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Synthesis and Biological Evaluation of a Phosphonate Analog of the Natural Acetyl Cholinesterase Inhibitor Cyclophostin

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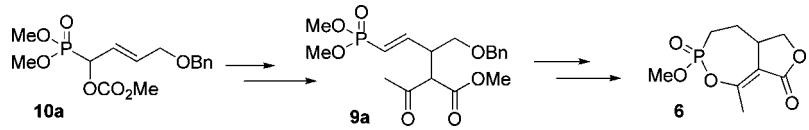

Two diastereomers of a phosphonate analog **6** of the AChE inhibitor cyclophostin were synthesized. The substitution reaction of phosphono allylic carbonate **10a** with methyl acetoacetate gave the vinyl phosphonate **9a**. Attempted hydrogenation/debenzylation gave an unexpected enolether lactone. Alternatively, selective hydrogenation, demethylation, cyclization and debenzylation gave the phosphonate analog of cyclophostin as a separable mixture of diastereomers **6**. The *trans* phosphonate isomer was more active than the *cis* isomer against AChE from two sources.

Introduction

Cyclophostin **1**, a novel bicyclic organophosphate, was isolated from a fermentation solution of *Streptomyces lavendulae* (strain NK901093) during a search for natural insecticides.[1] The natural product **1** showed potent inhibition of acetyl cholinesterase (AChE) from housefly (CSMA strain) and the brown plant hopper with reported IC_{50} of 7.6×10^{-10} M. The structure of cyclophostin was first assigned by spectroscopic methods and then confirmed by single crystal X-ray diffraction studies as a bicyclic structure with a seven-membered cyclic enol-phosphate triester fused to a butyrolactone ring. There are chiral centers at both C3a and the phosphorus atom. The absolute configurations of the chiral centers were determined to be 3a*R*, 6*S* by the anomalous scattering method.

The unusual bicylic enolphosphate is found in some related natural compounds **2** and **3** and the enolphosphate moiety adjacent to a carbonyl is also found in the synthetic insecticides monocrotphos **4** and phosphamidan **5**.[2−4] The unnamed tetrahydrofuran fused enolphosphates **2a** and **2b** were isolated during an earlier search for insecticides and were shown to be AChE inhibitors.[3] The cyclipostins **3** possess a core structure similar to that of cyclophostin but differ in the phosphate ester.[4] The cyclipostins **3** are phosphate esters of long chain lypophilic alcohols of various lengths and structures and all are potent inhibitors of hormone sensitive lipase.[4]

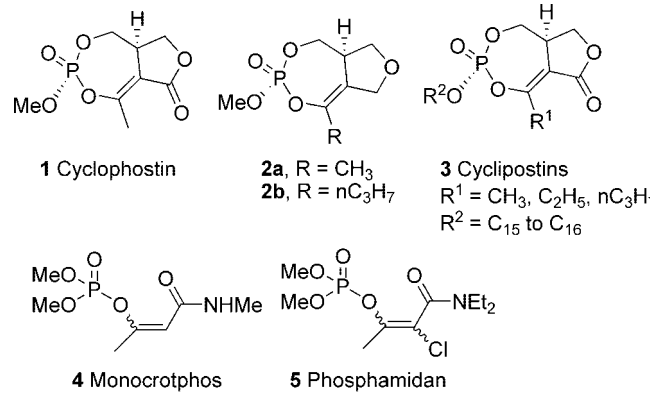

FIGURE 1. Cyclophostin and related structures.

AChE has been identified as a therapeutic target for myasthenia gravis,[5] glaucoma,[6] and Alzheimer's disease[7] and is well-

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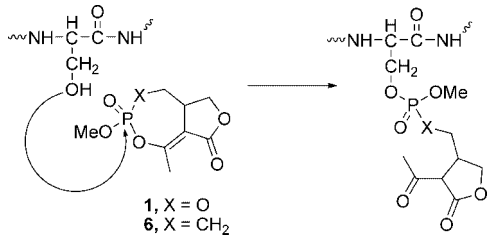


FIGURE 2. Proposed reaction with the active site serine and a phosphonate analog of cyclophostin.

known as the target for insecticides and "nerve gas" chemical warfare agents. The exact mode of inhibition of AChE by cyclophostin has not been reported. Because other phosphate inhibitors of AChE are known to form a covalent bond between the phosphorus and the serine residue of enzyme active site, it is likely that the mode of inhibition by cyclophostin involves a similar kind of interaction (Figure 2). It is also probable that the enolphosphate acts as a leaving group on reaction with the active site serine.

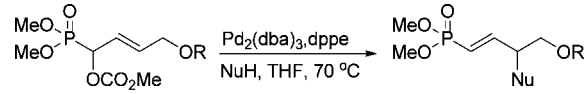
Phosphonate analogs of biologically active phosphates have been shown to be an extremely useful tool in investigating mechanistic detail of various enzymatic systems.[8] This success is usually attributed to the nonhydrolyzability of a P−C bond (phosphonate analog) when compared to the P−O bond of the corresponding phosphate leading to enhanced compound lifetime in vivo. It should be possible to replace the noncritical oxygen at position 5 in cyclophostin (and the cyclipostins) with a methylene and still retain the AChE inhibitory activity (Figure 2), whereas loss of the enol oxygen (position 7) should eliminate activity. Herein, we report the synthesis of the first phosphonate analog **6** of cyclophostin.

