family, triphenyl phosphite ozonide (TPPO, **2**), undergoes decomposition at temperatures less than −30 °C to yield $^1O_2$, resulting in product distributions indistinguishable from photosensitized oxidations (eq 2). However, at temperatures above −30 °C, oxidations proceed via direct oxygen transfer from TPPO to substrate.[11]

$$(C_6H_5O)_3P + O_3 \xrightarrow{-78\ ^\circ C} (C_6H_5O)_3PO_3 \qquad (1)$$

1 **2**



(2)

The use of chiral phosphite ozonides at low temperature would seem to offer the possibility of asymmetric dioxygenation. While a number of different phosphite ozonides have been prepared in search of increased thermal stability, only one has been investigated for use in asymmetric oxidation.[10] In that example, the ozonide derived from menthyl diphenyl phosphite was shown to oxidize sulfides to sulfoxides in very low enantiomeric excess.[12] It seemed likely that an effective chiral oxidant might be found in phosphite ozonides derived from C_2 symmetric auxiliaries such as binaphthol and α,α,α′,α′-tetraaryl-2,2-dimethyl-1,3-dioxolane-4,5-dimethanol (TADDOL).[13,14] We report herein approaches to stereoselective dioxygenations with chiral phosphite ozonides and provide the first systematic comparison of the relative reactivity of phosphite ozonides and $^1O_2$.

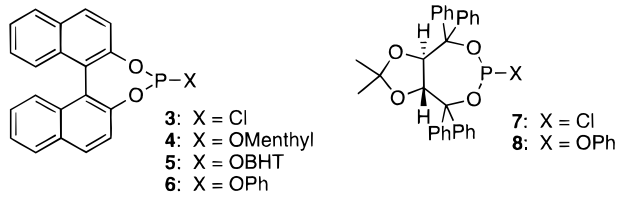


Figure 1.

Results and Discussion

The phosphite substrates, illustrated in Figure 1, were prepared through conversion of binaphthol or TADDOL to the corresponding phosphorochloridates (**3** and **7**) followed by reaction with an appropriate alcohol or phenol.[15] The need to resolve binaphthol prior to formation of the mixed phosphite was obviated by a modification of a recently reported procedure describing resolution as diastereomeric menthyl phosphites.[16] Reaction of menthol with **3**, followed by crystallization, afforded a single enantiomer of **4** from which enantiomerically pure binaphthol was available via reduction with $LiAlH_4$.

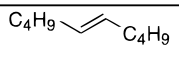
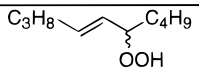
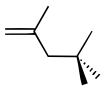
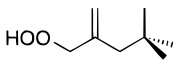
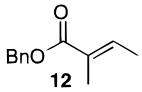
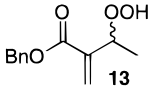
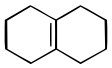
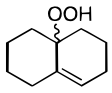
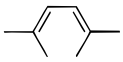
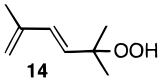
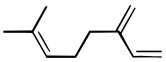
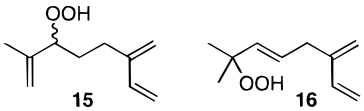
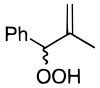
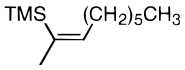
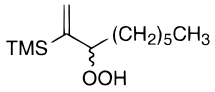
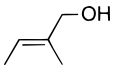
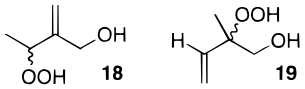
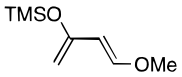
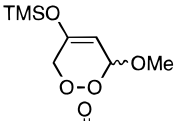
Deprotonation of butylated hydroxytoluene (BHT) with butyllithium, followed by reaction with racemic binaphthyl phosphorochloridate, provided phosphite **5**; repetition of the same reaction with phenol afforded phosphite **6**. An enantiomerically pure sample of **5** could be prepared similarly beginning with *R*-binaphthol derived from **4**. Phenyl-TADDOL phosphite (**8**) was prepared in a similar manner.[15,17]

Ozonide formation was accomplished by slow addition of a dilute solution of the phosphite into a −78 °C aliquot of CH_2Cl_2 saturated with O_3/O_2. Variable temperature ^{31}P NMR revealed that the ozonide derived from **4** was stable to approximately −20 °C at which point a slow decomposition to phosphate was observed. The results of reaction between the phosphite ozonides, employed in slight theoretical excess, and a variety of substrates are illustrated in Table 1. Also presented in most cases are the results of comparison photooxygenations.

