

## Molecular Analysis of the Interaction of *Bordetella pertussis* Adenylyl Cyclase with Fluorescent Nucleotides

Martin Göttle, Stefan Dove, Phillip Steindel, Yuequan Shen, Wei-Jen Tang, Jens Geduhn, Burkhard König, and Roland Seifert

Departments of Pharmacology and Toxicology (M.G., P.S., R.S.) and Pharmaceutical and Medicinal Chemistry II (S.D.), Institute of Pharmacy, University of Regensburg, Germany; Ben May Department for Cancer Research, the University of Chicago (W.-J.T.); the College of Life Sciences, Nankai University, China (Y.S.); and Institute of Organic Chemistry, University of Regensburg, Germany (J.G., B.K.)

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### ABSTRACT

The calmodulin (CaM)-dependent adenylyl cyclase (AC) toxin from *Bordetella pertussis* (CyaA) substantially contributes to the pathogenesis of whooping cough. Thus, potent and selective CyaA inhibitors may be valuable drugs for prophylaxis of this disease. We examined the interactions of fluorescent 2',3'-*N*-methylanthraniloyl (MANT)-, anthraniloyl- and trinitrophenyl (TNP)-substituted nucleotides with CyaA. Compared with mammalian AC isoforms and *Bacillus anthracis* AC toxin edema factor, nucleotides inhibited catalysis by CyaA less potently. Introduction of the MANT substituent resulted in 5- to 170-fold increased potency of nucleotides.  $K_i$  values of 3'MANT-2'd-ATP and 2'MANT-3'd-ATP in the AC activity assay using  $Mn^{2+}$  were 220 and 340 nM, respectively. Natural nucleoside 5'-triphosphates, guanine-, hypoxanthine- and pyrimidine-MANT- and TNP nucleotides and di-MANT nucleotides inhibited CyaA, too. MANT nucleotide binding to CyaA generated fluorescence

resonance energy transfer (FRET) from tryptophans Trp69 and Trp242 and multiple tyrosine residues, yielding  $K_d$  values of 300 nM for 3'MANT-2'd-ATP and 400 nM for 2'MANT-3'd-ATP. Fluorescence experiments and docking approaches indicate that the MANT- and TNP groups interact with Phe306. Increases of FRET and direct fluorescence with MANT nucleotides were strictly CaM-dependent, whereas TNP nucleotide fluorescence upon binding to CyaA increased in the absence of CaM and was actually reduced by CaM. In contrast to low-affinity MANT nucleotides, even low-affinity TNP nucleotides generated strong fluorescence increases upon binding to CyaA. We conclude that the catalytic site of CyaA possesses substantial conformational freedom to accommodate structurally diverse ligands and that certain ligands bind to CyaA even in the absence of CaM, facilitating future inhibitor design.

*Bordetella pertussis* toxin CyaA is a 1706-amino acid virulence factor interacting with surface receptors of eukaryotic host cells and translocating its AC domain into the cytosol (Confer and Eaton, 1982; Hewlett et al., 1989; Ladant and Ullmann, 1999). After activation by calmodulin (CaM), an endogenous calcium sensor, CyaA catalyzes massive synthesis of cAMP (Mock and Ullmann, 1993; Shen et al., 2002; Ahuja et al., 2004). cAMP inhibits phagocyte function and

facilitates respiratory tract infection by *Bordetella pertussis* (Boyd et al., 2005; Carbonetti et al., 2005; Hewlett et al., 2006). Substrate analogs may be used to inhibit the catalytic activity of CyaA (Johnson and Shoshani, 1990; Soelaiman et al., 2003; Gille et al., 2004) and prophylaxis of *B. pertussis* infection. We have discovered *N*-methylanthraniloyl (MANT)-substituted NTPs as competitive inhibitors of mammalian and bacterial ACs, including CyaA (Gille and Seifert, 2003; Gille et al., 2004). In addition, 2',3'-(2,4,6-trinitrophenyl) (TNP)-substituted NTPs are potent inhibitors of mammalian AC (Mou et al., 2006). Furthermore, adefovir, a drug for the treatment of chronic hepatitis B virus infection, is a potent CyaA inhibitor (Shen et al., 2004).

Mammals express nine membranous AC isoforms (ACs 1-9) and a soluble AC. We have employed the cytosolic

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**ABBREVIATIONS:** CyaA, *Bordetella pertussis* adenylyl cyclase; AC, adenylyl cyclase; CaM, calmodulin; PMEApp, 9-[2-(phosphonomethoxy)ethyl]adenine diphosphate; MANT, methylanthraniloyl-; ANT, anthraniloyl-; FRET, fluorescence resonance energy transfer; TNP, 2,4,6-trinitrophenyl-; PDB, Protein Data Bank; NDP, nucleoside 5'-diphosphate; NTP, nucleoside 5'-triphosphate.

catalytic domains C1 of type 5 AC and C2 of type 2 AC for molecular AC analysis (Gille et al., 2004; Mou et al., 2005, 2006). Comparing the crystal structures of C1:C2 bound to MANT-GTP, MANT-ATP, and TNP-ATP, we found the catalytic site of AC to consist of three binding pockets, accommodating the base, the 2',3'-ribosyl substituent and the phosphate chain. We have also reported the crystal structure of CyaA in complex with CaM and 9-[2-(phosphonomethoxy)ethyl]adenine diphosphate (PMEApp), the active metabolite of adefovir (Guo et al., 2005). Forty-nine amino acid residues of CyaA and 41 residues of CaM form salt bridges, hydrogen bonds, and hydrophobic contacts, resulting in high affinity of CyaA for CaM ( $K_d = 0.2$  nM). However, the precise conformational changes in the catalytic site of CyaA underlying its activation by CaM are still unknown. An understanding of these processes will greatly facilitate future inhibitor design.

To monitor nucleotide binding to and conformational changes in CyaA, several different approaches can be employed. First, MANT- and ANT nucleotides are environmentally sensitive probes displaying increased fluorescence and blue shift of the emission maximum upon exposure to a hydrophobic environment (Hiratsuka, 1983; Jameson and Eccleston, 1997). As is obvious from the CyaA crystal structure in complex with PMEApp (Guo et al., 2005), the catalytic site contains the hydrophobic residue F306. Nucleotide binding to CyaA allows hydrophobic interactions between the MANT/ANT group and Phe306, resulting in an increased fluorescence signal (Sarfati et al., 1990; Guo et al., 2005). This notion is supported by the fact that CyaA-F306A does not increase the fluorescence signal of 3'ANT-2'd-ATP (Guo et al., 2005). Second, the catalytic domain of CyaA bears two tryptophan residues, Trp69 and Trp242, located 21 and 38 Å, respectively, away from the catalytic site (Guo et al., 2005). These distances allow fluorescence resonance energy transfer (FRET) (Lakowicz, 1999) from tryptophan (excitation wavelength, 280 nm; emission wavelength, 350 nm) to MANT (excitation wavelength, 350 nm; emission wavelength, 450 nm) (Gilles et al., 1990; Mou et al., 2005, 2006). Third, TNP nucleotides are environmentally sensitive fluorescence probes, too (Hiratsuka, 2003). Like MANT nucleotides, TNP nucleotides show a blue shift in emission in a hydrophobic environment (Hiratsuka, 2003). Compared with MANT/ANT nucleotides, TNP nucleotides are more rigid because the fluorophore is attached through both the 2'- and the 3'-ribosyl positions, avoiding potential problems with fluorophore isomerization (Jameson and Eccleston, 1997; Hiratsuka, 2003). A potential advantage of TNP nucleotides compared with MANT nucleotides is the fact that the relative fluorescence increases can be substantially larger, depending on the specific protein studied (Jameson and Eccleston, 1997; Hiratsuka, 2003; Mou et al., 2005, 2006).