Results and Discussion

A retrosynthetic analysis of the bicyclic phosphonate **6** suggested that either the lactone or the enol phosphonate bond could be formed first giving rise to intermediates **7** and **8**, respectively. The common intermediate **9** could be formed via a palladium catalyzed substitution reaction of the carbonate derivative **10** of an allylic hydroxy phosphonate with an acetoacetate ester. We reported the use of a similar strategy for the synthesis of the lignan enterolactone.[9]

It is now well established that allylic hydroxy phosphonate derivatives can be used as intermediates in the synthesis of γ-substituted vinyl phosphonates by 1,3-transposition of functionality.[10−12] Following the original work of Zhu and Lu,[11] we reported that the facile addition of soft nucleophiles to optically pure carbonate derivatives proceeded with complete transfer of chirality.[9,12]

TABLE 1. Palladium Catalyzed Allylic Substitution Reactions with Acetoacetates and Malonates



10a, b **9a-d**

carbonate	R	NuH	base	product	yield
10a	Bn	$CH_3COCH_2CO_2Me$	none	**9a**	85%
10a	Bn	$CH_3COCH_2CO_2t$-Bu	none	**9b**	56%
10b	TBS	$CH_3COCH_2CO_2Me$	none	**9c**	64%
10a	Bn	t-$BuO_2CCH_2CO_2Me$	BSA	**9d**	81%

4-Benzyloxy- and 4-(*tert*-butyldimethyl)silyloxy-*cis*-2-buten-1-ol **11a** and **11b** were oxidized using PCC in CH_2Cl_2 to give the known aldehydes **12a** and **12b**, respectively.[13] The Et_3N catalyzed Pudovik reaction of the α,β-unsaturated aldehydes with dimethyl phosphite gave the racemic hydroxy phosphonates **13a** and **13b**, which were converted into the corresponding carbonate derivatives **10a** and **10b** by reaction with methyl chloroformate in pyridine.

The palladium catalyzed substitution reaction of phosphono allylic carbonates **10a** and **10b** with acetoacetates and malonates was investigated. The reaction of methyl acetoacetate with phosphonate **10a** gave the vinyl phosphonate **9a** in 85% yield (Table 1). The formation of the vinyl phosphonate **9a** was always accompanied by diene formation, especially after prolonged reaction times. However, the use of freshly distilled methyl acetoacetate and careful monitoring of the reaction (^{31}P NMR spectroscopy) minimized diene formation. The phosphonate **10b** reacted with methyl acetoacetate similarly to give the vinyl phosphonate **9c** in 64% yield. The reaction of *tert*-butyl acetoacetate with phosphonate **10a** was slower than with the methyl acetoacetate, and a moderate amount of diene formation was always observed. The palladium (0) catalyzed malonate susbstitution reaction of phosphono allylic carbonate **10a** was again comparatively slow and required the presence of a weak base like BSA. In each case, the products **9a-d** were formed as a mixture of diastereomers.

The attempted concomitant hydrogenation and debenzylation of vinyl phosphonate **9a** with hydrogen over palladium on carbon unexpectedly gave the lactone methylenolether **14a** independent of the solvent used (Scheme 3). More surprisingly, a similar product was also observed with *t*-butyl acetoacetate substituted vinyl phosphonate **9b** giving the *t*-butyl enolether substituted butyrolactone **14b** in quantitative yield. The TBS protected phosphonate **9c** was uneventfully hydrogenated to give the saturated phosphonate **15**. Attempted deprotection and lactonization of phosphonate **15** with HF/Py also produced the lactone methylenolether **14a**. All attempts to cleave either the methyl or *t*-butyl enolether failed to produce desired 2-acetyl butyrolactone system.

An alternate strategy (Scheme 4) involving the construction of the seven membered enolphosphonate ring prior to the butyrolactone was pursued. Selective hydrogenation of vinyl

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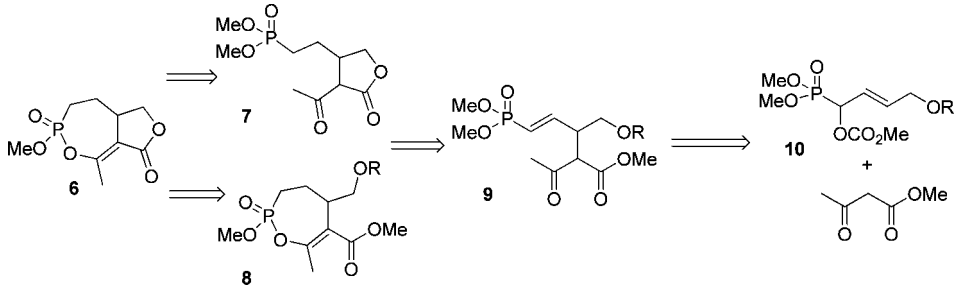
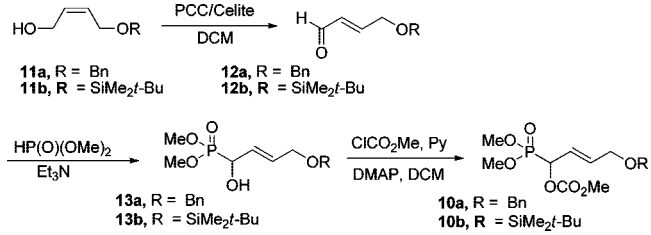
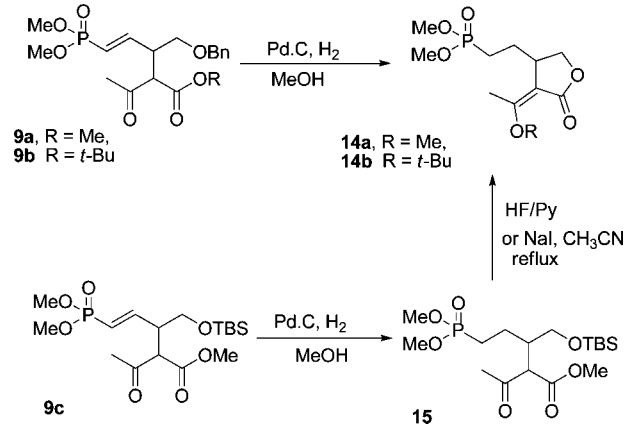
SCHEME 1. Retrosynthetic Analysis for the Phosphonate Analog of Cyclophostin



