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An $^1O_2$ Route to γ-Hydroxyalkenal Phospholipids by Vitamin E-Induced Fragmentation of Hydroperoxydiene-Derived Endoperoxides

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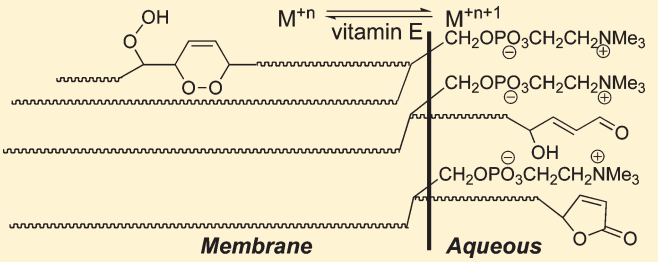
Supporting Information

ABSTRACT: Biologically active phospholipids that incorporate an oxidatively truncated acyl chain terminated by a γ-hydroxyalkenal are generated in vivo. The γ-hydroxyalkenal moiety protrudes from lipid bilayers like whiskers that serve as ligands for the scavenger receptor CD36, fostering endocytosis, e.g., of oxidatively damaged photoreceptor cell outer segments by retinal pigmented endothelial cells. They also covalently modify proteins generating carboxyalkyl pyrroles incorporating the ε-amino group of protein lysyl residues. We postulated that γ-hydroxyalkenals could be generated, e.g., in the eye, through fragmentation of hydroperoxy endoperoxides produced in the retina through reactions of singlet molecular oxygen with polyunsaturated phospholipids. Since phospholipid esters are far more abundant in the retina than free fatty acids, we examined the influence of a membrane environment on the fate of hydroperoxy endoperoxides. We now report that linoleate hydroperoxy endoperoxides in thin films and their phospholipid esters in biomimetic membranes fragment to γ-hydroxyalkenals, and fragmentation is stoichiometrically induced by vitamin E. The product distribution from fragmentation of the free acid in the homogeneous environment of a thin film is remarkably different from that from the corresponding phospholipid in a membrane. In the membrane, further oxidation of the initially formed γ-hydroxyalkenal to a butenolide is disfavored. A conformational preference for the γ-hydroxyalkenal, to protrude from the membrane into the aqueous phase, may protect it from oxidation induced by lipid hydroperoxides that remain buried in the lipophilic membrane core.



INTRODUCTION

Phospholipids that incorporate an oxidatively truncated acyl chain terminated by a γ-hydroxyalkenal functional array are generated in vivo by oxidative fragmentation of polyunsaturated phospholipids. The γ-hydroxyalkenal moiety protrudes from lipid bilayers like whiskers[1] that serve as ligands for the scavenger receptor CD36 (for a figure summarizing the structures of phospholipids and fatty acids mentioned in this article, see Supplementary Information), fostering endocytosis of oxidatively damaged photoreceptor cell outer segments by retinal pigmented endothelial cells.[2] The γ-hydroxyalkenal moiety also covalently modifies proteins generating carboxyalkyl pyrroles (Figure 1) that incorporate the ε-amino group of protein lysyl residues.[3,4] Carboxyethyl pyrroles (CEPs) are especially abundant in retinas from individuals with age-related macular degeneration (AMD).[5] They trigger toll-like receptor-mediated angiogenesis into and destruction of the retina, known as wet AMD, causing rapid loss of vision.[6−8] They also trigger an immune-mediated destruction of the retina known as dry AMD. Thus, mice immunized with CEP-modified mouse albumin develop a dry AMD-like phenotype that includes subretinal pigment epithelium (RPE) deposits and RPE lesions mimicking geographic atrophy.[9] Apparently γ-hydroxyalkenal-derived oxidative protein modifications, e.g., CEPs, participate in the pathogenesis of AMD.[10]

The retina is especially vulnerable to oxidative damage owing to its high proportion of polyunsaturated fatty acyls (PUFAs), high concentration of oxygen, and chronic exposure to light. Exposure of rats to intense visible light results in the consumption of PUFAs in the retina and the production of oxidatively truncated phosphatidylcholines (oxPCs)[2] and phosphatidylethanolamines (oxPEs).[11] Lipid oxidation can involve free radical, enzymatic, or singlet oxygen pathways. Ample evidence supports the premise that photo generated singlet oxygen contributes to oxidative injury in the eye. Light initiates an action potential by inducing isomerization of an 11-*cis* to an all-*trans* retinal-protein Schiff base in rhodopsin. This photosensitive receptor is reset through hydrolysis of the Schiff base releasing all-*trans* retinal that is reduced to all-*trans* retinol, and, through isomerization, oxidation, and, condensation with opsin, the initial Schiff base is regenerated.[12] However, before it is reduced to retinol, especially under conditions of oxidative stress where NADH levels are depleted, all-*trans* retinal can be excited to its triplet state that can transfer energy to molecular oxygen to give singlet oxygen.[13,14]

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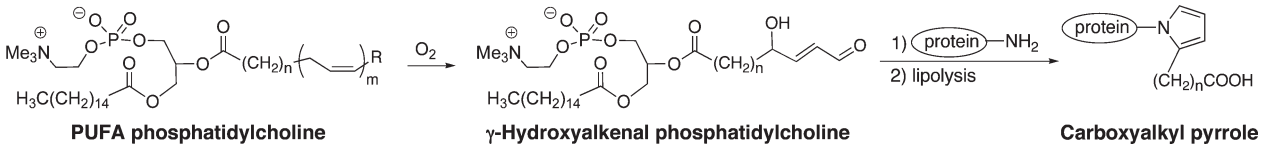


Figure 1. Oxidative cleavage of polyunsaturated fatty acyl (PUFA) phosphatidylcholines generates γ-hydroxyalkenal phosphatidylcholines that react with proteins to deliver carboxyalkyl pyrroles.

A reaction of singlet oxygen with linoleic acid (LA) generates the unconjugated hydroperoxyoctadecadienoate (10- and 12-HPODE) regioisomers and the conjugated hydroperoxydienes 9- and 13-HPODE (Figure 2). Through further reaction with singlet oxygen, 10- and 12-HPODE are transformed into the dihydroperoxydienes 9,12- and 10,13-diHPODE[15] that can undergo fragmentation to give γ-hydroxyalkenals.[15−17] A reaction of singlet oxygen with 9- and 13-HPODE delivers hydroperoxy endoperoxides (9- and 13-HP-Endo).[18] The present study was undertaken to determine if PUFA hydroperoxy endoperoxides undergo fragmentation to γ-hydroxyalkenals. Furthermore, because phospholipid esters are far more abundant than free fatty acids, it seemed pertinent to examine the influence of a membrane environment on the fate of hydroperoxy endoperoxides. We now report that linoleate hydroperoxy endoperoxides in thin films and their phospholipid esters in biomimetic membranes fragment to give γ-hydroxyalkenals that can be oxidized further to the corresponding butenolides (vide infra). Vitamin E promotes the fragmentation, and the product distribution from fragmentation of the free acid in the homogeneous environment of a thin film is remarkably different from that from the corresponding phospholipid in a model membrane.

EXPERIMENTAL PROCEDURES

General Methods. See Supporting Information.

Liqid Chromatograph/Mass Spectrometry. LC/ESI/MS/MS analysis of hydroperoxy endoperoxide fragmentation was performed on a Quattro Ultima (Micromass, Wythenshawe, UK) connected to a Waters 2690 solvent delivery system with an autoinjector. The source temperature was maintained at 100 °C, and the desolvation temperature was kept at 200 °C. The drying gas (N_2) was maintained at ca. 450 L/h, and the core flow gas was kept at ca. 50 L/h. The multiplier was set at an absolute value of 500. Optimized parameters for hydroperoxy endoperoxides and their fragmentation products were obtained with authentic samples. MS scans at m/z 80−1000 were obtained for standard compounds (Table S1 in Supporting Information).

Argon was used as collision gas at a pressure of 5 psi for MS/MS analysis. For MS/MS analysis, the collision energy was optimized for each compound. For selected reaction monitoring (SRM) experiments, the optimum collision energy (giving the strongest signal) was determined for each m/z parent−daughter ion pair (Table S2 in Supporting Information). FOA (8-(furan-2-yl)octanoic acid) did not give daughter fragments during collision and, therefore, was monitored by selected ion recording (SIR, m/z = 209).

Online chromatographic separation was achieved using a 150 × 2.0 mm i.d. Prodigy ODS-5 μm column (Phenomenex, Torrance, CA), using binary solvent gradients, water/acetonitrile or water/methanol supplemented with 0.2% formic acid or 2 mM NH_4OAc. For the carboxylic acids, the water/acetonitrile gradient started with 35% acetonitrile for 10 min, then rose to 60% in 0.5 min, and linearly rose to 75% in 15 min. The gradient was then reversed to 35% acetonitrile in 0.5 min and held for 6 min. For HODA methoxime derivatives, the methanol/water gradient, supplemented with 2 mM NH_4OAc, started

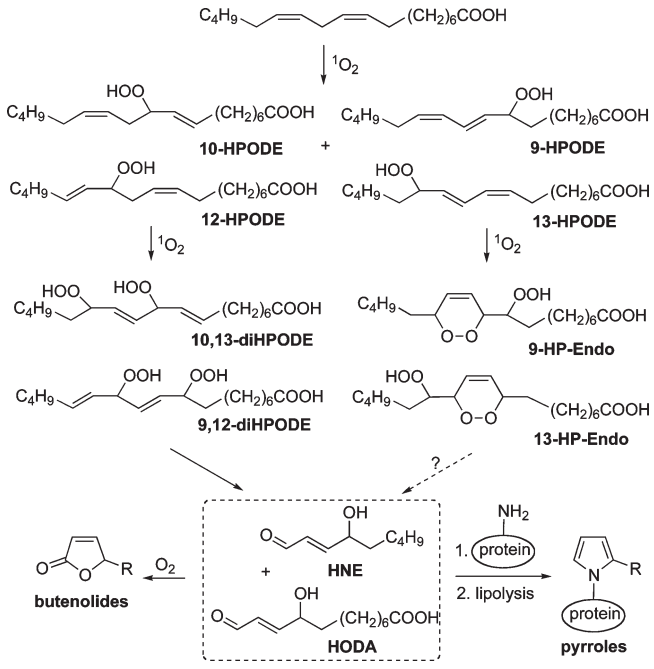


Figure 2. Singlet molecular oxygen reaction pathways to γ-hydroxyalkenals. Further oxidation produces butenolides in competition with adduction to proteins to generate carboxyalkyl pyrroles.

with 5% methanol and rose to 100% methanol in 15 min, then was held at 100% methanol for another 15 min. The gradient was then reversed to 5% methanol in 0.5 min and held at 5% methanol for 4.5 min before the next run. For ODFO-PFB ester derivatives, the methanol/water gradient, supplemented with 2 mM NH_4OAc, started with 50% methanol and rose to 100% methanol in 10 min, then was held at 100% methanol for another 15 min. The gradient was then reversed to 50% methanol in 0.5 min and held for 4.5 min before the next run. For the phospholipids, the methanol/water gradient, supplemented with 0.2% formic acid, started with 85% methanol and rose to 100% in 15 min, then was held at 100% methanol for another 15 min. The gradient was then reversed to 85% methanol in 0.5 min and held at 85% methanol for 4.5 min before the next run. The solvents were all delivered at 200 μL/min.