In the present study, we used MANT/ANT- and TNP nucleotides as probes to determine their potencies at inhibiting CyaA and to investigate conformational changes in the catalytic site. Nucleotides **12**, **14**, **15**, **18**, **19**, **20**, **25**, **30**, and **31** represent newly synthesized fluorescent probes. Moreover, the binding mode of nucleotides was explored by docking of representative derivatives to a CyaA model derived from the crystal structure in complex with PMEApp (Shen et al., 2004; Guo et al., 2005).

## Materials and Methods

**Materials.** MANT- and ANT-substituted NTPs of adenosine, cytidine, inosine, and uridine were synthesized according to a documented procedure (Hiratsuka, 1983). The modification of the synthesis by lowering the pH value from 9.6 to 8.6 induced higher yields. In the case of the starting material methylisatoic anhydride, the major portion of the excessive compound was removed by  $\text{CHCl}_3$  extraction. In general, the separation of starting materials could be achieved by using size exclusion chromatography with Sephadex LH-20 in water. However, high-performance liquid chromatography analysis and liquid chromatography/mass spectrometry coupling still showed by-products of the corresponding (MANT)-diphosphate residue. Pure MANT nucleotides were obtained by preparative reversed-phase HPLC with a Phenomenex Luna C18(2) column (particle size, 10  $\mu\text{m}$ ; length, 250 mm; inner diameter, 21.2 mm). The nucleoside 5'-diphosphates were also collected because of their putative inhibitory effects. (MANT)-nucleoside 5'-diphosphates and triphosphates were obtained in high purity of 99%. Di-MANT-IMP (**31**) bearing two MANT groups at the 2',3'-ribosyl position was also found as a by-product of our synthesis and was purified to 99% content, too.

MANT-ATP (**8**), MANT-GTP (**10**), ANT-GTP (**24**), 3'MANT-2'd-ATP (**21**), 2'MANT-3'd-ATP (**22**), TNP-CTP (**28**), TNP-UTP (**29**), and  $\gamma\text{S}$ -substituted MANT nucleotides (**9**, **11**, **13**) were obtained from Jena Bioscience (Jena, Germany). In the case of MANT-ATP, the MANT group isomerizes between the 2' and 3' positions of the ribose ring, whereas in 2'MANT-3'd-ATP and 3'MANT-2'd-ATP, the MANT group is fixed to the corresponding position due to the absence of the neighboring hydroxyl group. PMEApp (**1**) was supplied by Gilead Sciences (Foster City, CA). TNP-ATP (**26**) and TNP-GTP (**27**) were from Invitrogen (Carlsbad, CA). ITP was from Sigma-Aldrich (Seelze, Germany); GTP was from Roche (Mannheim, Germany). UTP and CTP were from Boehringer Ingelheim (Ingelheim, Germany). The catalytic domain of *B. pertussis* AC protein (CyaA, amino acids 1–373) was purified as described previously (Shen et al., 2002). Lyophilized calmodulin from bovine brain was purchased from Calbiochem (Darmstadt, Germany). [ $\alpha$ - $^{32}\text{P}$ ]ATP (800 Ci/mmol) was purchased from PerkinElmer Life and Analytical Sciences, Waltham, MA. Aluminum oxide 90 active, neutral (activity 1; particle size, 0.06–0.2 mm) was purchased from Merck (Darmstadt, Germany). Albumin from bovine serum, fraction V, highest quality, was from Sigma-Aldrich.  $\text{MnCl}_2$  tetrahydrate and  $\text{MgCl}_2$  hexahydrate (highest quality) were from Merck.

**FRET and Direct Fluorescence Experiments with MANT Nucleotides.** Experiments were performed using a quartz UV ultramicrocuvette from Hellma (Müllheim, Germany) (type 105.251-QS; light path length, 3 mm; center, 15 mm; total volume, 70  $\mu\text{l}$ ). Measurements were performed in a Cary Eclipse fluorescence spectrometer (Varian, Inc., Palo Alto, CA) at a constant temperature of 25°C (slit width, 5 nm; scan rate, 120 nm/min; averaging time, 0.5 s; data interval, 1 nm; PMT voltage, 700 V). The cuvette contained at first 64  $\mu\text{l}$  of 75 mM HEPES/NaOH buffer, 100  $\mu\text{M}$   $\text{CaCl}_2$ , 100 mM KCl, and 5 mM  $\text{MnCl}_2$ , pH 7.4. Next, nucleotide, CyaA, and CaM were added successively. The cuvette content (final volume, 70  $\mu\text{l}$ ) was mixed after each addition. In FRET experiments, nucleotides were used at final concentrations from 10 nM to 2  $\mu\text{M}$ , and CyaA and CaM were 300 nM each. The excitation wavelength was 280 nm, and emission was scanned from 300 to 550 nm. To investigate the kinetics of CyaA interaction with MANT nucleotides, the excitation wavelength was 280 nm, and changes in fluorescence intensity were measured over time at 430 nm. Nucleotides, CyaA, and CaM were applied at a final concentration of 300 nM. MANT nucleotides were finally displaced from CyaA using PMEApp (10 nM to 3  $\mu\text{M}$ ). In saturation studies, independent FRET experiments were performed using MANT nucleotides from 10 nM to 2  $\mu\text{M}$  final concentration; CyaA and CaM were 300 nM each. Saturation curves were obtained by subtracting the fluorescence intensity at 430 nm after the addition of CyaA from the maximal fluorescence (FRET) after the addition of CyaA/CaM.

In direct fluorescence experiments, MANT nucleotides were excited at 350 nm, and emission spectra were recorded from 380 to 550 nm. To obtain large increases in direct fluorescence, CyaA and CaM (final concentrations, 2.4  $\mu\text{M}$ ) were used in excess relative to MANT nucleotides (final concentration, 100 nM), ensuring complete binding of the nucleotide to CyaA. For an estimation of the hydrophobic properties of the binding site interacting with the MANT group, direct fluorescence of the nucleotides was determined in water and in 30% (v/v) dimethyl sulfoxide.

**Fluorescence Studies with TNP Nucleotides.** Fluorescence studies with TNP nucleotides were essentially performed as for MANT nucleotides with some modifications. In particular, the concentrations of TNP nucleotides, CyaA, and CaM were each 5  $\mu\text{M}$ . The higher protein concentrations were necessary to compensate for the lower quantum yield with TNP nucleotides compared with MANT nucleotides (Jameson and Eccleston, 1997; Hiratsuka, 2003). The excitation wavelength was 405 nm, and emission was scanned from 480 to 620 nm.