(1) *Singlet Oxygen*; Wasserman, H. H., Murray, R. W., Ed.; Academic Press: New York, 1979.
(2) Dussault, P. H.; Hayden, M. R. *Tetrahedron Lett.* **1992**, *33*, 443.
(3) Dussault, P. H.; Woller, K. R.; Hillier, M. C. *Tetrahedron* **1994**, *50*, 8929.
(4) Dussault, P. H.; Lee, R. J. *J. Am. Chem. Soc.* **1994**, *116*, 4485.
(5) Prein, M.; Adam, W. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 477.
(6) Gerdil, R.; Barchietto, G.; Jefford, C. W. *J. Am. Chem. Soc.* **1984**, *106*, 8004.
(7) Weber, L.; Imiolczyk, I.; Haufe, G.; Rehorek, D.; Hennig, H. *J. Chem. Soc., Chem. Commun.* **1992**, 301.
(8) Kuroda, Y.; Sera, T.; Ogoshi, H. *J. Am. Chem. Soc.* **1991**, *113*, 2793.
(9) Thompson, Q. E. *J. Am. Chem. Soc.* **1961**, *83*, 845.
(10) Mendenhall, G. D. In *Advances in Oxygenated Processes*; A. L. Baumstark, Ed.; JAI: Greenwich: Connecticut, 1990; Vol. 2, p 203.
(11) Bartlett, P. D.; Mendenhall, G. D. *J. Am. Chem. Soc.* **1970**, *92*, 210.
(12) Shereshovets, V. V.; Korotseva, N. M.; Komissarov, V. D.; Tolstikov, G. A. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1990**, 2133.
(13) Kless, A.; Holz, J.; Heller, D.; Kadyrov, R.; Selke, R.; Fischer, C.; Börner, A. *Tetrahedron Asymm.* **1996**, *7*, 33.
(14) Seebach, D.; Hayakawa, M.; Sakaki, J.-i.; Schweizer, W. B. *Tetrahedron* **1993**, *49*, 1711.
(15) Pastor, S. D.; Shum, S. P.; Rodebaugh, R. K.; Debellis, A. D.; Clarke, F. H. *Helv. Chim. Acta* **1993**, *76*, 900.
(16) Brunel, J.-M.; Buono, G. *J. Org. Chem.* **1993**, *58*, 7313.
(17) Zelikman, E. S.; Yur'ev, Y. N.; Berezova, L. V.; Tsyskovskii, V. K. *Zh. Org. Khim.* **1971**, *7*, 641.

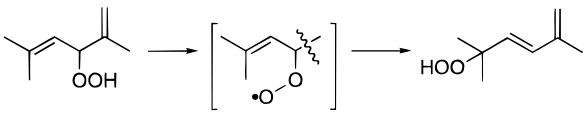
S0022-3263(96)01564-2 CCC: $14.00

Table 1. Comparison of Oxygenation with Phosphite Ozonides and $^1O_2$

entry	Substrate	Product(s)	Phosphite	% Yield[a]	% ee	% Yield $^1O_2$[a,b]
1			**1**	NR	—	—
2			(±)-**5**	NR	—	40
3			**1** (±)-**4**	NR NR	— —	60
4			(±)-**5**	28	—	91
5			(±)-**5**	23	—	65
6		**9-11**	(*S*)-**4** (±)-**5** (*RR*)-**8**	13 21 26	0[c] — 0	86
7			**1** (*RR*)-**8**	33 27	— 0	83
8			(*RR*)-**8**	NR	—	—
9			(±)-**4** (±)-**6**	NR NR	— —	60 -84
10			(±)-**4** (±)-**6**	NR NR	— —	95
11			(*R*)-**4**	NR	—	—
12			(*S*)-**4** (*R*)-**5** (*RR*)-**8**	80 70 97	11(*R*)[d] 6 (*R*)(+) 19 (*S*)(-)	—

a) Isolated yield; b) hν, TPP/CCl_4; c) determined by Mosher ester analysis of corresponding alcohols; d) determined by optical rotation