(9*Z*,11*E*)-13-(2-Methoxypropan-2-ylperoxy)octadeca-9,11-dienoic Acid (13-HP-MiP). 13-HPODE (120 mg, 0.38 mmol) and pyridinium *p*-toluene sulfonate (PPTs, 10 mg) were dissolved in dry CH_2Cl_2 (10 mL). Then 2-methoxypropene (100 μL, excess) was added dropwise via a syringe. The resulting mixture was stirred for 0.5 h under argon. Then solvents were removed by rotary evaporation, and the crude product was then flash chromatographed on silica gel eluting with hexane and ethyl acetate (2/1) to afford the pure 13-HP-MiP (114 mg, 30 mmol, yield = 78%); R_f = 0.38 with hexane and ethyl acetate (1/1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.41 (dd, J = 15.6, 10.8, 1H), 5.92 (t, J = 10.8, 1H), 5.53 (dd, J = 15.2, 8, 1H), 5.37 (dt, J = 10.8, 7.6, 1H), 4.33 (m, 1H), 3.23 (s, 3H), 2.27 (t, J = 7.6 Hz, 2H), 2.11 (m, 2H), 1.50−1.65 (2H), 1.10−1.40 (22H), 0.81 (t, J = 6.8, 3H). ^{13}C NMR

(400 MHz, $CDCl_3$): δ 180.3, 133.1, 133.0, 128.2, 128.1, 104.8, 84.9, 49.4, 34.3, 33.3, 32.0, 29.7, 29.3, 29.2, 27.9, 25.3, 24.8, 23.2, 23.0, 22.7, 14.3. HRMS (FAB) m/z $[M + Na]^+$ calcd for $C_{22}H_{40}O_5Na$, 407.2774; found, 407.2783.

8-(6-(1-(2-Methoxypropan-2-ylperoxy)hexyl)-3,6-dihydro-1,2-dioxin-3-yl)octanoic Acid (13-HP-Endo-MiP). A solution of 13-HP-MiP (142 mg, 0.37 mmol) and tetraphenylporphine (TPP, 9 mg) in CH_2Cl_2 (60 mL) was cooled to 0 °C in a pyrex photoreaction apparatus. Oxygen was bubbled through the solution through a gas dispersion tube and the mixture illuminated by an internal tungsten lamp (500 W) inside an internal cold finger condenser for 72 h. Then the solvent was removed by rotary evaporation, and the crude product was flash chromatographed on silica gel eluting with hexane and ethyl acetate (1/1) to get 13-HP-Endo-MiP (102 mg, 0.25 mmol, yield = 68%); R_f = 0.36. ^1H NMR (400 MHz, $CDCl_3$): δ 5.90−6.10 (m, 2H), 4.40−4.90 (2H), 4.00−4.20 (1H), 3.14 (s, 3H), 2.32 (t, J = 7.2 Hz, 2H), 1.20−1.70 (26H), 0.80−0.90 (3H). HRMS (FAB) m/z $[M + Na]^+$ calcd for $C_{22}H_{40}O_7Na$, 439.2672; found, 439.2674.

8-(6-(1-Hydroperoxyhexyl)-3,6-dihydro-1,2-dioxin-3-yl)-octanoic Acid (13-HP-Endo). 13-HP-Endo-MiP (20 mg, 0.048 mmol) and pyridinium *p*-toluene sulfonate (PPTs, 2 mg) were dissolved in dry methanol (5 mL). The mixture was stirred under argon for 24 h. The solvent was removed by rotary evaporation, and the crude product purified by flash chromatography on silica gel eluting with hexane and ethyl acetate (1/1) to give 13-HP-Endo (9 mg, 0.032 mmol, yield = 67%); R_f = 0.31. ^1H NMR (400 MHz, $CDCl_3$): δ 5.90−6.05 (2H), 4.40−4.80 (2H), 4.05−4.21 (1H), 2.35 (t, J = 7.2 Hz, 2H), 1.44−1.64 (6H), 1.43−1.20 (14H), 0.80−0.96 (3H). HRMS (FAB) m/z $[M + H]^+$ calcd for $C_{18}H_{33}O_6$, 345.2277; found, 345.2274. ESI-MS/MS analysis yielded the following diagnostic fragments: m/z 343.2 $[M - H]^-$, m/z 213, 209, 207, 185, 125, 109, 99 (see Supporting Information).

13-HP-Endo was further purified by HPLC using a 250 × 4.6 mm luna 5 μm C18(2) column (Phenomenex, Torrance, CA), with a binary solvent (water and acetonitrile) gradient at 1 mL/min. The gradient started with 60% acetonitrile and rose to 100% acetonitrile linearly in 30 min. The gradient was then reversed to 60% acetonitrile in 0.5 min and then held for 4.5 min at 60% acetonitrile.

8-(2-Hydroxy-5-oxo-2,5-dihydrofuran-2-yl)octanoic Acid (HODFO). To a magnetically stirred solution of NaH_2PO_4 (110 mg, 0.81 mmol) and $NaClO_2$ (80% purity, 180 mg, 1.59 mmol) in 5 mL *t*-BuOH/water (5:1) was added FOA (112 mg, 0.53 mmol) in 5 mL *t*-BuOH/water (5:1) solution dropwise via a syringe. The resulting mixture was stirred at room temperature for 1.5 h. Solvents were removed by rotary evaporation, and the crude product was purified by flash chromatography on silica gel eluting with methanol and chloroform (1:10) to give the pure HODFO (102.8 mg, 0.425 mmol, yield = 80%); R_f = 0.25 with 15% methanol in chloroform. ^1H NMR (400 MHz, $CDCl_3$): δ 7.10−7.22 (1H), 6.07 (d, J = 6.4 Hz, 1H), 2.24−2.38 (2H), 1.85−2.05 (2H), 1.50−1.65 (2H), 1.20−1.40 (8H). HRMS (FAB) m/z $[M + Na]^+$ calcd for $C_{12}H_{18}O_5Na$, 265.1052; found, 265.1028.

8-(5-Oxo-2,5-dihydrofuran-2-yl)octanoic Acid (ODFO). HODFO (16 mg, 0.066 mmol) was dissolved in methanol (3 mL), and the mixture was cooled in an ice bath. $NaBH_4$ (15 mg, excess) was added in small portions, and the resulting mixture was stirred for 1 h at room temperature. Water (100 μL) was then added, and the mixture was stirred for another 1 h. Then 1 M HCl was added to acidify the solution to pH 3, and the resulting mixture was stirred at room temperature for 30 min. The product was extracted into $CHCl_3$ (10 mL × 3) and solvents evaporated. Chromatography on silica gel eluting with 5% CH_3OH in $CHCl_3$ delivered pure ODFO (12 mg, 0.053 mmol, yield = 80%); R_f = 0.25 with 10% methanol in chloroform. ^1H NMR (400 MHz, $CDCl_3$): δ 7.38 (dd, J = 5.6, 1.6 Hz, 1H), 6.05 (dd, J = 6.0, 2.4 Hz, 1H), 4.97 (m, 1H), 2.28 (t, J = 7.6 Hz, 2H), 1.65 (m, 1H), 1.50−1.63 (3H), 1.30−1.42 (2H), 1.20−1.32 (6H). ^{13}C NMR (400 MHz, CD_3OD): δ 176.5, 174.6, 158.4, 120.4, 84.4, 33.7, 32.9, 29.1, 29.0, 28.9, 24.8, 24.8. HRMS (FAB) m/z $[M + H]^+$ calcd for $C_{12}H_{19}O_4$, 227.1283; found, 227.1274. ESI-MS/MS analysis yielded the following diagnostic fragments: m/z 225.2 $[M - H]^-$; m/z 207, 181, 136, 110, 97 (see Figure 6B).

1-Hexadecanoyl-2-(8-(6-(1-(2-methoxypropan-2-ylperoxy)hexyl)-3,6-dihydro-1,2-dioxin-3-yl)octanoyl)-*sn*-glycero-3-phosphocholine (13-HP-Endo-PC-MiP). A solution of 13-HP-PC-MiP (24 mg, 0.027 mmol) and tetraphenylporphine (TPP, 4 mg) in CH_2Cl_2 (50 mL) was cooled to 0 °C in a pyrex photoreaction apparatus. Oxygen was bubbled through the solution through a gas dispersion tube, and the mixture was illuminated by an internal tungsten lamp (500 W) inside an internal annular cold finger for 96 h. Solvent was removed by rotary evaporation, and the crude product was purified by HPLC using a 250 × 10.00 mm luna 5 C18(2) semipreparative column (Phenomenex, Torrance, CA). The column was eluted with methanol/water (100:5, v/v) containing 5 mM NH_4OAc at 5 mL/min. The fractions were collected and analyzed by ESI-MS on a Thermo Finnigan LCQ DecaXP instrument in the positive mode using nitrogen as the sheath and auxiliary gas. The heated capillary temperature was 200 °C, the source voltage was 4.50 kV, and the capillary voltage was 20.00 V. 13-HP-PC-MiP (9 mg, 0.01 mmol) was recovered, and the title compound 13-HP-Endo-PC-MiP was obtained (9 mg, 0.01 mmol, yield = 58%). ^1H NMR (400 MHz, $CDCl_3$): δ 5.90 (m, 2H), 5.15 (s, 1H), 3.60−4.80 (11H), 3.30 (s, 9H), 3.25 (s, 3H), 2.16−2.27 (4H), 1.80−2.00 (4H), 1.00−1.60 (42 H), 0.70−0.90 (12H). ESI-MS analysis yielded the following diagnostic peaks: m/z 894.9 $[M + H]^+$, m/z 916.8 $[M + Na]^+$, m/z 823.0 $[M + H-MiP]^+$, m/z 1788.3 $[2M + H]^+$ (see Figure S4 in the Supporting Information). HRMS (FAB) m/z $[M + H]^+$ calcd for $C_{46}H_{89}NO_{13}P$, 894.6071; found, 894.6059.