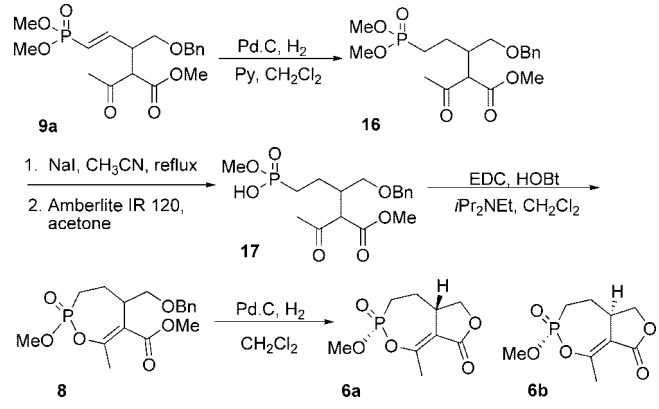
SCHEME 2. Preparation of the Allylic Hydroxy Phosphonates



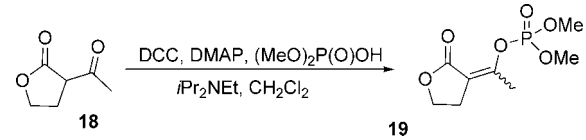
SCHEME 3. Hydrogenation and Debenzylation of the Vinyl Phosphonates



SCHEME 4. Synthesis of the Phosphonate Analog



SCHEME 5. Synthesis of an Enol Phosphate Analog of Cyclophostin



phosphonate **9a** using hydrogen over palladium on carbon poisoned with pyridine cleanly generated methyl acetoacetate substituted saturated phosphonate **16**. The phosphonate was selectively monodemethylated using one equivalent of sodium iodide in refluxing acetonitrile. The sodium salt was protonated with Amberlite resin (IR 120) to generate the corresponding phosphonic acid **17**. Enol phosphonate ring formation was successfully achieved by reaction of the phosphonic acid **17** with EDC, HOBt and Hunig's base in CH_2Cl_2 giving monocyclic enolphosphonate **8** as a 1:1.4 mixture of diastereomers. Finally, selective debenzylation of **8** with hydrogen over palladium on carbon resulted in clean hydrogenolysis to give the primary alcohol which cyclized to the butyrolactone without over reduction of enolphosphonate. The phosphonate analogue of cyclophostin **6** was obtained as a mixture of two diastereoisomers having characteristic peaks in the ^{31}P NMR spectrum at 21 (**6a**) and 25 (**6b**) ppm. Mixture of diastereomers was separated using silica gel chromatography. The diastereoisomer **6b** is a crystalline solid and was further purified by crystallization from EtOAc and hexane. An X-ray crystal structure (Figure 3) showed the relative stereochemistry of the C3a and the phosphorus atom to be the same as the natural product (H and methoxy are *cis*).

To examine the effect of the bicylic ring structure on the AChE activity, a simple enolphosphate analog **19** was prepared for comparison (Scheme 5). Phosphorylation of 2-acetyl butyrolactone **18** was accomplished by reaction with dimethyl chlorophosphate using a reported procedure.[14] Alternatively, the

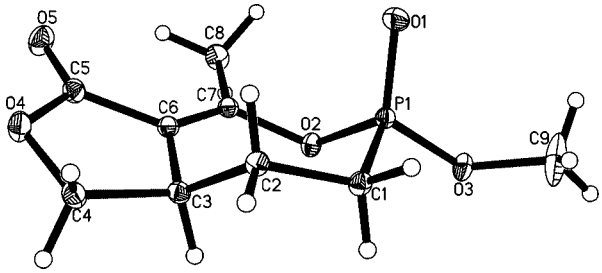
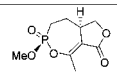
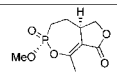
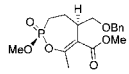
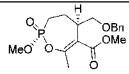
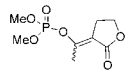
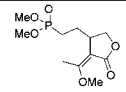


FIGURE 3. Projection view of the phosphonate **6b** with 50% thermal ellipsoids.

enol phosphate **19** was formed as a mixture of geometrical isomers by reaction of 2-acetyl butyrolactone **18** with dimethyl phosphoric acid and DCC.

The new compounds were examined for inhibitory activity against AChE from human and electric eel using an Elman assay.[15] Surprisingly, the phosphonate analog **6a** with the "unnatural" relative stereochemistry (Table 2, Entry 1) showed the most potent activity against both human and electric eel acetylcholinesterase (AChE). Interestingly, compound **6a** is more effective against AChE from human than eel. This type

TABLE 2. Inhibition Data for AChE from Human and Eel

Entry	Compound	Structure	IC_{50}(uM) Eel AChE	IC_{50}(uM) Human AChE
1	6a		~70	~3
2	6b		>400	~30
3	8a		~150	~35
4	8b	 4:1 mixture	~110	~6
5	18		>1000	>1000
6	14a		>1000	>1000

of species dependent difference in inhibition has been observed with phosphate inhibitors like soman, tabun, and VX.[16] The phosphonate analog **6b** with natural relative stereochemistry was 10-fold less potent against AChE from both sources when compared to the diastereomer **6a** (Table 2, Entry 2). However, the phosphonate analogs were significantly less potent than the natural product cyclophostin **1** (reported for insect AchE only). The fused butyrolactone did not appear to be necessary for activity since the monocyclic diastereomers **8a** and **8b** (Table 2, Entries 3 and 4) showed IC_{50} similar to those of the bicycles **6a** and **6b**. However, the more active monocycle **8b** had the opposite relative stereochemistry to the more active bicycle **6a**. Furthermore, the simple enolphosphate derivative **19** of acetyl butyrolactone was inactive (Table 2, Entry 5). Not surprisingly, the methyl enolether **14a** was also inactive (Table 2, Entry 6).

In summary, two diastereomers of a phosphonate analog of cyclophostin were synthesized. The *trans* isomer was more active than *cis* isomer against AChE from two sources. Because the natural product has the *cis* configuration, the unnatural isomer may well prove more potent. We are currently pursuing a synthesis of both isomers of the natural product.

