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# Structure−Activity Relationship of Purine and Pyrimidine Nucleotides as Ecto-5′-Nucleotidase (CD73) Inhibitors

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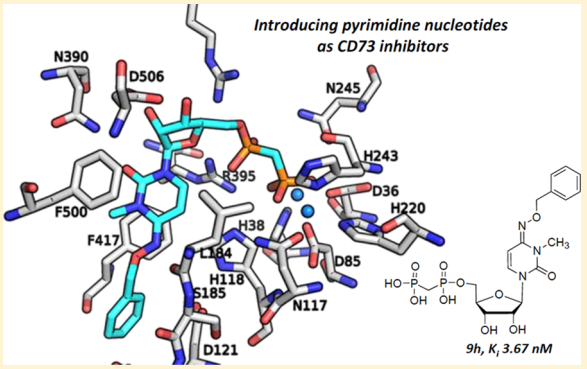
Supporting Information

**ABSTRACT:** Cluster of differentiation 73 (CD73) converts adenosine 5′-monophosphate to immunosuppressive adenosine, and its inhibition was proposed as a new strategy for cancer treatment. We synthesized 5′-*O*-[(phosphonomethyl)phosphonic acid] derivatives of purine and pyrimidine nucleosides, which represent nucleoside diphosphate analogues, and compared their CD73 inhibitory potencies. In the adenine series, most ribose modifications and 1-deaza and 3-deaza were detrimental, but 7-deaza was tolerated. Uracil substitution with $N^3$-methyl, but not larger groups, or 2-thio, was tolerated. 1,2-Diphosphono-ethyl modifications were not tolerated. $N^4$-(Aryl)alkyloxy-cytosine derivatives, especially with bulky benzyloxy substituents, showed increased potency. Among the most potent inhibitors were the 5′-*O*-[(phosphonomethyl)phosphonic acid] derivatives of 5-fluorouridine (**4l**), $N^4$-benzoyl-cytidine (**7f**), $N^4$-[*O*-(4-benzyloxy)]-cytidine (**9h**), and $N^4$-[*O*-(4-naphth-2-ylmethyloxy)]-cytidine (**9e**) ($K_i$ values 5−10 nM at human CD73). Selected compounds tested at the two uridine diphosphate-activated P2Y receptor subtypes showed high CD73 selectivity, especially those with large nucleobase substituents. These nucleotide analogues are among the most potent CD73 inhibitors reported and may be considered for development as parenteral drugs.




## INTRODUCTION

Ecto-5′-nucleotidase (ecto-5′-NT, eN, CD73, EC 3.1.3.5) is a glycosylphosphatidylinositol (GPI)-linked cell surface enzyme that dephosphorylates extracellular nucleoside monophosphates.[1−3] The enzyme can be cleaved from its GPI linker and is also present in a soluble active form in serum. The vertebrate enzyme selectively hydrolyzes adenosine 5′-monophosphate (AMP) over adenosine 2′- or 3′-monophosphates, leading to elevated extracellular concentrations of adenosine.[1] The X-ray crystallographic structures of the enzyme in complex with either an inhibitor or a substrate have been reported.[4,5] There is a marked conformational rearrangement of the structure as catalysis occurs. Two conformational classes have been determined: an open and a closed form.

Although the substrate, AMP, is not a potent agonist of adenosine receptors (ARs), the enzymatic reaction product, adenosine, activates four AR subtypes ($A_1$AR, $A_{2A}$AR, $A_{2B}$AR, and $A_3$AR).[6] One of the important activities of adenosine is the suppression of inflammation.[6] Thus, cluster of differentiation 73 (CD73) upregulation and the increased production of adenosine are beneficial in chronic inflammatory diseases. A coexpression of CD73 and $A_{2A}$AR found in many tissues

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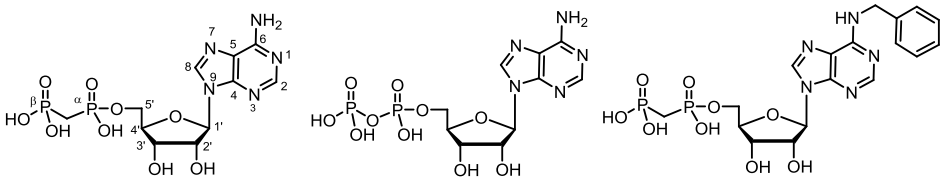
J. Med. Chem. XXXX, XXX, XXX−XXX

**Chart 1. Selected Inhibitors of Ecto-5′-Nucleotidase (eN, CD73)[20]**

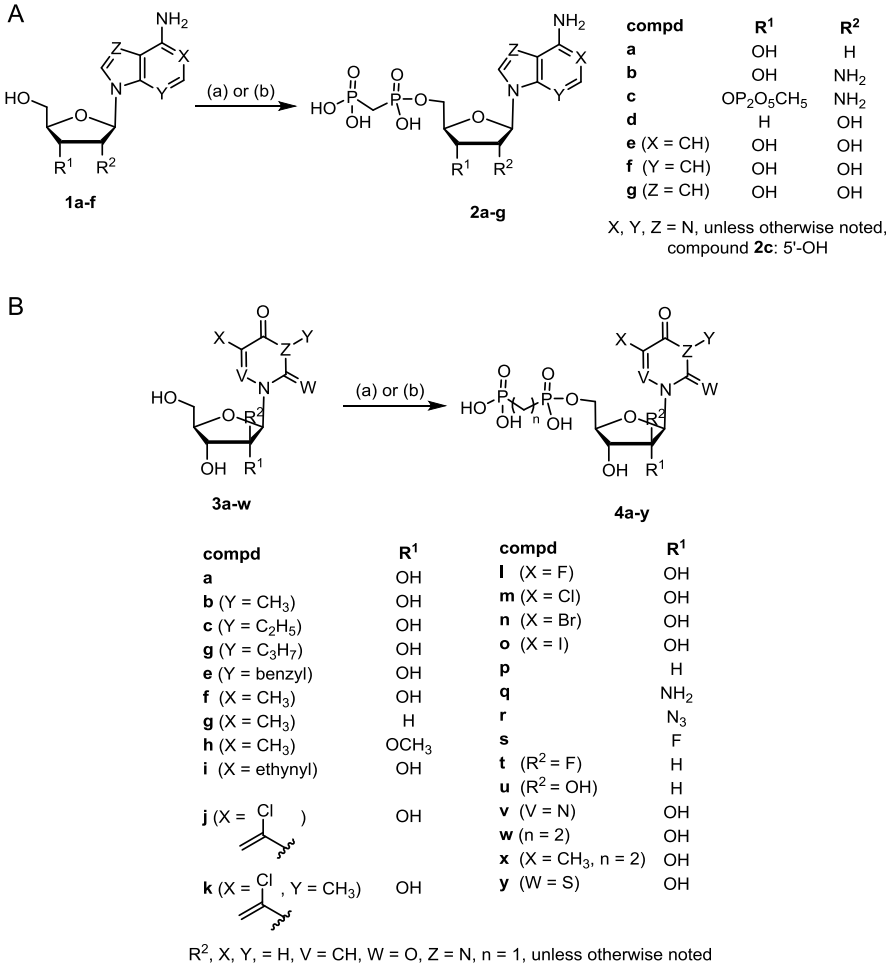



$K_i$ rat *e*N: 197± 5.0 nM
$K_i$ human *e*N: 88.4 ± 4.0 nM
$K_i$ human serum *e*N: 487 ± 186 nM

$K_i$ rat *e*N: 3380 nM

$K_i$ rat *e*N: 9.03 ± 1.24 nM
$K_i$ human *e*N: 2.21± 0.40 nM
$K_i$ human serum *e*N: 18.8 ± 12.5 nM

**Scheme 1. Synthesis of Adenosine 2a−g and Uridine Derivatives 4a−y[a]**




| compd | $R^1$ | $R^2$ |
|---|---|---|
| a | OH | H |
| b | OH | $NH_2$ |
| c | $OP_2O_5CH_5$ | $NH_2$ |
| d | H | OH |
| e (X = CH) | OH | OH |
| f (Y = CH) | OH | OH |
| g (Z = CH) | OH | OH |

X, Y, Z = N, unless otherwise noted, compound **2c**: 5′-OH

| compd | $R^1$ |
|---|---|
| a | OH |
| b (Y = $CH_3$) | OH |
| c (Y = $C_2H_5$) | OH |
| g (Y = $C_3H_7$) | OH |
| e (Y = benzyl) | OH |
| f (X = $CH_3$) | OH |
| g (X = $CH_3$) | H |
| h (X = $CH_3$) | $OCH_3$ |
| i (X = ethynyl) | OH |
| j (X =  ) | OH |
| k (X =  , Y = $CH_3$) | OH |

| compd | $R^1$ |
|---|---|
| l (X = F) | OH |
| m (X = Cl) | OH |
| n (X = Br) | OH |
| o (X = I) | OH |
| p | H |
| q | $NH_2$ |
| r | $N_3$ |
| s | F |
| t ($R^2$ = F) | H |
| u ($R^2$ = OH) | H |
| v (V = N) | OH |
| w (n = 2) | OH |
| x (X = $CH_3$, n = 2) | OH |
| y (W = S) | OH |

$R^2$, X, Y, = H, V = CH, W = O, Z = N, n = 1, unless otherwise noted

[a]Reagents and conditions: (a) DCC (3 equiv), methylene diphosphonic acid (1.5 equiv), DMF, room temp, 3−24 h; for compounds **4w** and **4x**: DCC (3 equiv), ethylene diphosphonic acid (1.5 equiv), DMF, room temp, 3 h (b) methylenebis(phosphonic dichloride) (3 equiv), trimethyl phosphate, 0 °C, 30 min, then TEAC buffer pH 8.4−8.6, rt, 30 min.

including the brain and immune cells, especially when inflammation is present, allows the concerted activation of this receptor.[2,7,8] However, in the tumor microenvironment, elevated CD73 and adenosine counteract the body's immune defense against the tumor.[9−14] This is particularly important in cancer immunotherapy, for which coadministration of either an $A_{2A}$AR antagonist or an inhibitor of CD73 offers synergistic antitumor activity. A CD73 inhibitor also potentiates the in vivo anticancer effect of inhibitors of nicotinamide phosphoribosyltransferase,[15] which is required for the biosynthesis of intracellular $NAD^+$. Antibodies against CD73 are currently undergoing clinical trials for cancer therapy.[16,17] The development of CD73 assays[18,19] has led to reports of diverse inhibitors of the enzyme.[20−24] Among the first potent inhibitors to be identified was adenosine-5′-*O*-[(phosphonomethyl)phosphonic acid (**I**, *α*,*β*-methylene-ADP, AOPCP) (Chart 1).[25] Also, various anthraquinone[21] and sulfonamide[22] derivatives were found to be competitive inhibitors, whereas polyphenols[26] and polyoxometalates[27] are noncompetitive CD73 inhibitors. Recently, adenine nucleotide analogues of **I** that display low nanomolar potency in inhibition of CD73 were identified.[12] Modeling based on the X-ray structures of CD73 has aided in the design of novel inhibitors.[28] The present work complements that study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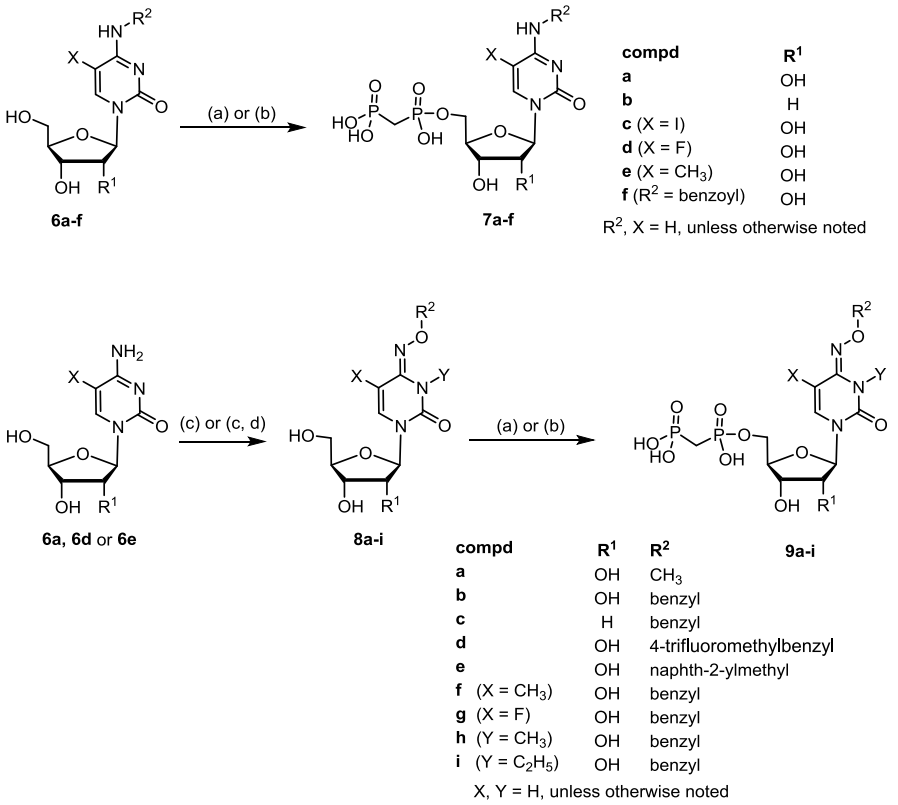
J. Med. Chem. XXXX, XXX, XXX−XXX

**Scheme 2. Synthesis of Cytosine-Derived 5′-*O*-[(Phosphonomethyl)phosphonic Acid] Derivatives 7a−f and 9a−i**[a]




[a]Reagents and conditions: (a) DCC (3 equiv), methylene diphosphonic acid (1.5 equiv), DMF, room temp, 3−24 h; (b) methylenebis(phosphonic dichloride) (3 equiv), trimethyl phosphate, 0 °C, 30 min, then TEAC buffer pH 8.4−8.6, rt, 30 min: (c) $R^3$-*O*-$NH_2$*x*HCl, pyridine, 80 °C, 12 h. (d) alkyl iodide (ol, 1.5 equiv), $K_2CO_3$ (1.7 equiv) in DMF/acetone (1:1) at 50 °C for 3 d.

through the exploration of the structure−activity relationships (SARs) of both purine and pyrimidine nucleotides as inhibitors of CD73. An advantage of inhibitors derived from pyrimidines would be that if hydrolyzed to the parent nucleoside, they would not activate ARs, unlike adenine nucleotide **I** and its congeners.

## RESULTS

**Chemistry.** There are several commonly used multistep methods for the preparation of nucleoside-5′-*O*-[(phosphonomethyl)phosphonic acid] derivatives, that is, either reacting the protected nucleoside with activated bisphosphonate or utilizing methylene diphosphonic acid and coupling reagents.[29−31] However, despite the use of protecting groups, these synthetic strategies suffer overall from very low yields. Previously, we were able to demonstrate that phosphonylation reactions of unprotected nucleosides using methylenebis(phosphonic dichloride) in trimethyl phosphate provided the nucleoside-5′-*O*-[(phosphonomethyl)phosphonic acids] as the main products under optimized conditions.[20] Furthermore, reacting unprotected nucleosides with 1.5 equiv methylene diphosphonic acid and 3 equiv dicyclohexylcarbodiimide (DCC) in dimethylformamide (DMF) led to the formation of nucleoside-5′-*O*-[(phosphonomethyl)phosphonic acids] as the main products as well. Therefore, we employed solely unprotected nucleosides as starting materials in our syntheses. When additional phosphonylation occurred at the 2′- and/or 3′-position, these side products were easily separated from the desired 5′-substituted product through a combination of ion-exchange and reverse-phase C18 chromatography. The SAR of the purine scaffold in AOPCP derivatives was extensively explored in a previous study, leading to CD73 inhibitors with potency in the low nanomolar range.[12] However, the SAR of the ribose moiety of AOPCP derivatives had not been explored. Therefore, we prepared 2′-deoxy (**2a**), 2′-amino-2′-deoxy (**2b**), and 3′-deoxy (**2d**) AOPCP derivatives by reacting the respective nucleoside with methylene diphosphonic acid in the presence of DCC in DMF (Scheme 1). In the case of **2b**, the reaction proceeded very slowly, and the 3′-phosphonate side product (**2c**) was formed to an equal extent (0.5% yield). Compound **2c** was isolated, and its structure was unequivocally determined using $^1$H−$^1$H-COSY NMR spectroscopy. To address ring variations of the adenine moiety, the 1-deaza (**2e**), 3-deaza (**2f**), and 7-deaza (**2g**) AOPCP derivatives were prepared by the reaction of unprotected nucleosides with methylenebis(phosphonic dichloride) in trimethyl phosphate to increase yields (Scheme 1).