1-Hexadecanoyl-2-(8-(6-(1-hydroperoxyhexyl)-3,6-dihydro-1,2-dioxin-3-yl)octanoyl)-*sn*-glycero-3-phosphocholine (13-HP-Endo-PC). 13-HP-Endo-PC-MiP (7.6 mg, 0.0085 mmol) and pyridinium *p*-toluene sulfonate (PPTs, 3 mg) were dissolved into 5 mL of chloroform/methanol (1/1) and the solution stirred under argon for 24 h. The solvents were then removed by rotary evaporation. The residue was dissolved into water (10 mL) and extracted with chloroform (3 × 10 mL) to remove the PPTs. The crude product was further purified by HPLC using a 250 × 4.60 mm luna 5 C18(2) column (Phenomenex, Torrance, CA). The column was eluted with methanol/water (90/10, v/v) containing 5 mM NH_4OAc at 1 mL/min. 13-HP-Endo-PC was obtained (4 mg, 0.0049 mmol, yield = 58%). HRMS (FAB) m/z $[M + H]^+$ calcd for $C_{42}H_{81}NO_{12}P$, 822.5496; found, 822.5456. ESI-MS/MS analysis yielded the following diagnostic fragments: m/z 822.8 $[M + H]^+$, m/z 184.1 (see Supporting Information).

1-Hexadecanoyl-2-(8-(5-oxo-2,5-dihydrofuran-2-yl)octanoyl)-*sn*-glycero-3-phosphocholine (ODFO-PC). ODFO (24 mg, 0.11 mmol), 1-hexadecanoyl-2-hydroxy-*sn*-glycero-3-phosphocholine (lyso-PC, 40 mg, 0.08 mmol), dicyclohexylcarbodiimide (DCC, 100 mg, 0.48 mmol), and 4-dimethylaminopyridine (DMAP, 10 mg, 0.08 mmol) were dissolved in dry chloroform (5 mL) and the solution stirred at room temperature for 72 h. Solvents were removed by rotary evaporation to get the crude product, and the residue was purified on a silica gel column ($CHCl_3/CH_3OH/H_2O$ = 16/9/1) to give pure ODFO-PC (30.2 mg, 0.04 mmol, yield = 50%). ^1H NMR (400 MHz, $CDCl_3/CD_3OD$): δ 7.58 (dd, J = 5.6, 1.6 Hz, 1H), 6.08 (dd, J = 6.0, 2.4 Hz, 1H), 5.18 (m, 1H), 5.07 (m, 1H), 4.38 (dd, J = 12, 3.2 Hz, 1H), 4.20 (m, 2H), 4.12 (dd, J = 12, 6.4 Hz, 1H), 3.96 (t, J = 6.4 Hz, 2H), 3.57 (m, 2H), 3.20 (s, 9H), 2.32−2.20 (4H), 1.50−1.62 (4H), 1.20−1.40 (34H), 0.84(t, J = 6.8 Hz, 3H). HRMS (FAB) m/z $[M + H]^+$ calcd for $C_{36}H_{67}NO_{10}P$, 704.4502; found, 704.4503. ESI-MS/MS analysis yielded the following diagnostic fragments: m/z 704.6 $[M + H]^+$, m/z 184.1 (see Supporting Information).

Thermal Decomposition of the Linoleate Derived Hydroperoxy Endoperoxide 13-HP-Endo. Small 3 dram glass vials, each containing 13-HP-Endo (10 μg, 0.03 μmol) as a dry film, were incubated at 37 °C for various times. After incubation, the vials were sealed under argon and kept at −80 °C until LC-MS/MS analysis. For the decomposition of 13-HP-Endo with vitamin E, vials containing 13-HP-Endo (10 μg, 0.03 μmmol) and one equivalent of vitamin E as a dry film were incubated at 37 °C for various times. After incubation, the vials were sealed under argon and kept at −80 °C until LC-MS/MS analysis. Vials containing 13-HP-Endo (10 μg, 0.03 μmmol) and various amounts of vitamin E as a dry film were incubated at 37 °C for 2 h. After incubation, the vials were sealed under argon and kept at −80 °C until LC-MS/MS analysis. For the decomposition of 13-HP-Endo with vitamin E and DTPA, vials containing 13-HP-Endo (10 μg, 0.03 μmmol) and various amounts of vitamin E and 5 equivalents of DTPA as a dry film were incubated at 37 °C for 2 h. After incubation, the vials were sealed under argon and kept at −80 °C until LC-MS/MS analysis. Before analysis, 100 μL of internal standard solution (8-(furan-2-yl)-8-oxooctanoic acid, 1 ng/μL) in methanol was added, and 10 μL of this mixture solution was injected into the LC/MS/MS system each time. The amounts of HODA, ODFO, KODA, and FOA were monitored simultaneously.

9-Hydoxy-12-(methoxyimino)dodec-10-enoic Acid (HODA Methoxime). To authentic HODA (50 μg) in a small vial was added pyridine (200 μL) containing 2 wt % of methoxylamine hydrochloride. The mixture was kept under argon at room temperature overnight. Pyridine was then removed under a stream of argon. The residue was dissolved in 0.5 mL of water (pH 3) and extracted with ethyl ether (1 mL and then 0.5 mL). Solvent was removed from the extract and the residue analyzed via ESI-MS/MS, producing the following fragments: m/z 256.3 $[M - H]^-$; m/z 197 (see Supporting Information).

13-HP-Endo (50 μg, 0.15 μmmol) and one equivalent of vitamin E were incubated as a dry film at 37 °C for 2 h. Then pyridine (200 μL) containing 2 wt % of methoxylamine hydrochloride was added, and the mixture was kept under argon at room temperature overnight. Pyridine was then removed under a stream of argon. The residue was then dissolved in 0.5 mL of water (pH 3), and the solution was extracted with ethyl ether (1 mL and then 0.5 mL). Solvent was then removed from the extract, and the residue was sealed under argon and kept at −80 °C until LC-MS/MS analysis.

Perfluorobenzyl 8-(5-oxo-2,5-dihydrofuran-2-yl)octanoate (ODFO-PFB Ester). To authentic ODFO (50 μg) in a small vial was added dry acetonitrile (100 μL) containing 10 wt % of pentafluorobenzyl bromide and 20 wt % of *N*,*N*-diisopropylethylamine. The resulting mixture was kept at room temperature for 2 h, and the solvent was removed with a stream of argon. The residue was dissolved in 1 mL of water, and the product was extracted into ethyl acetate (1 mL). ESI-MS/MS analysis in the positive mode gave $[M + NH_4]^+$ and characteristic daughter fragments at m/z 209, 181, 163, 145, 135 (see Supporting Information).

13-HP-Endo (50 μg, 0.15 μmmol) and one equivalent of vitamin E were incubated as a dry film at 37 °C for 2 h. Then dry acetonitrile (100 μL) containing 10 wt % of pentafluorobenzyl bromide and 20 wt % of *N*,*N*-diisopropylethylamine was added. The mixture was kept under argon at room temperature for 2 h and solvents removed under a stream of argon. The residue was dissolved in water (1 mL), and the solution was extracted with ethyl acetate (1 mL). Solvent was removed from the extract, and the residue was sealed under argon and kept at −80 °C until LC-MS/MS analysis.

Thermal Decomposition of Linoleate Derived Hydroperoxy Endoperoxide Phosphocholine Ester 13-HP-Endo-PC in a Model Membrane. Vesicles comprising 13-HP-Endo-PC and vitamin E were prepared by extrusion by a method described previously.[19] Specifically, 13-HP-Endo-PC (100 μg), with 1-stearoyl-2-palmitoyl-*sn*-glycero-3-phosphocholine (SP-PC, 900 μg) as carrier, and one equivalent of vitamin E were initially dissolved into methanol, vortexed for 1 min, and the solvent removed under a stream of argon. Lipids were fully hydrated by the addition of phosphate saline buffer (1 mL, 50 mM, pH 7.4) with or without DTPA (100 μM). Following vortexing to disperse the hydrated lipids, small unilamellar vesicles (SUVs) were generated by extrusion through a polycarbonate filter until a clear solution was produced (about 15 times) using an Avanti Mini-Extruder Set (Avanti Polar Lipids, Alabaster, AL). The buffer solution of vesicles was aliquoted into small vials (100 μL in each) of a buffer solution containing 13-HP-Endo-PC (10 μg), and the vials incubated at 37 °C for various times. After incubation, DT-PC (100 ng) was added as internal standard, and the mixture was immediately extracted by the Bligh and Dyer method. The extracts were sealed under argon and stored in −80 °C until LC-MS/MS analysis (less than 24 h).

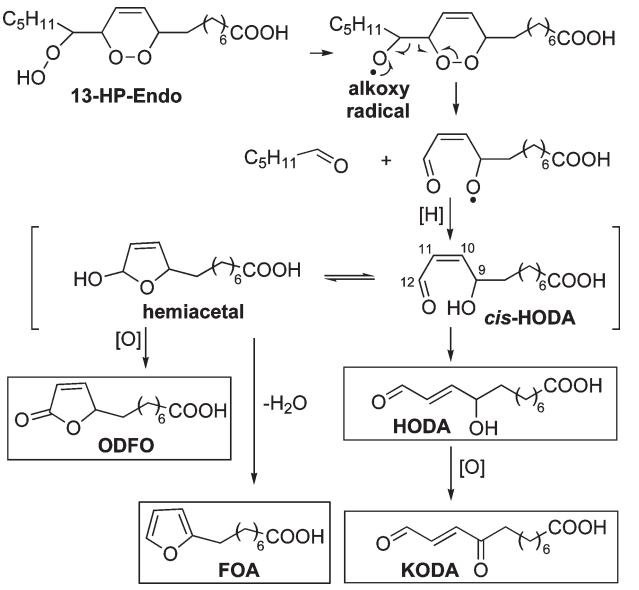


Figure 3. Postulated fragmentation products from 13-HP-Endo.

Thermal Decomposition of Linoleate Derived Hydroperoxy Endoperoxide Phosphocholine Ester 13-HP-Endo-PC in Homogeneous Solution. 13-HP-Endo-PC (10 μg), with SP-PC (90 μg) and one equivalent of vitamin E, was dissolved in a homogeneous mixture of methanol (100 μL) and PBS buffer (100 μL, 50 mM, pH 7.4). The vial was incubated at 37 °C for 4 h. After incubation, DT-PC (100 ng) was added as internal standard, and the mixture was immediately extracted by Bligh and Dyer method. The extract was sealed under argon and stored in −80 °C until LC-MS/MS analysis (less than 24 h).

