Total Synthesis and Bioactivity of 18(R)-Hydroxyeicosapentaenoic Acid

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Supporting Information

ABSTRACT: Resolvins are family of lipid mediators derived from omega-3 polyunsaturated fatty acids, which are generated during the resolution phase of acute inflammation. Resolvin E1 is biosynthesized from eicosapentaenoic acid via 18(R)-hydroxyeicosapentaenoic acid (18R-HEPE) in the Cox-2 and lipoxygenase mediated pathway and has proven to exhibit potent anti-inflammatory activity. We report herein the first total chemical synthesis of 18R-HEPE and demonstrate that this compound displays in vivo bioactivity by blocking neutrophil infiltration in a murine model of zymosan-induced peritonitis.

Inflammation plays a central role in the onset and progression of Alzheimer’s disease, atherosclerosis, and cancer, in addition to arthritis and periodontal disease. Recently, Serhan and co-workers have identified novel oxygenated products that display potent anti-inflammatory activity within resolving inflammatory exudates. Derived from omega-3 polyunsaturated fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), these compounds have been termed E- and D-series resolvins, respectively. As an example, resolvin E1 (RvE1) is a metabolite of EPA, which is produced by neutrophils from 18(R)-hydroxy-5(Z),8(Z),11(Z),14(Z),16(E)-eicosapentaenoic acid (18R-HEPE) through a 5-lipoxygenase-mediated pathway. RvE1 serves as an on-demand negative feedback switch that dramatically reduces inflammatory responses, including neutrophil and dendritic cell migration and interleukin-12 production. Efforts to generate synthetic analogues of resolvins, as well as other lipid mediators that possess significant anti-inflammatory and pro-resolution properties, have been recently reported. Herein, we report the first total chemical synthesis of 18R-HEPE and characterize its anti-inflammatory activity in vivo.

Our retrosynthetic approach for the synthesis of 18R-HEPE is outlined in Scheme 1. According to this strategy, the E,Z-conjugated diene system of 18R-HEPE is constructed using Cu(I)/Pd(0) coupling as the key step. This approach uses the terminal acetylene 7 and the vinyl iodide 13 as requisite building blocks.

The synthesis of 7 began with cross coupling of commercially available 4-chlorobut-2-yn-1-ol and hex-5-ynoic acid methyl ester 2, in the presence of Cul, which afforded 3 in 74% yield. The alcohol 3 was converted to the corresponding bromide 4 in the presence of CBr₄/PPh₃. Subsequent coupling of 4 with 1(trimethylsilyl)-1,4-pentadiyne in the presence of Cul, NaI, and K₂CO₃ afforded tetrayne 5 in 71% yield. Selective hydrogenation of 5 with Brown’s P-2 Ni method gave the TMS-protected triene 6 in 91% yield (Scheme 2).

The synthesis of vinyl iodide fragment 13 was achieved from commercially available bis(trimethylsilylacetylene) 8, which was...
converted to the corresponding ketone 9 via treatment with propionyl chloride in the presence of AlCl₃ as an activator. The known Noyori’s asymmetric transfer hydrogenation produced the chiral TMS-acetylenic alcohol 10. In contrast to published work using 5–10% of the Noyori catalyst (R,R)-TSDPEN)Ru(p-cymene)Cl₂, a simple modification of this procedure leads to higher turnover numbers. Thus, freshly prepared catalyst (0.01%) was added to the degassed 2-propanol under argon atmosphere, and this was followed by slow addition of TMS-acetylenic ketone 9 in 2-propanol over 3 h. The reaction mixture was stirred for 12 h, the solvent evaporated, and the product purified by flash chromatography to give the chiral alcohol 10 in 81% yield with very high enantioselectivity. TIPS protection of the free hydroxyl functionality followed by selective desilylation of the TMS group with potassium carbonate afforded alkyne 12 in 95% yield. Hydrostannylation of 12 was achieved by heating with Bu₃SnH in the presence of AIBN as an initiator, followed by exchanging the stannane for iodine. The key vinyl iodide fragment 13 was obtained in 72% overall yield and the Cu(I)—Pd(0) coupling reaction with 7 investigated. Thus, slow addition of the alkyne 7 (2 equiv) over a 2 h period using a syringe pump to a reaction mixture containing vinyl iodide 13 (1 equiv), tetrakis-triphenylphosphine palladium (0) (0.05 equiv), and copper iodide (0.1 equiv) produced the desired coupled product 14 in 88% yield. Under these reaction conditions, only a minimal amount (<5%) of glacier coupling of alkyne 7 was observed. The triple bond was selectively reduced by zinc—copper couple to provide the protected HEPE 15 in 56% yield. All other (Z)-selective methods, such as Lindlar hydrogenation, palladium(0) poisoned with BaSO₄, and Brown’s P-2 Ni protocol failed to produce 15, leading only to the recovery of the starting material. Deprotection of the TIPS ether in 15 with excess TBAF followed by alkaline hydrolysis of the methyl ester afforded 18R-HEPE I (Scheme 3).