Then, we turned our focus to pyrimidine-derived 5′-*O*-[(phosphonomethyl)phosphonic acids, for example, UOPCP (**4a**), prepared by phosphonylation of uridine (**3a**). Furthermore, $N^3$-substituted nucleosides **3b−e** were prepared via nucleophilic substitution using **3a** (Supporting Information), and their subsequent phosphonylation afforded compounds **4b−e**. Substitution of the uracil 5-position was explored with methyl **4f−h** and halogen **4l−o** derivatives. The reaction of 5-ethynyl-uridine with methylenebis(phosphonic dichloride) led, besides the desired 5-ethynyl-uridine derivative **4i**, to the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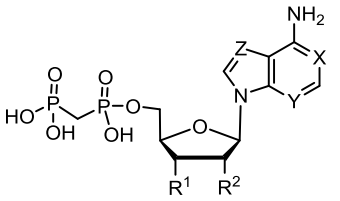
formation of 5-(1-chlorovinyl)uridine- (**4j**) and 5-(1-chlorovinyl)-3-methyluridine-5′-*O*-[(phosphonomethyl)phosphonic acid] (**4k**) through the addition of HCl to the alkyne bond. In order to explore the variations of the 2′-position at the ribose moiety, 2′-deoxy (**4p**), 2′-amino-2′-deoxy (**4q**), 2′-azido-2′-deoxy (**4r**), and 2′-fluoro-2′-deoxy (**4s**) derivatives were prepared. The role of the stereochemistry at the 2′-position was addressed through the synthesis of 2′-*ara*-fluoro-2′-deoxyuridine- (**4t**) and 1-(β-D-arabinofuranosyl)-uridine-5′-*O*-[(phosphonomethyl)phosphonic acid (**4u**). Synthesis of 6-azauridine derivative (**4v**) allowed the introduction of an H-bond acceptor at the 6-position. In addition to the methylene group, the linker between the two phosphonate groups was extended to an ethylene moiety by reacting ethylene diphosphonic acid with the respective nucleosides **3a** and **3f** to afford uridine- (**4w**) and 5-methyluridine-5′-*O*-[(phosphonoethyl)phosphonic acid] (**4x**). 2-Thiouridine derivative **4y** was prepared following a previously published procedure.[41]

Next, cytidine derivatives varying at the 2′-position (**7a** and **7b**), as well as at the 5-position (**7c**–**e**), were prepared (Scheme 2). The $N^4$-benzoyl COPCP derivative **7f** displayed gradual decomposition when left at room temperature (rt) over several weeks in aqueous solution to UOPCP (**4a**) and COPCP (**7a**) (Supporting Information). In order to introduce bulky aromatic substituents at the 4-position of the cytosine moiety without the inherent instability issues as seen with the $N^4$-benzoyl COPCP derivative **7f**, we turned our focus toward alkoxyimino derivatives **9a**–**i**. The required nucleosides were prepared by either reacting cytidine (**6a**), 2′-deoxycytidine (**6b**), 5-fluorocytidine (**6d**), or 5-methylcytidine (**6e**) with respective alkoxyamino derivatives in pyridine,[7] followed by the phosphonylation reaction to afford compounds **9a**–**f**, or by reacting cytidine (**6a**) with benzyloxyamine, followed by nucleophilic substitution at the 3-position (Supporting Information) and subsequent 5′-*O*-phosphonylation of the nucleosides to afford compounds **9h** and **9i** (Scheme 2). Furthermore, 3-deazauridine-5′-α,β-methylene-diphosphate (**10**), (*S*)-methanocarba-5′-α,β-methylene-diphosphate (**11**), and the ethyl ester of 2-thio-uridine diphosphate (UDP) (**12**)[32] were prepared to extend the exploration of SAR of the nucleotide analogues as CD73 inhibitors. All phosphonate-substituted nucleotides were purified to homogeneity by ion-exchange chromatography, followed by reverse-phase C18 HPLC.

**Pharmacological Evaluation.** The potency of the compounds to inhibit CD73 was determined by a radiometric CD73 assay using [2,8-$^3$H]AMP as a substrate and recombinant soluble rat CD73.[29,33] After the enzymatic reaction, the substrate was separated from its product [2,8-$^3$H]adenosine by precipitation with lanthanum chloride, followed by filtration through glass fiber filters.[34] For compounds that inhibited CD73 activity by more than 50% at an initial screening concentration of 1 μM, full concentration–response curves were determined in at least three separate experiments performed in duplicates using 10 different concentrations of the inhibitor. $K_i$ values were calculated from the obtained $IC_{50}$ values using the Cheng–Prusoff equation.[30] Results are summarized in Tables 1–3, and concentration–inhibition curves are shown in Figures 1 and 2. Rat CD73 is similar to the human isoform (87% sequence identity, BLAST algorithm[35,36]), and the active sites only differ in a single amino acid (Phe in the human enzyme is replaced by Tyr in rat).[34] Previous studies had shown that the potency of competitive inhibitors targeting rat CD73 showed comparable or higher potency for human CD73.[12] Nevertheless, the most potent compounds (**4l**, **7f**, **9d**, **9e**, **9g**, and **9h**) were analyzed using recombinant soluble human CD73. Furthermore, to study the inhibitors in a less artificial environment, they were investigated on membrane-anchored CD73 using membrane preparations derived from the triple-negative breast cancer (TNBC) cell line MDA-MB-231. These cells overexpress CD73, serve as an in vitro model for TNBC, and had previously been used for the development of therapeutic antibodies against CD73.[16,37–40]

**Table 1. Inhibitory Potency of Adenine-Based AOPCP Analogues 2a–g at Rat CD73**[a]




**2a-g**

| compd | substitution | $R^1$ | $R^2$ | $K_i$ ± SEM (nM) (% inhibition at indicated concentration), rat CD73 |
|---|---|---|---|---|
| **I**, (AOPCP) | | OH | OH | 167 ± 53 |
| **2a** | | OH | H | >1000 (30%) |
| **2b** | | OH | $NH_2$ | >1000 (2%) |
| **2c** | 5′-OH | $OP_2O_5CH_5$ | $NH_2$ | >1000 (8%) |
| **2d** | | H | OH | 1970 ± 220 |
| **2e** | X = CH | OH | OH | >1000 (36%) |
| **2f** | Y = CH | OH | OH | >1000 (36%) |
| **2g** | Z = CH | OH | OH | 88.6 ± 4.0 |

[a]X, Y, Z = N, unless otherwise noted, compound **2c**: 5′-OH.

**Structure–Activity Relationships.** AOPCP (**I**) displays moderate CD73 inhibitory activity ($K_i$, nM) (167, Table 1), whereas UOPCP (**4a**, 1830, Table 2) and COPCP (**7a**, 898, Table 3) are 11- to 5-fold less active. Variations at the ribose moiety **2a**–**2d**, **4p**–**4u**, and **7b** are not tolerated, with the exception for 2′-*ara*-fluoro-2′-deoxyuridine 5′-α,β-methylene-diphosphate (**4t**, 1750 nM) that displays similar inhibitory activity compared to UOPCP (**4a**). 3-Deaza (**2e**) and 1-deaza (**2f**) derivatives of AOPCP are inactive, whereas the 7-deaza analogue (**2g**, 88.6 nM) displays 2-fold higher CD73 inhibitory activity than AOPCP.

Introduction of a substituent larger than a methyl group at the uridine 3-position is not tolerated: 3-methyluridine (**4b**, 1864 nM) is equipotent to UOPCP (**4a**), whereas 3-ethyl- (**4c**), 3-propyl- (**4d**), and the 3-benzyl-uridine-5′-α,β-methylene-diphosphate (**4e**) are inactive. These results indicate the limited size of the binding pocket. Substitution at the uridine 5-position showed the following rank order of potency ($K_i$, nM): 5-F (**4l**, 14.8) > 5-Cl (**4m**, 86.7) = 5-Br (**4n**, 88.7) > 5-I (**4o**, 162) ≥ 5-ethynyl (**4i**, 276) ≥ 5-methyl (**4f**, 338) ≥ 5-(1-chlorovinyl) (**4j**, 424). Combination of a 5-methyl group with variations at the ribose 2′-position [2′-deoxy (**4g**, 639 nM) and 2′-methoxy (**4h**, inactive)] as well as combining a 5-(1-chlorovinyl) group with a 3-methyl substituent (**4k**, 1050 nM) reduced inhibitory activity. Extending the distance between the phosphonate groups by introducing an ethylene linker (**4w**,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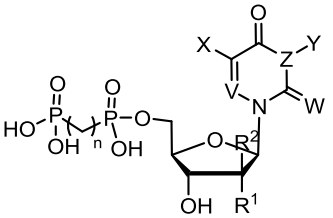
J. Med. Chem. XXXX, XXX, XXX–XXX

**Table 2. Inhibitory Potency of Uridine-Derived Nucleotides 4a–y as Rat CD73 Inhibitors**[a]



**4a-y**

| compd | substitution | $R^1$ | $R^2$ | $K_i$ ± SEM (nM) (% inhibition at indicated concentration), rat CD73 |
|---|---|---|---|---|
| UOPCP **4a** | | OH | H | 1830 ± 530 |
| **4b** | Y = $CH_3$ | OH | H | 1860 ± 400 |
| **4c** | Y = $C_2H_5$ | OH | H | >1000 (4%) |
| **4d** | Y = $C_3H_7$ | OH | H | >1000 (7%) |
| **4e** | Y = benzyl | OH | H | >1000 (3%) |
| **4f** | X = $CH_3$ | OH | H | 338 ± 56 |
| **4g** | X = $CH_3$ | H | H | 639 ± 65 |
| **4h** | X = $CH_3$ | $OCH_3$ | H | >1000 (3%) |
| **4i** | X = ethynyl | OH | H | 276 ± 37 |
| **4j** | X = 1-chlorovinyl | OH | H | 424 ± 27 |
| **4k** | X = 1-chlorovinyl, Y = $CH_3$ | OH | H | 1050 ± 290 |
| **4l** | X = F | OH | H | 14.8 ± 1.9 |
| **4m** | X = Cl | OH | H | 86.7 ± 7.6 |
| **4n** | X = Br | OH | H | 88.7 ± 12.5 |
| **4o** | X = I | OH | H | 162 ± 4 |
| **4p** | | H | H | >1000 (37%) |
| **4q** | | $NH_2$ | H | >1000 (2%) |
| **4r** | | $N_3$ | H | >1000 (9%) |
| **4s** | | F | H | >1000 (11%) |
| **4t** | | H | F | 1750 ± 380 |
| **4u** | | H | OH | >1000 (8%) |
| **4v** | V = N | OH | H | >1000 (21%) |
| **4w** | *n* = 2 | OH | H | >1000 (4%) |
| **4x** | *n* = 2, X = $CH_3$ | OH | H | >1000 (9%) |
| **4y** | W = S | OH | H | >1000 (7%) |

[a] $R^2$, X, Y = H, W = O, V = CH, Z = N, *n* = 1, unless otherwise noted.

**4x**) led to a complete loss of CD73 inhibition. Furthermore, replacement of 2-oxo by 2-thio (**4y**) or the introduction of a nitrogen atom at the 6-position was not tolerated.

Because the SAR around the uridine scaffold appeared to be rather limited, tolerating only a small methyl group at the 3-position (**4b**) and rather small, highly electronegative substituents at the 5-position, such as fluoro (**4l**), we decided to further explore the cytidine scaffold. COPCP (**7a**) was twice as potent as UOPCP (**4a**). However, for the COPCP derivatives, introduction of a substituent at the 5-position had a less pronounced effect, leading to an increase in potency in the following rank order ($K_i$, nM): 5-$CH_3$ (**7e**, 2030) < 5-H (**7a**, COPCP, 898) ≤ 5-I (**7c**, 502) ≤ 5-F (**7d**, 349) but altogether rather moderate activity. Surprisingly, introduction of a benzylamide at the 4-position (**7f**) provided a 5′-*α*,*β*-methylene-diphosphate derivative with a CD73 inhibitory potency of 13.9 nM. This high potency indicated the presence of a large hydrophobic subpocket that could be probed by further structural modification of the inhibitor. Unfortunately, quality control liquid chromatography–mass spectrometry (LC–MS) experiments displayed decomposition of compound **7f** to UOPCP, which was additionally confirmed via NMR experiments (Supporting Information, Figure S1). In order to address the hydrophobic subpocket of CD73, we envisaged the introduction of an alkoxyimino group at the 4-position, leading to an increase in potency in the following order ($K_i$, nM): $H_3CON$= (**9a**, 257) < benzyloxy-N= (**9b**, 112) < 4-$F_3C$-benzyloxy-N= (**9d**, 30.3) ≤ naphthalen-2-ylmethoxy-N= (**9e**, 18.8). Combination of a 4-benzyloxyimino group with a methyl group at the 5-position (**9f**, 321 nM) did not improve the CD73 inhibitory activity, and introduction of a 5-F substituent had no effect (**9g**, 85.1 nM). Remarkably, introduction of a methyl group at the 3-position of the benzyloxyimino derivative (**9h**, 3.67 nM) led to a 23-fold increase in inhibitory activity and provided the most potent compound of the series. However, the tolerated size of the substituent remained limited to a methyl group, as the ethyl derivative (**9i**, 262 nM) displayed a 100-fold drop in inhibitory potency. 3-Deazauridine-5′-*α*,*β*-methylene-diphosphate (**10**), (*S*)-methanocarba-uridine-5′-*α*,*β*-methylene-diphosphate (**11**), and the ethyl ester of 2-thio-UDP (**12**)[32] were inactive at CD73.

Although it is well-known that rat and human CD73 share identical orthosteric binding sites, and species differences for competitive inhibitors are therefore moderate, the most potent compounds (**4l**, **7f**, **9d**, **9e**, **9g**, and **9h**) were additionally evaluated for the inhibition of human CD73. We employed a recombinantly expressed soluble enzyme (Figure 3) as well as membrane preparations of CD73-expressing MDA-MB-231 cells (Figure 4). The comparison of potencies measured with the different sources of CD73 (see Table 4 and Figure 5) confirmed the observation that AOPCP analogues are usually slightly more potent at human CD73 as compared to the rat enzyme.[4,20] Compounds **4l**, **7f**, **9d**, and **9e** are 2- to 3-fold more potent, whereas **9g** is 5-fold more potent. However, the most potent compound at rat CD73 (**9h**, 3.67 nM) is slightly less potent at the human enzyme ($K_i$, soluble CD73, 10.6 nM; membrane preparation, 7.96 nM). All tested inhibitors were similarly potent at soluble CD73 as compared to the membrane-bound enzyme.

**Selectivity.** *UDP-Activated Receptors.* Various pyrimidine-derived nucleoside 5′-diphosphonates were previously shown to activate two subtypes of P2Y receptors, $P2Y_6$ and $P2Y_{14}$ receptors, both of which are UDP-activated.[41] Therefore, the activity of representative compounds **4l**, **7f**, and **9h** was tested at human $P2Y_6$ and $P2Y_{14}$ receptors, and the results are summarized in Table 5. A calcium assay of $P2Y_6$ receptor activation in astrocytoma cells[42] and a fluorescent binding competition assay in whole mammalian cells (CHO) expressing the $P2Y_{14}$ receptor[43] were used. 5-Fluorouridine-5′-*α*,*β*-methylene-diphosphate (**4l**) activated the $P2Y_6$ receptor ($EC_{50}$ 203 nM) and also showed affinity for the $P2Y_{14}$ receptor ($IC_{50}$ 362 nM). The 4-benzoylcytidine derivative (**7f**) was less potent at $P2Y_6$ and $P2Y_{14}$ receptors with potencies in the micromolar range. However, the benzyloxyimino-3-methylcytidine-5′-*α*,*β*-methylene-diphosphate (**9h**) was completely inactive at $P2Y_6$ and $P2Y_{14}$ receptors even at high concentration (3.0 *μ*M) (Table 6).

*Cytosolic Nucleotidases.* The synthesized compounds are negatively charged under physiological conditions, and membrane permeability is therefore expected to be low. However, cellular uptake via transporters cannot be completely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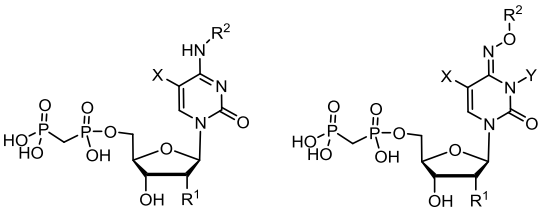
J. Med. Chem. XXXX, XXX, XXX–XXX

Table 3. Inhibitory Potency of Cytosine Derivatives 7a−f and 9a−i at Rat CD73




| compd | substitution | $R^1$ | $R^2$ | $K_i$ ± SEM (nM) (% inhibition at indicated concentration) rat CD73 |
|---|---|---|---|---|
| COPCP **7a** | | OH | H | 898 ± 63 |
| **7b** | | H | H | >1000 (18%) |
| **7c** | X = I | OH | H | 502 ± 83 |
| **7d** | X = F | OH | H | 349 ± 41 |
| **7e** | X = $CH_3$ | OH | H | 2030 ± 670 |
| **7f** | | OH | benzoyl | 13.9 ± 1.6 |
| **9a** | | OH | $CH_3$ | 257 ± 39 |
| **9b** | | OH | benzyl | 112 ± 15 |
| **9c** | | H | benzyl | 780 ± 15 |
| **9d** | | OH | 4-trifluoromethylbenzyl | 30.3 ± 4.2 |
| **9e** | | OH | naphth-2-ylmethyl | 18.8 ± 3.2 |
| **9f** | X = $CH_3$ | OH | benzyl | 321 ± 9 |
| **9g** | X = F | OH | benzyl | 85.1 ± 7.5 |
| **9h** | Y = $CH_3$ | OH | benzyl | 3.67 ± 0.26 |
| **9i** | Y = $C_2H_5$ | OH | benzyl | 262 ± 46 |

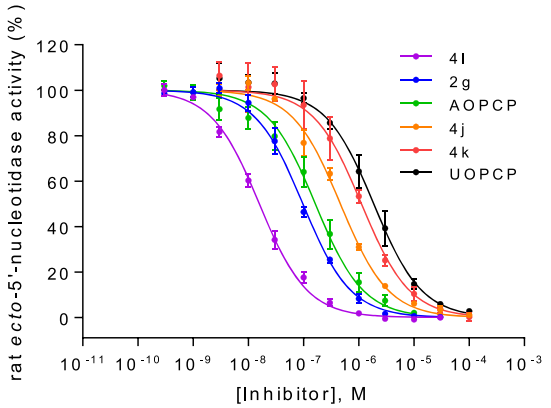



Figure 1. Concentration−inhibition curves of selected compounds at soluble rat CD73. Rat enzyme $K_m$: 53 μM; AMP concentration: 5 μM; data points are from three separate experiments performed in duplicates. For $K_i$ values, see Tables 1 and 2.