RESULTS

Synthesis of a Linoleate-Derived Hydroperoxy Endoperoxide and Its Predicted Fragmentation Products. We postulated that fragmentation of the hydroperoxy endoperoxide 13-HP-Endo would deliver the γ-hydroxyalkenal HODA through fragmentation of an intermediate alkoxy radical by β-scission in conjunction with homolysis of the dialkyl peroxide and hydrogen atom abstraction to produce the γ-hydroxy alkenal *cis*-HODA (Figure 3). The *cis* γ-hydroxy alkenal is expected to be unstable. It can isomerize into the *trans* γ-hydroxy alkenal HODA or be oxidized further to the lactone ODFO in the oxidative environment. The unsaturated aldehyde HODA can also be oxidized further, e.g., to deliver KODA (Figure 3).[20,21] We previously found that a HODA ester of 2-lysophosphatidylcholine

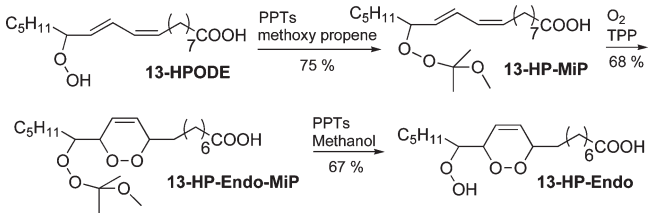


Figure 4. Structurally specific synthesis of a 13-hydroperoxyendoperoxide.

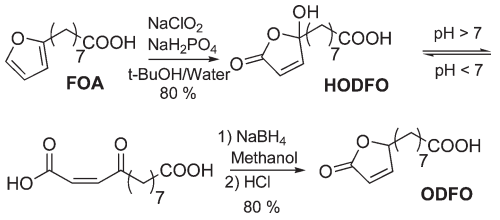


Figure 5. Synthesis of the butenolide ODFO.

cyclizes and loses one molecule of water to give a PC ester of the furan FOA under biomimetic reaction conditions presumably through prior isomerization to *cis*-HODA.[22]

A structurally nonspecific synthesis of linoleate-derived hydroperoxy endoperoxides was accomplished previously by treating a mixture of linoleate 9- and 13-hydroperoxyoctadecadienoate (9- and 13-HPODE) with singlet oxygen, generated by gaseous O_2 in the presence of a photosensitizer.[18] Isolation of the pure hydroperoxy endoperoxides from the complex reaction product mixture required tedious HPLC. However, the reaction with singlet molecular oxygen is quite slow and requires many days of irradiation to achieve a high conversion. This is problematic because both 13-HPODE and 13-HP-Endo are not stable under these conditions and decompose during prolonged reaction with singlet molecular oxygen. Therefore, the yield is low, and much effort is required to isolate pure 13-HP-Endo from the complex reaction product mixture (Figure S1A, Supporting Information) by HPLC. We designed a structurally specific synthesis of pure 13-HP-Endo (Figure 4) that proceeded in much higher yields starting from a pure monohydroperoxide (13-HPODE) that is available through an enzymatic peroxidation of linoleic acid.[23] The hydroperoxy group was protected by treatment with 2-methoxypropene and a catalytic amount of pyridinium *p*-toluene sulfonate (PPTs).[24] The α-methoxyisopropyl (MiP) protected hydroperoxy endoperoxide 13-HP-Endo-MiP was obtained after the reaction of 13-HP-MiP with singlet molecular oxygen. Then PPTs-catalyzed deprotection in methanol delivered the final product 13-HP-Endo. Introduction of the protecting group lengthens the synthesis compared to the direct reaction of 13-HPODE with singlet molecular oxygen. However, the extra steps are worthwhile because the MiP protected hydroperoxides are quite stable under the reaction conditions, and the desired product is obtained in good yield from a relatively simple product mixture (Figure S1B, Supporting Information). The MiP protecting group is also valuable for the synthesis of a linoleate-derived hydroperoxy endoperoxide phosphocholine ester (vide infra).

Authentic samples of several likely fragmentation products 9-hydroxy-12-oxo-10-dodecenoic acid (HODA), 9-keto-12-oxo-10-dodecenoic acid (KODA), and 8-(2-furyl)octanoic acid (FOA) were prepared as described previously.[25−27] The butenolide, 8-(5-oxo-2,5-dihydrofuran-2-yl)octanoic acid (ODFO), was prepared from the furan FOA (Figure 5). Oxidation of FOA in the presence of sodium chlorite in a slightly acidic aqueous solution at room temperature generates hydroxy butenolide HODFO.[28] The cyclic forms of such hydroxy butenolide compounds are not stable and can open to form 4-oxo-2 (*Z*) alkenoic acids depending on pH.[28] Sodium borohydride can effectively reduce the free keto group into a hydroxyl group and after cyclization under acidic conditions gives the butenolide compound ODFO.[29]

MS/MS Similarity of Two Expected Products, KODA and ODFO, from Fragmenation of 13-HP-Endo. LC-ESI/MS/MS was chosen to monitor the reaction profile. This technique allows simultaneous quantification of each specific product based on selected reaction monitoring (SRM), i.e., monitoring unique transitions between the mass-to-charge (m/z) ratio of the parent ion ($[M - H]^-$ or $[M + H]^+$) and characteristic daughter ions for each species, as well as their characteristic LC retention time that could be established using authentic samples prepared by unambiguous syntheses. The technique gives specific peaks with high signal-to-noise ratio and is suitable for quantification. During the development of an MS/MS protocol for monitoring the fragmentation of 13-HP-Endo, we found that ODFO has an ESI-MS/MS spectrum similar to that of KODA. Both KODA and ODFO have isobaric parent ions and nearly identical patterns of daughter ions (Figure 6A and B). The slight differences between the mass spectra of these two molecules are that KODA produces a dominant daughter ion at m/z 109 and a weak daughter ion at m/z 110, while ODFO gives a dominant daughter ion at m/z 110. Possible fragments that may correspond to these daughter ions are presented in Figure 6. Furthermore, KODA and ODFO exhibited the same LC retention times when eluting with methanol and water. Although the mass spectra of both molecules show peaks in the 225 → 110 and 225 → 109 channels with reversed intensity, it is difficult to distinguish them in a mixture (Figure 6C). We subsequently found that, with an acetonitrile and water LC eluant system, these two compounds are well separated and show the expected reversed intensity in the two channels (Figure 6D). The LC-MS/MS similarity of KODA and ODFO provides a good example that demonstrates the importance of having authentic samples, obtained through unambiguous chemical synthesis, to confirm the putative identities of molecules characterized by LC-MS/MS.

Vitamin E Promotes the Fragmentation the Hydroperoxy Endoperoxide 13-HP-Endo. It was anticipated that vitamin E (α-tocopherol), that can inhibit free radical-induced oxidation by hydrogen atom transfer that neutralizes reactive radicals, would prevent the oxidative destruction of HODA, e.g., to produce ODFO and KODA. The linoleate-derived hydroperoxy endoperoxide 13-HP-Endo was incubated at 37 °C as a dry film in open glass vials in the absence or in the presence of one equivalent of vitamin E (α-tocopherol). The amounts of potential fragment products (HODA, ODFO, KODA, and FOA) were monitored by LC-ESI/MS/MS (Figure 7). In the absence of α-tocopherol, only a small amount of ODFO was slowly generated during the incubation (yield <3%). The addition of α-tocopherol greatly promotes the fragmentation of 13-HP-Endo and increases the yields of HODA, ODFO, and FOA. A large increase in the generation of HODA was found. The yield of HODA increased from below 0.2% to more than 4%, a more than 20-fold increase. The yield of ODFO also increased from

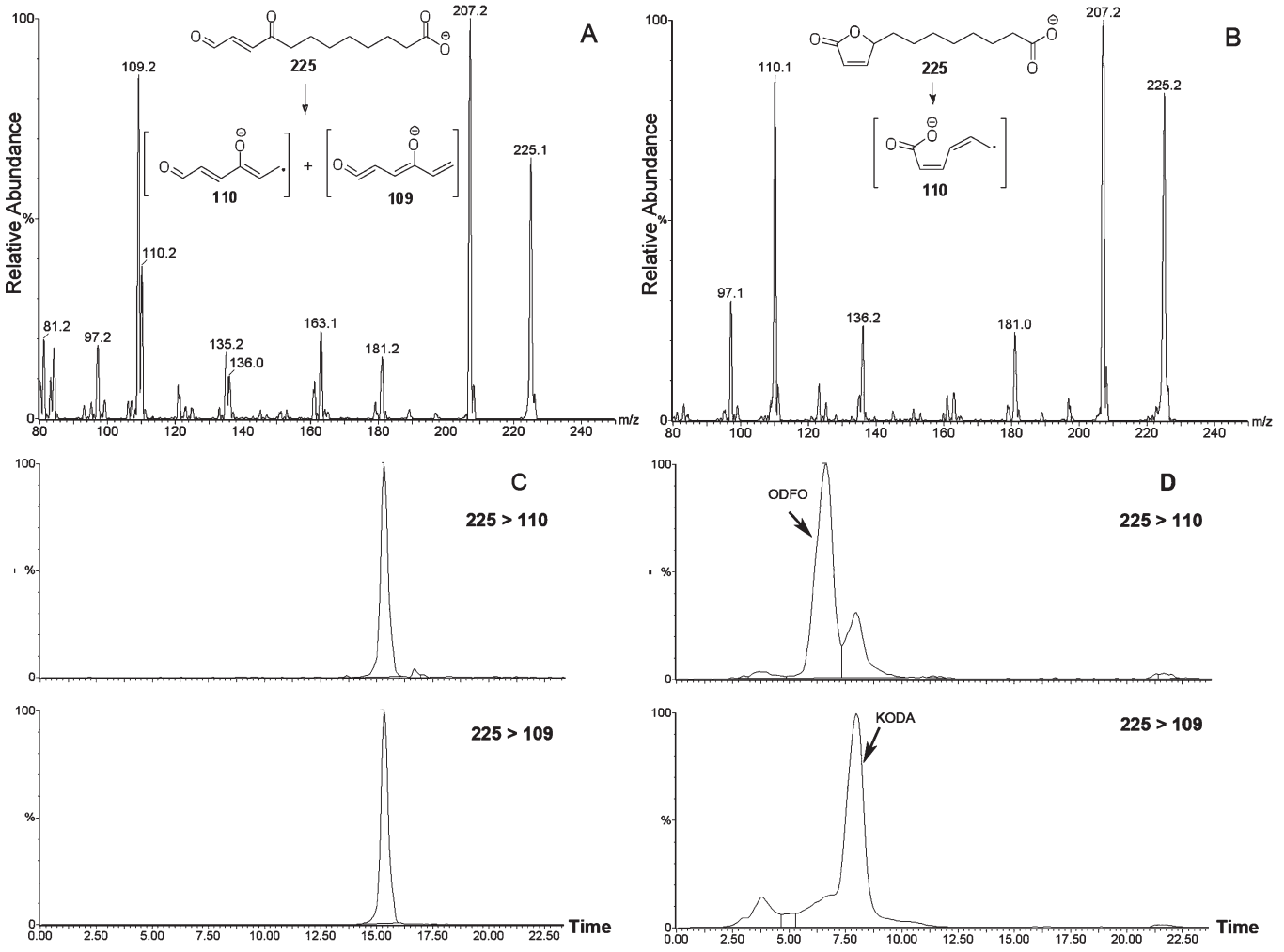


Figure 6. Negative ESI-MS/MS spectrum of KODA (A) and ODFO (B), and HPLC chromatogram of KODA and ODFO (1:1 mixture) eluting with methanol/water (C) and acetonitrile/water (D). The chromatogram was monitored by LC-MS in the negative ion mode with SRM of appropriate mass transitions as noted.