Experimental Section

Dimethyl [1-(methoxycarbonyloxy)-4-(benzyloxy)-2-butenyl]phosphonate 10a. To a mixture of dimethyl phosphite (8.2 mL, 89 mmol) and aldehyde **12a**[13]a (9.2 g, 52 mmol) was added Et_3N (3.1 mL, 22 mmol). The reaction mixture was stirred overnight and then the volatiles were evaporated in vacuo to give crude hydroxy phosphonate **13a** (16.9 g). The crude hydroxy phosphonate **13a** (16.9 g, 59.1 mmol) was dissolved in anhydrous CH_2Cl_2 (60 mL) and the solution was cooled to 0 °C. Pyridine (7.6 mL, 88 mmol) and DMAP (0.10 g, 0.8 mmol) were added to the solution, followed by the slow addition of methyl chloroformate (9.1 mL, 120 mmol). After the complete addition of methyl chloroformate, the reaction mixture was slowly allowed to warm up to room temperature and then it was stirred until the reaction was complete (TLC, 24 h). The reaction mixture was washed with H_2O (2×) and saturated $CuSO_4$ (2×), and then the organic layer was dried over $MgSO_4$. The solvent was evaporated in vacuo and the crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 60: 40) to give **10a** as a colorless oil (10.4 g, 61% in two steps). IR (neat) 1758 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.31−7.36 (5H, m), 6.09 (1H, m), 5.89 (1H, m), 5.55 (1H, ddd, J_{HH} = 1.1, 6.6 Hz, J_{HP} = 14 Hz), 4.52 (2H, s), 4.08 (2H, m), 3.84 (3H, s), 3.83 (6H, d, J_{HP} = 10.7 Hz); ^{13}C NMR ($CDCl_3$) δ 154.9 (d, J_{CP} = 9.3 Hz), 138.2, 133.1 (d, J_{CP} = 12 Hz), 128.6, 127.95, 127.92, 122.8 (d, J_{CP} = 3.9 Hz), 72.5 (d, J_{CP} = 169 Hz), 72.6, 69.5 (d, J_{CP} = 1.5 Hz), 55.7, 54.2 (d, J_{CP} = 7.0 Hz), 54.0 (d, J_{CP} = 6.5 Hz); ^{31}P NMR ($CDCl_3$) δ 19.7; HRMS (FAB, *NBA*, MH^+) calcd. for $C_{15}H_{22}O_7P$: 345.1103. Found: 345.1108; Anal. Calcd for $C_{15}H_{21}O_7P$: C, 52.33; H, 6.15. Found: C, 52.35; H, 6.02.

Dimethyl [1-(methoxycarbonyloxy)-4-(*t*-butyldimethylsilyloxy)-2-butenyl]phosphonate 10b. To a mixture of dimethyl phosphite (3.8 mL, 41 mmol) and aldehyde **12b**[13b] (4.73 g, 23.6 mmol) was added Et_3N (1.5 mL, 11 mmol). The reaction mixture was stirred overnight then the volatiles were evaporated in vacuo to give the crude hydroxy phosphonate **13b** (6.6 g). The crude hydroxyphosphonate **13b** (6.6 g, 21 mmol) was dissolved in anhydrous CH_2Cl_2 (60 mL) and the solution was cooled to 0 °C. Pyridine (2.9 mL, 36 mmol) and DMAP (0.41 g, 3.4 mmol) were added to the solution, followed by the slow addition of methyl chloroformate (3.74 mL, 48.4 mmol). After the addition of methyl chloroformate was complete, the reaction mixture was slowly allowed to warm up to room temperature then it was stirred until the reaction was complete (TLC, 24 h). The reaction mixture was washed with H_2O (2×) and saturated $CuSO_4$ (2×), and then the organic layer was dried over $MgSO_4$. The solvent was evaporated in vacuo and the crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 60: 40) to give **10b** as a colorless oil (4.09 g, 46% in two steps). IR (neat) 1757 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.04 (1H, m), 5.85 (1H, m), 5.54 (1H, ddd, J_{HH} = 1.2, 7.1 Hz, J_{HP} = 13.4 Hz), 4.23 (2H, m), 3.83 (3H, s), 3.82 (6H, d, J_{HP} = 10.7 Hz), 0.91 (9H, s), 0.07 (6H, s); ^{13}C NMR ($CDCl_3$) δ 154.7 (d, J_{CP} = 9.3 Hz), 136.0 (d, J_{CP} = 10 Hz), 119.8 (d, J_{CP} = 3.4 Hz), 71.0 (d, J_{CP} = 169 Hz), 62.6, 55.3, 53.8 (d, J_{CP} = 6.8 Hz), 25.9, 18.3, −5.4; ^{31}P NMR ($CDCl_3$) δ 20.0; HRMS (FAB, *NBA*, MNa^+) calcd. for $C_{14}H_{29}O_7PSiNa$: 391.1319. Found: 391.1321.

(*E*)-Methyl 2-Acetyl-3-(benzyloxymethyl)-5-(dimethoxyphosphoryl)pent-4-enoate 9a. $Pd_2(dba)_3$ (0.049 g, 0.053 mmol) and dppe (0.063 g, 0.16 mmol) were dissolved in anhydrous THF (15 mL). The reaction mixture was stirred at room temperature for 3−4 min under argon. Freshly distilled methyl acetoacetate (0.58 mL, 5.4 mmol) was added followed by a solution of phosphonate **10a** (0.93 g, 2.7 mmol) in anhydrous THF (5 mL). The resulting reaction mixture was heated at 70 °C in a preheated oil bath for 2.5 h. The reaction mixture was allowed to cool to room temperature and was then partitioned between brine and Et_2O. After separation, the aqueous layer was re-extracted with Et_2O and the combined organic layers were dried over anhydrous Na_2SO_4. The solvent was evaporated *in vacuo* and the crude product was purified by chromatography (SiO_2, EtOAc: Hexane, 60: 40) to give of **9a** as a colorless oil (1.2:1 mixture of diastereomers, 0.89 g, 86%). IR (neat) 1742, 1717 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.30 (5H, m), 6.73 (1H, m), 5.75 (1H, m), 4.43 (2H, m), 3.87 (1H, dd, J_{HH} = 3.5, 8.9 Hz), 3.67 (9H, m), 3.56 (1H, m), 3.48 (1H, m), 3.31 (1H, m), 2.22 (1.5H, s), 2.21 (1.5H, s); ^{13}C NMR ($CDCl_3$) δ 201.3, 201.1, 168.4, 168.3, 150.8 (d, J_{CP} = 3.9 Hz), 150.7 (d, J_{CP} = 4.8 Hz), 137.7, 137.6, 128.5, 128.4, 127.9, 127.81, 127.78, 119.1 (d, J_{CP} = 185 Hz), 118.9 (d, J_{CP} = 185 Hz), 73.7, 70.0, 69.8, 59.9, 59.8, 52.6, 52.5 (d, J_{CP}