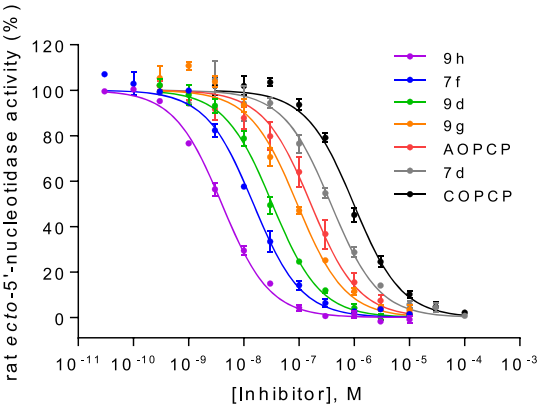



Figure 2. Concentration−inhibition curves of selected compounds at soluble rat CD73. Rat enzyme $K_m$: 53 μM; AMP concentration: 5 μM. Data points are from three separate experiments performed in duplicates. For $K_i$ values, see Table 3.

excluded. To test whether the developed CD73 inhibitors can additionally block cytosolic nucleotidases, we utilized a cytosolic preparation of CD73 knockout melanoma cells[44] and tested inhibition of AMP hydrolysis by selected compounds **4l**, **7f**, **9h**, and **9e**. Results are collected in Table 7. While a mixture of the phosphatase inhibitors NaF[45] and levamisole[46] inhibited adenosine 5′-triphosphate hydrolysis under the applied conditions by 70%, none of the four investigated CD73 inhibitors showed any significant inhibition of AMP hydrolysis. Adding one of the CD73 inhibitors to the mixture of NaF and levamisole did not change the percentage of AMP hydrolysis. This clearly indicates that the investigated compounds selectively inhibit AMP hydrolysis by CD73 but not by cytosolic nucleotidases.

**In Situ Ecto-Nucleotidase Activity Assay.** Different analytic approaches have been employed for the measurement of ecto-nucleotidase activities, including colorimetric $P_i$-liberating assays, capillary electrophoresis, chromatography-based assays, and lead nitrate-based enzyme histochemistry.[3] The latter technique is of particular importance in defining the distribution of ecto-nucleotidase activities within a tissue, taking advantage of the abilities of these enzymes to generate inorganic phosphorus ($P_i$) when incubated with appropriate nucleotide substrates in the presence of lead nitrate, $Pb(NO_3)_2$. This technique was originally employed by Wachstein and Meisel for the histochemical characterization of hepatic phosphatases.[48] Using this approach, tissue localization of CD73 and other ecto-nucleotidases has been characterized as brown signal in images of the murine brain,[3] thoracic aortas,[4] as well as other human and rodent tissues.[3]

Figure 6 depicts representative staining images of human tonsillar CD73-mediated AMPase activity, showing selective and spatially distinct localization of enzymatic activity in the germinal centers and connective tissues. Compound **9h** at 1,



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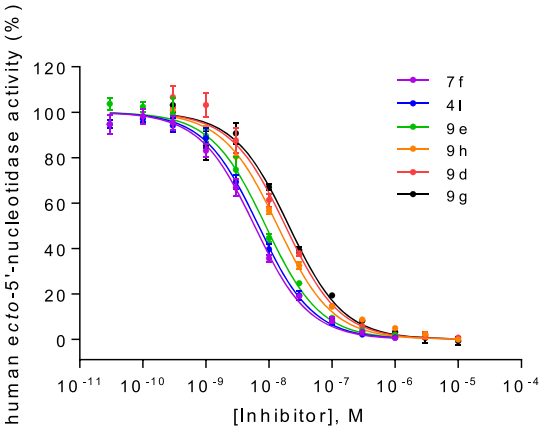



**Figure 3.** Concentration−inhibition curves of selected compounds at soluble human CD73. Human enzyme $K_m$: 17 $\mu$M; AMP concentration: 5 $\mu$M. Data points are from three separate experiments performed in duplicates. For $K_i$ values, see Table 5.

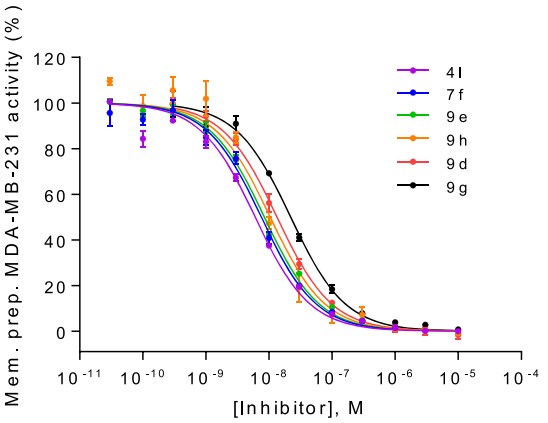



**Figure 4.** Concentration−inhibition curves of selected compounds at membrane preparations of the human TNBC cell line MDA-MB-231, which natively expresses CD73. $K_m$: 14.8 $\mu$M; AMP concentration: 5 $\mu$M; data points are from three separate experiments performed in duplicates. For $K_i$ values, see Table 5.

10, and 100 nM concentrations inhibited the catalytic activity of CD73 in a concentration-dependent manner, in situ more potently than AOPCP, but it is a highly reversible CD73 inhibitor. Therefore, it was necessary for **9h** to remain in the assay medium during both the tissue pretreatment with the inhibitor tested and subsequent incubation with the AMP substrate.

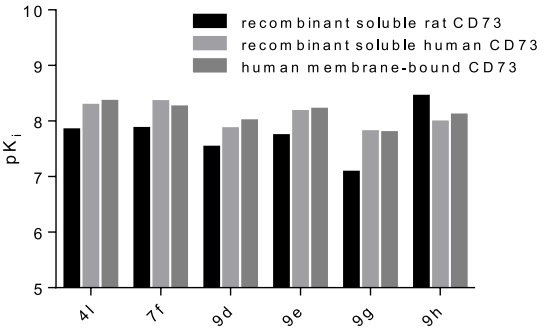



**Figure 5.** Comparison of p$K_i$ values of selected compounds **4l**, **7f**, **9e**, **9h**, **9d**, and **9g** determined at recombinant soluble rat and human and at membrane-bound native CD73.

**Table 5. Potencies of Selected Compounds at Human Soluble and Membrane-Bound CD73**

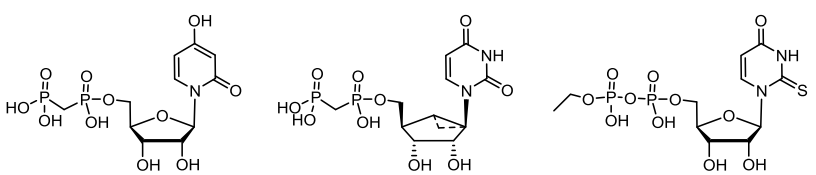
| compd | rat soluble CD73 $K_i$ ± SEM (nM) | human soluble CD73 $K_i$ ± SEM (nM) | human membrane-bound CD73 $K_i$ ± SEM (nM) |
|---|---|---|---|
| **4l** | 14.8 ± 1.9 | 5.33 ± 0.73 | 4.51 ± 0.13 |
| **7f** | 13.9 ± 1.6 | 4.58 ± 0.55 | 5.68 ± 0.75 |
| **9d** | 30.3 ± 4.2 | 14.0 ± 1.6 | 10.1 ± 1.4 |
| **9e** | 18.8 ± 3.2 | 6.88 ± 1.05 | 6.29 ± 0.45 |
| **9g** | 85.1 ± 7.5 | 15.9 ± 1.1 | 16.6 ± 0.7 |
| **9h** | 3.67 ± 0.26 | 10.6 ± 0.4 | 7.96 ± 0.57 |

**Table 6. Potency of $\alpha,\beta$-Methylene Analogues of UDP and CDP as Agonists at the Human $P2Y_6R$ and Inhibitors of Fluorescent Ligand Binding at the Human $P2Y_{14}R$**

| compd | hP2Y$_6$ $EC_{50}$ ± SEM (nM) (% activation at indicated concentration) | hP2Y$_{14}$ $IC_{50}$ ± SEM (nM) (% inhibition at indicated concentration) | CD73 $K_i$ ± SEM (nM) rat eN |
|---|---|---|---|
| **4l** | 203 ± 30 | 362 ± 90 | 14.8 ± 1.9 |
| **7f** | 1390 ± 220 | 6660 ± 4740 | 13.9 ± 1.6 |
| **9h** | >3000 (3.6%) | >3000 (inactive) | 3.67 ± 0.26 |

**Molecular Modeling.** Recently, a high-resolution (2.0 Å, PDB ID: 4H2I) CD73−AOPCP complex structure in the closed form was reported, and this crystal structure provided insight into the interaction patterns of the purine derivative, AOPCP, with the amino acid residues and the two zinc ions in the binding site.[49] In order to gain further insights into the molecular determinants involved in binding of the pyrimidine derivatives, we subsequently docked one of the potent and selective molecules, **9h**, into the human CD73 binding site and

**Table 4. Inhibitory Potency at Rat Ecto-5′-Nucleotidase of 3-Deazauridine-Derived (10), (*S*)-Methanocarba-Based (11) Nucleotides, and Ethyl Ester 12**



**10** **11** **12**

| compd | $K_i$ (nM) (% inhibition at indicated concentration) rat CD73 |
|---|---|
| **10** | >1000 (19%) |
| **11** | >1000 (12%) |
| **12** | >1000 (10%) |



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**Table 7. Inhibition of Cytosolic AMP Hydrolysis by Selected CD73 Inhibitors Investigated in a CD73-Knockout Melanoma Cell Line**

| compound (concentration) | inhibition of AMP hydrolysis ± SEM (%)[a] |
|---|---|
| levamisole (1 mM) and NaF (5 mM) | 70 ± 1 |
| **4l** (100 μM) | 4 ± 13 |
| **7f** (100 μM) | −3 ± 6 |
| **9e** (100 μM) | −5 ± 5 |
| **9h** (100 μM) | −2 ± 3 |

[a]Determined in a malachite green assay using a cytosolic extract of MaMel.65-CD73$^{ko}$ cells (for details, see Experimental Section). Data are from three independent experiments performed in duplicate.

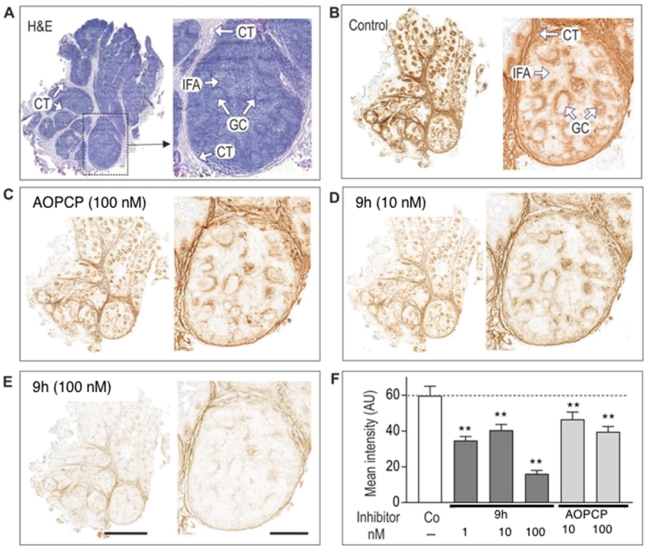


**Figure 6.** Histochemical analysis of the distribution of eN/CD73 in human tonsils. (A) Tissue samples were stained with hematoxylin and eosin. (B–E) Tonsillar eN/CD73 (AMPase) activity was assayed by incubating tissue cryosections with 100 μM AMP and 1.5 mM $Pb(PO_4)_2$ in the absence (control) or presence of the indicated concentrations of AOPCP and **9h**, followed by microscopic detection of the nucleotide-derived $P_i$ as a brown precipitate. All images were captured as tile scans of adjacent areas by using the Pannoramic 250 slide scanner. CT, connective tissue; GC, germinal center; IFA, interfollicular area. Scale bars: 4 mm (left images) and 1 mm (right). (F) Quantification of the enzymatic activities using ImageJ are shown as mean pixel intensities (mean ± SE) of five germinal centers. $^{**}P < 0.01$ compared with control, determined by one-way analysis of variance with Dunnett's multiple comparison test.

studied its interactions with the enzyme (Figure 7). Similar to AOPCP, the results from the docking studies with **9h** showed that it occupies the same binding site (Supporting Information, Figure S3), and the diphosphonate chain (PCP) is bound between the two zinc ions, α-phosphonate forming H-bond interactions with Asn245, Arg354, and Arg395 and the β-phosphonate group with Asn117, His118, and Arg395 (Figure 7A–D). The binding orientation of AOPCP obtained from the crystal structure shows that the ribose hydroxyl groups form H-bond interactions with Arg354, Arg395, and Asp506. This interaction could be important for positioning the ligand in the correct orientation in the binding pocket of CD73. The importance of the ribose 2′- and 3′-hydroxyl groups was confirmed with derivatives **2a–d**, where modification of the two hydroxyl groups in AOPCP was not tolerated. In

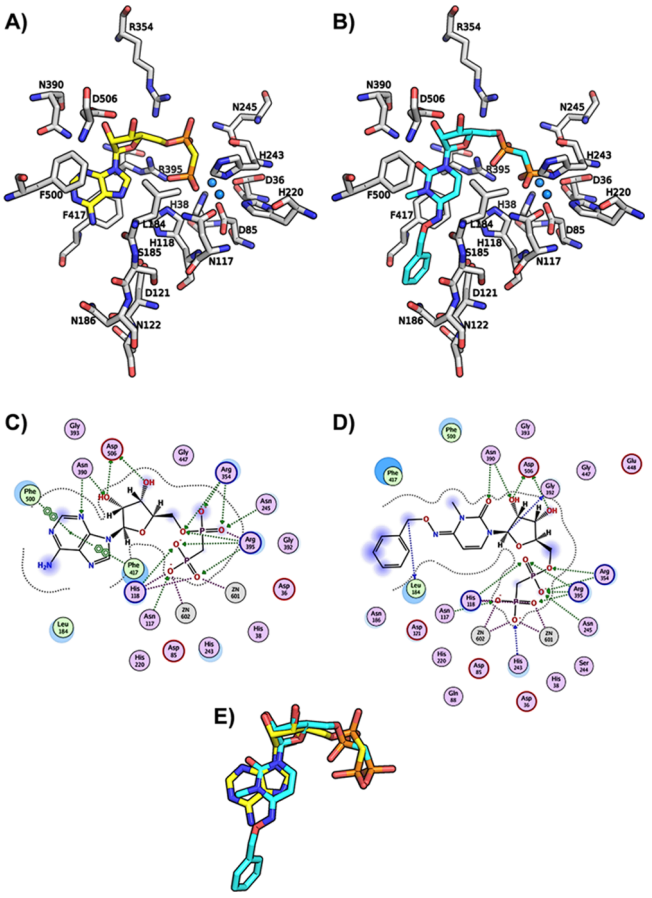


**Figure 7.** Binding poses of AOPCP and **9h**. (A) Binding pose of AOPCP (yellow) obtained from the X-ray structure (PDB ID: 4H2I used as a starting point) and (B) docked pose of **9h** (cyan) with important residues (gray) and zinc ions (marine blue) in the binding site of the human CD73. 2D interaction diagrams of (C) AOPCP and (D) **9h**. (E) Binding pose comparison of the AOPCP crystal structure (yellow) and docked **9h** (cyan). The amino acid residues (gray), AOPCP (yellow), and **9h** (cyan) are shown as stick models, and the zinc ions in the active site are represented as spheres (marine blue). Oxygen atoms are colored in red, nitrogen atoms in blue, and phosphorus atoms in orange.

particular, modification of the 2′-OH group leads to a large decrease in potency (**2a**) and indicates the importance of its interaction and presumably its role in ligand orientation in the substrate binding pocket. The docked pose of **9h** shows the same interaction profile and binding orientation in the enzyme active site. Although the pyrimidine moiety of **9h** (like the adenine ring of AOPCP) is stacked between Phe417 and Phe500 and stabilized through H-bonding interactions between the diphosphonate group (PCP) and the enzyme, it is expected to have weaker π–π interactions with the aromatic residues than the adenine ring of AOPCP. Because of the interactions of N3 (H-bond interaction with Asn390) and N1 (interaction with a water molecule) of the adenine ring with the enzyme, the N1- (**2e**) and N3-deaza analogues (**2f**) were not tolerated. In contrast, an N7-deaza-adenine modification (**2g**) is tolerated because N7 does not form any interaction with the amino acid residues or water molecules inside the binding pocket of CD73. The keto group at position 2 of the cytidine ring is oriented in the same direction as the N3 of the adenine ring and likely forms an interaction with the same residue, Asn390, as seen with AOPCP (Figure 7E). Adjacent to


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J. Med. Chem. XXXX, XXX, XXX–XXX

the exocyclic 6-amino group of the adenine ring, a large pocket is exposed to the surface with bound water molecules. This pocket was explored with different substitutions at the cytidine ring, and among them, the benzyloxyimino residue at the 4-position of cytidine (**9h**) was found to confer high CD73 inhibitory activity (see Table 5). Upon exploring the pocket further, three loops (Asp121−Val124, Leu184−Asn190, and Leu415−Thr420) were observed adjacent to the binding pocket of **9h**, which possibly provide hydrophobic as well as the polar or charged residues as potential interaction partners (Figure S4). On the other hand, the small electronegative substituent fluorine at the 5-position of the uracil moiety provided high potency in comparison to the other substituents including H, I, and $CH_3$. A possible explanation for this SAR pattern is that the electronegative fluorine atom is located at a distance of approximately 4 Å from His118 potentially forming a H-bond interaction directly with, or mediated through, the water molecules (located at a distance of ∼3 Å) inside the binding pocket.