**AC Activity Assay.** For the determination of the potency of CyaA inhibitors, assay tubes contained 10  $\mu\text{l}$  of inhibitor at final concentrations from 10 nM to 100  $\mu\text{M}$  and 20  $\mu\text{l}$  of CyaA protein (final concentration, 10 pM) in 75 mM HEPES/NaOH, pH 7.4, containing 0.1% (m/v) bovine serum albumin. Tubes were preincubated for 2 min at 25°C, and reactions were initiated by the addition of 20  $\mu\text{l}$  of

reaction mixture consisting of the following components to yield the given final concentrations: 100 mM KCl, 10  $\mu\text{M}$  free  $\text{Ca}^{2+}$ , 5 mM free  $\text{Mn}^{2+}$  or  $\text{Mg}^{2+}$ , 100  $\mu\text{M}$  EGTA, 100  $\mu\text{M}$  cAMP, and 100 nM calmodulin. ATP was added as nonlabeled substrate at a final concentration of 40  $\mu\text{M}$  and as radioactive tracer [ $\alpha$ - $^{32}\text{P}$ ]ATP (0.2  $\mu\text{Ci}/\text{tube}$ ). For the determination of  $K_m$  and  $V_{\text{max}}$  values, 10  $\mu\text{M}$  to 2 mM ATP/ $\text{Mn}^{2+}$  or ATP/ $\text{Mg}^{2+}$  were added, plus 5 mM free  $\text{Mn}^{2+}$  or  $\text{Mg}^{2+}$ . To ensure linear reaction progress, tubes were incubated for 10 min at 25°C, and reactions were stopped by the addition of 20  $\mu\text{l}$  of 2.2 N HCl. Denaturated protein was sedimented by a 1-min centrifugation at 12,000g. [ $^{32}\text{P}$ ]cAMP was separated from [ $\alpha$ - $^{32}\text{P}$ ]ATP by transferring the samples to columns containing 1.4 g of neutral alumina. [ $^{32}\text{P}$ ]cAMP was eluted by the addition of 4 ml of 0.1 M ammonium acetate solution, pH 7.0. Blank values were approximately 0.02% of the total added amount of [ $\alpha$ - $^{32}\text{P}$ ]ATP; substrate turnover was <3% of the total added [ $\alpha$ - $^{32}\text{P}$ ]ATP. Samples collected in scintillation vials were filled up with 10 ml of double-distilled water and Čerenkov radiation was measured in a Tri-Carb 2800TR liquid scintillation analyzer (PerkinElmer Life and Analytical Sciences).

Free concentrations of divalent cations were calculated with WinMaxC (<http://www.stanford.edu/~cpatton/maxc.html>).  $K_i$  values reported in Table 1 and  $K_d$  values obtained from saturation experiments were calculated using the Prism 4.02 software (GraphPad, San Diego, CA).

TABLE 1

Potencies of inhibitors at CyaA

AC toxin activities were determined as described under *Materials and Methods*. Apparent  $K_m$  and  $V_{\text{max}}$  values were obtained by nonlinear regression analysis of substrate-saturation experiments and are the means  $\pm$  S.E.M. of three to five independent experiments.  $K_m$  values are given in micromolar,  $V_{\text{max}}$  values are given as molar turnover numbers ( $\text{s}^{-1}$ ).  $K_i$  values are given in micromolar and are the means  $\pm$  S.E.M. of at least three experiments performed in duplicate. For determination of the inhibitory potencies of various purine and pyrimidine nucleotides, reaction mixtures contained 100 mM KCl, 10  $\mu\text{M}$  free  $\text{Ca}^{2+}$ , 5 mM free  $\text{Mn}^{2+}$  or  $\text{Mg}^{2+}$ , 100  $\mu\text{M}$  EGTA, 40  $\mu\text{M}$  ATP, 0.2  $\mu\text{Ci}/\text{tube}$  [ $\alpha$ - $^{32}\text{P}$ ]ATP, 100  $\mu\text{M}$  cAMP, 100 nM calmodulin, 10 pM CyaA in 75 mM HEPES/NaOH, pH 7.4, and nucleotides at concentrations from 100 pM to 2 mM as appropriate to construct concentration-response curves. The  $K_i$  value for **1** under  $\text{Mg}^{2+}$ -conditions was taken from Shen et al. (2004). The  $K_i$  values for **4**, **7**, and **17** under  $\text{Mn}^{2+}$ -conditions were taken from Gille et al. (2004). Inhibition curves were analyzed by non-linear regression using the Prism 4.02 software (GraphPad Software, San Diego, CA).

Compound		$K_i$	
		$\text{Mn}^{2+}$	$\text{Mg}^{2+}$
		$\mu\text{M}$	
	ATP	45 $\pm$ 6 <sup>a</sup>	609 $\pm$ 62 <sup>a</sup>
	ATP	165 $\pm$ 21 <sup>b</sup>	861 $\pm$ 106 <sup>b</sup>
<b>1</b>	PMEApp	0.001 $\pm$ 0.0003	0.025 $\pm$ 0.002
<b>2</b>	GTP	27 $\pm$ 6	260 $\pm$ 32
<b>3</b>	ITP	100 $\pm$ 20	1,100 $\pm$ 220
<b>4</b>	ITP- $\gamma\text{S}$	77	ND
<b>5</b>	CTP	35 $\pm$ 1	270 $\pm$ 43
<b>6</b>	UTP	120 $\pm$ 14	330 $\pm$ 80
<b>7</b>	UTP- $\gamma\text{S}$	36	ND
<b>8</b>	MANT-ATP	4.3 $\pm$ 0.4	51 $\pm$ 1
<b>9</b>	MANT-ATP- $\gamma\text{S}$	1.2 $\pm$ 0.4	15 $\pm$ 2
<b>10</b>	MANT-GTP	5.9 $\pm$ 1.0	16 $\pm$ 2
<b>11</b>	MANT-GTP- $\gamma\text{S}$	5.4 $\pm$ 0.5	7.4 $\pm$ 0.1
<b>12</b>	MANT-ITP	0.6 $\pm$ 0.1	16 $\pm$ 4
<b>13</b>	MANT-ITP- $\gamma\text{S}$	1.8 $\pm$ 0.3	31 $\pm$ 2
<b>14</b>	MANT-CTP	1.1 $\pm$ 0.1	36 $\pm$ 4
<b>15</b>	MANT-UTP	2.6 $\pm$ 0.3	42 $\pm$ 9
<b>16</b>	MANT-ADP	12 $\pm$ 2	91 $\pm$ 16
<b>17</b>	MANT-GDP	60	ND
<b>18</b>	MANT-IDP	11 $\pm$ 3	>100
<b>19</b>	MANT-CDP	18 $\pm$ 3	>100
<b>20</b>	MANT-UDP	43 $\pm$ 1	>100
<b>21</b>	3'MANT-2'd-ATP	0.2 $\pm$ 0.04	32 $\pm$ 7
<b>22</b>	2'MANT-3'd-ATP	0.3 $\pm$ 0.04	22 $\pm$ 4
<b>23</b>	ANT-ATP	1.3 $\pm$ 0.1	20 $\pm$ 3
<b>24</b>	ANT-GTP	29 $\pm$ 0.3	>100
<b>25</b>	ANT-ADP	11 $\pm$ 1	>100
<b>26</b>	TNP-ATP	6.5 $\pm$ 0.2	110 $\pm$ 23
<b>27</b>	TNP-GTP	20 $\pm$ 3	320 $\pm$ 7
<b>28</b>	TNP-CTP	10 $\pm$ 0.4	410 $\pm$ 9
<b>29</b>	TNP-UTP	58 $\pm$ 8	780 $\pm$ 38
<b>30</b>	MANT-IMP	>100	>100
<b>31</b>	Di-MANT-IMP	20 $\pm$ 3	37 $\pm$ 3

<sup>a</sup>  $K_m$  values (micromolar).<sup>b</sup>  $V_{\text{max}}$  values (seconds<sup>-1</sup>).