The phosphite ozonides were unreactive toward disubstituted alkenes (entries 1 and 2) or alkenes bearing electron-withdrawing substituents (entry 3). However, reaction with tri- and tetrasubstituted alkenes occurred more readily (entries 4−7), reaction with tetrasubstituted alkenes occurring so rapidly that the formation of allylic hydroperoxide from tetramethylethylene could be used to verify the continued presence of phosphite ozonide during prolonged oxidations of less reactive substrates. Myrcene (entry 7) reacted in modest yield to give a mixture of two regioisomeric hydroperoxides (**15** and **16**) derived from selective dioxygenation of the trisubstituted alkene. No difference in product yield or rate of product formation was observed for reactions run at −30 °C or −78 °C. Interestingly, reaction with 2,5-dimethyl-2,4-hexadiene (entry 5) furnished not the expected secondary hydroperoxide but rather a tertiary hydroperoxide derived from allylic rearrangement via the corresponding peroxyl radical (eq 3).[18]



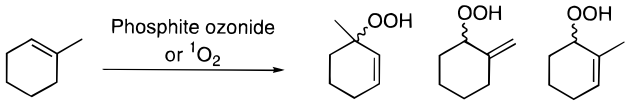
(3)

Vinylsilanes and allylic alcohols are synthetically important substrates which undergo highly regioselective, and in some cases stereoselective, oxygenations with $^1O_2$.[5,19] However, neither a vinyl silane (entry 9) nor an allylic alcohol (entry 10) underwent reaction with the phosphite ozonide, even after prolonged reaction. A similar result was observed for the silyl ether of the allyl alcohol. Similarly, while $^1O_2$ smoothly forms cycloadducts with alkoxy and trimethylsiloxy-substituted butadienes,[20]

(18) Porter, N. A.; Mills, K. A.; Caldwell, S. E.; Dubay, G. R. *J. Am. Chem. Soc.* **1994**, *116*, 6697. Adam, W.; Staab, E. *Tetrahedron Lett.* **1988**, *29*, 531.

(19) Fristad, W. E.; Bailey, T. R.; Paquette, L. A. *J. Org. Chem.* **1980**, *45*, 3028. Adam, W.; Richter, M. J. *J. Org. Chem.* **1994**, *59*, 3335.

Table 2. Regioselectivity in Oxidation of Methylcyclohexene



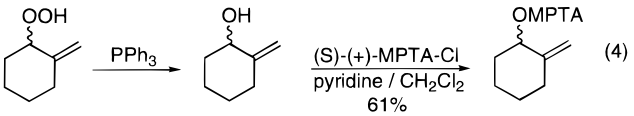
oxidant[a]	reference	**9**	**10**	**11**
(*S*)-**4**	this work	27	63	9
hν, TPP, CH_2Cl_2	20	41	43	16
hν, RB, MeOH	21	36	44	20
hν, MB, MeCN	22	45	43	13

[a] TPP = tetraphenylporphyrin, RB = rose bengal, MB = methylene blue.

no reaction was observed between an electron-rich enol ether and (*R*)-**4** (entry 11). However, the lack of cycloaddition was not entirely unexpected as the reduced tendency of dienes to form cycloadducts in the presence of TPPO was an important piece of evidence in establishing the ozonides as discrete oxidants.[11]

1-Methyl-1-cyclohexene (entry 6) reacted quickly with all phosphite ozonides, in each case furnishing a modest yield of three hydroperoxides as a similar mixture of three inseparable regioisomers (**9**−**11**). The regioselectivity obtained for oxidation with the phosphite ozonide (63:27:9) is significantly different than observed during photosensitized oxygenations (Table 2).[21−23] This is in keeping with a previous report in which TPPO was employed to achieve altered chemoselectivity during oxygenation of medium ring alkenes.[24]