The biological activity of 18R-HEPE 1 was examined using a murine model of peritonitis (Figure 1). Eight-week-old male C57BL/6 mice were injected intraperitoneally with zymosan A (1 mg/mL) in sterile saline. 18R-HEPE (2.5 μg) was suspended in 5 μL of ethanol and dissolved in 95 μL of sterile saline. Test compound or vehicle alone was administered intraperitoneally at the time of zymosan A injection and 1 h later. Mice were sacrificed 4 h after zymosan injection, and peritoneal lavage was performed to characterize the inflammatory cell infiltrate by flow cytometry. 18R-HEPE significantly reduced neutrophil (PMN) infiltration as compared to vehicle alone (6.06 × 10⁶ ± 0.94 × 10⁶ vs 10.52 × 10⁶ ± 2.20 × 10⁶, n = 8/group, p < 0.01).

In summary, the total synthesis of 18R-HEPE was achieved in a convergent manner using terminal acetylene 7 and vinyl iodide 13 fragments. These fragments were coupled using Cu(I)—Pd(0) to obtain the E,Z-conjugated diene system of 18R-HEPE. Synthetic 18R-HEPE proved to be biologically active by blocking neutrophil infiltration in a murine peritonitis model.

### EXPERIMENTAL SECTION

**General Experimental Methods.** All reagents were purchased from a commercial supplier and used as received, unless otherwise indicated. 4-Chloro-2-butyn-1-ol, hex-5-ynoic acid methyl ester, and 1-trimethylsilyl-1,4-pentadiyne were purchased from commercial suppliers. All reactions were carried out under nitrogen with anhydrous solvents, unless otherwise stated. All organic extracts were dried over sodium sulfate and concentrated under aspirator vacuum. H and 13C NMR were recorded with a Varian 400 MHz spectrometer with CDCl₃ as solvent. High resolution ESI-mass spectra were recorded by the Emory University Mass Spectrometry Center using a JEOL JMS-SX102 instrument.

**Synthesis of 10-Hydroxydec-5,8-diynoic Acid Methyl Ester (3).** 4-Chloro-2-butyn-1-ol (3.0 g, 28.7 mmol) and hex-5-ynoic acid methyl ester (3.62 g, 28.7 mmol) were added to a suspension of CuI (11.0 g, 57.4 mmol), NaI (8.61 g, 57.4 mmol), and K₂CO₃ (5.94 g, 43 mmol) in 10 mL of anhydrous DMF under Ar atmosphere. The mixture was stirred overnight at room temperature and then quenched with saturated aqueous NH₄Cl and the lipophilic products were extracted with Et₂O. The combined organic extracts were washed with water and brine and dried with Na₂SO₄. After rotary evaporation of solvents, the residue was chromatographed on silica gel to afford alcohol 3 (4.1 g, 74% yield) as colorless oil: Rf = 0.25 (30% EtOAc in hexanes); IR (neat) 3405, 2245, 1730, 1025 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz) δ = 4.18 (t, J = 2.4 Hz, 2H), 3.61 (s, 3H), 3.11 (p, J = 2.0 Hz, 2H), 2.37 (t, J = 7.2 Hz, 2H), 2.16 (tt, J = 7.0 Hz, J = 2.0 Hz, 2H), 1.74 (p, J = 7.2 Hz, 2H); 13C NMR (CDCl₃, 100 MHz) δ = 173.9, 80.4, 79.8, 78.8, 74.7, 51.8, 51.2, 33.0, 23.9, 18.3, 9.9; ESI-FTMS calc for C₁₅H₂₂O₃ [M + Na] 217.0835, obsd 217.0836.
Synthesis of 10-Bromodeca-5,8-diyanoic Acid Methyl Ester (4). A solution of PPh3 (6.09 g, 23.2 mmol) in dry CH2Cl2 (15 mL) was added dropwise to a stirred solution of alcohol (34.1 g, 21.1 mmol) and CB4 (7.45 g, 23.2 mmol) in 15 mL of dry CH2Cl2 at 0°C. Then the mixture was stirred for another 1.5 h at 0°C. The solvent was evaporated, and the residue was diluted with EtO and filtered through a short pad of Celite. The filtrate was concentrated and then chromatographed on silica gel to provide bromide (5.33 g, 85% yield) as a yellow oil: Rf = 0.7 (10% EtOAc in hexanes); IR (neat) 2948, 2920, 2845, 2250, 1730, 1460, 1305, 1210 cm⁻¹; 1H NMR (CDCl3, 400 MHz) δ = 5.45–5.44 (m, 2H), 3.57–3.54 (m, 4H), 3.64 (s, 3H), 2.98–2.94 (m, 2H), 2.81–2.77 (m, 4H), 2.32 (t, J = 7.6 Hz, 2H), 2.09 (t, J = 7.0 Hz, J = 2.0 Hz, 2H), 1.96 (t, J = 2.8 Hz, 1H), 1.70 (p, J = 7.2 Hz, 2H); 13C NMR (CDCl3, 100 MHz) δ = 174.3, 130.3, 129.2, 129.0, 128.8, 127.4, 124.2, 82.7, 68.3, 51.7, 33.6, 29.8, 26.7, 25.7, 24.9, 17.1; ESI-HRMS calcd for C16H13O2Br [M + H⁺] 283.0438, obsd 283.0432.