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= 6.9 Hz), 52.4 (d, J_{CP} = 5.6 Hz), 43.6 (d, J_{CP} = 22 Hz), 43.5 (d, J_{CP} = 22 Hz), 30.7, 30.6; ^{31}P NMR ($CDCl_3$) δ 20.6, 20.5 ppm; HRMS (EI, MH^+) calcd. for $C_{18}H_{26}O_7P$: 385.1416. Found: 385.1418.

(*E*)-Tert-butyl 2-Acetyl-3-(benzyloxymethyl)-5-(dimethoxyphosphoryl)pent-4-enoate 9b. $Pd_2(dba)_3$ (0.13 g, 0.14 mmol) and dppe (0.17 g, 0.43 mmol) were dissolved in anhydrous THF (15 mL). The reaction mixture was stirred at room temperature for 3−4 min under argon. *tert*-Butyl acetoacetate (0.96 mL, 5.8 mmol) was added followed by a solution of phosphonate **10a** (0.50 g, 1.5 mmol) in anhydrous THF (5 mL). The resulting reaction mixture was heated at 70 °C in a preheated oil bath for 2 h. The reaction mixture was allowed to cool to room temperature and was then partitioned between brine and Et_2O. After separation, the aqueous layer was re-extracted with Et_2O and the combined organic layers were dried over anhydrous Na_2SO_4. The solvent was evaporated in *vacuo* and the crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 60: 40) to give **9b** as a colorless oil (1.4:1 mixture of diastereomers, 0.38 g, 62%). IR (neat) 1736, 1712 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.29 (5H, m), 6.74 (1H, m) 5.74 (1H, m), 4.45 (2H, m), 3.78 (2H, m), 3.69 (6H, d, J_{HP} = 12 Hz), 3.48 (1H, m), 3.26 (1H, m), 2.20 (3H, s), 1.43 (9H, s); ^{13}C NMR ($CDCl_3$) δ 201.81, 201.76, 167.2, 167.0, 151.5 (d, J_{CP} = 4.9 Hz), 151.3 (d, J_{CP} = 5.0 Hz), 138.0, 137.8, 128.6, 128.0, 127.94, 127.87, 118.8 (d, J_{CP} = 185 Hz), 118.7 (d, J_{CP} = 186 Hz), 82.8, 73.5, 70.2, 61.2, 61.0, 52.5 (d, J_{CP} = 5.7 Hz), 43.9 (d, J_{CP} = 22 Hz), 43.6 (d, J_{CP} = 22 Hz) 30.3, 30.1, 28.03, 28.01; ^{31}P NMR ($CDCl_3$) δ 20.80, 20.76; HRMS (FAB, NBA, MH^+) calcd. for $C_{21}H_{31}O_7P$: 426.1876. Found. 371:1323 (M-*tert*-Bu); Anal. Calcd for $C_{21}H_{31}O_7P\cdot H_2O$: C, 58.32; H, 3.38. Found: C, 58.32; H, 3.37.

(*E*)-Methyl 2-Acetyl-3-((tert-butyldimethylsilyloxy)methyl)-5-(dimethoxyphosphoryl)pent-4-enoate 9c. $Pd_2(dba)_3$ (0.09 g, 0.09 mmol) and dppe (0.11 g, 0.28 mmol) were dissolved in anhydrous THF (20 mL). The reaction mixture was stirred at room temperature for 3−4 min under argon. Freshly distilled methyl acetoacetate (0.82 mL, 7.6 mmol) was added followed by a solution of phosphonate **10b** (1.4 g, 3.8 mmol) in anhydrous THF (5 mL). The resulting reaction mixture was heated at 70 °C in a preheated oil bath for 2 h. The reaction mixture was allowed to cool to room temperature and was then partitioned between brine and Et_2O. After separation, the aqueous layer was re-extracted with Et_2O and the combined organic layers were dried over anhydrous Na_2SO_4. The solvent was evaporated in *vacuo* and the crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 60: 40) to give **9c** as a colorless oil (1.2:1 mixture of diastereomers, 0.99 g, 64%). IR (neat) 1740, 1715 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.71 (1H, m), 5.65 (1H, m), 3.88 (1H, dd, J_{HH} = 4.2, 9.0 Hz), 3.70 (10H, m), 3.60 (1H, m), 3.17 (1H, m), 2.27 (1.5H, s), 2.22 (1.5H, s), 0.87 (9H, s), 0.02 (6H, s); ^{13}C NMR ($CDCl_3$) δ 201.7, 201.5, 168.7, 168.6, 151.0 (d, J_{CP} = 4.8 Hz), 119.3 (d, J_{CP} = 185 Hz), 119.0 (d, J_{CP} = 185 Hz), 63.4, 63.3, 59.6, 59.5, 52.7 (d, J_{CP} = 5.4 Hz), 52.6 (d, J_{CP} = 5.1 Hz), 52.5, 45.9 (d, J_{CP}= 21 Hz), 45.7 (d, J_{CP}= 21 Hz), 30.6, 30.4, 26.0, 18.5, −5.4; ^{31}P NMR ($CDCl_3$) δ 20.6, 20.5; HRMS (FAB, NBA, MH^+) calcd. for $C_{17}H_{34}O_7PSi$: 409.1812. Found: 409.1817.