**Modeling of the Nucleotide Binding Mode to CyaA.** Docking studies were performed with the molecular modeling package SYBYL 7.3 (Tripos Inc., St. Louis, MO) on an Octane workstation (SGI, Mountain View, CA). An initial computer model of CyaA in complex with PMEApp was generated from the PDB crystal structure 1zot (Guo et al., 2005). Hydrogens were added and AMBER\_FF99 charges were assigned to the protein and the water molecules, followed by a rough preoptimization of the model (100 cycles) with the AMBER\_FF99 force field (Cornell et al., 1995) and fixed PMEApp. The three  $Mg^{2+}$  ions received formal charges of 2. Starting conformations of 3'MANT-2'd-ATP (**21**), 2'MANT-3'd-ATP (**22**), and TNP-ATP (**26**) were derived from complexes of 3'MANT-ATP and TNP-ATP with mammalian AC (PDB structures 2gvz and 2gvd, respectively) (Mou et al., 2005, 2006). PMEApp and the ligands **21**, **22**, and **26** were provided with Gasteiger-Hueckel charges. Initial docking positions resulted from superposition of roughly optimized conformations with PMEApp, allowing the modification of rotatable bonds, and from consideration of the fluorescence data (interaction of the MANT- and TNP-groups with Phe306). Water molecules in the catalytic site were removed. Each complex was refined in a stepwise approach. First, ~50 minimization cycles with fixed ligand (AMBER\_FF99 force field, steepest descent method) were performed; second, ~100 minimization cycles of the ligand and the surrounding (distance up to 6 Å) protein residues (Tripos force field) (Clark et al., 1989), and, third, ~100 minimization cycles with fixed ligand (AMBER\_FF99 force field, Powell conjugate gradient). The second and third steps were repeated with larger number of cycles until an root-mean-square force of  $0.05 \text{ kcal/mol} \cdot \text{Å}^{-1}$  was approached. To avoid overestimation of electrostatic interactions, a distance-dependent dielectric constant of 4 was applied. Molecular surfaces and lipophilic potentials [protein variant with the new Crippen parameter table (Heiden et al., 1993; Ghose et al., 1998)] were calculated and visualized by the program MOLCAD (MOLCAD, Darmstadt, Germany) contained within SYBYL.

## Results

**Overview on Nucleotide Structures.** We examined the inhibitory effects of 31 nucleotides on the catalytic activity of CyaA (Table 1). Nucleotides differed from each other in base, phosphate chain length, phosphate chain substitution, and MANT, ANT, or TNP substituents at the 2',3'-ribosyl position. In compounds **8–20**, **23–25**, and **30**, the MANT- or ANT group undergoes spontaneous isomerization between the 2'- and 3'-ribosyl position (Jameson and Eccleston, 1997). In **21** and **22**, the MANT group is fixed to the 2'- or 3'-position because the neighboring ribosyl position is deoxygenated, thus preventing isomerization. In **23–25**, an ANT group is attached to the ribosyl residue instead of the MANT group. Compounds **26–29** contain TNP substituents. Because the TNP-group is attached to the ribosyl ring via the 2'- and 3'-position, isomerization is not possible in TNP nucleotides (Hiratsuka, 2003). In **31**, two MANT-substituents are attached to the 2'- and 3'-ribosyl position. In **9**, **11** and **13**, the  $\gamma$ -phosphate group is substituted by a  $\gamma$ -thiophosphate group. The potencies of the different nucleotides were determined in the AC activity assay in the presence of either  $Mn^{2+}$  or  $Mg^{2+}$ .

**Structure/Activity Relationships under  $Mn^{2+}$  Conditions.** Under  $Mn^{2+}$  conditions, MANT-ITP (**12**) displayed the highest potency of all MANT-NTPs examined, exhibiting 7-fold higher potency than MANT-ATP (**8**). The rank order of potencies was MANT-ITP > MANT-CTP > MANT-UTP > MANT-ATP > MANT-GTP. MANT-GTP (**10**) exhibited 10-fold lower potency compared with MANT-ITP. For MANT-NDPs, the order of potency was MANT-IDP ~ MANT-ADP > MANT-CDP >

MANT-UDP; MANT-IDP was 4-fold more potent than MANT-UTP. For ANT nucleotides, the adenine base was advantageous compared with guanine; ANT-ATP (**23**) was 22-fold more potent than ANT-GTP (**24**). Among  $\gamma$ S-substituted MANT nucleotides, the rank order of potency was MANT-ATP $\gamma$ S > MANT-ITP $\gamma$ S > MANT-GTP $\gamma$ S; MANT-ATP $\gamma$ S (**9**) was 4- to 5-fold more potent than MANT-GTP $\gamma$ S (**11**).

TNP-ATP (**26**) was the most potent TNP nucleotide; the rank order was TNP-ATP > TNP-CTP > TNP-GTP > TNP-UTP. Among the nucleotides bearing no fluorescent substituent at the 2',3'-ribosyl position, GTP (**2**) displayed the highest affinity, which was 4-fold higher than the affinity of ITP (**3**) and UTP (**6**). Interestingly, the  $K_i$  constants of GTP and CTP were lower than the  $K_m$  value of the natural substrate ATP. Compared with the nonsubstituted NTPs, the MANT group increased inhibitor potency 5-fold, 31-fold, 45-fold, and 166-fold for MANT-GTP, MANT-CTP, MANT-UTP, and MANT-ITP, respectively. The TNP group increased inhibitory potency in the case of TNP-CTP and TNP-UTP just by factors of 3 and 2, respectively, and TNP-GTP (**27**) was only slightly more potent than GTP (**2**). MANT-substituted nucleotides were 2, 3, 9, and 22 times more potent in inhibiting CyaA compared with TNP nucleotides (**8** versus **26**, **10** versus **27**, **14** versus **28**, and **15** versus **29**, respectively). Although ANT-ATP (**23**) was 3-fold more potent than MANT-ATP (**8**), the potency of ANT-GTP (**24**) was 5-fold lower compared with MANT-GTP (**10**).

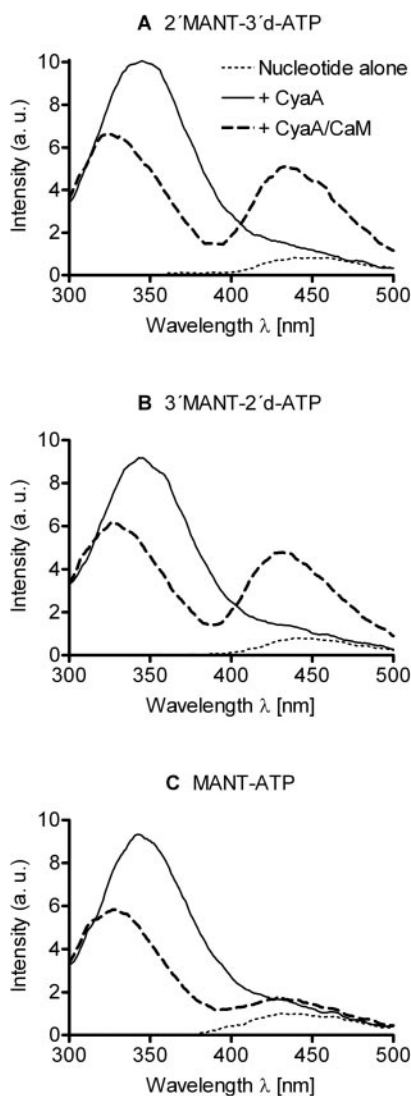
Omission of the  $\gamma$ -phosphate group resulted in substantially decreased potencies at all nucleotides. Specifically, MANT-ADP (**16**) was 3-fold less potent than MANT-ATP (**8**), MANT-GDP 10-fold less than MANT-GTP (Gille et al., 2004), MANT-CDP (**19**) 15-fold less than MANT-CTP (**14**), MANT-UDP (**20**) 17-fold less than MANT-UTP (**15**), and MANT-IDP (**18**) 18-fold less than MANT-ITP (**12**). ANT-ADP (**25**) was 9-fold less potent than ANT-ATP (**23**).

Adding the  $\gamma$ S-substitution to MANT-NTPs decreased potency of MANT-ITP 3-fold (**12** versus **13**), increased potency of MANT-ATP 4-fold (**8** versus **9**), and left the potency of MANT-GTP unchanged (**10** versus **11**). Most strikingly, 3'MANT-2'd-ATP (**21**) and 2'MANT-3'd-ATP (**22**) were 22- and 14-fold more potent, respectively, than MANT-ATP (**8**).