Synthesis of 1-(Trimethylsilyl)-1-pentyn-3-one (9). Bis(trimethylsilylacetylene) (3.0 g, 17.6 mmol) and propionyl chloride (1.68 g, 17.6 mmol) were dissolved in dichloromethane (60 mL) and the mixture cooled to 0°C. To this solution was added aluminum chloride (2.7 g, 17.6 mmol), and the reaction mixture was stirred for 3 h. After 3 h, the mixture was poured into 3 N HCl (50 mL) and extracted with EtOAc (3 x 30 mL). The combined organic layer was washed, concentrated and purified by chromatography on silica gel (1% EtOAc in hexanes) to afford the title compound 9 (2.41 g, 89% yield) as a colorless oil: Rf = 0.8 (3% EtOAc in hexanes); IR (neat) 2964, 2940, 2150, 1737, 1680, 1459, 1415, 1353, 1262, 1198 cm⁻¹; 1H NMR (CDCl3, 400 MHz) δ = 5.1 (d, J = 6.4 Hz, J = 12.0 Hz, 2H), 1.07 (t, J = 7.6 Hz, 3H), 0.18 (s, 9H); 13C NMR (CDCl3, 100 MHz) δ = 188.5, 101.9, 97.7, 38.5, 81.8, −0.6 (3C); ESI-HRMS calcd for C8H14O2Si [M + H⁺] 155.0867, obsd 155.0865.

Synthesis of 1-(Trimethylsilyl)-1-pentyn-3(3)-ol (10). Catalyst ([R,R]-TsDPEN)Ru[p-cymene]Cl2 (22 mg, 0.005 equiv) was dissolved in 50 mL of degassed 2-propanol under Ar atmosphere. To this solution was added a solution of ketone 9 (1.46 g, 9.4 mmol) dissolved in 2-propanol (5 mL) over a period of 3 h using a syringe pump. The reaction was allowed to stir for an additional 12 h, and the solvent was concentrated to provide a crude propargyl alcohol which was purified by chromatography on silica gel (5% EtOAc in hexanes) to afford the title compound 10 (1.52 g, 95% yield) as a colorless oil.

Synthesis of 3(R)-Trisopropylsilyloxy-1-trimethylsilyl-1-pentene (11). Alcohol 10 (1.3 g, 8.3 mmol) was dissolved in CH2Cl2 (20 mL) to which TIPS-Cl (2.4 g, 12.5 mmol) and imidazole (0.85 g, 12.5 mmol) were added at 0°C. The reaction was slowly warmed to room temperature and stirred for 12 h. After 12 h, the reaction mixture was washed with saturated NH4Cl (30 mL) and brine (20 mL). The dichloromethane layer was collected, dried, and concentrated under reduced pressure. Subsequent purification by chromatography over silica gel (5% EtOAc in hexanes) afforded TIPS ether 11 (2.1 g, 82% yield) as a colorless oil: Rf = 0.8 (5% EtOAc in hexanes); IR (neat) 2950, 1540, 1225, 1077 cm⁻¹; [α]D24 = +38.3 (c, 1, CHCl3); 1H NMR (CDCl3, 100 MHz) δ = 4.37 (t, J = 6.0 Hz, 1H), 1.71–1.64 (m, 2H), 1.48–1.10 (m, 21H), 0.97 (t, J = 7.6 Hz, 3H), 0.14 (s, 9H); 13C NMR (CDCl3, 100 MHz) δ = 107.9, 84.5, 64.8, 32.0, 18.2, 12.4, 9.6, 0.01; ESI-HRMS calcd for C16H34O6Si [M – H2O]− 319.0376, obsd 319.0372.