(*E*)-1-Tert-butyl 3-Methyl 2-(1-(benzyloxy)-4-(dimethoxyphosphoryl)but-3-en-2-yl)malonate 9d. $Pd_2(dba)_3$ (0.21 g, 0.23 mmol) and dppe (0.27 g, 0.68 mmol) were dissolved in anhydrous THF (30 mL). The reaction mixture was stirred at room temperature for 3−4 min under argon. A mixture of *tert*-Butyl methyl malonate (3.4 mL, 20 mmol) and BSA (4.85 mL, 19.8 mmol) in THF (5 mL) was added followed by a solution of phosphonate **10a** (3.08 g, 8.91 mmol) in anhydrous THF (5 mL). The resulting reaction mixture was heated at 70 °C in a preheated oil bath for 6 h. The reaction mixture was allowed to cool to room temperature and was then partitioned between brine and Et_2O. After separation, the aqueous layer was re-extracted with Et_2O and the combined organic layers were dried over anhydrous Na_2SO_4. The solvent was evaporated in *vacuo* and the crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 70: 30) to give **9d** as a colorless oil (unresolved mixture of diastereomers, 3.21 g, 81%). IR (neat) 1748, 1730 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.30 (5H, m), 6.79 (1H, m), 5.76 (1H, m), 4.46 (2H, m), 3.79 (1H, m), 3.67 (6H, d, J_{HP} = 10.9 Hz), 3.66 (3H, s), 3.58 (2H, m), 3.22 (1H, m), 1.42 (9H, s); ^{13}C NMR ($CDCl_3$) δ 168.9, 168.7, 167.0, 166.8, 150.8 (d, J_{CP} = 5.3 Hz), 138.0, 128.60, 128.59, 127.96, 127.91, 119.0 (d, J_{CP} = 187 Hz), 82.8, 73.5, 70.2, 70.0, 53.6, 53.5, 52.59 (d, J_{CP} = 5.7 Hz), 52.57 (d, J_{CP} = 9 Hz), 44.2 (d, J_{CP} = 22 Hz), 44.0 (d, J_{CP} = 22 Hz), 28.1; ^{31}P NMR (CDCl3) δ 20.7; HRMS (FAB, NBA, MNa^+) calcd. for $C_{21}H_{31}O_8PNa$: 465.1654. Found: 465.1653.

Dimethyl 2-(4-(1-Methoxyethylidene)-5-oxotetrahydrofuran-3-yl)ethylphosphonate 14a. Vinyl phosphonate **9a** (0.4 g, 1.0 mmol) was dissolved in CH_2Cl_2 (3 mL). The reaction flask was flushed with argon for 10 min and then 5% Pd on C (0.10 g) was added. The resulting reaction mixture was flushed with argon for another 5 min and then with hydrogen. The reaction mixture was stirred under hydrogen (balloon) for 6 h and then filtered through Celite. The Celite was washed with CH_2Cl_2 and the solvent was evaporated in *vacuo* to give **14a** (0.28 g, 100%) as an oil. IR (neat) 1693, 1638 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.42 (1H, dd, J_{HH} = 9.6, 9.6 Hz), 4.14 (1H, dd, J_{HH} = 4.5, 9.5 Hz), 3.75 (3H, d, J_{HP} = 10.8 Hz), 3.74 (3H, d, J_{HP} = 10.8 Hz), 3.72 (3H, s), 3.26 (1H, m), 2.20 (3H, d, J_{HH} = 1.1 Hz), 1.68 (4H, m); ^{13}C NMR ($CDCl_3$) δ 170.1, 166.4, 105.2, 75.2, 52.6 (d, J_{CP} = 6.4 Hz), 51.0, 42.4 (d, J_{CP} = 18 Hz), 26.1 (d, J_{CP} = 4.5 Hz), 21.5 (d, J_{CP} = 141 Hz), 14.5; ^{31}P NMR ($CDCl_3$) δ 35.2; HRMS (EI, M^+) calcd. for $C_{11}H_{19}O_6P$: 278.0919. Found: 278.0923; Anal. Calcd for $C_{11}H_{19}O_6P\cdot 3H_2O$: C, 46.2; H, 7.00 Found: C, 46.13; H, 7.00.

Dimethyl 2-(4-(1-Tert-butoxyethylidene)-5-oxotetrahydrofuran-3-yl)ethylphosphonate 14b. Vinyl phosphonate **9b** (0.10 g, 0.23 mmol) was dissolved in MeOH (3 mL). The reaction flask was flushed with argon for 10 min. Then 5% Pd on C (0.05 g) was added and the reaction mixture was flushed with argon for another 5 min and then with hydrogen. The reaction mixture was stirred under hydrogen (balloon) for 6 h and then filtered through Celite. The Celite was washed with CH_2Cl_2 and the solvent was evaporated in *vacuo* to give **14b** (0.07 g, quantitative) as an oil. IR (neat) 1689, 1638 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.37 (1H, dd, J_{HH} = 9.7, 9.7 Hz), 4.07 (1H, dd, J_{HH} = 4.6, 9.5 Hz), 3.72 (3H, d, J_{HP} = 10.8 Hz), 3.72 (3H, d, J_{HP} = 10.8 Hz), 3.20 (1H, m), 2.15 (3H, d, J_{HH} = 1.0 Hz) 1.75 (4H, m), 1.47 (9H, s); ^{13}C NMR ($CDCl_3$) δ 168.8, 165.5, 106.5, 79.9, 74.9, 52.6 (d, J_{CP} = 6.5 Hz), 42.7 (d, J_{CP} = 18 Hz), 28.6, 26.0 (d, J_{CP} = 4.4 Hz), 21.4 (d, J_{CP} = 141 Hz), 14.5; ^{31}P NMR ($CDCl_3$) δ 35.4; HRMS (EI, M^+) calcd. for $C_{14}H_{25}O_6P$: 320.1389. Found: 320.1389.