## DISCUSSION

We have prepared a range of nucleoside 5′-$\alpha,\beta$-methylene-diphosphates by standard synthetic methods[31,41,42,50−53] and evaluated them in vitro as CD73 inhibitors. The assay method using the radiolabeled AMP substrate has been validated to have high reproducibility.[34] This indirect approach to correcting an imbalance of excess adenosine that occurs in the microenvironment of a wide range of tumors holds promise as a cotherapy in the immunotherapy of cancer, and potent CD73 inhibitors (both small molecules and monoclonal antibodies) are already in preclinical and clinical development.[12,17,32,54−58] Coinhibition of CD73 and the $A_{2A}$AR is also being considered for anticancer therapeutic development.[59] In addition to cancer, CD73 inhibitors might have utility in preeclampsia, pulmonary edema, infectious disease, and other conditions.[33,60,61]

The current study presents important new SAR for AOPCP, UOCPC, and COPCP analogues as inhibitors of CD73 (Figure 8). Furthermore, the recognition of a potent COPCP

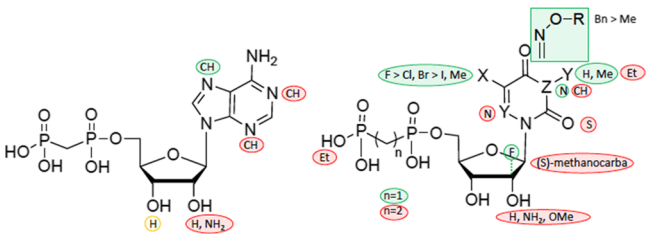


**Figure 8.** Summary of SAR for nucleotide derivatives as CD73 inhibitors in the purine (left) and pyrimidine series (right).

analogue **9h** in the enzyme active site was modeled using a CD73 X-ray crystallographic structure, and this binding mode can be used to facilitate a structure-based approach in future SAR studies. While most of the ribose modifications resulted in weak inhibition or inactivity, substantial enhancement of CD73 inhibitory activity was observed with various nucleobase, both purine and pyrimidine, modifications. In the adenine series, most ribose modifications and 1-deaza and 3-deaza substitutions were detrimental, but 7-deaza was well tolerated. For example, on the ribose moiety, 2′-methoxy and 2′-amino modifications or a [3.1.0]bicyclohexyl (*S*)-methanocarba modification resulted in a loss of potency; only 2′-deoxy (intermediate) and 2′-deoxy-2′-fluoro (arabino, potent) analogues retained inhibitory activity. In the uracil series, the nucleobase N3 could be substituted with methyl but not larger alkyl groups. 2-Thiouracil, 3-deaza-uracil, 6-aza-uracil, or 1,2-diphosphono-ethyl modifications were not tolerated. However, the uracil-5-position was amenable to various substitutions, with a rank order of potency of F > Cl, Br > I, Me.

The most successful modification was found in $N^4$-(aryl)alkyloxy-cytosine derivatives, especially with bulky benzyloxy substituents, which increased the inhibitory potency at CD73. The $\alpha,\beta$-methylene 5′-diphosphate derivatives of 5-fluorouridine (**4l**), 4-benzoylcytidine (**7f**), $N^4$-[*O*-(naphthalen-2-ylmethoxy)]-cytidine (**9e**), and $N^4$-[*O*-(4-benzyloxy)]-3-methyl-cytidine (**9h**) are the most potent CD73 inhibitors prepared in this work. At the human CD73 isoform, most of the potent inhibitors examined were at least several-fold more potent than at the rat isoform. Compound **9h** displayed $K_i$ values of (nM) 3.67 (soluble CD73, rat); 10.6 (soluble CD73, human); and 7.96 (membrane-bound CD73, human). A major advantage of such pyrimidine-based inhibitors over adenine nucleotide analogues is that their hydrolysis products, the parent nucleosides, do not activate ARs, which would counteract the intended effects in cancer treatment. Also, 7-deazaadenosine derivatives are inactive or only very weakly active at ARs,[47,71] and the 7-deazaadenine scaffold is therefore preferable to adenine for the development of CD73 inhibitors. In the CD73 crystal structure with bound AOPCP, the adenine N7 does not participate in any apparent stabilizing protein interactions, such as H-bonding. Thus, its replacement with CH in the more potent 7-deaza analogue **2g** might conceivably displace a water molecule, but in the current X-ray structure, no water is detected in this region.

The observed SAR was rationalized by docking **9h** into the substrate binding site of human CD73. We were also concerned about off-target activity of the phosphonate analogues derived from uracil at the UDP-activated $P2Y_6$ and $P2Y_{14}$ receptors. The 5-F derivative **4l** interacted with these two P2Y receptors at higher nanomolar concentrations, but the 4-benzoylcytidine derivative (**7f**) was less potent at $P2Y_6$ and $P2Y_{14}$ receptors. The potent inhibition by compound **9h** of CD73 in situ in human tonsils was demonstrated, and it was more potent than the reference CD73 inhibitor AOPCP. Importantly, benzyloxyimino-3-methyl-$\alpha,\beta$-methylene-diphosphate (**9h**) was completely inactive at $P2Y_6$ and $P2Y_{14}$ receptors and in inhibition of cytosolic CD73, making it a particularly useful pharmacological tool compound for the in vitro and in vivo exploration of CD73 inhibition and an excellent starting point for future development of CD73 drugs that act parenterally.

## CONCLUSIONS

A series of 50 purine- and pyrimidine-based nucleoside 5′-$\alpha,\beta$-methylene-diphosphates were synthesized and obtained in high purity. The synthesized nucleosides were evaluated as inhibitors of CD73 in two species: rat and human (selected analogues). The AOPCP-derived nucleotides were modified at the ribose and the adenine moiety to complement the existing SAR in the adenine series and to explore an alternative series of pyrimidine bases. These uridine- and cytosine-derived $\alpha,\beta$-methylene diphosphonates represent an entirely new class of CD73 inhibitors. Analysis of their SAR allowed optimization, leading to the development of inhibitors with $K_i$ values in the


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J. Med. Chem. XXXX, XXX, XXX−XXX

low nanomolar range. $N^4$-(Aryl)alkyloxy-cytosine derivatives, especially with bulky benzyloxy substituents, increased potency. The most potent inhibitors at rat CD73 were 5-fluorouridine (**4l**, 14.8 nM), 4-benzoylcytidine (**7f**, 13.9 nM), $N^4$-[*O*-(naphthalen-2-ylmethoxy)]-cytidine (**9e**, 18.8 nM), and $N^4$-[*O*-(4-benzyloxy)]-3-methyl-cytidine (**9h**, 3.67 nM) 5′-$\alpha,\beta$-methylene-diphosphates. Compound **9h** displayed particularly high selectivity for CD73 compared to UDP-activated P2Y ($P2Y_6$ and $P2Y_{14}$) receptors and cytosolic 5′-nucleotidase. Thus, we have expanded the SAR of both purine and pyrimidine nucleotide analogues as inhibitors of CD73 and achieved low nanomolar affinity. 5-Halo- and alkyl-uracil derivatives were also potent CD73 inhibitors. The presented compounds include the most potent CD73 inhibitors reported to date and are likely to become useful pharmacological tools to further elucidate the enzyme's (patho)physiological role and its potential as a drug target in cancer immunotherapy and in other conditions.

## EXPERIMENTAL SECTION

**Chemical Synthesis.** *General. Reagents and Instrumentation.* All reagents were commercially obtained from various producers (Alfa Aesar, Carbosynth, and Sigma-Aldrich) and used without further purification. The purity of all compounds including the starting material was more than 95%, as determined using high-performance LC (HPLC). Commercial solvents of specific reagent grades were used, without additional purification or drying. Analytical thin-layer chromatography was carried out on Sigma-Aldrich TLC plates, and compounds were visualized with UV light at 254 nm. Silica gel flash chromatography was performed using 230−400 mesh silica gel. Unless noted otherwise, reagents and solvents were purchased from Sigma-Aldrich (St. Louis, MO). The $^1$H, $^{31}$P, and $^{13}$C NMR spectra were recorded using a Bruker 400 MHz spectrometer and a DD2 400 MHz or DD2 600 MHz NMR spectrometer (Agilent). DMSO-$d_6$, MeOD-$d_4$, $CDCl_3$, or $D_2O$ were used as solvents. Shifts are given in parts per million relative to the remaining protons of the deuterated solvents used as internal standard ($^1$H, $^{13}$C NMR). Purification of final compounds was performed by semipreparative HPLC (column: Luna 5 $\mu$m C18(2) 100 Å, LC column 250 × 4.6 mm). Eluent: 10 mM triethylammonium acetate buffer−$CH_3CN$ from 80:20 to 20:80 in 40 min, with a flow rate of 5 mL/min. Purities of all tested compounds were ≥95%, as estimated by analytical HPLC: method A: eluent: 5 mM triethylammonium phosphate monobasic solution−$CH_3CN$ from 100:0 to 50:50 in 20 min and then triethylammonium phosphate monobasic solution−$CH_3CN$ to 100:0 in 5 min with a flow rate of 1 mL/min (column: Zorbax SB-Aq 5 $\mu$m analytical column, 50 × 4.6 mm; Agilent Technologies, Inc.). Method B: eluent: 5 mM triethylammonium phosphate monobasic solution−$CH_3CN$ from 90:10 to 0:100 in 20 min and then triethylammonium phosphate monobasic solution−$CH_3CN$ from 0:100 to 90:10 in 5 min with a flow rate of 1 mL/min (column: Zorbax SB-Aq 5 $\mu$m analytical column, 150 × 4.6 mm; Agilent Technologies, Inc.). Method C: eluent: 5 mM triethylammonium phosphate monobasic solution−$CH_3CN$ from 80:20 to 20:80 in 20 min and then triethylammonium phosphate monobasic solution−$CH_3CN$ from 20:80 to 80:20 in 10 min with a flow rate of 1 mL/min (column: Zorbax SB-Aq 5 $\mu$m analytical column, 150 × 4.6 mm; Agilent Technologies, Inc.). Peaks were detected by UV absorption (254 nm) using a diode array detector. All derivatives tested for biological activity showed >95% purity in the HPLC system. Low-resolution MS was performed with a JEOL SX102 spectrometer with 6 kV Xe atoms following desorption from a glycerol matrix or on an Agilent LC/MS 1100 MSD, with a Waters (Milford, MA) Atlantis C18 column. High-resolution mass spectroscopic (HRMS) measurements were performed on a proteomics optimized Q-TOF-2 (Micromass-Waters) using external calibration with polyalanine. For lyophilization, a freeze dryer (Labconco FreeZone 4.5) was used.

**Preparation of Triethylammonium Hydrogen Carbonate Buffer.** A 1 M solution of triethylammonium hydrogen carbonate (TEAC) was prepared by adding dry ice slowly to 1 M triethylamine solution in deionized water for several hours until the pH of approximately 8.4−8.6 was indicated using a pH meter.

**Purification of Nucleotides.** *Ion-Exchange Chromatography.* The crude nucleoside-5′-*O*-[(phosphonomethyl)phosphonic acid] derivatives were purified by ion-exchange chromatography on an HPLC instrument UltiMate 3000 (Dionex Corp.) with a HiScale 26 20 BH, 26 mm × 130 mm length column. The column was packed with Source 15Q gel, swelled in a 20% EtOH-solution. Before purification, the column was washed and equilibrated with deionized water. The sample was prepared by dissolving crude product in 0.5−1 mL of aqueous TEAC buffer. Separation was achieved by running a solvent gradient of TEAC buffer: deionized water from 0:100 for 5 min, then from 0:100 to 100:0 in 25 min, followed by a gradient from 100:0 to 0:100 in 20 min, and holding 0:100 for 10 min with a flow rate of 5 mL/min. The UV absorption was detected at 254, 210, and 280 nm. Fractions were collected, and appropriate fractions were pooled, diluted in water, and lyophilized.

**General Procedure A for the Synthesis of Nucleotides.** To a solution of DCC (3 equiv) and the unprotected nucleoside in DMF (2 mL), methylene diphosphonic acid (1.5 equiv) was added at rt, and the mixture was allowed to stir at rt for 6−24 h. Samples were withdrawn at 3−12 h interval for LC−MS to check the disappearance of nucleosides and to monitor the formation of the desired nucleotide. On the disappearance of a nucleoside, 10 mL of cold TEAC solution was added. The mixture was stirred at rt for 30 min, followed by filtration and lyophilization of the aqueous solution. The mixture of nucleotide and dinucleotide was separated by ion-exchange chromatography on Source 15Q. Fractions containing the product were pooled and evaporated to dryness. The compound was then purified by reverse-phase (RP)-HPLC using a gradient of 10 mM triethylammonium acetate buffer−$CH_3CN$ from 80:20 to 20:80 in 40 min, and suitable fractions were pooled and lyophilized to obtain the final product as a glassy solid.

**General Procedure B for the Synthesis of Nucleotides.** A solution of methylenebis(phosphonic dichloride) (3 equiv) in trimethyl phosphate (2 mL) cooled to 0 °C was added to a suspension of the corresponding nucleoside in trimethyl phosphate at 0 °C. The reaction mixture was stirred at 0 °C, and samples were withdrawn at 10 min interval for LC−MS to check the disappearance of nucleosides. After 30 min, on the disappearance of a nucleoside, 7 mL of cold 1 M aqueous TEAC buffer solution (pH 8.4−8.6) was added. It was stirred at 0 °C for 15 min, followed by stirring at rt for 30 min. Trimethyl phosphate was extracted using (2 × 100 mL) of *tert*-butyl methyl ether, and the aqueous layer was lyophilized. The mixture of mononucleotide and dinucleotide was separated by ion-exchange chromatography on Source 15Q. Fractions containing the mononucleotide product were pooled and evaporated to dryness. The compound was then purified by RP-HPLC using a gradient of 10 mM triethylammonium acetate buffer−$CH_3CN$ from 80:20 to 20:80 in 40 min, then 10 mM triethylammonium acetate buffer−$CH_3CN$ from 100:0 to 90:10 in 40 min, and then 100:0 in 5 min, with a flow rate of 5 mL/min, and suitable fractions were pooled and lyophilized to obtain the final product as a glassy solid.

*2′-Deoxyadenosine-5′-O-[(phosphonomethyl)phosphonic acid] (**2a**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 33.6 mg, 15%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.41 (s, 1H), 8.16 (s, 1H), 6.41 (t, $J$ = 5.9 Hz, 1H), 4.17 (s, 1H), 4.08−3.90 (m, 3H), 3.10 (q, $J$ = 7.3 Hz, 11H), 2.76 (dt, $J$ = 13.3, 6.0 Hz, 1H), 2.55−2.43 (m, 1H), 2.04 (t, $J$ = 18.6 Hz, 2H), 1.18 (t, $J$ = 7.3 Hz, 16H). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 21.8, 11.8. MS (ESI, $m/z$): 408.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{16}N_5O_8P_2$, 408.0474; found, 408.0479 [M − H]$^-$. HPLC purity 95% ($R_t$ = 4.8 min, method HPLC-A).

*2′-Amino-2′-deoxyadenosine-5′-O-[(phosphonomethyl)-phosphonic acid] (**2b**).* Method A. The product was obtained as a colorless solid after lyophilization (0.5 equiv $Et_3N$-salt, 1.5 mg, 0.6%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.59 (s, 1H), 8.28 (s, 1H), 6.45 (d, $J$ =


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J. Med. Chem. XXXX, XXX, XXX−XXX

7.4 Hz, 1H), 4.88−4.84 (m, 1H), 4.64 (t, $J$ = 5.6 Hz, 1H), 4.52 (s, 1H), 4.18 (q, $J$ = 11.7, 10.7 Hz, 2H), 3.20 (q, $J$ = 7.3 Hz, 3H), 2.19 (t, $J$ = 19.0 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 5H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 155.7, 153.0, 149.3, 140.1, 118.8, 86.0 (d, $J$ = 6.0 Hz), 84.6, 70.1, 63.7, 56.3, 46.8 (2C), 27.6 (t, $J$ = 124.3 Hz), 8.3 (2C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.6, 14.6. MS (ESI, $m/z$): 423.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_6O_8P_2$, 423.0583; found, 423.0590 $[M - H]^-$. HPLC purity 98% ($R_t$ = 9.9 min, method HPLC-B).

*2′-Amino-2′-deoxyadenosine-3′-O-[(phosphonomethyl)-phosphonic acid] (**2c**).* Method A. The product was obtained as a colorless solid after lyophilization (0.66 equiv $Et_3N$-salt, 1.1 mg, 0.5%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.37 (s, 1H), 8.28 (s, 1H), 6.50 (d, $J$ = 7.6 Hz, 1H), 5.22 (t, $J$ = 5.6 Hz, 1H), 4.79 (s, 1H), 4.59 (s, 1H), 3.94 (d, $J$ = 2.7 Hz, 2H), 3.21 (q, $J$ = 7.3 Hz, 4H), 2.29 (t, $J$ = 19.4 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 6H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 155.9, 152.9, 148.7, 141.0, 119.5, 87.3, 86.4, 73.3, 61.3, 54.8, 46.8 (2C), 28.2 (t, $J$ = 124.4 Hz), 8.3 (2C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.8, 14.2. MS (ESI, $m/z$): 423.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_6O_8P_2$, 423.0583; found, 423.0582 $[M - H]^-$. HPLC purity 98% ($R_t$ = 6.9 min, method HPLC-B).