below 3% to more than 8%. Furthermore, in the presence of α-tocopherol, the generation of these fragmentation products was very fast. The yields of HODA and ODFO reach their maxima in less than 2 h. The amount of HODA decreases during further incubation due to additional oxidation and fragmentation. Compared with HODA, ODFO was relatively stable, and the yield only slightly decreased during further incubation. KODA is not a major product in the fragmentation of hydroperoxy endoperoxide 13-HP-Endo under these conditions. Only small amounts of KODA were generated, possibly due to the further oxidation of HODA, during the incubation (<0.2%) even in the presence of α-tocopherol. The yield of the furan compound FOA also increased with the addition of α-tocopherol and reached its maximum after 4 h of incubation.

HODA and ODFO are two major products from the fragmentation of 13-HP-Endo in the presence of vitamin E. To verify their identities, two derivatizations were applied. An authentic sample of HODA and the fragmentation reaction product mixture from 13-HP-Endo were both derivatized with methoxylamine hydrochloride in pyridine. The methoxime derivative of HODA ($[M - H]^-$, m/z 256) gives a dominant daughter ion m/z 197. For the HPLC analysis, the HODA methoxime derivative was detected by ESI-MS/MS using SRM monitoring of the 225 → 197 mass transition. Before derivatization, HODA was detected in the reaction product mixture from 13-HP-Endo by ESI-MS/MS using SRM monitoring of the 227 → 84 mass transition. After derivatization, the HODA peak disappeared, and the HODA methoxime derivative was detected (Figure S2, Supporting Information). The generation of ODFO from 13-HP-Endo was further confirmed by pentafluorobenzyl (PFB) esterification. The ODFO-PFB ammonia adduct ($[M + 18]^+$, m/z 424) gives characteristic daughter ions with m/z 181 and m/z 163. The HPLC chromatogram of ODFO-PFB was monitored by ESI-MS/MS with SRM of the 424 → 181 mass transition. Reaction with PFB-Br caused the disappearance of ODFO. The concomitant formation of ODFO-PFB from the putative ODFO generated by fragmentation of 13-HP-Endo was confirmed through comparison with an authentic sample (Figure S3, Supporting Information).

Vitamin E Stoichiometrically Induces the Decomposition of 13-HP-Endo. To further understand the role of α-tocopherol in the decomposition of the hydroperoxy endoperoxide, we incubated 13-HP-Endo in the presence of various amounts of α-tocopherol at 37 °C for 2 h as a dry film and monitored the

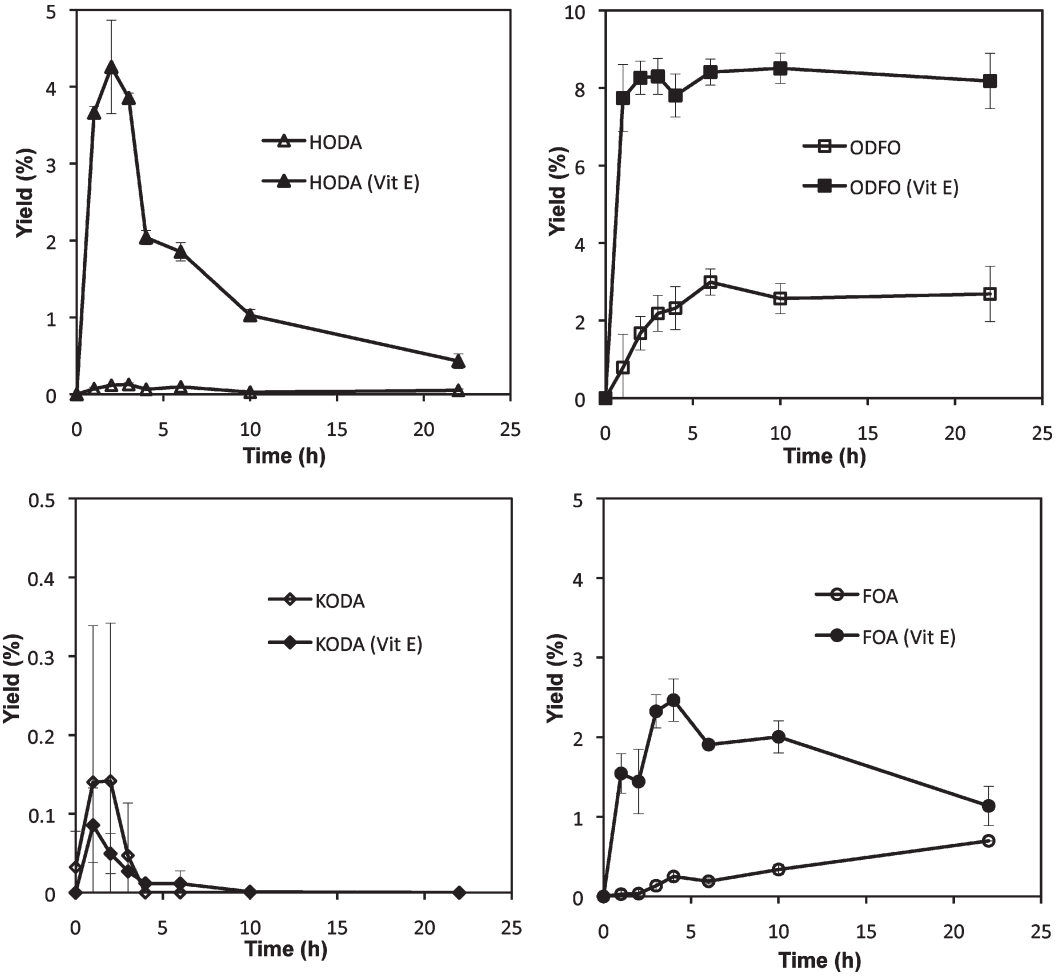


Figure 7. Time courses for the generation of HODA, ODFO, KODA, and FOA during the thermal decomposition of 13-HP-Endo in the absence (open symbols) or presence (solid symbols) of α-tocopherol (Vit E). Error bars are the deviation from average of duplicate runs within less than 24 h.

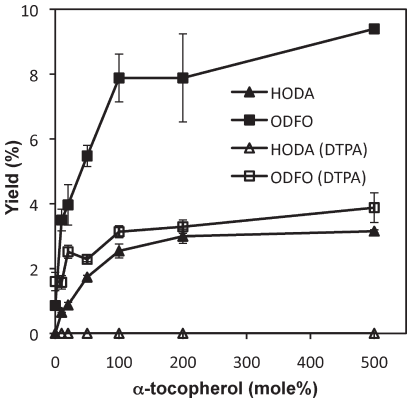


Figure 8. Formation of HODA and ODFO from 13-HP-Endo with various amounts of α-tocopherol in the absence and presence of the chelating agent diethene triamine pentaacetic acid (DTPA). Error bars are the deviation from average of duplicate runs within less than 24 h.

yields of HODA and ODFO simultaneously (Figure 8). The yields of HODA and ODFO are greatly increased by the addition of α-tocopherol and plateau after the addition of one equivalent. The stoichiometry is consistent with a mechanism in which α-tocopherol transfers an electron to the hydroperoxy group to

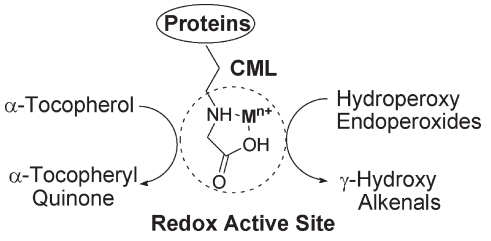


Figure 9. CML-bound redox-active metal ions may catalyze reductive fragmentation of hydroperoxy endoperoxides to γ-hydroxyalkenals.

generate an alkoxyl radical. Such chemistry has not been reported previously for α-tocopherol. However, it is pertinent to note that vitamin C is reported to promote fragmentation of hydroperoxides through a reductive homolysis pathway.[30]

However, reductive cleavage of hydroperoxides to generate alkoxyl radicals can be induced by redox active metal ions, e.g., through a Fenton reaction. We previously showed that electron transfer from α-tocopherol reduces Fe^{3+} to its Fe^{2+} that then reductively cleaves hydroperoxides, and therefore, Fe^{n+} can catalyze the reductive homolysis of hydroperoxides by α-tocopherol.[31] Catalysis by redox active metal ions is especially likely *in vivo* because, e.g., sugar-derived *N*-(carboxy-