Methyl 2-Acetyl-3-(tert-butyldimethylsilyloxymethyl)-5-(dimethoxyphosphoryl)pentanoate 15. The vinyl phosphonate **9c** (0.3 g, 0.7 mmol) was dissolved in MeOH (3 mL) and the reaction flask was flashed with argon for 5 min. 10% Pd on C (0.08 g) was added and the reaction flask was flushed with argon for another 5 min and then with hydrogen. The reaction mixture was stirred under hydrogen (balloon) for 3 h, and then through Celite. The Celite was washed with CH_2Cl_2 and the solvent was evaporated in *vacuo* to give the saturated phosphonate **15** (1:1 mixture of diastereoisomers, 0.3 g, 100%) as a colorless oil. IR (neat) 1743, 1716 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 3.72 (9H, m), 3.49 (3H, m), 2.34 (1H, m), 2.27 (1.5H, s), 2.26 (1.5H, s), 1.74 (4H, m), 0.88 (9H, s), 0.02 (6H, s); ^{13}C NMR ($CDCl_3$) δ 202.9, 202.8, 169.50, 169.48, 62.0, 60.9, 60.8, 52.6, 52.5 (d, J_{CP} = 6.5 Hz), 40.93 (d, J_{CP} = 17 Hz), 40.90 (d, J_{CP} = 17 Hz), 30.5, 30.1, 26.0, 22.7 (d, J_{CP} = 140 Hz), 22.6 (d, J_{CP} = 140 Hz), 22.0 (d, J_{CP} = 6.5 Hz), 21.9 (d, J_{CP} = 6.6 Hz), 18.4, −5.5 (m); ^{31}P NMR ($CDCl_3$) δ 34.6; HRMS (FAB, *NBA*, MH^+) calcd. for $C_{17}H_{36}O_7PSi$: 411.1968. Found: 411.1969.

Methyl 2-Acetyl-3-(benzyloxymethyl)-5-(dimethoxyphosphoryl)pentanoate 16. The vinyl phosphonate **9a** (1.5 g, 3.9 mmol) was dissolved in MeOH (3 mL) and the reaction flask was flushed with argon for 5 min. 5% Pd on C (0.68 g) and pyridine (0.05 mL) were added. The resulting reaction mixture was flushed with argon for another 5 min and then hydrogen. The mixture was stirred under hydrogen (balloon) for 6 h, and then filtered through Celite. The

Celite was washed with CH_2Cl_2 (100 mL) and the solvent was evaporated in *vacuo* to give the saturated phosphonate **16** (1:1 mixture of diastereomers, 1.52 g, 100%). IR (neat) 1740, 1712 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.33 (5H, m), 4.43 (1H, s), 4.42 (1H, s), 3.72 (10H, m), 3.45 (2H, m), 2.49 (1H, m), 2.25 (1.5H, s), 2.22 (1.5H, s), 1.70 (4H, m);^{13}C NMR ($CDCl_3$) δ 202.5, 202.2, 169.11, 169.07, 137.8, 137.7, 128.1, 128.2, 127.6, 127.5, 73.0, 69.2, 69.1, 60.7, 52.2, 52.1 (d, J_{CP} = 6.6 Hz), 38.8 (d, J_{CP} = 17 Hz), 29.9, 29.7, 22.20 (d, J_{CP} = 140 Hz), 22.24 (d, J_{CP} = 4.4 Hz), 22.1 (d, J_{CP} = 140 Hz); ^{31}P NMR ($CDCl_3$) δ 34.6, 34.5; HRMS (FAB, *NBA*, MH^+) calcd. for $C_{15}H_{28}O_7P$: 387.1573. Found: 387.1555.

Synthesis of Monocyclic Phosphonate Analog 8. To a solution of phosphonate **16** (1.13 g, 2.91 mmol) in CH_3CN (1.5 mL) was added NaI (0.44 g, 2.9 mmol). The resulting mixture was heated at reflux overnight. The solvent was removed in *vacuo* to obtain the monosodium salt as a white solid (1.43 g, crude). To a suspension of the sodium salt in acetone (5 mL) was added Amberlite IR 120 resin. The resulting mixture was shaken on an orbital shaker until the sodium salt completely dissolved and the color of the solution became amber. The resin was removed by filtration and washed with acetone to give the phosphonic acid **17** as an amber colored solution in acetone. The acetone was evaporated in *vacuo* to obtain the crude monophosphonic acid as a red viscous liquid (1.03 g). To a solution of the monophosphonic acid (1.03 g, 2.75 mmol) in freshly distilled CH_2Cl_2 (14 mL) was added EDC (0.67 g, 3.5 mmol), HOBt (0.54 g, 4.0 mmol) and Hunig's base (0.66 mL, 3.9 mmol). After stirring the resulting solution for 24 h the solvent was evaporated in *vacuo*. The resulting crude product was dissolved in EtOAc (150 mL) and washed with 0.5 M HCl (2x) and saturated $NaHCO_3$ (2x). The organic layer was dried over $MgSO_4$ and the solvent was evaporated in *vacuo*. The crude product was purified by column chromatography (SiO_2, EtOAc: Hexane, 70: 30) to give a 1:1.4 diastereomeric mixture of **8** as a colorless oil (0.73 g, 73% in 3 steps). Further chromatographic separation (SiO_2, EtOAc: Hexane, 50: 50) gave the pure diastereomer **8a**. IR (neat) 1717, 1643 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.32 (5H, m), 4.50 (2H, m), 3.80 (3H, d, J_{HP} = 11 Hz), 3.73 (3H, s), 3.65 (1H, d, J_{HH} = 9.2 Hz), 3.53 (1H, dd, J_{HH} = 6.5, 9.3 Hz), 3.38 (1H, m), 2.24 (3H, s), 2.07 (4H, m); ^{13}C NMR ($CDCl_3$) δ 168.6, 157.4 (d, J_{CP} = 7.5 Hz), 138.3, 128.6, 127.9, 127.8, 120.2 (J_{CP} = 5.0 Hz), 73.1, 68.9, 52.3 (J_{CP} = 7.0 Hz), 52.2, 37.7, 22.12 (J_{CP} = 134 Hz), 22.5 (J_{HP} = 7.1 Hz), 21.6; ^{31}P NMR ($CDCl_3$) δ 26.6. HRMS (FAB, NBA, MH^+) calcd. for $C_{17}H_{23}O_6P$: 354.1232. Found: 355.1315.