Analysis of stereochemistry was performed through reduction of the crude hydroperoxides to the corresponding allylic alcohols followed by conversion of the major product (**10**) into diastereomeric Mosher esters (eq 4).[25] A 1:1 mixture of diastereomers was evident in both the ^{13}C and ^{19}F NMR of the Mosher esters of the alcohols following reduction of the hydroperoxide from oxygenations with ozonides derived from (*S*)-**4** or (*RR*)-**8**. Oxidation of myrcene with the ozonide derived from (*RR*)-**8** also proceeded with no stereoselection, based upon the Mosher ester of the secondary hydroperoxide (**15**).



(4)

Oxidation of thioanisole with phosphite ozonides derived from (*S*)-**4**, (*R*)-**5**, and (*RR*)-**8** proceeded rapidly and in good yield (Table 1, entry 12). Comparison of sulfoxide optical rotations with previously reported values[26] indicated that the enantioselection, while superior to a previous report involving a simple menthyl phosphite, was not competitive with other methods for sulfoxide formation.[27]

Conclusions

Our results, the first systematic study of phosphite ozonide reactivity and selectivity, clearly indicate that the ozonides are much less reactive than $^1O_2$ and are effectively limited to oxygenation of tri- and tetrasubstituted alkenes as well as sulfides. The failure to achieve significant enantioselection, despite the use of chiral auxiliaries proven effective in other applications, implies that approach of the substrate to the reactive oxygen centers is able to occur on a trajectory allowing minimal interaction with the auxiliaries.

Experimental Section

All reagents and solvents were used as purchased, except THF, which was distilled from Na/Ph_2CO. Melting points are uncorrected. ^1H and ^{13}C NMR spectra were recorded on 300-, 360-, or 500-MHz spectrometers in $CDCl_3$; individual peaks are reported as (multiplicity, number of hydrogens, coupling constant (Hz)). Infrared spectra were recorded on neat films. Optical rotations were obtained in a 1-dm cell in $CHCl_3$ unless otherwise noted. Elemental analyses were obtained from M-H-W Laboratories, Phoenix, AZ, or Desert Analytics, Tucson, AZ. All hydroperoxides were handled and stored in the presence of approximately 0.1% butylated hydroxytoluene (BHT) added from a 1 M stock solution in CH_2Cl_2. Progress of reactions involving peroxides was monitored by TLC, using an *N*,*N*′-dimethyl-*p*-phenylenediamine indicator; hydroperoxides yield an immediate reddish-pink spot.[28] The following substrates or products have been previously described. Hydroperoxides: 1-methyl-2-cyclohexenyl, 2-methylenecyclohexyl, and 2-methyl-2-cyclohexenyl,[21] 1,1-dimethyl-5-methylene-2,6-heptadienyl and 4-methylene-1-(1-methylethenyl)-5-hexenyl,[29] 1,1,4-trimethyl-2,4-pentadienyl,[19] 2-methyl-1-phenyl-2-propenyl,[30] octahydryonaphthalenyl.[31] Others: 4,4-dimethyl-2-methylenepentanol,[32] (3-methoxy-1-methylene-2-propenyloxy)trimethylsilane,[20] (methylsulfinyl)-benzene.[27]

General Procedure for the Formation of Phosphite Ozonides. Into a −78 °C aliquot of CH_2Cl_2 (10 mL) saturated with a stream of O_3/O_2 was added a solution of phosphite in CH_2Cl_2 (typically 0.1 M) at a rate so as to maintain the blue color of dissolved ozone. After the addition was completed, excess ozone was removed with a stream of N_2. A solution of substrate (alkene or sulfide) in CH_2Cl_2 was then added to the ozonide solution via a precooled syringe.