*3′-Deoxyadenosine-5′-O-[(phosphonomethyl)phosphonic acid] (**2d**).* Method A. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 2.5 mg, 6%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.49 (s, 1H), 8.25 (s, 1H), 6.10 (s, 1H), 4.77−4.65 (m, 1H), 4.25 (d, $J$ = 10.2 Hz, 1H), 4.13−4.01 (m, 1H), 3.19 (q, $J$ = 7.3 Hz, 10H), 2.42 (ddd, $J$ = 14.5, 9.2, 5.7 Hz, 1H), 2.25−2.09 (m, 3H), 1.27 (t, $J$ = 7.3 Hz, 15H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 154.7, 151.4, 148.4, 140.3, 118.8, 90.6, 80.4 (d, $J$ = 7.3 Hz), 75.4, 64.9, 46.8 (4C), 33.0, 27.5 (t, $J$ = 124.5 Hz), 8.3 (4C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.9. MS (ESI, $m/z$): 408.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{16}N_5O_8P_2$, 408.0474; found, 408.0471 $[M - H]^-$. HPLC purity 99% ($R_t$ = 17.1 min, method HPLC-B).

*1-Deazaadenosine-5′-O-[(phosphonomethyl)phosphonic acid] (**2e**).* Method B. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 1.7 mg, 8%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.50 (s, 1H), 7.99 (d, $J$ = 5.9 Hz, 1H), 6.67 (d, $J$ = 5.9 Hz, 1H), 6.14 (d, $J$ = 5.9 Hz, 1H), 4.53 (s, 1H), 4.37 (s, 1H), 4.15 (s, 2H), 3.18 (q, $J$ = 7.3 Hz, 7H), 2.17 (t, $J$ = 19.5 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 12H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 147.9, 145.3, 144.2, 139.7, 104.3, 87.0, 84.0 (d, $J$ = 6.2 Hz), 73.9, 70.4, 63.7, 46.7 (4C), 27.4, 8.3 (4C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.6, 14.6. MS (ESI, $m/z$): 425.0 $[M + H]^+$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{19}N_4O_9P_2$, 425.0622; found, 425.0626 $[M + H]^+$. HPLC purity 98% ($R_t$ = 8 min, method HPLC-C).

*3-Deazaadenosine-5′-O-[(phosphonomethyl)phosphonic acid] (**2f**).* Method B. $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.58 (s, 1H), 7.75 (s, 1H), 7.32 (d, $J$ = 6.2 Hz, 1H), 6.06 (d, $J$ = 6.2 Hz, 1H), 4.69 (t, $J$ = 5.9 Hz, 1H), 4.58−4.52 (m, 1H), 4.41 (s, 1H), 4.20 (s, 2H), 3.21 (q, $J$ = 7.3 Hz, 3H), 2.17 (t, $J$ = 19.3 Hz, 3H), 1.28 (t, $J$ = 7.3 Hz, 6H). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.8, 14.4. MS (ESI, $m/z$): 423.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{17}N_4O_9P_2$, 423.0476; found, 423.0473 $[M - H]^-$. HPLC purity 97% ($R_t$ = 9.9 min, method HPLC-C).

*7-Deazaadenosine-5′-O-[(phosphonomethyl)phosphonic acid] (**2g**).* Method B. The product was obtained as a colorless solid after lyophilization (1 equiv $Et_3N$-salt, 13.5 mg, 14%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 8.13 (br s, 1H), 7.61 (s, 1H), 6.70 (s, 1H), 6.14 (d, $J$ = 5.4 Hz, 1H), 4.52 (t, $J$ = 5.5 Hz, 1H), 4.47 (t, $J$ = 4.4 Hz, 1H), 4.36−4.31 (m, 1H), 4.29 (d, $J$ = 11.6 Hz, 1H), 4.17 (d, $J$ = 11.5 Hz, 1H), 3.18 (q, $J$ = 7.3 Hz, 6H), 2.24 (t, $J$ = 20.5 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 9H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 150.8, 146.9, 142.9, 124.6, 102.6, 102.1, 86.7, 83.7 (d, $J$ = 5.4 Hz), 74.6, 70.3, 63.9, 46.7 (3C), 27.6 (t, $J$ = 124.5 Hz), 8.3 (3C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.5, 15.1. MS (ESI, $m/z$): 423.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{17}N_4O_9P_2$, 423.0476; found, 423.0476 $[M - H]^-$. HPLC purity >99% ($R_t$ = 4.3 min, method HPLC-C).

*Uridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4a**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 6 mg, 5%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.91 (d, $J$ = 8.1 Hz, 1H), 5.90−5.80 (m, 2H), 4.34−4.24 (m, 2H), 4.17−4.14 (m, 1H), 4.13−4.02 (m, 2H), 3.10 (q, $J$ = 7.3 Hz, 12H), 2.04 (t, $J$ = 19.6 Hz, 2H), 1.17 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 166.5, 152.0, 141.9, 102.6, 88.7, 83.4 (d, $J$ = 6.9 Hz), 73.9, 69.5, 63.3, 46.8 (6C), 27.8 (t, $J$ = 122.4 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 20.6, 12.7. MS (ESI, $m/z$): 401.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{15}N_2O_{11}P_2$, 401.0157; found, 401.0154 $[M - H]^-$. HPLC purity 99% ($R_t$ = 5.6 min, method HPLC-B).

*3-Methyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4b**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 4.8 mg, 19%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.00 (d, $J$ = 8.0 Hz, 1H), 6.02 (d, $J$ = 8.0 Hz, 1H), 5.98 (d, $J$ = 3.0 Hz, 1H), 4.38 (d, $J$ = 3.6 Hz, 2H), 4.27 (s, 1H), 4.20 (s, 2H), 3.30 (s, 3H), 3.21 (q, $J$ = 7.3 Hz, 12H), 2.12 (t, $J$ = 19.3 Hz, 2H), 1.29 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 165.7, 152.3, 139.7, 101.8, 89.8, 83.1, 74.0, 69.3, 63.1, 46.8 (6C), 27.8, 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 20.2, 13.2. MS (ESI, $m/z$): 415.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_2O_{11}P_2$, 415.0308; found, 415.0311 $[M - H]^-$. HPLC purity 96% ($R_t$ = 3.7 min, method HPLC-C).

*3-Ethyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4c**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 26.1 mg, 11%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.01 (d, $J$ = 7.1 Hz, 1H), 6.00 (d, $J$ = 6.5 Hz, 1H), 5.97−5.94 (m, 1H), 4.47−4.34 (m, 2H), 4.30−4.16 (m, 3H), 3.93 (q, $J$ = 6.9 Hz, 2H), 3.19 (q, $J$ = 7.4 Hz), 2.19−1.94 (m, 2H), 1.27 (t, $J$ = 7.3 Hz), 1.18 (t, $J$ = 7.1 Hz). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 165.3, 151.8, 139.8, 102.0, 89.8, 83.1, 74.1, 69.0, 62.9, 46.7 (6C), 36.8, 11.8, 8.3 (6C). The signal for $PCH_2P$ could not be observed. $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 21.1, 12.0. MS (ESI, $m/z$): 429.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{19}N_2O_{11}P_2$, 429.0470; found, 429.0470 $[M - H]^-$. HPLC purity 97% ($R_t$ = 9.8 min, method HPLC-C).

*3-Propyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4d**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 11 mg, 5%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.00 (d, $J$ = 7.8 Hz, 1H), 6.03 (d, $J$ = 7.7 Hz, 1H), 6.00 (d, $J$ = 3.5 Hz, 1H), 4.43−4.39 (m, 2H), 4.32−4.27 (m, 1H), 4.26−4.13 (m, 2H), 3.87 (dd, $J$ = 8.7, 6.6 Hz, 2H), 3.22 (q, $J$ = 7.3 Hz, 12H), 2.30−2.11 (m, 2H), 1.64 (dq, $J$ = 14.8, 7.5 Hz, 2H), 1.30 (t, $J$ = 7.3 Hz, 18H), 0.92 (t, $J$ = 7.5 Hz, 3H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 165.5, 152.1, 139.8, 102.1, 89.5, 83.3, 73.9, 69.5, 63.3, 46.8 (6C), 43.2, 27.2 (1C, $PCH_2P$), 20.3, 10.6, 8.3 (6C). The signal for $PCH_2P$ could not be observed in the one-dimensional (1D) experiment. $^{13}$C NMR shift of $PCH_2P$ was determined using heteronuclear single quantum correlation (HSQC). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.5. MS (ESI, $m/z$): 443.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{13}H_{21}N_2O_{11}P_2$, 443.0626; found, 443.0634 $[M - H]^-$. HPLC purity 95% ($R_t$ = 10.3 min, method HPLC-C).

*3-Benzyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4e**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 3.7 mg, 2%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.07 (d, $J$ = 7.9 Hz, 1H), 7.44−7.38 (m, 2H), 7.38−7.32 (m, 3H), 6.09 (d, $J$ = 7.9 Hz, 1H), 5.99 (d, $J$ = 3.7 Hz, 1H), 5.16 (d, $J$ = 15.1 Hz), 5.11 (d, $J$ = 15.2 Hz), 4.39 (d, $J$ = 3.9 Hz, 2H), 4.30−4.26 (m, 1H), 4.20 (q, $J$ = 11.4 Hz, 2H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.20 (t, $J$ = 18.3 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 165.2, 152.1, 140.1, 136.1, 128.9 (2C), 127.8, 127.1 (2C), 102.1, 89.5, 83.3 (1C), 74.0, 69.5, 63.2, 46.7 (6C), 44.6, 27.5 (t, $J$ = 124.1 Hz, 1C, $PCH_2P$), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.9. MS (ESI, $m/z$): 491.1 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{17}H_{21}N_2O_{11}P_2$, 491.0626; found, 491.0622 $[M - H]^-$. HPLC purity 98% ($R_t$ = 11.2 min, method HPLC-C).

*5-Methyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4f**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 54 mg, 24%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.77 (s, 1H), 5.99 (d, $J$ = 5.0 Hz, 1H), 4.46−4.34 (m, 2H), 4.26 (s, 1H), 4.16 (q, $J$ = 4.7, 4.1 Hz, 2H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.20 (t, $J$ = 19.7 Hz, 2H), 1.94 (s, 3H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 166.6, 152.1, 137.3, 111.9, 88.1, 83.6 (d, $J$


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J. Med. Chem. XXXX, XXX, XXX−XXX

= 8.0 Hz), 73.5, 69.9, 63.6 (d, $J$ = 4.3 Hz), 59.0, 46.7 (6C), 27.6 (t, $J$ = 124.2 Hz), 11.7, 8.3 (6C), 7.5. $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.1 (d, $J$ = 9.4 Hz), 14.7 (d, $J$ = 9.4 Hz). MS (ESI, $m/z$): 415.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_2O_{11}P_2$, 415.0308; found, 415.0302 [M − H]$^-$. HPLC purity 95% ($R_t$ = 2.9 min, method HPLC-B).

*Thymidine-5′-O-[(phosphonomethyl)phosphonic acid] (**4g**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 28.35 mg, 12%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.74 (d, $J$ = 1.3 Hz, 1H), 6.34 (dd, $J$ = 7.5, 6.3 Hz, 1H), 4.62 (dt, $J$ = 6.4, 3.4 Hz, 1H), 4.19−4.14 (m, 1H), 4.14−4.07 (m, 2H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.45−2.30 (m, 2H), 2.18 (t, $J$ = 19.8 Hz, 2H), 1.93 (s, 3H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 151.8, 137.5, 111.8, 109.9, 85.5 (d, $J$ = 7.2 Hz), 85.0, 71.0, 63.9, 46.7 (6C), 38.4, 26.9 (t, $J$ = 124.2 Hz), 11.7, 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.1, 14.7. MS (ESI, $m/z$): 399.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_2O_{10}P_2$, 399.0358; found, 399.0357 [M − H]$^-$. HPLC purity 97% ($R_t$ = 9.3 min, method HPLC-B).

*2′-O-Methyl-5-methyluridine-5′-O-[(phosphonomethyl)-phosphonic acid] (**4h**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 21 mg, 9%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.79 (d, $J$ = 1.3 Hz, 1H), 6.03 (d, $J$ = 5.1 Hz, 1H), 4.53 (t, $J$ = 5.0 Hz, 1H), 4.26−4.22 (m, 1H), 4.22−4.14 (m, 2H), 4.13 (t, $J$ = 5.2 Hz, 1H), 3.49 (s, 3H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.20 (td, $J$ = 19.5, 2.0 Hz, 2H), 1.94 (d, $J$ = 1.2 Hz, 3H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 166.6, 151.8, 137.2, 111.9, 86.7, 83.6 (d, $J$ = 8.1 Hz), 82.4, 68.3, 63.4 (d, $J$ = 5.2 Hz), 58.1, 46.7 (6C), 27.5 (t, $J$ = 124.0 Hz), 11.7, 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.0, 14.7. MS (ESI, $m/z$): 429.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{19}N_2O_{11}P_2$, 429.0464; found, 429.0465 [M − H]$^-$. HPLC purity 95% ($R_t$ = 9.5 min, method HPLC-B).

*5-Ethynylyluridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4i**).* Method B. The product was obtained as a brown solid after lyophilization (2 equiv $Et_3N$-salt, 6.7 mg, 3%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 8.26 (s, 1H), 5.92 (d, $J$ = 4.0 Hz, 1H), 4.37 (dt, $J$ = 13.8, 4.9 Hz, 2H), 4.28−4.24 (m, 1H), 4.20 (d, $J$ = 10.0 Hz, 1H), 4.14 (d, $J$ = 11.6 Hz, 1H), 3.63 (s, 1H), 3.18 (q, $J$ = 7.3 Hz, 12H), 2.25−2.12 (m, 2H), 1.26 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 164.7, 150.7, 145.4, 98.8, 89.2, 83.7, 83.4, 74.5, 74.1, 69.4, 62.9, 46.7 (6C), 27.3 (t, $J$ = 126.5 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 17.1 (br). MS (ESI, $m/z$): 429.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{15}N_2O_{11}P_2$, 425.0157; found, 425.0165 [M − H]$^-$. HPLC purity 99% ($R_t$ = 8.6 min, method HPLC-C).

*5-(1-Chlorovinyl)uridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4j**).* The compound was obtained as a side product during the synthesis of compound **4i** via method B. The product was obtained as a brown solid after lyophilization (3 equiv $Et_3N$-salt, 2.7 mg, 1%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 8.10 (d, $J$ = 0.7 Hz, 1H), 6.01 (dd, $J$ = 1.6, 0.7 Hz, 1H), 5.95 (d, $J$ = 5.1 Hz, 1H), 5.71 (d, $J$ = 1.7, 0.8 Hz, 1H), 4.42 (t, $J$ = 5.2 Hz, 1H), 4.35 (t, $J$ = 4.9 Hz, 1H), 4.27 (q, $J$ = 3.8 Hz, 1H), 4.17−4.13 (m, 2H), 3.18 (q, $J$ = 7.3 Hz, 18H), 2.18 (t, $J$ = 19.9 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 27H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 163.1, 151.0, 140.8, 130.3, 119.0, 113.1, 89.2, 83.7 (d, $J$ = 8.1 Hz), 73.8, 69.8, 63.4 (d, $J$ = 5.4 Hz), 46.7 (9C), 27.5 (t, $J$ = 124.5 Hz), 8.3 (9C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.1, 15.2. MS (ESI, $m/z$): 461.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{16}ClN_2O_{11}P_2$, 460.9923; found, 460.9923 [M − H]$^-$. HPLC purity 95% ($R_t$ = 9.8 min, method HPLC-C).

*5-(1-Chlorovinyl)-3-methyluridine-5′-O-[(phosphonomethyl)-phosphonic acid] (**4k**).* The compound was obtained as a side product during the synthesis of compound **4i** via method B. The product was obtained as a brown solid after lyophilization (3 equiv $Et_3N$-salt, 5.6 mg, 2%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 8.10 (d, $J$ = 0.8 Hz, 1H), 5.97 (dd, $J$ = 4.6, 0.9 Hz, 1H), 5.96 (dd, $J$ = 1.6, 0.7 Hz, 1H), 5.71 (dd, $J$ = 1.6, 1.0 Hz, 1H), 4.41 (t, $J$ = 5.0 Hz, 1H), 4.34 (t, $J$ = 5.2 Hz, 1H), 4.27 (q, $J$ = 3.9 Hz, 1H), 4.20−4.12 (m, 2H), 3.30 (s, 3H), 3.18 (q, $J$ = 7.3 Hz, 18H), 2.18 (t, $J$ = 19.6 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 27H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 162.6, 151.4, 138.7, 131.0, 119.1, 112.5, 90.2, 83.4 (d, $J$ = 8.0 Hz), 73.9, 69.6, 63.3 (d, $J$ = 5.1 Hz), 46.7 (9C), 28.1, 27.5 (t, $J$ = 125.0 Hz), 8.3 (9C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.0, 15.4. MS (ESI, $m/z$): 475.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{13}H_{18}ClN_2O_{11}P_2$, 475.0080; found, 475.0093 [M − H]$^-$. HPLC purity 95% ($R_t$ = 10.4 min, method HPLC-C).

*5-Fluorouridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4l**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 32.2 mg, 6%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 8.19 (d, $J$ = 6.5 Hz, 1H), 5.96 (dt, $J$ = 2.7, 1.6 Hz, 1H), 4.41−4.37 (m, 2H), 4.31−4.26 (m, 1H), 4.23 (ddd, $J$ = 11.7, 4.8, 2.7 Hz, 1H), 4.17 (ddd, $J$ = 11.7, 5.6, 3.0 Hz, 1H), 3.22 (q, $J$ = 7.3 Hz, 12H), 2.24 (t, $J$ = 19.9 Hz, 2H, PC$H_2$P), 1.29 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 159.5 (d, $J$ = 26.0 Hz), 150.4, 140.9 (d, $J$ = 233.4 Hz), 125.7 (d, $J$ = 34.8 Hz), 88.8, 83.5 (d, $J$ = 8.0 Hz), 73.9, 69.5, 63.2 (d, $J$ = 5.3 Hz), 46.7 (6C), 27.4 (t, $J$ = 125.0 Hz, PC$H_2$P), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.0, 15.4. MS (ESI, $m/z$): 419.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}FN_2O_{11}P_2$, 419.0062; found, 419.0057 [M − H]$^-$. HPLC purity 97% ($R_t$ = 9.3 min, method HPLC-C).