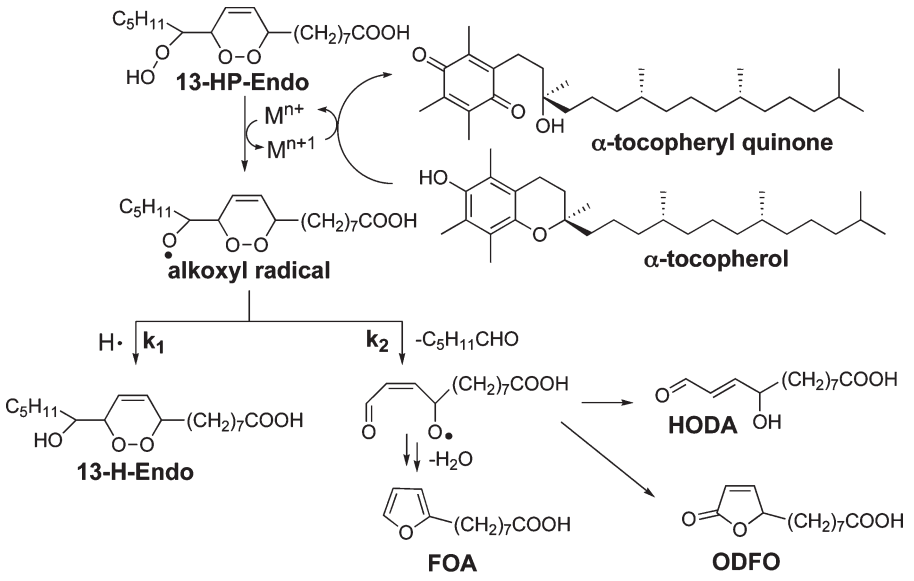
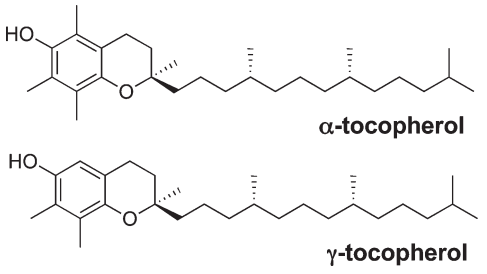


Figure 10. Possible redox metal ion catalyzed reductive homolysis of 13-HP-Endo by α-tocopherol.

Chart 1



methyl)lysine (CML) oxidative modifications in proteins bind metal ions, and these protein-bound metal ions can catalyze the oxidation of ascorbate by H_2O_2.[32,33] Electron transfer from (oxidation of) ascorbate or α-tocopherol would be accompanied by electron transfer to (reduction of) metal ions. The reduced metal ions would subsequently be reoxidized by electron transfer to H_2O_2 or to lipid hydroperoxides. It is likely that, in the presence of vitamin E, protein-bound redox active metal ions can catalyze the fragmentation of hydroperoxy endoperoxides to deliver toxic γ-hydroxyalkenals (Figure 9).

Although metal ions were not added to the incubation of hydroperoxy endoperoxide 13-HP-Endo, it is conceivable that, in the presence of α-tocopherol, traces of redox active metal ions, e.g., Fe^{n+}, efficiently catalyze these reactions (Figure 10). As proposed in Figure 10, metal ion-induced reductive cleavage of the hydroperoxy endoperoxide would produce an alkoxyl radical that can further fragment to a γ-alkoxyl-α,β-unsaturated aldehyde, which gives rise to HODA, ODFO, and FOA, or can be trapped by hydrogen atom transfer to form the hydroxy endoperoxide 13-H-Endo. The competition between these alternatives would depend on the rate constants k_1 and k_2 and the concentration of accessible hydrogen atom donors such as α-tocopherol.[34] We expected that an excess of vitamin E (up to five equivalents) would reduce the yields of fragmentation products because it would favor production of the hydroxy endoperoxide. One possible explanation for the lack of a decrease in the yields of those products is that the rate constant k_2 is much

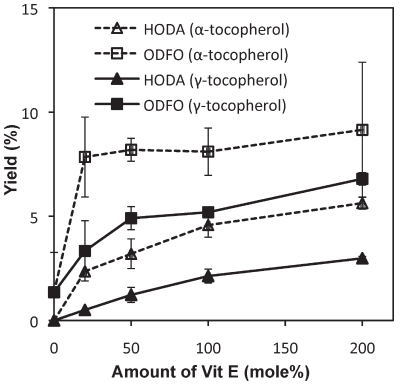


Figure 11. Formation of HODA and ODFO from 13-HP-Endo in the presence of various amounts of α-tocopherol or γ-tocopherol.

larger than k_1. This seems likely since the β-scission with concomitant homolysis of a dialkyl hydroperoxide is expected to be very favorable owing to the simultaneous formation of two new carbonyl groups (Figure 3). This scenario is consistent with the belief that α-tocopherol is *not* an efficient scavenger for hydroxyl or alkoxyl radicals *in vivo*.[35]

DTPA, a Metal Ion-Chelating Agent, Suppresses Vitamin E-Induced Fragmentation of 13-HP-Endo. To test the hypothesis that traces of redox active metal ions are required for vitamin E-promoted fragmentation of 13-HP-Endo, diethylene triamine pentaacetic acid (DTPA) was introduced into our system. It was reported previously that after chelation, redox active metal ions are relatively resistant to reduction and thus lose the ability to react with α-tocopherol.[36,37] If the fragmentation were metal ion independent, the addition of DTPA would not affect the reaction. We incubated a mixture of DTPA and the hydroperoxy endoperoxide with various amounts of α-tocopherol at 37 °C for 2 h as a dry film. The addition of DTPA totally quenched the generation of HODA and greatly suppressed the generation of ODFO (Figure 8). This supports our hypothesis that the fragmentation is metal ion-dependent.[31] We favor this explanation over the possibility that DTPA suppresses the direct

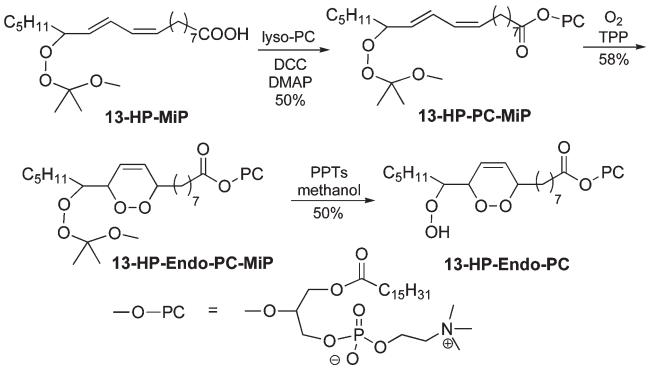


Figure 12. Synthesis of a hydroperoxy endoperoxide phosphocholine ester 13-HP-Endo-PC.

reduction of hydroperoxy endoperoxides by tocopherol in some unprecedented alternative manner.

γ-Tocopherol-Promoted Decomposition of 13-HP-Endo Causes Less Fragmentation than α-Tocopherol. The term "vitamin E" designates a group of tocopherols and tocotrienols. Among them, α-tocopherol has been most studied and is often said to have the highest biological activity.[38] However, recent studies indicate that γ-tocopherol, the major form of vitamin E in the US diet, has some unique biological activities, such as trapping electrophilic mutagens,[39] and thus may be important to human health.[38,40,41] It is also found that γ-tocopherol does not reduce Cu(II) as rapidly as α-tocopherol, partly owing to its lack of one methyl substituent on the chromanol headgroup (Chart 1).[35,42] Incubation of the hydroperoxy endoperoxide 13-HP-Endo with various amounts of γ-tocopherol at 37 °C for 1.5 h as a dry film generated HODA and ODFO, but in lower yields than with α-tocopherol (Figure 11). Presumably, the lower reducing ability of γ-tocopherol results in less fragmentation products. This suggests the possibility that replacement of α-tocopherol with γ-tocopherol may result in less pro-oxidant effects *in vivo*.

Synthesis of Hydroperoxy Endoperoxide Phosphocholine Ester 13-HP-Endo-PC. *In vivo*, polyunsaturated fatty acids (PUFAs) are present mainly esterified, for example, in phospholipids. Therefore, we prepared the hydroperoxy endoperoxide phosphocholine ester 13-HP-Endo-PC through chemical synthesis (Figure 12). The 2-methoxyisopropyl (MiP) derivative of 13-HPODE, 13-HP-MiP, could be esterified to 2-lyso-PC in the presence of dicyclohexylcarbodiimide (DCC) and 4-dimethylaminopyridine (DMAP).[43] Then reaction with singlet molecular oxygen, followed by removal of the MiP protecting group, delivered the title compound 13-HP-Endo-PC. The MiP protecting group is very important for the overall success of the synthesis because the reaction with singlet molecular oxygen proceeds very slowly and was not complete even after 4 days of irradiation. With the protecting group, the hydroperoxy endoperoxide derivative 13-HP-Endo-PC-Mip is easily separated from the starting material, 13-HP-PC-MiP, and other oxidation products (Figure S4, Supporting Information). 2-Methoxypropene also has been used recently as the protecting group to prepare other lipid hydroperoxides.[44] The potential fragmentation product HODA-PC was prepared as previously described,[25] and ODFO-PC was prepared through direct esterification of ODFO.

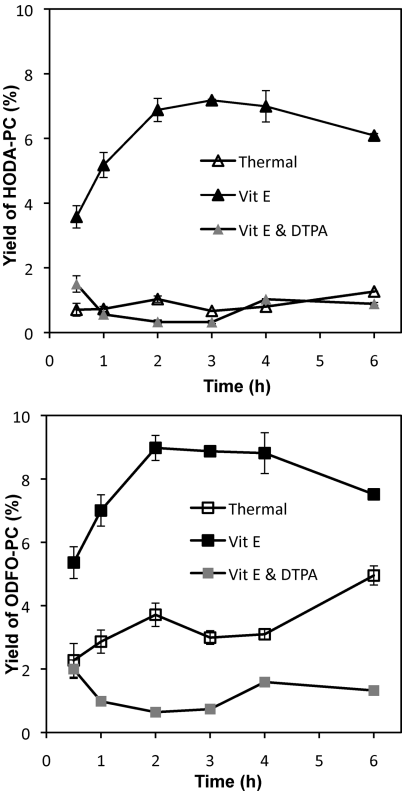


Figure 13. Formation of HODA-PC and ODFO-PC from 13-HP-Endo-PC in small unilamellar vesicles, in PBS buffer (50 mM), with one equivalent of α-tocopherol (Vit E) in PBS buffer (50 mM), or with one equivalent of α-tocopherol in PBS buffer (50 mM) with DTPA (100 μM).