General Procedure for Reference Photooxygenations. Alkene photooxygenations were carried out in a jacketed Pyrex cell into which was placed a CH_2Cl_2 solution of substrate (0.1 M) and sensitizer (5,10,15,20-tetraphenyl-21H,23H-porphine (TPP), typically 0.001 M). The solution was aspirated with oxygen and photolyzed with a 200 W illuminator (Dolan-Jenner Industries) at a distance of 10 cm. Reactions were followed by TLC and stopped after the disappearance of the starting material (typically 1−4 h).

(*R*)-Binaphthyl-BHT Phosphite (5). To a −78 °C solution of BHT (3.90 g, 17.7 mmol) in THF (25 mL) was added n-BuLi (7.1 mL, nominally 2.4 M in hexanes). After 15 min a solution of **7** (6.2 g, 17.7 mmol) in THF (25 mL) was added. The solution was allowed to warm to room temperature and stirred for 2 h. The reaction mixture was then filtered, and the solvent was removed in vacuo to afford 9 g (95%) of the phosphite as an off white solid: mp = 94−97 °C; [α] = −133.5 (*c* = 1, THF); ^{31}P NMR (202 MHz): δ = 148.4; ^1H NMR (500 MHz) δ = 8.0−7.22 (12H), 7.21 (s, 2H) 1.56 (s, 18H), 1.49 (s, 3H); ^{13}C NMR (125 MHz) δ = 143.9, 133.3, 132.3, 130.3, 129.1, 128.9, 128.2, 127.8, 127.0, 126.7, 126.2, 125.9, 122.6, 122.3, 36.3, 33.0, 31.1; IR: 3055, 2953, 2910, 2867, 1230, 1200, 1180, 1070, 863, 827 cm^{-1}. Anal. Calcd for $C_{35}H_{35}O_3P$: C, 78.6; H, 6.6. Found: C, 78.6; H, 6.8. HRMS calcd (M^+) 534.2324, found: 534.2307.

(20) Clennan, E. L.; L'Esperance, R. P. *Tetrahedron Lett.* **1983**, *24*, 4291.
(21) Courtneidge, J. L.; Bush, M.; Loh, L.-S. *J. Chem. Soc., Perkin Trans. 1* **1992**, 1539.
(22) Foote, C. S. *Acc. Chem. Res.* **1968**, *1*, 104.
(23) Jefford, C. W.; Rimbault, C. G. *Tetrahedron Lett.* **1981**, *22*, 91.
(24) Sam, T. W.; Sutherland, J. K. *J. Chem. Soc., Perkin Trans. 1* **1975**, 2336.
(25) Dale, J. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 512.
(26) Folli, U.; Iarossi, D.; Montanari, F.; Torre, G. *J. Chem. Soc.* **1968**, 1317.
(27) Komatsu, N.; Hashizume, M.; Sugita, T.; Uemura, S. *J. Org. Chem.* **1993**, *58*, 4529.
(28) Smith, L. L.; Hill, F. L. *J. Chromatogr.* **1972**, *66*, 101.
(29) Ruecker, G.; Mayer, R.; Manns, D. *J. Nat. Prod.* **1987**, *50*, 287.
(30) Matsumoto, K.; Kuroda, K. *Synth. Commun.* **1981**, *11*, 987.
(31) Dang, H.-S.; Davies, A. G.; Davison, I. G. E.; Schiesser, C. H. *J. Org. Chem.* **1990**, *55*, 1432.
(32) Bilas, W.; Hoebold, W.; Pritzkow, W. *J. Prakt. Chem.* **1982**, 125.

2-Methyl-2-butenoic Acid, 1-Benzyl Ester (12). To a solution of benzyl alcohol (1.62 g, 15 mmol) in CH_2Cl_2 (50 mL) was added 4-(dimethylamino)pyridine (DMAP, 0.5 g, 4.1 mmol) and 2-methyl-2-butenoic acid (1.5 g, 15 mmol). After 10 min, dicyclohexyl carbodiimide (DCC, 3.9 g, 19 mmol) was added, and the solution was stirred for 10 h. After removal of solvent at reduced pressure, the residue was suspended in dry ether (75 mL) and filtered to remove insoluble urea. Concentration, followed by flash chromatography on silica gel (10% EA/hex) afforded 2.65 g (93%) of the ester: $R_f = 0.47$ (20% EA/Hex); ^{1}H NMR (300 MHz) $\delta = 7.39-7.27$ (m, 5H), 6.93 (dq, 1H, $J = 1.4$, 7.2), 5.19 (s, 2H), 1.87 (t, 3H, $J = 1.2$), 1.78 (dt, 3H, $J = 7.2$, 1.2); ^{13}C (75 MHz): $\delta = 168.4$, 138.2, 128.7, 128.6, 66.8, 35.6, 26.2, 25.3, 15.0, 12.7, IR (neat) 1712 cm^{-1}. Anal. Calcd for $C_{12}H_{14}O_2$: C, 75.8; H, 7.4. Found: C, 75.8; H, 8.2.