**Structure/Activity Relationships under  $Mg^{2+}$  Conditions.** The exchange of  $Mn^{2+}$  by  $Mg^{2+}$  increased  $K_m$  and  $V_{max}$  by 14- and 5-fold, respectively. Inhibitory potencies of all tested nucleotides were differentially lowered when  $Mg^{2+}$  was used instead of  $Mn^{2+}$ . While the potency of MANT-GTP $\gamma$ S was only minimally reduced, 3'MANT-2'd-ATP and 2'MANT-3'd-ATP showed ~160-fold and ~70-fold lower potency with  $Mg^{2+}$ . The rank order of potency for MANT-substituted NTPs was MANT-GTP = MANT-ITP > MANT-CTP > MANT-UTP > MANT-ATP. Whereas MANT-GTP (**10**) displayed the lowest potency of all MANT-NTPs under  $Mn^{2+}$ -conditions, it was—together with MANT-ITP (**12**)—the most potent MANT-NTP when  $Mg^{2+}$  was used. ANT-ATP (**23**) was 3-fold more potent than MANT-ATP (**8**) and exceeded ANT-GTP (**24**) in potency. MANT-GTP $\gamma$ S (**11**) was the most potent  $\gamma$ S-substituted nucleotide tested, being 2-fold more potent than MANT-ATP $\gamma$ S (**9**) and 4-fold more potent than MANT-ITP $\gamma$ S (**13**). The introduction of the MANT group increased the potency of CTP, UTP and GTP by 7- to 16-fold. Most strikingly, MANT-ITP (**12**) was ~70-fold more potent than ITP (**3**). Among TNP nucleotides, potency decreased in the order TNP-ATP, TNP-GTP, TNP-CTP, and TNP-UTP. It is noteworthy that the TNP group did not increase

potency compared with nonsubstituted NTPs; potency even decreased (2 versus 27, 5 versus 28, and 6 versus 29).

**FRET Experiments with MANT Nucleotides.** In FRET experiments, 2'MANT-3'd-ATP, 3'MANT-2'd-ATP, and MANT-ATP (final concentrations, 300 nM each) were added first to the buffer, and autofluorescence of MANT nucleotides as a result of excitation at 280 nm was detected at 450 nm (Fig. 1, dotted line). When CyaA was added, tryptophan and tyrosine fluorescence occurred at 350 nm (Fig. 1, solid line). Upon addition of CaM, FRET (decrease in emission at 350 nm and increase in emission at 430 nm) occurred for 2'MANT-3'd-ATP and 3'MANT-2'd-ATP (Fig. 1, A and B, dashed lines), but not for MANT-ATP (Fig. 1C), MANT-GTP, MANT-ITP, MANT-CTP, and MANT-UTP (data not shown). When FRET experiments were performed using the tryptophan-specific excitation wavelength of 295 nm (Lakowicz, 1999), fluorescence intensity



**Fig. 1.** Monitoring of MANT nucleotide binding to the catalytic site of CyaA using FRET. The assay buffer consisted of 75 mM HEPES/NaOH, 100  $\mu$ M CaCl<sub>2</sub>, 100 mM KCl, and 5 mM MnCl<sub>2</sub>, pH 7.4. Nucleotides (A, 2'MANT-3'd-ATP; B, 3'MANT-2'd-ATP; C, MANT-ATP) were added to the buffer to yield a final concentration of 300 nM, and emission was scanned at an excitation wavelength of 280 nm. CyaA protein and calmodulin were added successively to yield a final concentration of 300 nM. Shown are superimposed recordings of a representative experiment. Similar data were obtained in three independent experiments. a.u., arbitrary unit.

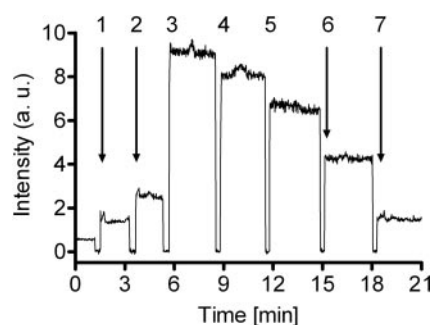
at 350 nm decreased 3- to 4-fold. The relative magnitude of FRET with 2'MANT-3'd-ATP and 3'MANT-2'd-ATP remained unchanged upon tryptophan-selective excitation (data not shown). Thus, FRET resulted from excitation of Trp69 and Trp242 and tyrosine residues. Tyr75, Tyr122, Tyr263, Tyr333, Tyr345, and Tyr350 are located in a distance of less than 20 Å from the catalytic site. Thus, to obtain high FRET signals, it is favorable to excite both tyrosine and tryptophan residues.

PMEApp (1) inhibited FRET in a concentration-dependent manner (Fig. 2). Half-maximal displacement of 300 nM 3'MANT-2'd-ATP occurred at a PMEApp concentration of approximately 50 nM, which is compatible with the notion that PMEApp is a much more potent CyaA inhibitor than 3'MANT-2'd-ATP (Table 1). Kinetics of CyaA FRET stimulation by CaM and inhibition by PMEApp occurred within mixing time (few seconds). These data show that FRET was specific and reversible.

By determining FRET with MANT nucleotides at increasing concentrations after addition of CaM, saturation curves were obtained (Fig. 3). Apparent  $K_d$  values were 400 nM for 2'MANT-3'd-ATP (A) and 300 nM for 3'MANT-2'd-ATP (B). For MANT-ATP, MANT-GTP, MANT-ITP, MANT-CTP, and MANT-UTP,  $K_d$  values could not be determined because of absent or minimal FRET (data not shown). Thus, MANT isomerization may impede energy capture of the fluorophore from tryptophan and tyrosine residues.

We used CyaA at a final concentration of just 300 nM in an assay volume of 70  $\mu$ l in FRET studies, corresponding to 0.8  $\mu$ g of CyaA for one measurement. Because the consumption of protein is low, because the production of CyaA can be accomplished at large scale (Shen et al., 2002) and because kinetics occur within seconds (Fig. 2), fluorimetric high-throughput screening of potential novel inhibitors is feasible, avoiding the use of radioactive AC assays. Because fluorescent nucleotides (e.g., 3'MANT-2'd-ATP) were competitively displaced from CyaA by PMEApp (Fig. 2), the affinity of nonlabeled inhibitors may also be estimated using this approach. In saturation experiments (Fig. 3), apparent  $K_d$  values were estimated to be 400 nM for 2'MANT-3'd-ATP (A) and 300 nM for 3'MANT-2'd-ATP (B). The results from FRET experiments are in good agreement with the corresponding  $K_i$  values determined in the AC activity assay (Table 1).

**Direct Fluorescence Experiments with MANT Nucleotides.** Nucleotides were excited at 350 nm and emission



**Fig. 2.** Time-resolved activation of CyaA by CaM and stepwise abolishment of FRET by PMEApp. Excitation wavelength was 280 nm and emission was detected at 430 nm over time. 300 nM 3'MANT-2'd-ATP (1), 300 nM CyaA protein (2), 300 nM CaM (3), and PMEApp in the given final concentrations (addition steps 4, 10 nM; 5, 30 nM; 6, 70 nM; 7, 1.6  $\mu$ M) were added in sequence. A recording of a representative experiment is shown. Similar data were obtained in four independent experiments. a.u., arbitrary unit.