*5-Chlorouridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4m**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 23.1 mg, 10%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.19 (d, $J$ = 0.7 Hz, 1H), 5.92 (d, $J$ = 4.4 Hz, 1H), 4.40−4.34 (m, 2H), 4.28−4.24 (m, 1H), 4.19 (ddd, $J$ = 11.6, 4.6, 2.7 Hz, 1H), 4.13 (ddd, $J$ = 11.8, 5.7, 3.1 Hz, 1H), 3.18 (q, $J$ = 7.3 Hz, 12H), 2.22 (t, $J$ = 19.9 Hz, 2H), 1.26 (t, $J$ = 7.4 Hz, 18H). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.2, 14.9. MS (ESI, $m/z$): 435.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}ClN_2O_{11}P_2$, 434.9767; found, 434.9776 [M − H]$^-$. HPLC purity 97% ($R_t$ = 8.9 min, method HPLC-C).

*5-Bromouridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4n**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 4.1 mg, 2%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.29 (s, 1H), 5.96 (d, $J$ = 4.5 Hz, 1H), 4.46−4.38 (m, 2H), 4.32−4.28 (m, 1H), 4.25−4.16 (m, 2H), 3.22 (q, $J$ = 7.3 Hz, 12H), 2.25 (t, $J$ = 18.7 Hz, 2H, PC$H_2$P), 1.30 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 162.0, 151.2, 141.0, 97.0, 89.0, 83.6, 74.0, 69.6, 63.1, 46.8 (6C), 27.5 (PCH$_2$P), 8.3 (6C). The signal for PCH$_2$P could not be observed in the 1D experiment. $^{13}$C NMR shift of PCH$_2$P was determined using HSQC. $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.6, 14.8. MS (ESI, $m/z$): 479.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}{}^{79}BrN_2O_{11}P_2$, 478.9262; found, 478.9264 [M − H]$^-$. HPLC purity 95% ($R_t$ = 9.3 min, method HPLC-C).

*5-Iodouridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4o**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 17.5 mg, 9%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 8.27 (s, 1H), 5.93 (d, $J$ = 4.7 Hz, 1H), 4.39 (dt, $J$ = 13.0, 5.1 Hz, 2H), 4.31−4.21 (m, 1H), 4.22−4.10 (m, 2H), 3.21 (q, $J$ = 7.3 Hz, 12H), 2.27 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 163.6, 151.9, 145.9, 88.9, 83.6 (d, $J$ = 8.4 Hz), 73.9, 69.7, 68.7, 63.2, 46.7 (6C), 28.0 (t, $J$ = 124.0 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.7. MS (ESI, $m/z$): 526.9 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}N_2O_{11}IP_2$, 526.9118; found, 526.9123 [M − H]$^-$. HPLC purity 98% ($R_t$ = 9.6 min, method HPLC-B).

*2′-Deoxyuridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4p**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 16.2 mg, 13%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.98 (d, $J$ = 8.1 Hz, 1H), 6.31 (t, $J$ = 6.8 Hz, 1H), 5.94 (d, $J$ = 8.1 Hz, 1H), 4.65−4.51 (m, 1H), 4.21−4.14 (m, 1H), 4.15−4.07 (m, 2H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.39 (dd, $J$ = 6.8, 5.0 Hz, 2H), 2.17 (t, $J$ = 19.9 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 166.4, 151.7, 142.2, 102.5, 85.8 (d, $J$ = 7.5 Hz), 85.4, 70.9, 63.8 (d, $J$ = 4.7 Hz), 46.7 (6C), 38.8, 27.5 (t, $J$ = 124.0 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.3, 14.7. MS (ESI, $m/z$): 385.0 [M − H]$^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{15}N_2O_{10}P_2$, 385.0202; found, 385.0201 [M − H]$^-$. HPLC purity 99% ($R_t$ = 16 min, method HPLC-B).

*2′-Amino-2′-deoxyuridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4q**).* Method A. The product was obtained as a colorless solid


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J. Med. Chem. XXXX, XXX, XXX−XXX

after lyophilization (1 equiv $Et_3N$-salt, 4 mg, 8%), containing 8% of methylenediphosphonic acid. $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.02 (d, $J$ = 8.1 Hz, 1H), 6.28 (d, $J$ = 7.6 Hz, 1H), 6.00 (d, $J$ = 8.1 Hz, 1H), 4.70 (d, $J$ = 4.6 Hz, 1H), 4.44 (s, 1H), 4.23−4.08 (m, 3H), 3.21 (q, $J$ = 7.3 Hz, 6H), 2.18 (td, $J$ = 19.8, 4.0 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 9H). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.5, 15.9 (8% methylenediphosphonic acid), 14.4. MS (ESI, $m/z$): 400.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{16}N_3O_{10}P_2$, 400.0311; found, 400.0304 $[M - H]^-$. HPLC purity 96% ($R_t$ = 1.8 min, method HPLC-A).

*2′-Azido-2′-deoxyuridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4r**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 11 mg, 8%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.02 (d, $J$ = 8.1 Hz, 1H), 6.02 (d, $J$ = 5.2 Hz, 1H), 5.97 (d, $J$ = 8.1 Hz, 1H), 4.62 (t, $J$ = 5.2 Hz, 1H), 4.40 (t, $J$ = 5.4 Hz, 1H), 4.27−4.09 (m, 3H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.19 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.3, 151.7, 141.6, 102.7, 87.1, 83.7 (d, $J$ = 8.0 Hz), 70.1, 65.4, 63.0 (d, $J$ = 3.8 Hz), 46.7 (6C), 27.5 (t, $J$ = 124.6 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.6. MS (ESI, $m/z$): 426.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}N_5O_{10}P_2$, 426.0216; found, 426.0222 $[M - H]^-$. HPLC purity 99% ($R_t$ = 17.5 min, method HPLC-B).

*2′-Fluoro-2′-deoxyuridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4s**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 25.3 mg, 10%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.97 (d, $J$ = 8.1 Hz, 1H), 6.08 (dd, $J$ = 17.8, 1.8 Hz, 1H), 5.93 (d, $J$ = 8.1 Hz, 1H), 5.52 (ddd, $J$ = 52.5, 4.6, 1.8 Hz), 4.52 (ddd, $J$ = 21.6, 7.8, 4.6 Hz, 1H), 4.38−4.25 (m, 2H), 4.19 (ddd, $J$ = 11.7, 5.8, 2.8 Hz, 1H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.20 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.4, 151.4, 142.1, 102.3, 93.5 (d, $J$ = 185.9 Hz), 88.4 (d, $J$ = 35.1 Hz), 81.6 (d, $J$ = 7.9 Hz), 67.7 (d, $J$ = 15.9 Hz), 62.1 (d, $J$ = 4.9 Hz), 46.7 (6C), 27.5 (t, $J$ = 124.6 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.7. MS (ESI, $m/z$): 403.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}N_2O_{10}FP_2$, 403.0108; found, 403.0105 $[M - H]^-$. HPLC purity 98% ($R_t$ = 9.5 min, method HPLC-B).

*2′-ara-Fluoro-2′-deoxyuridine-5′-O-[(phosphonomethyl)-phosphonic acid] (**4t**).* Method A. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 11 mg, 8%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.93 (dd, $J$ = 8.1, 1.7 Hz, 1H), 6.32 (dd, $J$ = 15.5, 4.3 Hz, 1H), 5.92 (d, $J$ = 8.1 Hz, 1H), 5.23 (td, $J$ = 51.7, 3.6 Hz, 1H), 4.57 (dt, $J$ = 19.8, 3.6 Hz, 1H), 4.25−4.08 (m, 3H), 3.21 (q, $J$ = 7.3 Hz, 9H), 2.19 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 14H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.3, 151.4, 142.9, 101.9, 94.6 (d, $J$ = 191.8 Hz), 83.6 (d, $J$ = 16.9 Hz), 82.1, 73.2 (d, $J$ = 26.0 Hz), 62.7, 46.8 (4C), 27.5, 8.3 (4C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 20.6, 12.8. MS (ESI, $m/z$): 403.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{14}N_2O_{10}FP_2$, 403.0108; found, 403.0112 $[M - H]^-$. HPLC purity 98% ($R_t$ = 9.6 min, method HPLC-B).

*1(β-D-Arabinofuranosyl)-uridine-5′-O-[(phosphonomethyl)-phosphonic acid] (**4u**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 21.3 mg, 9%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.96 (d, $J$ = 8.1 Hz, 1H), 6.23 (d, $J$ = 5.5 Hz, 1H), 5.94 (d, $J$ = 8.1 Hz, 1H), 4.46 (t, $J$ = 5.5 Hz, 1H), 4.29 (t, $J$ = 6.0 Hz, 1H), 4.21 (tt, $J$ = 11.6, 6.6 Hz), 4.10 (dt, $J$ = 7.4, 3.9 Hz, 1H), 3.22 (q, $J$ = 7.3 Hz, 12H), 2.21 (t, $J$ = 19.7 Hz, 2H), 1.30 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.2, 151.4, 143.0, 101.3, 84.7, 81.2, 75.2, 73.8, 62.4, 46.7 (6C), 27.4 (t, $J$ = 124.8 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.9. MS (ESI, $m/z$): 401.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{15}N_2O_{11}P_2$, 401.0157; found, 401.0144 $[M - H]^-$. HPLC purity 99% ($R_t$ = 8.6 min, method HPLC-C).

*6-Azauridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4v**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 17.7 mg, 7%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.66 (s, 1H), 6.15 (d, $J$ = 3.7 Hz, 1H), 4.65 (dd, $J$ = 5.1, 3.7 Hz, 1H), 4.48 (t, $J$ = 5.2 Hz, 1H), 4.30−4.21 (m, 1H), 4.16−3.98 (m, 2H), 3.22 (q, $J$ = 7.3 Hz, 12H), 2.13 (t, $J$ = 17.8 Hz, 2H, $PCH_2P$), 1.30 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 158.6, 150.0, 137.2, 89.7, 83.1, 72.6, 70.5, 64.0, 46.7 (6C), 27.1 (1C, $PCH_2P$), 8.3 (6C). The signal of $PCH_2P$ could not be observed in the 1D experiment. $^{13}C$ NMR shift of $PCH_2P$ was determined using HSQC. $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.3, 15.0. MS (ESI, $m/z$): 403.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_9H_{14}N_3O_{11}P_2$, 402.0109; found, 402.0098 $[M - H]^-$. HPLC purity 96% ($R_t$ = 9.1 min, method HPLC-C).

*Uridine-5′-O-[(phosphonoethyl)phosphonic acid] (**4w**).* Method A. The product was obtained as a colorless solid after lyophilization (3 equiv $Et_3N$-salt and 1 equiv $H_3CCO_2H$, 60 mg, 8%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.93 (d, $J$ = 8.1 Hz, 1H), 6.14−5.71 (m, 2H), 4.32 (p, $J$ = 5.1 Hz, 2H), 4.28−4.22 (m, 1H), 4.17−4.01 (m, 2H), 3.18 (q, $J$ = 7.3 Hz, 18H), 1.90 (s, 3H, $H_3CCO_2H$), 1.85−1.64 (m, 4H), 1.26 (t, $J$ = 7.3 Hz, 27H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 181.0, 166.2, 151.8, 141.6, 102.6, 88.6, 83.4 (d, $J$ = 7.7 Hz), 73.9, 69.7, 63.1 (d, $J$ = 5.5 Hz), 46.7 (9C), 23.2, 22.1 (dd, $J$ = 133.5, 5.5 Hz), 20.4 (dd, $J$ = 135.4, 4.2 Hz), 8.3 (9C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 27.2 (d, $J$ = 73.5 Hz), 24.0 (d, $J$ = 73.5 Hz). MS (ESI, $m/z$): 415.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{17}N_2O_{11}P_2$, 415.0308; found, 415.0311 $[M - H]^-$. HPLC purity 99% ($R_t$ = 8.7 min, method HPLC-B).

*5-Methyluridine-5′-O-[(phosphonoethyl)phosphonic acid] (**4x**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 68 mg, 10%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.74 (s, 1H), 5.99 (d, $J$ = 5.3 Hz, 1H), 4.44−4.32 (m, 2H), 4.30−4.23 (m, 1H), 4.16−4.03 (m, 2H), 3.20 (q, $J$ = 7.3 Hz, 12H), 1.94 (s, 3H), 1.90−1.65 (m, 4H), 1.28 (t, $J$ = 7.3 Hz, 17H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.6, 152.0, 137.1, 112.0, 88.1, 83.6 (d, $J$ = 7.9 Hz), 73.6, 70.0, 63.4 (d, $J$ = 5.5 Hz), 46.7 (6C), 22.0 (dd, $J$ = 133.4, 5.0 Hz), 20.4 (dd, $J$ = 134.8, 4.8 Hz), 11.8, 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 27.3 (d, $J$ = 73.5 Hz), 24.1 (d, $J$ = 73.5 Hz). MS (ESI, $m/z$): 429.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{19}N_2O_{11}P_2$, 429.0464; found, 429.0472 $[M - H]^-$. HPLC purity 99% ($R_t$ = 9.1 min, method HPLC-B).

*2-Thiouridine-5′-O-[(phosphonomethyl)phosphonic acid] (**4y**).*[7] The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.21 (d, $J$ = 8.2 Hz, 1H), 6.63 (d, $J$ = 2.8 Hz, 1H), 6.24 (d, $J$ = 8.1 Hz, 1H), 4.51−4.40 (m, 1H), 4.35 (t, $J$ = 5.7 Hz, 1H), 4.33−4.26 (m, 2H), 4.25−4.16 (m, 1H), 3.20 (q, $J$ = 7.4 Hz, 10H), 2.17 (t, $J$ = 19.6 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 15H). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 19.2, 14.0.

*Cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7a**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 10.3 mg, 8%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.02 (d, $J$ = 7.6 Hz, 1H), 6.13 (d, $J$ = 7.5 Hz, 1H), 5.98 (d, $J$ = 4.1 Hz, 1H), 4.35 (dq, $J$ = 9.2, 5.0 Hz, 2H), 4.30−4.10 (m, 3H), 3.20 (q, $J$ = 7.3 Hz, 12H), 2.19 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 166.0, 157.4, 141.8, 96.5, 89.4, 82.9 (d, $J$ = 7.3 Hz), 74.3, 69.3, 63.1, 46.8 (6C), 27.5 (t, $J$ = 124.3 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.4, 14.6. MS (ESI, $m/z$): 403.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{16}N_3O_{10}P_2$, 400.0311; found, 400.0309 $[M - H]^-$. HPLC purity 96% ($R_t$ = 15.6 min, method HPLC-B).

*2′-Deoxycytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7b**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 34 mg, 14%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.14 (d, $J$ = 7.7 Hz, 1H), 6.28 (t, $J$ = 6.5 Hz, 1H), 6.21 (d, $J$ = 7.7 Hz, 1H), 4.60 (dt, $J$ = 7.1, 3.8 Hz, 1H), 4.31−4.18 (m, 1H), 4.16−4.06 (m, 2H), 3.20 (q, $J$ = 7.3 Hz, 9H), 2.51−2.28 (m, 2H), 2.17 (t, $J$ = 19.8 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 14H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 162.2, 152.4, 143.5, 95.7, 86.4, 86.1 (d, $J$ = 7.3 Hz), 70.7, 63.6 (d, $J$ = 4.3 Hz), 46.7 (4C), 39.5, 27.5 (t, $J$ = 124.7 Hz), 8.3 (4C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.3, 14.7. MS (ESI, $m/z$): 384.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{16}N_3O_9P_2$, 384.0362; found, 384.0365 $[M - H]^-$. HPLC purity 99% ($R_t$ = 8.8 min, method HPLC-B).

*5-Iodocytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7c**).* Method B. The product was obtained as a colorless solid after lyophilization (1.75 equiv $Et_3N$-salt, 9.4 mg, 5%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 8.26 (s, 1H), 5.93 (d, 1H, $J$ = 3.2 Hz), 4.41−4.33 (m, 2H), 4.31−4.27 (m, 1H), 4.21 (m, 2H), 3.22 (q, $J$ = 7.3 Hz, 10.5H), 2.29 (t, $J$ = 17.9 Hz, 2H, $PCH_2P$), 1.30 (t, $J$ = 7.3 Hz, 15.75H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 164.6, 156.6, 147.6, 89.8, 83.1, 74.4, 69.2,


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J. Med. Chem. XXXX, XXX, XXX−XXX

62.9, 46.7 (5.25C), 27.7 ($PCH_2P$), 8.3 (5.25C). The signal for $PCH_2P$ could not be observed in the 1D experiment. $^{13}C$ NMR shift of $PCH_2P$ was determined using HSQC. $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.5, 15.1. MS (ESI, $m/z$): 525.9 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{16}IN_3O_{10}P_2$, 525.9283; found, 525.9275 $[M - H]^-$. HPLC purity 99% ($R_t$ = 9.0 min, method HPLC-C).

*5-Fluorocytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7d**).* Method B. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 15.5 mg, 7%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 8.15 (d, $J$ = 6.3 Hz, 1H), 5.90 (dd, $J$ = 3.9, 1.4 Hz, 1H), 4.34 (t, $J$ = 5.3 Hz, 1H), 4.30 (dd, $J$ = 5.1, 3.8 Hz, 1H), 4.27–4.19 (m, 2H), 4.14 (d, $J$ = 11.8 Hz, 1H), 3.18 (q, $J$ = 7.3 Hz, 9H), 2.19 (t, $J$ = 19.2 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 15H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 158.1 (d, $J$ = 15.1 Hz), 155.4, 137.6 (d, $J$ = 248.3 Hz), 126.0 (d, $J$ = 33.0 Hz), 89.7, 82.9 (d, $J$ = 6.7 Hz), 74.4, 69.1, 62.9 (d, $J$ = 3.6 Hz), 46.7 (4.5C), 27.5 (t, $J$ = 119.5 Hz), 8.3 (4.5C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.9, 15.1. MS (ESI, $m/z$): 418.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{10}H_{15}FN_3O_{10}P_2$, 418.0222; found, 418.0235 $[M - H]^-$. HPLC purity 98% ($R_t$ = 8.8 min, method HPLC-C).