2-Methylene-3-hydroperoxybutanoic Acid, Benzyl Ester (13). Benzyl tiglate (207 mg, 1.1 mmol) was subjected to dye-sensitized photooxygenation as described above to furnish, after flash chromatography on silica gel (10 → 20% EA/hex), 144 mg (59%) of the hydroperoxide: $R_f = 0.21$ (10% EA/hex); ^{1}H NMR (300 MHz): $\delta = 8.80$ (s, 1H), 7.38 (m, 5H), 6.42 (s, 1H), 5.97 (s, 1H), 5.23 (s, 2H), 5.03 (q, 1H, $J = 5.7$), 1.36 (d, 3H, $J = 6.4$); ^{13}C NMR (75 MHz): $\delta = 166.6$, 141.2, 136.4, 129.3, 129.0, 128.8, 126.7, 80.1, 67.4, 19.2; IR (neat) 3403, 1713 cm^{-1}. Anal. Calcd for $C_{12}H_{14}O_4$: C, 64.9; H, 6.4. Found: C, 63.9; H, 6.4.

1,1,4-Trimethyl-2(*E*),4-pentadienyl Hydroperoxide (14). 2,5-Dimethyl-2,4-hexadiene (77.3 mg, 0.7 mmol) dissolved in CH_2Cl_2 (5 mL) was added via a precooled syringe to a −78 °C solution of the ozonide generated from (+)-**4**. The solution was stirrred at −78 °C for 90 min. The solvent was removed in vacuo. Flash chromatography on silica gel (10% EA/hex) gave 23 mg (23%) of the tertiary hydroperoxide: $R_f = 0.22$ (10% EA/hex); ^{1}H NMR (300 MHz): $\delta = 7.67$ (s, 1H), 6.33 (d, 1H, $J = 16.2$), 5.73 (d, 1H, $J = 16.2$), 5.02 (m, 2H), 1.84 (d, 3H, $J = 0.7$), 1.38 (s, 6H); ^{13}C NMR (75 MHz): $\delta = 142.0$, 133.8, 133.4, 127.2, 118.1, 25.1, 19.1; IR (neat) 3397 cm^{-1}; Anal. Calcd for $C_8H_{14}0_2$: C, 67.6; H, 9.9. Found: C, 65.5, H, 9.6.

Dioxygenation of myrcene resulted in an inseparable 1:1 mixture of **15:16**. $R_f = 0.36$ (10% EA/hex); IR (neat) 3413 cm^{-1}. The two compounds could be characterized via HETCOR and COSY NMR experiments on the mixture:

4-Methylene-1-(1-methylethenyl)-5-hexenyl hydroperoxide (15): ^{1}H NMR (500 MHz): $\delta = 8.54$ (s, 1H), 6.34 (dd, 1H, $J = 17.7$, 10.5), 5.20 (d, 2H, $J = 17.7$), 5.03 (m, 2H), 5.0 (d, 2H, $J = 1.2$), 4.32 (t, 1H, $J = 6.9$), 2.23 (m, 2H), 1.71 (t, 3H, $J = 1.2$), 1.68 (m, 2H); ^{13}C NMR (125 MHz) $\delta = 17.8$, 28.0, 30.1, 89.7, 114.0, 114.8, 116.6, 139.3, 144.4, 144.6.