Synthesis of 3(R)-Trisopropylsilyloxy-1-phenyl-1-pentene (12). Compound 11 (1.0 g, 3.2 mmol) was dissolved in MeOH (20 mL) to which anhydrous K2CO3 (0.5 g, 3.8 mmol) solid was added and the mixture stirred at room temperature for 12 h. After 12 h, methanol was removed under reduced pressure, and the crude product was dissolved with Et2O (30 mL) and saturated NH4Cl (30 mL). The Et2O layer was separated, dried, and concentrated under reduced pressure. Subsequent purification by chromatography over silica gel (5% EtOAc in hexanes) produced the desired alkene 12 (730 mg, 95% yield) as colorless oil:
Synthesis of 1(E)-Iodo-3(R)-trisopropylsilyloxypentene (13). Alknyne 12 (200 mg, 0.83 mmol) was taken in a round-bottom flask to which AIBN (14 mg, 0.083 mmol) and tributylhydride (360 mg, 1.24 mmol) were added and heated to 130 °C for 3 h. After 3 h, the reaction was allowed to cool down to room temperature and cooled to 0 °C. To this was added a solution of I₂ (630 mg, 2.49 mmol) dissolved in CH₂Cl₂ (5 mL). The reaction was slowly warmed to room temperature and stirred for an additional 12 h. After 12 h, the reaction mixture was diluted with CH₂Cl₂ (30 mL) and washed with saturated aq Na₂SO₄ (10 mL) and saturated aq NH₄Cl (10 mL). The CH₂Cl₂ layer was then dried, concentrated, and purified by chromatography over silica gel (1% EtOAc in hexane) to afford the vinyl iodide (220 mg, 72% yield) as colorless oil: IR (neat) 2210, 1735, 710 cm⁻¹; [α]D° = 19.5 (c 1, CHCl₃); ¹H NMR (CDCl₃, 400 MHz) δ = 4.41 (dd, J = 8.1 Hz, J = 6.2 Hz, J = 2.0 Hz, 1H), 2.35 (d, J = 6.0 Hz, 1H); ¹³C NMR (CDCl₃, 100 MHz) δ = 85.7, 72.1, 64.2±3.2, 18.2, 12.4, 9.3; ESI-HRMS calcd for C₁₄H₂₃OSi [M + H]⁺ 241.19822, obsd 241.19822.

Synthesis of 18(R)-Hydroxy-(5Z,8Z,11Z,14Z,16E)-eicosapentaenoic Acid (1). Compound 15 (10 mg, 0.02 mmol) was dissolved in THF (1 mL) to which a 1 M TBAF in THF solution (0.1 mL, 0.1 mmol) was added under Ar atmosphere and stirred at room temperature for 10 h. The reaction was monitored by TLC, and after 10 h, the reaction was diluted with EtOAC (5 mL) and washed with saturated aq NH₄Cl (2 × 5 mL). The organic phase was extracted and concentrated under reduced pressure. The resulting crude was subsequently dissolved in THF/H₂O (1:1, 2 mL), and the reaction was allowed to stir at room temperature for 5 h. After 5 h, the organic phase was removed under reduced pressure and carefully acidified to pH 5 using 1 N HCl. The aqueous layer was extracted with EtOAc (3 × 5 mL), dried, concentrated, and purified by chromatography over silica gel (40% EtOAc in hexanes) to afford I (4.6 mg, 71% yield) as colorless oil: Rf = 0.3 (40% EtOAc in hexanes); IR (neat) 3410, 3475, 1730, 1665, 735, 710 cm⁻¹; [α]D° = -17.9 (c 0.4, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ = 6.51 (dd, J = 4.0 Hz, J = 15.2 Hz, 1H), 5.99 (t, J = 10.8 Hz, 1H), 5.63 (dd, J = 6.4 Hz, J = 14.8 Hz, 1H), 3.59–3.53 (m, 3H), 4.09 (q, J = 5.6 Hz, 2H), 2.95 (t, J = 2.4 Hz, 2H), 2.83 (t, J = 5.6 Hz, 2H), 2.78 (t, J = 3.2 Hz, 2H), 2.30 (t, J = 7.6 Hz, 2H), 2.08 (dd, J = 6.9 Hz, J = 13.6 Hz, 2H), 1.68 (dt, J = 15.6 Hz, J = 14.8 Hz, 2H), 1.57 (m, 2H), 0.87 (t, J = 7.2 Hz, 3H); ¹³C NMR (CDCl₃, 100 MHz) δ = 177.9, 136.0, 130.4, 129.2, 129.0, 128.8, 128.4, 128.2, 128.1, 127.8, 125.7, 74.2, 33.2, 30.3, 30.0, 26.6, 26.3, 25.9, 24.7, 19.9; ESI-HRMS calcd for C₂₀H₃₀O₃ [M − H]⁻, expected 371.2122, obsd 371.2124.

■ ASSOCIATED CONTENT

* Supporting Information. ¹H and ¹³C NMR spectra for new compounds 1, 3–7, and 9–15. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES