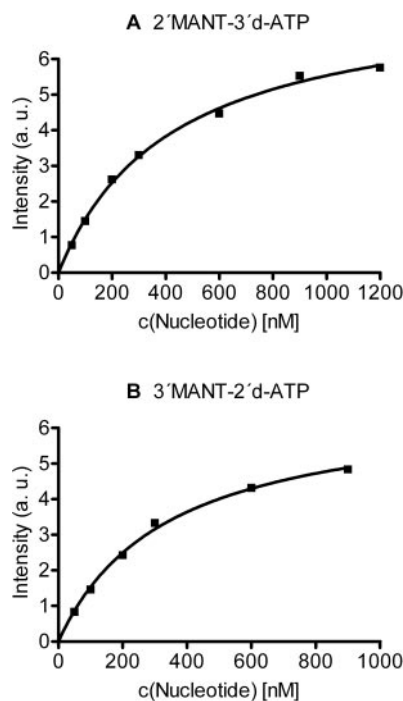
was scanned from 380 to 550 nm. Addition of CyaA to cuvettes containing 2'MANT-3'd-ATP or 3'MANT-2'd-ATP did not increase their intrinsic fluorescence (Fig. 4, A and B). However, upon addition of CaM, fluorescence increased by 120 and 130%, respectively. Moreover, the emission maximum of 2'MANT-3'd-ATP and 3'MANT-2'd-ATP showed a shift to shorter wavelengths (blue shift). Under these conditions, MANT-ATP fluorescence increased by only approximately 40% (data not shown). For comparison, direct fluorescence of nucleotides was determined in a polar environment (water) and a hydrophobic environment [30% (v/v) dimethyl sulfoxide]. Fluorescence of 100 nM 3'MANT-2'd-ATP increased by 160% when exposed to dimethyl sulfoxide (Fig. 4C). In addition, the emission maximum shifted to shorter wavelengths. Thus, binding of MANT nucleotides to CyaA transferred the MANT group into a hydrophobic environment, probably facilitating interaction with Phe306 (Guo et al., 2005).

#### Fluorescence Experiments with TNP Nucleotides.

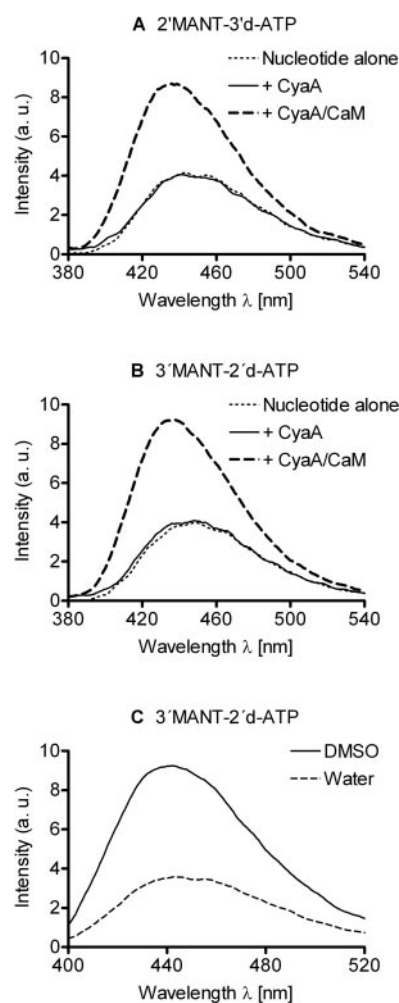
When excited at a wavelength of 405 nm, TNP-ATP, TNP-GTP, TNP-CTP, and TNP-UTP showed a fluorescence peak at ~550 nm (Fig. 5). The addition of CyaA to cuvettes containing TNP nucleotides increased fluorescence by 3- to 5-fold, with TNP-ATP and TNP-GTP showing the largest increases (Fig. 5, A and B). The fluorescence increases with TNP nucleotides were virtually instantaneous after CyaA addition (data not shown), indicative for rapid nucleotide/protein interaction. Moreover, we observed a blue shift of the emission maximum of TNP nucleotides to ~540 nm. These data indicate that binding of TNP nucleotides to CyaA trans-

fers the TNP-group into a hydrophobic environment. Furthermore, and in striking contrast to the results obtained with MANT nucleotides (Figs. 2–4), addition of CaM to CyaA reduced TNP nucleotide fluorescence. This reduction in fluorescence was dependent on the specific nucleotide studied; TNP-ATP showed the smallest relative reduction (Fig. 5A), and TNP-CTP and TNP-UTP showed the largest relative reductions (Fig. 5, C and D).

**Modeling of the Binding Modes of MANT- and TNP Nucleotides to CyaA.** The crystal structure of CyaA in complex with CaM and PMEApp (Guo et al., 2005) offered us the possibility of predicting the binding mode of MANT and TNP nucleotides. The AC domain of CyaA contains the catalytic site at the interface of two structural domains, C<sub>A</sub> (Met1–Gly61, Ala187–Ala364) and C<sub>B</sub> (Val62–Thr186). Compared with PMEApp, the substrate ATP and the fluorescent nucleotides are conformationally restricted because of the semirigid ribosyl moiety. However, the spacious cavity between C<sub>A</sub> and C<sub>B</sub> may accommodate the different scaffolds so that an alignment of the adenine base and the terminal



**Fig. 3.** Saturation curves of 2'MANT-3'd-ATP and 3'MANT-2'd-ATP binding to activated CyaA. Each data point was determined in an independent experiment as described under *Materials and Methods*. Final concentrations of CyaA and CaM were 300 nM each. The fluorescence increase at 430 nm was calculated by subtracting the fluorescence at 430 nm after addition of CyaA from the maximal fluorescence at 430 nm after addition of CyaA/CaM. Data were analyzed by nonlinear regression using the Prism 4.02 software. Similar data were obtained in three independent experiments. a.u., arbitrary unit.



**Fig. 4.** Direct fluorescence of MANT nucleotides. The excitation wavelength was 350 nm, and emission was scanned from 380 to 550 nm. 100 nM nucleotide, 2.4  $\mu$ M CyaA, and 2.4  $\mu$ M CaM were added to cuvettes A and B in sequence. To mimic binding of the MANT group to a hydrophobic binding pocket, 3'MANT-2'd-ATP was directly excited in water plus dimethyl sulfoxide (DMSO) 30% (v/v) (C). Shown are superimposed recordings of a representative experiment. Similar data were obtained in five independent experiments. a.u., arbitrary unit.

phosphates is possible (Fig. 6A). It becomes obvious that hydrophobic interactions, especially of the lipophilic edge of the desoxyribose moiety with Leu60 and of the 3'MANT group with Phe306, significantly contribute to the binding of 3'MANT-2'-d-ATP (**21**) to CyaA (Table 1 and Fig. 3B). In fact, nonsubstituted NTPs exhibited 5- to 170-fold lower affinities than their MANT-substituted analogs (e.g., ITP versus MANT-ITP), and CyaA-F306A failed to increase the fluorescence signal of 3'ANT-2'-d-ATP (Guo et al., 2005).

However, why is PMEApp (**1**) 4 orders of magnitude more potent at inhibiting CyaA than the natural and  $\gamma$ S-substituted NTPs (**2-7**) if the alignment indicates similar interactions? First, a reasonable superposition of the phosphates and the adenine bases as shown in Fig. 6A is only possible if the conformation of the nucleotide moiety retains a certain strain of approximately 3 kcal/mol. A complete minimization would displace the adenine base and, in particular, the phosphate groups from their optimal positions. Therefore, the "true" fit must be a balance between conformational strain and binding energy. Second, the ethoxy oxygen of PMEApp strongly interacts with Glu301 and Asn304 via a water molecule, and the ethylene bridge is also in close contact with the edge of Phe306.