Phosphonate Analog of Cyclophostin 6. The monocyclic enolphosphonate **8** (1.06 g, 2.99 mmol) was dissolved in MeOH (6 mL). The reaction flask was flushed with argon for 10 min. 10% Pd on C (0.50 g) was added and the reaction mixture was flushed with argon for another 5 min followed by hydrogen. The resulting mixture was stirred under hydrogen (balloon) for 3 h. The reaction mixture was filtered through Celite. The Celite was washed with CH_2Cl_2 and the solvent was evaporated in *vacuo* to give the bicyclic phosphonate **6** (1.4:1mixture of diastereoisomers, 0.70 g, 100%) as a colorless oil. Chromatographic separation (SiO_2, EtOAc: Hexane, 50: 50) gave *cis*-diastereomer **6b** was white crystalline solid which was further purified by crystallizing from EtOAc/hexane and the *trans*-diastereomer **6a** as a low melting solid.

***cis*-Phosphonate Analog of Cyclophostin 6b:** (mp 119 °C) IR (neat) 1747, 1673 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.5 (1H, dd, J_{HH} = 9.5, 9.0 Hz), 3.87 (3H, d, J_{HP} = 11 Hz), 3.83 (1H, m), 3.34 (1H, m), 2.46 (3H, s), 2.34 (1H, m), 2.04 (3H, m); ^{13}C NMR ($CDCl_3$) δ 170.2, 161.1 (d, J_{CP} = 6.6 Hz), 114.8 (d, J_{CP} = 3.8 Hz), 70.1, 52.8 (d, J_{CP} = 7.2 Hz), 39.1, 26.46 (d, J_{CP} = 136 Hz), 26.51 (d, J_{CP} = 6.9 Hz),18.92, 18.90; ^{31}P NMR ($CDCl_3$) δ 25.4.

***trans*-Phosphonate Analog of Cyclophostin 6a:** IR (neat) 1749, 1672 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.5 (1H, dd,, J_{HH} = 9.0, 6.0 Hz), 3.83 (3H, d,, J_{HP} =11 Hz), 3.81 (1H, app m), 3.40 (1H, m), 2.42 (3H, s), 2.05 (4H, m); ^{13}C NMR ($CDCl_3$) δ 170.2, 160.3 (d, J_{CP} = 9.8 Hz), 113.9, 69.9, 52.9 (d, J_{CP} = 6.8 Hz), 38.5, 26.1 (d, J_{CP} = 134 Hz), 26.8 (d, J_{CP} = 7.7 Hz), 18.6; ^{31}P NMR ($CDCl_3$) δ 21.9 ppm; HRMS (EI, M^+) calcd. for $C_9H_{13}O_5P$: 232.0501. Found: 232.0503.

Dimethyl 1-(2-Oxodihydrofuran-3(2H)-ylidene)ethyl Phosphate 19. A solution of 2-acetylbutyrolactone (0.37 g, 2.9 mmol) and Hunig's base in anhydrous CH_2Cl_2 (5 mL) was added to a solution of dimethylphosphoric acid (0.30 g, 2.4 mmol) and DCC (0.74 g, 3.6 mmol) in anhydrous CH_2Cl_2 (10 mL). Then DMAP (0.12 g, 0.98 mmol) was added and the reaction mixture was stirred overnight. The reaction mixture was diluted with CH_2Cl_2 and washed with water. The aqueous layer was extracted with CH_2Cl_2 (2×) and the combined organic layers were dried over $MgSO_4$. The solvent was evaporated in vacuo and the residue was purified by column chromatography (SiO_2, EtOAc:Hexane, 1:1) to yield the enolphosphate **19** (0.36 g, 64%) as a colorless oil. IR (neat) 1751, 1689 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.31 (2H, t, J_{HH} = 7.5 Hz), 3.87 (6H, d, J_{HP} = 11 Hz), 3.04 (2H, m), 2.53 (3H, d, J_{HP} = 4.4 Hz); ^{13}C NMR ($CDCl_3$) δ 170.7, 157.3 (d, J_{CP} = 7.1 Hz), 111.7 (d, J_{CP} = 9.1 Hz), 64.7, 55.2 (d, J_{CP} = 6.2 Hz), 26.1, 16.7; ^{31}P NMR ($CDCl_3$) δ −4.7; HRMS (EI, M^+) calcd. for $C_8H_{13}O_6P$: 236.0450 Found: 236.0447.

Quantitation of Antiacetylcholinesterase Activity. The action of the new compounds against recombinant human and electric eel acetylcholinesterase (AChE) were determined by using Ellman's assay.[15] The lyophilized AChE was solubilized in 20 mM Tris HCl buffer, pH 7.5 and 1% BSA. The compounds were solubilized in isopropanol and preincubated with the enzyme for 30 min at room temperature and the residual activity of the enzyme was determined with 0.5 mM acetylthiocholine iodide and 0.3 mM 5,5′-dithiobis-2-nitrobenzoic acid in 100 mM sodium phosphate, pH 8.0 at 37 °C. The absorbance of thionitrobenzoate anion at 412 nm was monitored every 2 s for 50 s. Reaction rates (average of triplicate) in absorbance/sec were converted to umol/min by using thionitrobenzoate anion extinction coefficient 14,150 $M^{-1}cm^{-1}$. In the assay, the concentration of isopropanol was always maintained below 10%. The activity of the enzyme was not altered by the presence of 10% of isopropanol. The enzyme activity at each concentration (0 − 320 μM) of test compound was expressed as a percent of the activity in the absence of compound to get % residual activity. Residual activity (%) was plotted against the compound concentration (uM) and the inhibitory action was calculated as an IC_{50}, defined as the concentration of compound (μM) required to inhibit 50% of enzymatic activity.

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Supporting Information Available: General experimental, ^1H and ^{13}C NMR spectra for compounds **10a**, **10b**, **9a**, **9b**, **9c**, **9d**, **14a**, **14b**, **15**, **16**, **8**, **8a**, **6b**, and **6a**. X-Ray data for compounds **6b**. This material is available free of charge via the Internet at http://pubs.acs.org.

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