*5-Methylcytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7e**).* Method B. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 47.7 mg, 22%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 7.92 (s, 1H), 5.99 (d, 1H, $J$ = 3.9 Hz), 4.42–4.35 (m, 2H), 4.32–4.25 (m, 1H), 4.25–4.13 (m, 2H, $J$ = 11.6 Hz), 3.21 (q, $J$ = 7.3 Hz, 9H), 2.21 (t, $J$ = 19.0 Hz, 2H, $PCH_2P$), 2.07 (s, 3H), 1.29 (t, $J$ = 7.3 Hz, 13.5H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 163.2, 153.8, 139.7, 89.2, 83.3, 74.2, 69.4, 63.3, 46.7 (4.5C), 27.5 (t, $J$ = 122.7 Hz, 1C, $PCH_2P$), 12.3, 8.3 (4.5C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.0, 14.8. MS (ESI, $m/z$): 414.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{19}N_3O_{10}P_2$, 414.0473; found, 414.0484 $[M - H]^-$. HPLC purity 99% ($R_t$ = 7.0 min, method HPLC-C).

*4-Benzoylcytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**7f**).* Method B. The product was obtained as a colorless solid after lyophilization (5 equiv $Et_3N$-salt, 39.2 mg, 13%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 8.47 (d, $J$ = 7.0 Hz, 1H), 7.89 (d, $J$ = 7.7 Hz, 2H), 7.67 (t, $J$ = 7.4 Hz, 1H), 7.55 (t, $J$ = 7.7 Hz, 2H), 7.52–7.44 (m, 1H), 5.96–5.94 (m, 1H), 4.39–4.33 (m, 2H), 4.33–4.28 (m, 2H), 4.20 (d, $J$ = 11.6 Hz, 1H), 3.18 (q, $J$ = 7.3 Hz, 30H), 2.29–2.10 (m, 2H), 1.26 (t, $J$ = 7.3 Hz, 45H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 169.5, 163.2, 156.7, 145.8, 133.6, 132.6, 129.0 (2C), 128.1 (2C), 98.8, 90.9 (d, $J$ = 3.4 Hz), 82.8, 74.8, 68.7, 62.7, 46.7 (15C), 27.4 (t, $J$ = 120.2 Hz), 8.3 (15C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.5, 15.1. MS (ESI, $m/z$): 504.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{17}H_{20}N_3O_{11}P_2$, 504.0579; found, 504.0588 $[M - H]^-$. HPLC purity 90% ($R_t$ = 10.5 min, method HPLC-C). However, the compound displayed decomposition in aqueous solution (Supporting Information) and was tested for its CD73 inhibition at a purity of 75%.

*$N^4$-[O-(Benzyloxy)]-2′-deoxycytidine-5′-O-[(phosphonomethyl)-phosphonic acid] (**9c**).* Method B. The product was obtained as a colorless solid after lyophilization (1.5 equiv $Et_3N$-salt, 4.3 mg, 4.4%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.50–7.37 (m, 5H), 7.20 (d, $J$ = 8.3 Hz, 1H), 6.28 (t, $J$ = 7.1 Hz, 1H), 5.71 (d, $J$ = 8.3 Hz, 1H), 5.03 (s, 2H), 4.57 (dt, $J$ = 5.9, 2.8 Hz, 1H), 4.16–3.97 (m, 3H), 3.19 (q, $J$ = 7.3 Hz, 9H), 2.33 (dt, $J$ = 14.1, 7.0 Hz, 1H), 2.23 (ddd, $J$ = 14.1, 6.4, 3.3 Hz, 1H), 2.14 (t, $J$ = 19.8 Hz, 2H), 1.27 (t, $J$ = 7.3 Hz, 14H). $^{13}C$ NMR (100 MHz, $D_2O$): $\delta$ 147.2, 137.3, 132.3, 130.2, 128.8 (2C), 128.5, 128.4 (2C), 98.2, 85.1 (d, $J$ = 7.8 Hz), 84.3, 75.6, 71.2, 63.9, 46.7 (4C), 37.7, 13.6, 8.3 (4C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 21.3, 12.0. MS (ESI, $m/z$): 492.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{17}H_{24}N_3O_{10}P_2$, 492.0937; found, 492.0928 $[M + H]^-$. HPLC purity 99% ($R_t$ = 10.9 min, method HPLC-B).

*$N^4$-[O-(4-Trifluoromethylbenzyloxy)]-cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**9d**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 32.1 mg, 17%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 7.69 (d, $J$ = 8.0 Hz, 2H), 7.54 (d, $J$ = 8.0 Hz, 2H), 7.22 (d, $J$ = 8.1 Hz, 1H), 5.91 (d, $J$ = 4.8 Hz, 1H), 5.71 (d, $J$ = 8.1 Hz, 1H), 5.10 (s, 2H), 4.35–4.31 (m, 2H), 4.22–4.19 (m, 1H), 4.12–4.07 (m, 2H), 3.18 (q, $J$ = 7.3 Hz, 12H), 2.16 (t, $J$ = 18.8 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 151.0, 147.0, 141.8, 132.2, 129.5 (q, $J$ = 31.9 Hz), 128.3 (2C), 125.5 (q, $J$ = 3.8 Hz, 2C), 124.3 (q, $J$ = 271.5 Hz), 98.3, 87.3, 83.4 (d, $J$ = 6.6 Hz), 74.5, 72.7, 70.2, 63.8, 46.7 (6C), 27.4 (t, $J$ = 124.4 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.2, 15.1. MS (ESI, $m/z$): 574.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{18}H_{21}F_3N_3O_{11}P_2$, 574.0609; found, 574.0616 $[M - H]^-$. HPLC purity >99% ($R_t$ = 12.5 min, method HPLC-C).

*$N^4$-[O-(Naphthalen-2-ylmethoxy)]-cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**9e**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 4.5 mg, 2%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 7.97–7.94 (m, 3H), 7.93–7.91 (m, 1H), 7.60–7.57 (m, 3H), 7.20 (d, $J$ = 8.2 Hz, 1H), 5.90 (d, $J$ = 5.5 Hz, 1H), 5.72 (d, $J$ = 8.2 Hz, 1H), 5.20 (s, 2H), 4.34–4.30 (m, 2H), 4.21–4.19 (m, 1H), 4.10–4.07 (m, 2H), 3.17 (q, $J$ = 7.3 Hz, 12H), 2.14 (t, $J$ = 19.2 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 18H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 151.1, 147.0, 135.1, 133.0, 132.9, 132.1, 128.4, 128.0, 127.8, 127.2, 126.7, 126.6, 126.2, 98.4, 87.3, 83.4 (d, $J$ = 7.2 Hz), 75.5, 72.6, 70.2, 63.8, 46.7 (6C), 27.5 (t, $J$ = 127.0 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.3, 14.6. MS (ESI, $m/z$): 556.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{21}H_{24}N_3O_{11}P_2$, 556.0892; found, 556.0901 $[M - H]^-$. HPLC purity 99% ($R_t$ = 12.2 min, method HPLC-C).

*$N^4$-[O-(4-Benzyloxy)]-5-methyl-cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**9f**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 17.5 mg, 9%). $^1H$ NMR (400 MHz, $D_2O$): $\delta$ 7.48–7.36 (m, 5H), 7.03–7.00 (m, 1H), 5.92–5.88 (m, 1H), 5.07 (s, 2H), 4.37–4.32 (m, 2H), 4.21–4.17 (m, 1H), 4.11–4.06 (m, 2H), 3.18 (q, $J$ = 7.3 Hz, 12H), 2.16 (t, $J$ = 19.6 Hz, 2H), 1.80 (s, 3H), 1.26 (t, $J$ = 7.3 Hz, 18H). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.0, 14.7. MS (ESI, $m/z$): 520.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{18}H_{24}N_3O_{11}P_2$, 520.0892; found, 520.0911 $[M - H]^-$. HPLC purity >99% ($R_t$ = 10.9 min, method HPLC-C).

*$N^4$-[O-(4-Benzyloxy)]-5-fluoro-cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**9g**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$- and 1 $H_2CO_3$-salt, 40.0 mg, 11%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 7.45–7.36 (m, 6H), 5.89 (d, $J$ = 5.3 Hz, 1H), 5.09 (s, 2H), 4.35–4.31 (m, 1H), 4.29 (t, $J$ = 5.5 Hz, 1H), 4.24–4.17 (m, 1H), 4.14–4.07 (m, 2H), 3.57 (q, $J$ = 7.2 Hz, 6H), 3.17 (q, $J$ = 7.3 Hz, 6H), 2.24–2.05 (m, 2H), 1.33 (t, $J$ = 7.2 Hz, 9H), 1.26 (t, $J$ = 7.3 Hz, 9H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 149.7, 140.6 (d, $J$ = 21.7 Hz), 137.9 (d, $J$ = 235.3 Hz), 137.0, 128.8 (2C), 128.5, 128.3 (2C), 116.4 (d, $J$ = 35.1 Hz), 87.6, 83.4, 75.9, 72.8, 70.1, 63.7, 58.5 (3C), 46.7 (3C), 27.2 (t, $J$ = 124.4 Hz), 8.3 (3C), 7.19 (3C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 16.5. MS (ESI, $m/z$): 524.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{17}H_{21}FN_3O_{11}P_2$, 524.0641; found, 524.0645 $[M - H]^-$. HPLC purity 99% ($R_t$ = 11.4 min, method HPLC-C).

*$N^4$-[O-(4-Benzyloxy)]-3-methyl-cytidine-5′-O-[(phosphonomethyl)phosphonic acid] (**9h**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 8.5 mg, 4%). $^1H$ NMR (600 MHz, $D_2O$): $\delta$ 7.48–7.44 (m, 2H), 7.44–7.41 (m, 2H), 7.40–7.37 (m, 1H), 7.32 (d, $J$ = 8.4 Hz, 1H), 6.44 (d, $J$ = 8.3 Hz, 1H), 5.94 (d, $J$ = 5.2 Hz, 1H), 5.01 (s, 2H), 4.34–4.30 (m, 2H), 4.20 (q, $J$ = 3.1 Hz, 1H), 4.12–4.08 (m, 2H), 3.21–3.14 (m, 15H), 2.16 (t, $J$ = 19.1 Hz, 2H), 1.26 (t, $J$ = 7.4 Hz, 18H). $^{13}C$ NMR (150 MHz, $D_2O$): $\delta$ 153.9, 151.5, 136.9, 132.7, 128.9 (2C), 128.7 (2C), 128.5, 94.1, 88.4, 83.2 (d, $J$ = 7.3 Hz), 75.6, 73.0, 70.0, 63.7 (d, $J$ = 4.4 Hz), 46.7 (6C), 29.3, 27.4 (t, $J$ = 124.2 Hz), 8.3 (6C). $^{31}P$ NMR (160 MHz, $D_2O$): $\delta$ 18.4, 15.0. MS (ESI, $m/z$): 520.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{18}H_{24}N_3O_{11}P_2$, 520.0892; found, 520.0889 $[M - H]^-$. HPLC purity >99% ($R_t$ = 11.6 min, method HPLC-C). The synthesis was further optimized: a solution of methylenebis(phosphonic dichloride) (719 mg, 2.88 mmol, 1.5 equiv) in trimethyl phosphate (10.5 mL) cooled to 0 °C was added to a suspension of **8h** (697 mg, 1.92 mmol, 1.0 equiv) in trimethyl phosphate at 0 °C. The reaction mixture was stirred at 0 °C, and samples were withdrawn at 10 min intervals for LC–MS. After 45 min, on the disappearance of **8h** formate $[M + CHO_2^-]^-$ ($[M - H^+]^+$ disappeared after ~30 min), 7 mL of cold 1 M aqueous TEAC buffer


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J. Med. Chem. XXXX, XXX, XXX–XXX

solution (pH 8.4−8.6) was added. It was stirred at 0 °C for 15 min, followed by stirring at rt for 30 min. Because of the high lipophilicity of the product, no extraction was performed, and instead, the aqueous layer was lyophilized directly. Separation of the mixture of nucleotide and dinucleotide was done following method B to obtain the final product as a glassy solid (2 equiv $Et_3N$-salt, 423 mg, 0.584 mmol, 30%).

*$N^4$-[O-(4-Benzyloxy)]-3-ethyl-cytidine-5′-O-[(phosphonomethyl)-phosphonic acid] (**9i**).* Method B. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 9.0 mg, 5%). $^1$H NMR (600 MHz, $D_2O$): $\delta$ 7.46 (dt, $J$ = 7.2, 1.3 Hz, 2H), 7.42 (tq, $J$ = 6.4, 1.1 Hz, 2H), 7.40−7.36 (m, 1H), 7.27 (dd, $J$ = 8.4, 1.1 Hz, 1H), 6.41 (dd, $J$ = 8.5, 1.2 Hz, 1H), 5.92 (dd, $J$ = 5.4, 1.2 Hz, 1H), 5.00 (s, 2H), 4.34−4.29 (m, 2H), 4.19 (q, $J$ = 3.2 Hz, 1H), 4.12−4.08 (m, 2H), 3.18 (q, $J$ = 7.3 Hz, 12H), 2.16 (t, $J$ = 18.9 Hz, 2H), 1.26 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (150 MHz, $D_2O$): $\delta$ 153.0, 151.1, 137.0, 132.7, 129.1 (2C), 128.7 (2C), 128.5, 94.3, 88.3, 83.2 (d, $J$ = 7.4 Hz), 75.6, 72.9, 70.0, 63.7 (d, $J$ = 4.6 Hz), 46.7 (6C), 27.4 (t, $J$ = 124.4 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.3, 15.0. MS (ESI, $m/z$): 534.1 $[M + H]^-$; ESI-HRMS: calcd $m/z$ for $C_{19}H_{26}N_3O_{11}P_2$, 534.1048; found, 534.1074 $[M - H]^-$. HPLC purity >99% ($R_t$ = 11.9 min, method HPLC-B).

*3-Deazauridine-5′-O-[(phosphonomethyl)phosphonic acid] (**10**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 19 mg, 15%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.92 (d, $J$ = 7.8 Hz, 1H), 6.31 (d, $J$ = 7.6 Hz, 1H), 6.19 (d, $J$ = 4.3 Hz, 1H), 5.87 (d, $J$ = 2.6 Hz, 1H), 4.37 (dt, $J$ = 18.0, 5.1 Hz, 2H), 4.33−4.27 (m, 1H), 4.27−4.09 (m, 2H), 3.21 (q, $J$ = 7.3 Hz, 12H), 2.20 (t, $J$ = 19.7 Hz, 2H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 169.7, 165.7, 134.7, 104.2, 88.4, 82.9 (d, $J$ = 7.8 Hz), 74.7, 69.4, 63.2, 46.7 (6C), 27.5 (t, $J$ = 124.3 Hz), 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 18.3, 14.7. MS (ESI, $m/z$): 400.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{11}H_{16}NO_{11}IP_2$, 400.0199; found, 400.0203 $[M - H]^-$. HPLC purity 96% ($R_t$ = 9.4 min, method HPLC-C).

*(S)-Methanocarbauridine-5′-O-[(phosphonomethyl)phosphonic acid] (**11**).* Method A. The product was obtained as a colorless solid after lyophilization (2 equiv $Et_3N$-salt, 1.4 mg, 5%). $^1$H NMR (400 MHz, $D_2O$): $\delta$ 7.76 (d, $J$ = 7.8 Hz, 1H), 5.83 (d, $J$ = 7.8 Hz, 1H), 4.67 (d, $J$ = 6.3 Hz, 1H), 4.12 (d, $J$ = 6.5 Hz, 1H), 4.10−3.98 (m, 2H), 3.21 (q, $J$ = 7.3 Hz, 12H), 2.35 (s, 1H), 2.22−2.02 (m, 2H), 1.86 (dd, $J$ = 9.5, 4.8 Hz, 1H), 1.68 (t, $J$ = 5.5 Hz, 1H), 1.28 (t, $J$ = 7.3 Hz, 18H). $^{13}$C NMR (100 MHz, $D_2O$): $\delta$ 166.9, 152.7, 148.2, 101.8, 75.0, 71.9, 65.4, 51.6, 48.3, 46.8 (6C), 24.8, 15.7, 8.3 (6C). $^{31}$P NMR (160 MHz, $D_2O$): $\delta$ 19.3, 14.1. MS (ESI, $m/z$): 411.0 $[M - H]^-$; ESI-HRMS: calcd $m/z$ for $C_{12}H_{17}N_2O_{10}P_2$, 411.0358; found, 411.0363 $[M - H]^-$. HPLC purity 96% ($R_t$ = 2.9 min, method HPLC-A).