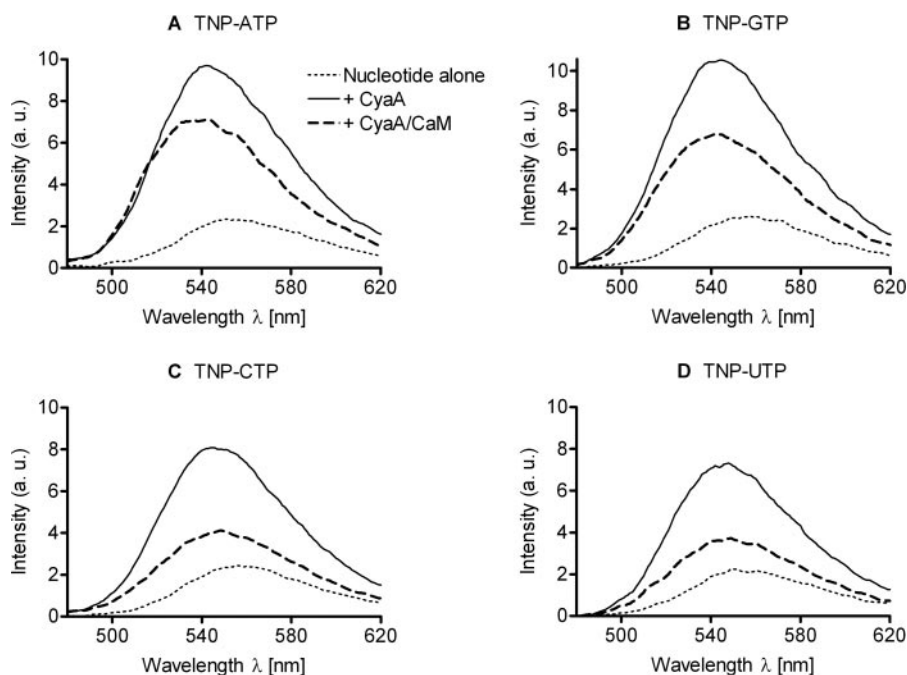
Fig. 6B represents the docking of 3'MANT-2'-d-ATP (**21**) into CyaA in more detail. The desoxyribose ring adopts a 3'-exo conformation like the ribosyl moiety of MANT-ATP in complex with mammalian AC (Mou et al., 2006). The three  $Mg^{2+}$  ions are in positions similar to those in the CyaA-PMEApp complex and form the same interactions. Two of them are coordinated with Asp188 and Asp190, one additionally with His298, and the third with the  $\alpha$ - and  $\beta$ -phosphate. The imidazolyl-NH of His298 may be H-bonded with an oxygen of the  $\alpha$ -phosphate. The  $\gamma$ -phosphate contacts the lysine residues Lys65 and Lys58 (O-N distances,  $\sim 2.8$  Å). These interactions account for the higher inhibitory potencies of the triphosphates compared with the diphosphate and monophosphate analogs in Table 1.

The adenine moiety is sandwiched between the side

chains of His298 and Asn304 whose amide  $NH_2$  group may form an additional H bond with the desoxyribose ring oxygen. The 6-amino substituent is in proximity to the backbone oxygens of Val271, Gly299, and Thr300. However, the loop between Gly299 and Asn304 may align all of the nucleobases in similar position. In the case of GTP, ITP, UTP, and their MANT- and TNP-derivatives, backbone NH functions of, for example, Gly299 and Val271 could serve as hydrogen donors for the carbonyl oxygens in the 6 and 4 positions, respectively. This diversity of possible interactions may account for the relatively small and inconsistent potency differences when comparing the impact of base substitution in different subsets of nucleotides [i.e., natural NTPs, MANT-NTPs, MANT-NDPs and TNP-NTPs (see Table 1)]. In addition, the affinity of each nucleotide may be affected by a specific arrangement of water molecules that cannot be simply transferred from the PMEApp-bound CyaA structure.

Fig. 6B also shows that the high potency of 3'MANT-2'-d-ATP (**21**) is due in particular to ideal stacking of the phenyl rings of the inhibitor and Phe306. This stacking also accounts for the efficient FRET and direct fluorescence observed with 3'MANT-2'-d-ATP (Figs. 1–4). The axial position of the hydrogen atom corresponding to the 2'-OH group in 3'MANT-ATP suggests that even the 2',3'-di-MANT-ATP derivative will be similarly potent because the 2'-MANT moiety may fit into a hydrophobic site consisting of Pro305 and Phe261.

This site would also be occupied by the 2'-MANT group in 2'MANT-3'-d-ATP (**22**) if the desoxyribose ring adopts a 3'-exo conformation. However, similar potencies of the positional isomers **21** and **22** in the AC assay (Table 1) and fluorescence assay (Fig. 3) as well as similar magnitudes of FRET and direct fluorescence (Figs. 1 and 4) rather indicate analogous interactions between the MANT group and Phe306 in the complexes of CyaA with 2'MANT-3'-d-ATP and 3'MANT-3'-d-ATP, respectively. Fig. 6C illustrates that docking of 2'MANT-3'-d-ATP may indeed reproduce the interac-



**Fig. 5.** Fluorescence analysis of the interactions of TNP nucleotides with CyaA. The excitation wavelength was 405 nm, and emission was scanned from 480 to 620 nm. 5  $\mu$ M nucleotide, 5  $\mu$ M CyaA, and 5  $\mu$ M CaM were added to the cuvette in sequence. A, TNP-ATP; B, TNP-GTP; C, TNP-CTP; D, TNP-UTP. Shown are superimposed recordings of a representative experiment. Similar data were obtained in three to five independent experiments. a.u., arbitrary unit.

tion pattern of 3'MANT-2'd-ATP with CyaA shown in Fig. 6B. The only difference is a 3'-endo conformation of the desoxyribose moiety as is present, e.g., in A-DNA.

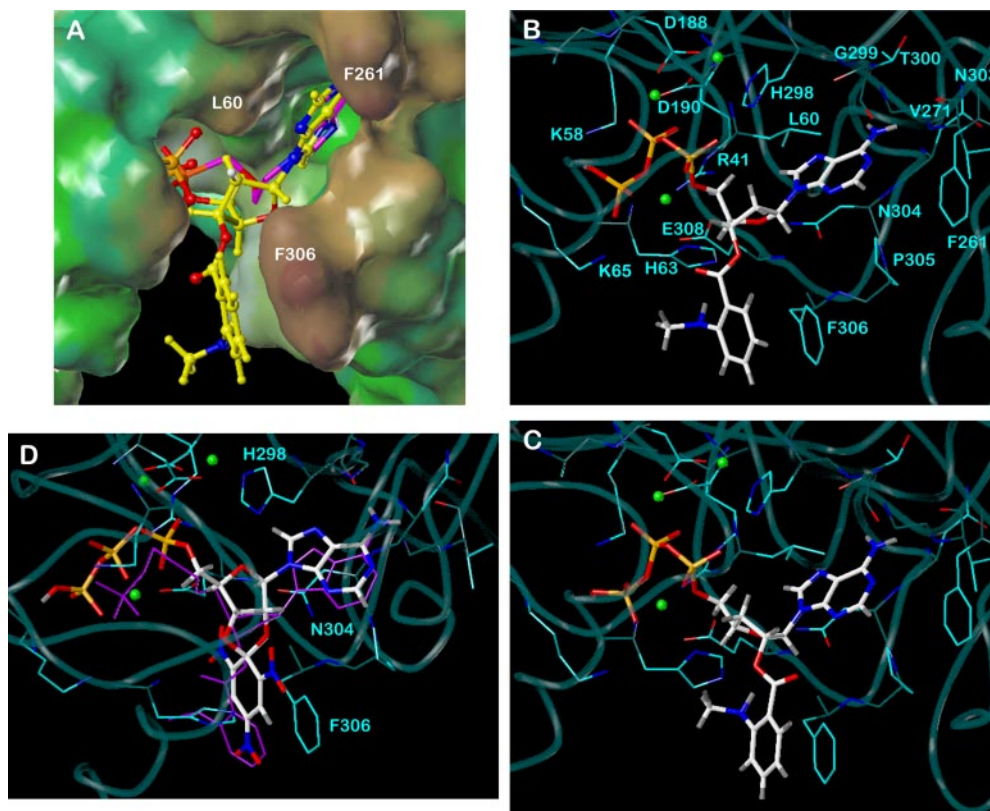
Fig. 6D shows the predicted binding mode of TNP-ATP (26), which has a potency similar to that of the isomerizing MANT-ATP derivative 8. Despite the rigidity of the tricyclic TNP-ATP scaffold, which contained a spiro junction, a sufficient alignment with 3'MANT-2'd-ATP is possible so that the phosphate groups, the adenine base, and the phenyl moieties may interact with the same CyaA sites. This superposition implies a relatively deep position of TNP-ATP in the cavity. The interaction of Phe306 with the TNP group is weaker than with MANT (no optimal position, lower hydrophobicity). However, hydrogen bonds of two ribosyl oxygens with the side chains of His298 and Asn304, respectively, may counterbalance, in part, the reduced hydrophobic interactions and higher conformational strain. In addition, the intrinsic fluorescence properties of TNP nucleotides (i.e., higher fluorescence increases upon transfer into a hydrophobic environment than with MANT nucleotides) (Jameson and Eccleston, 1997; Hiratsuka, 2003) more than compensate for the sub-optimal positioning of the TNP-group relative to Phe306, allowing for the detection of larger fluorescence increases than with MANT nucleotides (Figs. 4 and 5). It is notewor-