Fragmentation of 13-HP-Endo-PC in Unilamellar Vesicles. To evaluate the fragmentation of hydroperoxy endoperoxide 13-HP-Endo-PC in a model membrane under physiologically relevant conditions, we incubated unilamellar vesicles comprising 13-HP-Endo-PC (10 wt %) and 1-stearoyl-2-palmitoyl-*sn*-glycero-3-phosphocholine (SP-PC) as carrier (1:9 respectively) in pH 7.4 aqueous buffer at 37 °C for various times. Only a low yield of ODFO-PC was generated (Figure 13), even after six hours. When α-tocopherol is embedded in liposomes, the chromanol head of vitamin E is close to the interface of the aqueous phase and the bilayer membrane (Figure 14).[45] Incubation of the above unilamellar vesicles containing α-tocopherol (one equivalent), generated both HODA-PC and ODFO-PC in greatly increased yields, reaching maxima of 7% and 9%, respectively. The addition of DTPA effectively inhibited the generation of both HODA-PC and ODFO-PC, even in the presence of tocopherol. The effects of DTPA and tocopherol are similar to those observed with the free acid 13-HP-Endo. In the present study, it appears that redox active metal ions in the environment catalyze the reductive cleavage of the hydroperoxide group leading to fragmentation of the hydroperoxy endoperoxide 13-HP-Endo-PC under biomimetic conditions.

Membrane Environment Protects γ-Hydroxyalkenals against Oxidation to Butenolides. The product distribution between γ-hydroxyalkenal (HODA and HODA-PC) and their butenolide oxidation products (ODFO and ODFO-PC) exhibits interesting differences. Fragmentation of 13-HP-Endo in the homogeneous environment of a dry film gave HODA and ODFO

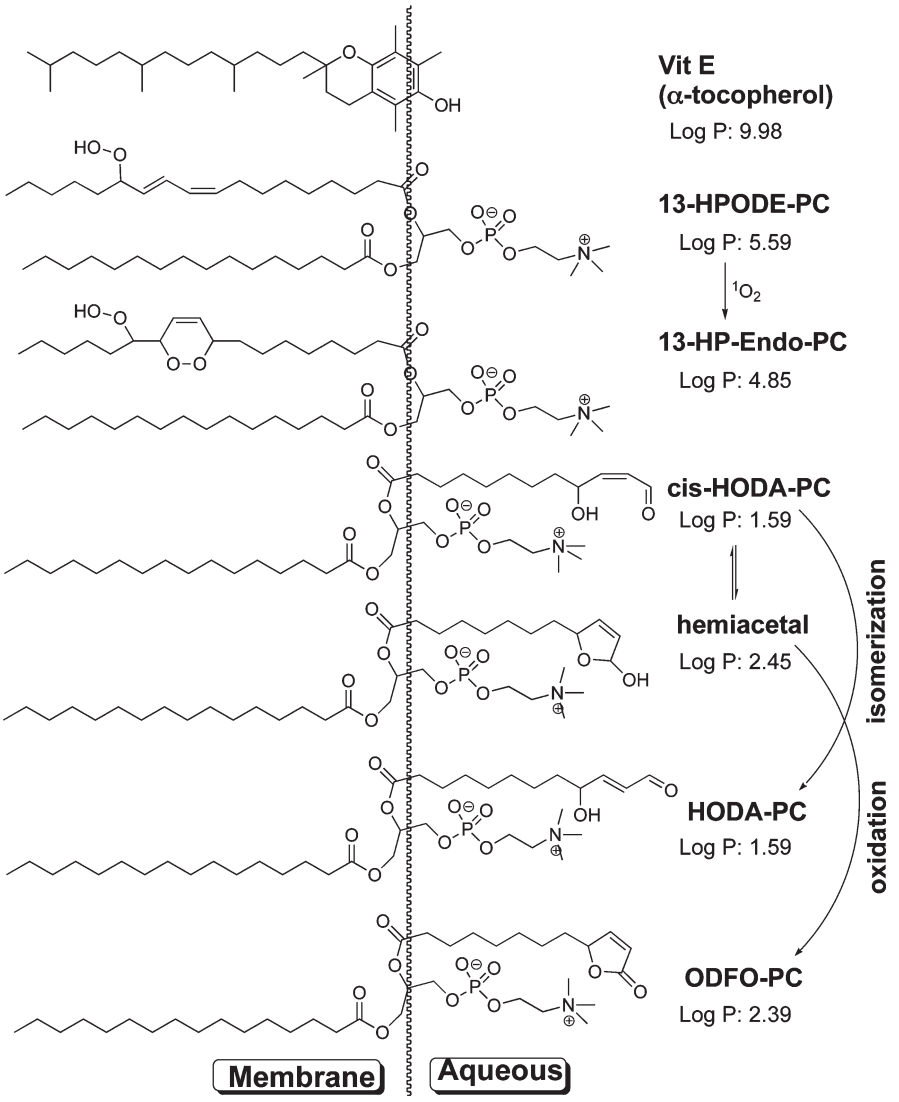


Figure 14. Fragmentation of 13-HP-Endo-PC in unilamellar vesicles. Octanol/water partition coefficients (log *P*) for α-tocopherol and the methyl esters of the oxidized PUFAs, calculated by ChemDraw, are shown as a measure of relative hydrophobicity.

in a 1:2−3 ratio. In contrast, the fragmentation of 13-HP-Endo-PC in a model membrane delivered HODA-PC and ODFO-PC in about a 1:1 ratio. Apparently, a membrane environment protects the γ-hydroxyalkenal against oxidation to a butenolide.

To further test this hypothesis, we incubated 13-HP-Endo-PC (10 wt %), SP-PC (90 wt %), and one equivalent of α-tocopherol in a homogeneous solution in methanol and PBS buffer (1:1) at 37 °C for 4 h. The yields of HODA-PC and ODFO-PC are presented in Figure 15 and are compared to the yields obtained from the corresponding reaction in a model membrane (SUV). In homogeneous solution, the product distribution from the fragmentation of 13-HP-Endo-PC is very similar to that obtained from the fragmentation of 13-HP-Endo (the free acid) in a dry film, and not like that obtained from 13-HP-Endo-PC in a model membrane. This supports the hypothesis that the membrane environment protects HODA-PC against further oxidation.

DISCUSSION

Membrane Environment Compartmentalizes Lipid Oxidation Intermediates and Products. As detailed in the mechanism of Figure 3 (see above), fragmentation of the hydroperoxy endoperoxide generates an unstable *cis*-γ-hydroxyalkenal, which can isomerize into a *trans*-γ-hydroxyalkenal or be converted, through further oxidation, into a butenolide. Notably, the ratio of γ-hydroxyalkenal to butenolide will depend on the oxidative environment. The lipid whisker model[1,46,47] predicts segregation of the γ-hydroxyalkenal from lipid hydroperoxide oxidants in the membrane environment, and this favors the accumulation of HODA-PC at the expense of ODFO-PC. Thus, when cellular membranes undergo peroxidation, lipid hydroperoxides, e.g., 13-HPODE-PC (Figure 14), remain buried in the hydrophobic core of the membrane. However, the PUFA side chain containing the hydroperoxide becomes more hydrophilic after further oxidation and truncation, and moves from the interior of the lipid bilayer to the aqueous exterior. Consequently, the membrane grows lipid whiskers on its surface. The model predicts that the oxygenated acyl groups of 13-HP-Endo-PC and its precursor 13-HPODE-PC prefer to remain embedded in the lipophilic core of the membrane bilayer (because they are relatively hydrophobic as indicated by the octanol/water partition coefficients log *P* = 4.85

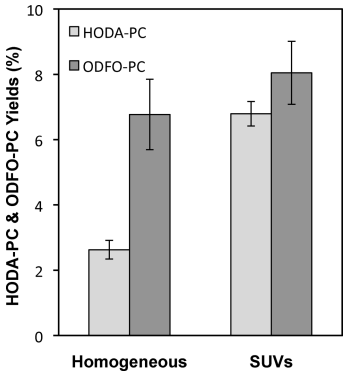


Figure 15. Formation of HODA-PC and ODFO-PC from 13-HP-Endo-PC in methanol and buffer homogeneous solution and in small unilamellar vesicles.

and 5.59), while the more polar γ-hydroxyalkenal acyl group (log P = 1.59) of HODA-PC prefers to extend into the aqueous phase (Figure 14). *cis*-HODA-PC (see Figure 14) partitions between isomerization to the trans isomer and oxidation to ODFO-PC. Oxidation would be disfavored in the membrane environment if lipid hydroperoxides, e.g., 13-HP-Endo-PC and 13-HPODE-PC, are required for the oxidation because the hydroperoxide of 13-HP-endo-PC and the γ-hydroxyalkenal acyl group of HODA-PC are localized in different phases, i.e., membrane hydrophobic core and aqueous phase, respectively. In contrast, the reaction of 13-HP-Endo-PC in an aqueous homogeneous environment (methanol/PBS, 1:1) or the reaction of 13-HP-Endo in the homogeneous environment of a dry film favors oxidation of *cis*-HODA-PC to ODFO-PC or of *cis*-HODA to ODFO because both *cis*-HODA and 13-HP-Endo or their PC esters are in the same phase.

To understand the free-radical-induced oxidative transformations of PUFAs *in vivo*, it is essential to investigate their chemistry when they are incorporated into phospholipids in membranes because the chemistry of the free fatty acids does not recapitulate their behavior in membranes. The structure and composition of the membrane environment profoundly influences product evolution. Previous studies of model membranes constructed from pure phospholipids, available by our unambiguous syntheses, established that the hydroperoxydiene modifications of PUFAs esterified into phospholipids, which are the major initial products of free radical- or singlet-oxygen-mediated oxidation, remain buried in the hydrophobic membrane core. With further oxidation and truncation, oxidized acyl groups become hydrophilic and adopt a conformation in which the oxidized acyl group protrudes from the membrane into the aqueous phase. Hydroperoxydienes are sources of chain-carrying alkoxy radicals that can either abstract doubly allylic hydrogen to generate pentadienyl radical precursors of additional hydroperoxides or abstract aldehydic hydrogen resulting in the oxidation of aldehydes to carboxylic acids.