**Soluble CD73 Enzyme Preparations.** Soluble rat CD73 was expressed in *Spodoptera frugiperda* 9 (Sf9) insect cells and purified as previously described.[29] The cDNA for the soluble human CD73 (genbank accession no. NM_002526) was obtained from Prof. Dr. Norbert Sträter (University of Leipzig, Germany).[49] In order to generate a soluble enzyme, the signaling sequence for anchoring the protein to the membrane via a GPI anchor had been omitted (N-terminal residues: 1−27, C-terminal residues: 550−574 including GPI-anchor attachment site).[49] In addition, a 6× His-tag was fused to the C-terminus and the construct was cloned into the vector pACGP67B, which provides an N-terminal signal peptide for the protein secretion. Sf9 insect cells were grown in Insect-XPRESS media (#: BE12-730Q, Lonza, Switzerland) with 10 mg/L gentamicin and split at a ratio of 1:3 every fourth day. For transfection, cells were seeded into cell culture flasks (25 $cm^2$) at 60−70% confluence. Cell medium (100 $\mu$L) and 1 $\mu$L of vector DNA (1000 ng/$\mu$L) were mixed with 2.5 $\mu$L of baculovirus genomic ProEasy vector DNA (AB vector, CA, USA) and combined with premixed 100 $\mu$L of cell medium and 8 $\mu$L of Cellfectin II Reagent (Thermo Fisher Scientific, MA, USA). The transfection mixture was left for 30 min at rt and then added dropwise to the cells into the cell culture flasks. The cells were incubated for 30 min at rt and for further 4 days at 27 °C. Cells from the transfection procedure were detached from the bottom of the flasks and centrifuged for 5 min at 2000$g$. The supernatant (1.5 mL, viral stock) was added to 75 $cm^2$ cell culture flasks containing Sf9 cells (60−70% confluence), and the cells were incubated for 4 days at 27 °C. Then, 1.5 mL of the supernatant was taken and added to uninfected Sf9 cells in a 75 $cm^2$ flask. This was repeated five more times, using more cells and larger flasks after the third round of infections (175 $cm^2$ to which 3.0 mL of the supernatant was added).

The final stock solution was used for infection of the cells. For protein expression, 3 mL of the virus solution was used to infect 150 mL of cell media containing 2 × $10^6$ cells/mL in a 500 mL Erlenmeyer flask, and the cells were incubated for 4 days at 27 °C with shaking (150 rpm). Then, cell suspensions were transferred to 50 mL Falcon tubes and centrifuged at 15 min at 5000$g$ at 4 °C. The supernatants were subjected to ultrafiltration using Amicon Ultra-15, 10 kDa cutoff (Merck Millipore, MA, USA) at 5000$g$ for 15−30 min at 4 °C. The concentrated protein was purified with HisPur $Ni^{2+}$−NTA spin columns (#: 88226, Thermo Fisher Scientific, MA, USA). The elution of the columns was performed as recommended in the instruction manual with adjusting the incubation time for protein binding to 1 h at 4 °C with an end-over-end mixer and an additional incubation step of 5 min with the elution buffer before eluting. Eluates were pooled and dialyzed (Membra-Cel, 14 kDa cutoff, 250 mm × 44 mm × 0.02 mm; Carl Roth, Germany) at 4 °C in 25 mM Tris buffer, pH 7.4, with a volume adjusted to 40 times the volume of the elution fraction. The buffer was exchanged after 8 h. The enzyme was aliquoted and stored at −80 °C until use.

**Cell Culture.** TNBC cells (MDA-MB-231), which natively express CD73, were grown in Dulbecco's modified Eagle medium (#: 41966, Thermo Fisher Scientific, MA, USA), and melanoma cancer cells with CRISPR-Cas9 knockout of CD73[70] (MaMel.65-$CD73^{ko}$) were cultivated in Roswell Park Memorial Institute medium 1640 (Thermo Fisher Scientific, Langerwehe, Germany) plus 2 mM L-glutamine (PAN Biotech, Germany). Both media were supplemented with 100 U/mL penicillin/100 $\mu$g/mL streptomycin (PAN Biotech, Germany) and 10% of fetal bovine serum (PAN Biotech, Germany) and cultivated at 37 °C with 5% $CO_2$. MDA-MB-231 and MaMel.65-$CD73^{ko}$ cells were split 1:20 and 1:5, respectively, every 72 h (at 80−90% cell confluence). To detach the adherent cells, growth medium was removed, and cells were washed with phosphate-buffered saline (PBS, 25 $cm^2$ flask: 2.5 mL, for larger flasks correspondingly larger amounts) and incubated with trypsin/ethylenediaminetetraacetic acid (EDTA) (0.05%/0.6 mM, PAN Biotech, Germany; 1 mL for a 25 $cm^2$ flask) for 5 min in an incubator at 37 °C. Detached cells were diluted with growth media (2 mL for a 25 $cm^2$ flask) and transferred to new culture flasks containing growth media (5 mL for a 25 $cm^2$ flask).

**Membrane Preparation of CD73 from MDA-MB-231 and Preparation of the Cytosolic Extract from MaMel.65-$CD73^{ko}$ Cells.** For both preparations, cells were expanded in 175 $cm^2$ culture flasks to 80−90% cell confluence. After detachment by trypsin/EDTA (0.05%/0.6 mM), $10^6$ cells per dish were transferred to cell culture dishes (150 $cm^2$) and incubated for 4 days at 37 °C with 5% $CO_2$. The culture medium was removed, and cells were washed with 10 mL of PBS and frozen at −20 °C. For membrane preparation, cells were treated with 1 mL of ice-cold buffer (50 mM Tris, 2 mM EDTA, pH 7.4), scraped off, collected in a conical tube, and centrifuged for 10 min at 1000$g$ (4 °C). The pellet was resuspended in membrane buffer [0.5 mL/dish; 25 mM Tris, 1 mM EDTA, 320 mM sucrose, 1:1000 protease inhibitor cocktail (Sigma-Aldrich, MO, USA), pH 7.4] and homogenized three times for 30 s each (20 500 rpm, ULTRA-TURRAX, IKA-Labortechnik, Germany). After centrifugation for 10 min, at 1000$g$ (4 °C), the supernatants were collected and centrifuged for 30 min at 48 000$g$ (4 °C). The resulting supernatants containing the cytosolic proteins were discarded, and the pellet was resuspended in washing buffer (0.5 mL/dish; 50 mM Tris, pH 7.4) and centrifuged again (same conditions). This step was repeated three times. Finally, the pellet was resuspended in washing buffer (0.1 mL/dish), aliquoted, and stored at −80 °C until use. For producing the cytosolic extract from MaMel.65-$CD73^{ko}$ cells, a published procedure was adopted.[62] The protein of the supernatant that was obtained after ultracentrifugation was precipitated with 40% aq ammonium sulfate


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J. Med. Chem. XXXX, XXX, XXX−XXX

and centrifuged for 10 min at 12 000*g* (4 °C). The resulting pellet was solubilized in 4 mL of *N*-(2-hydroxyethyl)piperazine-*N*′-ethanesulfonic acid (HEPES) buffer (40 mM HEPES, 1 mM EDTA, 5 mM $MgCl_2$, 1 mM dithiothreitol, 0.2 mM phenylmethylsulfonyl fluoride, 15% glycerol, pH 7.0), transferred to Amicon Ultra-0.5 tubes (10 kDa cutoff, Merck Millipore, MA, USA), and centrifuged for 20 min at 16 000*g* (Mikro 200R, Hettich, Germany) for the removal of ammonium sulfate, phosphate, and nucleotide contaminants. The protein samples were washed three times with 4 mL of the HEPES buffer by using the Amicon filtration tubes under the described centrifugation conditions, aliquoted, and stored at −80 °C.

**CD73 Enzyme Inhibition Assays.** The assay was performed essentially as previously described.[34] Stock solutions (10 mM) of the compounds were prepared in demineralized water, and further dilutions were performed in assay reaction buffer (25 mM Tris, 140 mM sodium chloride, 25 mM sodium dihydrogen phosphate, pH 7.4). The inhibitor solution (10 μL) was added to 70 μL of assay reaction buffer. After the addition of 10 μL of CD73-containing solution or suspension (rat CD73: 1.63 ng; human CD73: 0.365 ng; membrane preparation of MDA-MB-231 cells expressing CD73: 7.4 ng of protein per vial), the reaction was initiated by the addition of 10 μL of [2,8-$^3$H]AMP [specific activity $7.4 \times 10^8$ Bq/mmol (20 mCi/mmol)], American Radio-labeled Chemicals, MO, USA, distributed by Hartman Analytic, Germany), resulting in a final substrate concentration of 5 μM. The enzymatic reaction was performed for 25 min at 37 °C in a shaking water bath. Then, 500 μL of cold precipitation buffer (100 mM lanthanum chloride, 100 mM sodium acetate, pH 4.0) was added to stop the reaction and to facilitate the precipitation of free phosphate and unconverted [2,8-$^3$H]AMP. After the precipitation was completed (after at least 30 min on ice), the mixture was separated by filtration through GF/B glass fiber filters using a cell harvester (M-48, Brandel, Gaithersburg, MD, USA). After washing each reaction vial three times with 400 μL of cold (4 °C) demineralized water, 5 mL of the scintillation cocktail (ULTIMA Gold XR, PerkinElmer, MA, USA) was added, and radioactivity was measured by scintillation counting (Tri-Carb 2900 TR, Packard/PerkinElmer; counting efficacy: 49−52%). Two controls were included and measured as duplicates. One reaction was performed without the inhibitor, resulting in 100% enzyme activity (positive control), and the other was incubated without the inhibitor and the enzyme and served as background control. The resulting data were subtracted from the background and were normalized to the positive control. The results were plotted, and concentration−inhibition curves were fitted with GraphPad Prism 5 (GraphPad Software, La Jolla, USA). The mean $IC_{50}$ ± standard error of the mean (SEM) from three independent experiments was used to calculate the $K_i$ value with the Cheng−Prusoff equation[30] ($K_m$, rat CD73: 53.0 ± 4.1 μM; $K_m$, human CD73: 17.0 ± 2.1 μM; $K_m$, (MDA-MB-231): 14.8 ± 2.1 μM; Supporting Information, Figure S2).

To show that the triethylammonium salt form of the inhibitors did not affect is inhibitory activity, triethylammonium chloride was tested at 500 μM concentration and no reduction of enzymatic activity was detected (data not shown).

**Analysis of AMP Hydrolysis by the Cytosolic Extract Derived from MaMel.65-CD73$^{ko}$ Cells.** Reactions were performed in 50 mM Tris, pH 7.0, buffer containing 100 mM KCl, 5 mM $MgCl_2$, and 15.25 μg of the cytosolic extract derived from MaMel.65-CD73$^{ko}$ cells.[70] After preincubation of 5 min at 37 °C, the reactions were initiated by the addition of 5 mM AMP as a substrate. After 60 min, the reactions were terminated by heat inactivation (5 min at 95 °C), and samples were placed on ice. Reaction tubes were centrifuged for 5 min at 23 000*g* (4 °C), and the supernatant was transferred into the wells of a 96-well half-area microplate (clear, Greiner Bio-One, Austria). To enable phosphate detection, 20 μL of detection reagent I (final concentration 120 μM malachite green oxalate, 0.06% polyvinyl alcohol) and 30 μL of detection reagent II (final concentration: 6 mM ammonium heptamolybdate, 0.45 M $H_2SO_4$) were added. The plate was incubated at rt and 500 rpm for 20 min. The absorption of the formed colorimetric complex was analyzed at 600 nm (PHERAstar FS, BMG Labtech, Ortenberg, Germany). Compounds **4l**, **7f**, **9g**, and **9h** were analyzed at 100 μM, and a mixture of the phosphatase inhibitors levamisole (1 mM) and sodium fluoride (5 mM) was used as a positive control. As negative controls, reactions in the absence of any inhibitor or without AMP were performed. In addition, to the mixture of levamisole and NaF, one of the CD73 inhibitors (**4l**, **7f**, **9g**, or **9h**, respectively, 100 μM) was added; however, the CD73 inhibitors did not result in increased inhibition of AMP hydrolysis as compared to levamisole and NaF alone, even after an extended incubation time of up to 120 min.

**Human P2Y$_6$ Receptor Assay.** Calcium mobilization induced by the nucleotide derivatives was measured in a human astrocytoma cell line (1321N1) expressing the human $P2Y_6$ receptor, as previously described.[42]

**Human P2Y$_{14}$ Receptor Assay.** Inhibition of binding of a high-affinity fluorescent antagonist was measured using flow cytometry in a CHO cell line expressing the human $P2Y_{14}$ receptor, as previously described.[37]

**In Situ Ecto-5′-Nucleotidase Activity Assay.** For localization of AMPase activities in human tonsils, a modification of the lead nitrate method was employed.[63,64] In brief, palatine tonsils were obtained from adult patients with chronic tonsillitis undergoing routine tonsillectomy at Turku University Hospital (permission # TO6/033/18 from the Hospital Research Council). The tonsils were washed with physiological salt solution, embedded in the cryo-mold with Tissue-Tek O.C.T. compound (Sakura Finetek Europe B.V. The Netherlands), cut using a cryostat and stored at −80 °C. Tonsil cryosections were preincubated for 30 min in Trizma-maleate sucrose buffer (TMSB; 40 mM Trizma maleate; 0.25 M sucrose, pH 7.4) supplemented with the alkaline phosphatase inhibitor levamisole (2 mM) and different concentrations of CD73 inhibitor AOPCP or **9h**. The enzymatic reaction was then performed for 45 min at 37 °C in a final volume of 20 mL of TMSB-buffered substrate solution containing 1.5 mM $Pb(NO_3)_2$, 1 mM $CaCl_2$, 100 μM AMP, and tested CD73 inhibitor at the same concentration. The lead orthophosphate precipitated in the course of nucleotidase activity was visualized as a brown deposit by incubating sections in 0.5% $(NH_4)_2S$ for 30 s, followed by three washes in Trizma-maleate buffer for 5 min each. Slides were mounted with Aquatex medium (Merck, Germany). Multiple images of adjacent tissue areas were captured using a Pannoramic 250 slide scanner (3DHistech Ltd., Budapest, Hungary) and further stitched to a larger overview using the accompanying Pannoramic Viewer 1.15.4 software. The images of control and treated tissue were captured at identical exposure times and other settings and further acquired in parallel using Adobe Photoshop CS6 software. Nucleotidase activities were quantified as mean pixel intensities after grayscale conversion using ImageJ 1.52h software.

CD73 is highly expressed in the germinal centers, connective tissues, and, to lesser extent, in the interfollicular area. Such heterogeneity precludes proper quantification of "global" AMPase staining in the whole tissue. Therefore, we selected the same matched areas of germinal centers in the control and treated tonsils and further compared their mean pixel intensities. Also, the inhibitor concentrations are given as nanomolar for matched volumes, as we have noticed that the actual amount of inhibitor per tissue slide is an important factor.

**Molecular Docking Studies.** The recent cocrystal structure of the human CD73 (PDB ID: 4H2I)[49] with the antagonist AOPCP was obtained from the Research Collaboratory for Structural Bioinformatics Protein Data Bank.[65] The downloaded crystal structures were prepared using the protein preparation tool, and the hydrogen atoms were assigned according to Protonate 3D implemented in Molecular Operating Environment (MOE 2018.01).[66] The crystal structure of the human CD73 was applied for flexible ligand docking using AutoDock 4.2.[67−69] During the docking simulations, the ligands were fully flexible, while the residues of the enzyme were treated as rigid. The selected potent compound **9f** was docked into the active site of the enzyme to predict the binding mode of the compounds. The atomic partial charges were added and three-dimensional energy scoring grids for a box of 60 × 60 × 60 points with a spacing of 0.375


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Å were computed using AutoDockTools.[67,68] The grids were centered based on the cocrystallized ligand, AOPCP. Fifty independent docking calculations using the varCPSO-ls algorithm from PSO@Autodock implemented in AutoDock4.2 were performed and terminated after 500 000 evaluation steps.[69] Parameters of varCPSO-ls algorithm, the cognitive and social coefficients $c_1$ and $c_2$, were set at 6.05 with 60 individual particles as swarm size. All other parameters of the algorithm were set at their default values. Possible binding modes of the compounds were explored by visual inspection of the resulting docking poses.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jmedchem.9b00164.

$^1$H, $^{13}$C, and $^{31}$P NMR spectra of all compounds, plots of pharmacological data, molecular modeling figures, and atomic coordinates of the model of **9h** bound to CD73 (PDF)

Inhibitory potencies of selected compounds at rat CD73, human soluble CD73, and human membrane CD73 (CSV)

Docked complex of ligand **9h** and human CD73 (PDB)

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### Notes

The authors declare no competing financial interest.

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## ■ ABBREVIATIONS

AR, adenosine receptor; ACN, acetonitrile; ADP, adenosine 5′-diphosphate; AMP, adenosine 5′-monophosphate; ATP, adenosine 5′-triphosphate; AOPCP, *α,β*-methylene-ADP, adenosine-5′-*O*-[(phosphonomethyl)phosphonic acid], [{5-(6-aminopurin-9-yl)-3,4-dihydroxyoxolan-2-yl}-methoxyhydroxyphosphoryl]methylphosphonic acid; CD73, cluster of differentiation 73; CE, capillary electrophoresis; DMEM, Dulbecco's modified Eagle medium; DMAP, 4-dimethylaminopyridine; DMF, *N,N*-dimethylformamide; DMSO, dimethyl sulfoxide; EC, enzyme commission; EDTA, ethylenediaminetetraacetic acid; ESI, electrospray ionization; FBS, fetal bovine serum; GPI, glycophosphatidylinositol; HPLC, high-performance liquid chromatography; LC−MS, liquid chromatography−mass spectrometry; MeOD-$d_4$, deuterated methanol; MOE, Molecular Operating Environment; eN, ecto-5′-nucleotidase; eNPPs, ecto-nucleoside pyrophosphatases/phosphodiesterases; eNTPDases, ecto-nucleoside triphosphate diphosphohydrolases; PBS, phosphate-buffered saline; pdb, Protein Data Bank; POMs, polyoxometalates; PSB, Pharmaceutical Sciences Bonn; SAR, structure−activity relationship; Sf9, *Spodoptera frugiperda 9*; TEA, triethylamine; TEAC, triethylammonium hydrogen carbonate; THF, tetrahydrofuran; TLC, thin-layer chromatography; TNBC, triple-negative breast cancer; Tris, tris(hydroxymethyl)-aminomethane

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*J. Med. Chem.* XXXX, XXX, XXX−XXX