1,1-Dimethyl-5-methylene-2,6-heptadienyl (16): ^{1}H NMR (500 MHz): $\delta = 8.01$ (s, 1H), 6.34 (dd, 1H, $J = 17.7$, 10.5), 5.72 (dt, 1H, $J = 15.7$,6.9), 5.60 (dt, 1H, $J = 15.7$,1.2), 5.20 (d, 2H, $J = 17.7$), 5.03 (m, 2H), 2.93 (d, 2H, $J = 6.4$), 1.30 (s, 6H): ^{13}C NMR (125 MHz) $\delta = 24.9$, 35.1, 82.7, 114.0, 116.6, 129.4, 136.0, 139.3, 144.4, 146.3.

2-(Trimethylsilyl)-3-hydroperoxy-2(*Z*)-nonene (17). 2-(Trimethylsilyl)-2(*Z*)-nonene[33] (113 mg, 0.57 mmol) was subjected to dye-sensitized photooxygenation as described above to afford, after flash chromatography (5 → 10% EA/hex), 62 mg (60% based on recovered starting material) of the hydroperoxide: $R_f = 0.36$ (10% EA/hex); ^{1}H NMR (500 MHz): $\delta = 7.77$ (s, 1H), 5.84 (d, 1H, $J = 2.8$), 5.57 (d, 1H, $J = 2.4$), 4.52 (t, 1H, $J = 6.5$), 1.6 − 1.27 (10H), 0.88 (t, 3H, $J = 6.5$), 0.16 (s, 9H); ^{13}C NMR (125 MHz) $\delta = 152.4$, 127.5, 91.0, 33.9, 32.3, 29.8, 26.5, 23.2, 14.7, −0.12; IR (neat) 3411 cm^{-1}; Anal. Calcd for $C_{12}H_{26}SiO_2$: C, 62.6; H, 11.3. Found: C, 62.4; H, 11.5.

Dioxygenation of 2-Methyl-2-buten-1-ol. A solution of 2-methyl-2-buten-1-ol (237 mg, 2.75 mmol) in 10 mL of 0.001 M solution TPP/CH_2Cl_2 was subjected to photooxygenation as described above to afford, after flash chromatography (50% EA/hex), 297 mg (95%) of an inseparable mixture of regioisomeric hydroperoxides **18** and **19** which were characterized via HETCOR and COSY experiments: $R_f = 0.29$ (40% EA/hex); IR (neat) 3358 cm^{-1}. HRMS calcd for $C_5H_{10}O_3$ (M^+) 118.0630, found: 118.0631.

3-Hydroperoxy-2-methylenebutanol (18): ^{1}H NMR (300 MHz): δ 5.26 (bs, 1H), 5.20 (bs, 1H), 4.65 (q, 1H, $J = 6.7$), 4.19 (q, 2H, $J = 16.6$), 1.27 (d, 3H, $J = 6.7$); ^{13}C NMR (75 MHz) $\delta = 148.1$, 116.9, 83.8, 63.3, 18.2.

2-Hydroperoxy-2-methyl-3-buten-1-ol (19): ^{1}H NMR (300 MHz): δ 9.5 (bs, 1H), 5.90 (dd, 1H, $J = 17.9$, 11.2), 5.27 (bd, 1H, 17.9), 5.24 (bd, 1H, $J = 11.4$), 3.69 (q, 2H, $J = 11.9$), 1.27 (s, 3H); ^{13}C NMR (75 MHz) $\delta = 138.5$, 117.4, 83.4, 66.2, 19.9.

Acknowledgment. This research was supported by the American Cancer Society (CN-34). NMR spectrometers used in this research were purchased, in part, with funds from the NIH Shared Instrumentation Program (SIG-1-510-RR06307); we are grateful to Prof. Richard Shoemaker for assistance with NMR experiments.

Supporting Information Available: ^{1}H and ^{13}C NMR spectra for **5**, **12**, **13**, **14**, a mixture of **15**/**16**, **17**, and a mixture of **18**/**19** (14 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO961564H

(33) Eisch, J. J.; Damasevitz, G. A. *J. Org. Chem.* **1976**, *41*, 2214.