Potential Contributions of Vitamin E and Ascorbate to Promoting Oxidative Injury. It has been more than 80 years since vitamin E was first discovered.[48] Yet the role and importance of vitamin E *in vivo* is still unclear.[49,50] As an antioxidant, vitamin E can scavenge lipid peroxyl and alkoxyl radicals and thus protect the membrane from oxidative damage.[34,51] However, vitamin E can also potentially contribute to oxidative injury: (1) by promoting lipid peroxidation, a prooxidant activity, that has

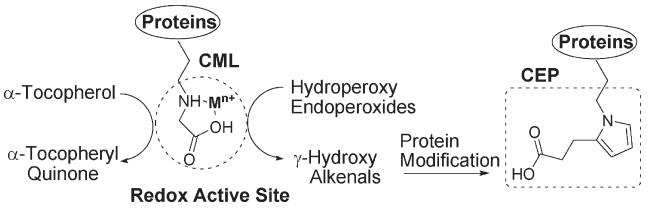


Figure 16. Possible mechanism that links elevated carboxymethyllysine (CML) accumulation with the generation of carboxyethylpyrroles (CEPs) in the retina of AMD eyes.

been noted previously and (2), as found in the present study, by promoting fragmentation of oxidized lipids to generate toxic aldehydes that can, *inter alia*, modify proteins by covalent adduction. A pro-oxidant effect of vitamin E, i.e., owing to H atom abstraction by the tocopheryl radical, is known,[52] but *in vivo* this pathway may be inhibited by coantioxidants, e.g., ascorbate. It was proposed that a deficiency of coantioxidants rather than α-tocopherol-mediated peroxidation alone may be responsible for lipoprotein lipid peroxidation in the aortic subendothelial space.[53] Indeed, in several animal models of atherosclerosis, administration of bisphenol, which is a kinetically inferior classical radical scavenger, yet efficient coantioxidant that can neutralize tocopheryl radicals, dramatically lowered aortic lipoprotein lipid peroxidation.[53]

Vitamins C and E can reduce metal ions that, paradoxically, can lead to oxidation of PUFAs. For example, a prooxidant effect of α-tocopherol may arise from either metal-catalyzed or direct electron transfer to lipid hydroperoxides. The resulting reductive cleavage generates hydroxyl and/or alkoxyl radicals that can initiate free radical chain reactions between PUFAs and oxygen. In other words, α-tocopherol might promote the oxidation of PUFAs by oxygen because it can cause single electron reduction of hydroperoxides and consequently generate free radical initiators of autoxidation. It was reported that α-tocopherol reduces Cu(II) to Cu(I) and concomitantly induces autoxidation in human lipoproteins.[54−60] This prooxidant effect of vitamin E was presumed to be "mediated by its capability to reduce Cu^{2+} to Cu^{+} which, in turn, produces, from lipid hydroperoxides, the highly reactive alkoxyl radicals".[55] Similarly, H_2O_2 was previously shown to generate hydroxyl radicals and oxidize ascorbate ~4 times faster in the presence of proteins from a cataractous lens than similar proteins from a normal lens. This is presumably because the endogenous level of Cu is significantly higher in a cataractous lens than in a normal lens. Ascorbate oxidizing activity at 24 h of crystallins, a structural lens protein, was significantly higher for crystallins isolated from cataractous lenses than from normal eyes. The metal ion chelator DTPA completely prevented this oxidation up to 24 h of incubation. Presumably, the oxidation of ascorbate reduces Cu(II) to Cu(I) that then reductively cleaves H_2O_2 to generate hydroxyl radicals.

Possible Contribution of Hydroperoxy Endoperoxide Fragmentation to Oxidative Injury in the Eye. The present study shows that vitamin E can promote the *fragmentation* of hydroperoxy endoperoxides, products that may be generated in the retina from the reaction PUFAs with singlet molecular oxygen, to give toxic aldehydes. These can, in turn, react with proteins, leading to oxidative lipid-derived protein modifications, such as the carboxyethylpyrrole (CEP) derivatives that trigger angiogenesis into the retina, as well as an immune-mediated destruction of the retina. Therefore, the use of vitamin E as a

supplement in clinical trials as a therapeutic intervention to prevent oxidative injury should consider not only its antioxidant but also its prooxidant effects[61,62] and its ability to promote the generation of toxic aldehydes through fragmentation of peroxidized lipids. Strong evidence is accumulating for a major role for lipid oxidation and lipid-derived protein modification in the pathogenesis of AMD. It seemed reasonable, therefore, to expect that antioxidants would have therapeutic benefits. Tocopherol's prooxidant effects and/or its ability to promote fragmentation of peroxidized lipids may help to explain why clinical trials have concluded that vitamin E in some cases provides a little but in most cases provides no benefit in ameliorating AMD.[63−65] Even if vitamin E successfully neutralizes chain carrying free radicals and free-radical-induced oxidation of lipids, it may concomitantly increase levels of toxic aldehydes generated by vitamin E-induced fragmentation.

The tocopherol-induced *in vitro* fragmentations of hydroperoxy endoperoxides that we described above may involve direct electron transfer leading to reductive cleavage or a process catalyzed by traces of redox active metal ions. Such catalysis is especially likely *in vivo* because carboxymethyl lysine (CML) modifications of proteins, which have been shown to bind redox active metal ions,[32,33] are found in eyes from individuals with AMD,[66] and levels are elevated in cataractous lenses.[67] Furthermore, it is likely that, in the presence of vitamin E, these protein-bound redox active metal ions will catalyze the reductive fragmentation of hydroperoxy endoperoxides by tocopherols to deliver toxic γ-hydroxyalkenals which, in turn, modify proteins, e.g., to produce CEPs (Figure 16). Mean levels of CEP adducts are ∼60% higher, and CML adducts are ∼54% higher in AMD relative to normal controls.[68,69] It is tempting to speculate that the correlation between elevated CML and elevated CEP in AMD eyes indicates a role for CMLs in promoting the generation of CEPs. Specifically, reactions of docosahexaenoate phospholipids with singlet molecular oxygen can generate hydroperoxy endoperoxides that can be converted to CEPs through the chemistry of detailed above.

The present study provides a basis for postulating that redox active metal ions contribute to lipid-derived oxidative protein modification that may be pathogenic, e.g., promoting both wet and dry forms of AMD. It also suggests a mechanism that may compromise the efficacy of dietary α-tocopoherol suplementation as a therapeutic modality. Testing these hypotheses will require, *inter alia*, comparing levels of redox active metals and tocopherols in eyes from individuals with AMD and from those with no disease. In a previous study, we found that dietary α-tocopherol supplementation offered no benefit for lowering levels of oxidative protein modifications in hemodialysis patients.[62] Rather, it caused a decrease in plasma γ-tocopherol levels, presumably by competitively inhibiting uptake of γ-tocopherol from the diet. Thus, supplementation with α-tocopherol resulted in a 2-fold increase in α-tocopherol levels and a concomitant halving of γ-tocopherol levels. The finding of the present study that γ-tocopherol-promoted decomposition of 13-HP-Endo causes less fragmentation than α-tocopherol suggests that dietary supplementation with γ-tocopoherol may be superior to α-tocopoherol as a therapeutic modality to prevent oxidative injury caused by the generation of toxic aldehydes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. General experimental methods and spectroscopic and analytical data for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ABBREVIATIONS

$^1O_2$, singlet oxygen; 9,12-diHPODE, 9,12-dihydroperoxyoctadeca-10,13-dienoic acid; 9-HP-Endo, 9-hydroperoxy-10,13-epidioxy-11-octadecenoic acid; 9-HPODE, 9-hydroperoxy-10,12-octadecadienoic acid; 10,13-diHPODE, 10,13-dihydroperoxyoctadeca-8,11-dienoic acid; 10-HPODE, 10-hydroperoxy-8,12-octadecadienoic acid; 12-HPODE, 12-hydroperoxy-9,13-octadecadienoic acid; 13-H-Endo, 13-hydroxy-9,12-epidioxy-10-octadecenoic acid; 13-HP-Endo, 13-hydroperoxy-9,12-epidioxy-10-octadecenoic acid; 13-HP-Endo-MiP, 8-(6-(1-(2-methoxypropan-2-ylperoxy)hexyl)-3,6-dihydro-1,2-dioxin-3-yl)octanoic acid; 13-HP-Endo-PC, 1-hexadecanoyl-2-(8-(6-(1-hydroperoxyhexyl)-3,6-dihydro-1,2-dioxin-3-yl)octanoyl)-*sn*-glycero-3-phosphocholine; 13-HP-Endo-PC-MiP, 1-hexadecanoyl-2-(8-(6-(1-(2-methoxypropan-2-ylperoxy)hexyl)-3,6-dihydro-1,2-dioxin-3-yl)-octanoyl)-*sn*-glycero-3-phosphocholine; 13-HP-MiP, (9*Z*,11*E*)-13-(2-methoxypropan-2-ylperoxy)octadeca-9,11-dienoic acid; 13-HPODE, 13-hydroperoxy-9,12-epidioxy-10-octadecenoic acid; 13-HP-PC-MiP, 1-hexadecanoyl-2-((9*Z*,11*E*)-13-(2-oxypropan-2-ylperoxy)octadeca-9,11-dienoyl)-*sn*-glycero-3-phosphocholine; AMD, age-related macular degeneration; CD36, cluster of differentiation 36; CEP, carboxyethylpyrrole; CML, *N*-(carboxymethyl)lysine; DCC, dicyclohexylcarbodiimide; DMAP, 4-dimethylaminopyridine; DTPA, diethylenetriaminepentaacetic acid; DT-PC, 1,2-ditridecanoyl-*sn*-glycero-3-phosphatidylcholine; ESI-MS/MS, electrospray ionization−tandem mass spectrometry; FOA, 8-(furan-2-yl)octanoic acid; HNE, 4-hydroxy-2-nonenal; HODA, 9-hydroxy-12-oxo-10(*E*)-dodecenoic acid; HODA-PC, 1-hexadecanoyl-2-(9-hydroxy-12-oxo-10(*E*)-dodecenoyl)-3-phosphatidylcholine; HODFO, 8-(2-hydroxy-5-oxo-2,5-dihydrofuran-2-yl)octanoic acid; HRMS, high resolution mass spectrometry; KODA, 9-keto-12-oxo-10-dodecenoic acid; LA, linoleic acid; Lyso-PC, 1-acyl-sn-glycero-3-phosphocholine; SRM, selected reaction monitoring; ODFO, 8-(5-oxo-2,5-dihydrofuran-2-yl)octanoic acid; ODFO-PC, 1-hexadecanoyl-2-(8-(5-oxo-2,5-dihydrofuran-2-yl)octanoyl)-*sn*-glycero-3-phosphocholine; oxPCs, oxidatively truncated phosphatidylcholines; oxPEs, oxidatively truncated phosphatidylethanolamine; PC, phosphatidylcholine; PFB, pentafluorobenzyl; PPTs, pyridinium p-toluene sulfonate; PUFA, polyunsaturated fatty acyl; RPE, retinal pigment epithelium; SIR, selected ion recording; SP-PC, 1-stearoyl-2-palmitoyl-*sn*-glycerol-3-phosphocholine; SUVs, small unilamellar vesicles; TPP, tetraphenylporphine; Vit E, vitamin E.

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