thy that the inhibitory potency of TNP derivatives 26–29 is more dependent on the specific nucleobase than in the corresponding subseries of MANT nucleotides 8, 10, 14, and 15 and the unsubstituted NTPs GTP (2), CTP (5), and UTP (6). The rigid scaffold of the TNP nucleotides probably does not enable an optimal fit of guanine and the pyrimidines to the backbone of the loop between Gly299 and Asn304.

The lower substrate  $K_m$  and  $V_{max}$  values as well as the generally 5- to 40-fold higher potency of the inhibitors under  $Mn^{2+}$  conditions than under  $Mg^{2+}$  conditions clearly point to considerably tighter binding with the former cation. This increase in the free energy of binding of up to  $\sim 2$  kcal/mol should be due mainly to stronger  $Mn^{2+}$ -phosphate binding. No further conclusions can be drawn from the docking approaches based on force field methods and without a CyaA crystal structure with  $Mn^{2+}$  instead of  $Mg^{2+}$ .

## Discussion

**Spacious Catalytic Site of CyaA.** The catalytic site of CyaA forms a large cavity with substantial conformational freedom to accommodate structurally diverse ligands. In particular, not only adenine nucleotides but also other purine and even pyrimidine nucleotides reduce the catalytic activity



**Fig. 6.** Docking of representative MANT- and TNP nucleotides to CyaA. The models are based on the crystal structure of CyaA in complex with PMEApp, PDB 1zot (Guo et al., 2005) (clockwise arrangement of the images for better comparability of B and C). Colors of atoms, unless otherwise indicated: orange, phosphorus; red, oxygen; blue, nitrogen; white, carbon; gray, hydrogen; green spheres, magnesium. A, overview of the binding site, represented by the lipophilic potential mapped onto a MOLCAD Connolly surface (brown, hydrophobic areas; green and blue, polar areas). Docked ligands: PMEApp (carbon atoms in magenta); 3'MANT-2'd-ATP (carbon and hydrogen atoms in yellow). B, docking of 3'MANT-2'd-ATP (21). Amino acids within a sphere of  $\sim 3$  Å around the ligand are labeled. The protein backbone is schematically represented by a tube. Carbon atoms of the backbone are colored in dark cyan; carbon atoms of the side chains are in light cyan. C, docking of 2'MANT-3'd-ATP (22). Representation of the backbone and the side chains as in B. For clarity, some labels are omitted (see B). D, docking of TNP-ATP (26). For comparison, 3'MANT-2'd-ATP is shown in the same position like in B (all atoms colored in magenta). Only amino acids with suggested interactions specific for TNP-ATP are labeled. Representation of the backbone and the side chains as in B.



of CyaA (Table 1) because of flexible fit to the backbone of the loop between Gly299 and Asn304 (Fig. 6). Effective interaction of CyaA with purine and pyrimidine nucleotides is also clearly documented in the fluorescence experiments with TNP-ATP, TNP-GTP, TNP-CTP, and TNP-UTP (Fig. 5), monitoring interaction of the TNP-group with Phe306 (Fig. 6D). The distinct fluorescence responses upon interaction of CyaA with various TNP nucleotides in the absence and presence of CaM are indicative for slightly different orientations of TNP nucleotides in the catalytic site of CyaA. Moreover, various MANT nucleotides (**12–15**) exhibiting higher affinity for CyaA than TNP nucleotides (Table 1) did not give rise to FRET with CyaA. These findings suggest that differences in affinity do not account for the different fluorescence responses with various nucleotides. Rather, the differences in fluorescence properties point to differences in orientation of the nucleotides in the catalytic site. Taken together, all those findings are in accordance with the modeling data and support the notion of a spacious catalytic site of CyaA.

**Toward the Development of Selective CyaA Inhibitors.** Because the inhibitory profile of CyaA differs considerably from that of mammalian ACs (Gille et al., 2004; Mou et al., 2005, 2006), development of more potent and selective CyaA inhibitors is feasible. For all inhibitors studied, the TNP substituent was substantially less effective in increasing nucleotide affinity than MANT/ANT. Whereas ANT-ATP was more potent than MANT-ATP, the MANT group was superior to ANT in case of MANT-GTP versus ANT-GTP. The additional methyl group in MANT compared with ANT may reduce mobility of the fluorescent group and thereby facilitate alignment with Phe306, depending on the specific nucleobase present.

For all MANT-NDP/NTP pairs studied so far, elimination of the  $\gamma$ -phosphate group substantially decreased inhibitor affinity. As an example, MANT-IDP (**18**) was almost 20-fold less potent than MANT-ITP (**12**), and the omission of the  $\beta$ -phosphate in MANT-IMP (**30**) further reduced affinity compared with MANT-IDP. The importance of the polyphosphate chain for effective interaction of nucleotides with the catalytic site is also supported by our modeling data (Fig. 6B). For future applications of MANT nucleotides in intact-cell assays, a nucleotide with a phosphate tail resistant to hydrolysis is needed (Rottlaender et al., 2007). As the potency of  $\gamma$ S-substituted MANT nucleotides was higher in case of MANT-ATP $\gamma$ S versus MANT-ATP and MANT-GTP $\gamma$ S versus MANT-GTP, the design of potent nucleotides resistant to hydrolysis is feasible.

An unexpected side product in our synthesis scheme of MANT-ITP (**12**) was di-MANT-IMP (**31**). Even more unexpectedly, addition of a second MANT group to the ribosyl ring in di-MANT-IMP (**31**) caused an increase in affinity compared with MANT-IMP (**30**) under  $Mn^{2+}$  and  $Mg^{2+}$  conditions (Table 1) that may be attributed to interactions of the 2'MANT group with a hydrophobic site consisting of Pro305 and Phe261 (Fig. 6B). Thus, the introduction of a second MANT/ANT group or other bulky substituents should be considered in future inhibitor design projects to increase inhibitor affinity. In addition, given the surprising differences in fluorescence responses between MANT and TNP nucleotides, di-MANT nucleotides may provide valuable conformational probes to better understand the mechanisms of CyaA activation.

Considering the bases, hypoxanthine is superior to other

purine and pyrimidine bases (Table 1). Moreover, 2'MANT-3'd-ATP and 3'MANT-2'd-ATP are considerably more potent than MANT-ATP. Therefore, 2'MANT-3'd-ITP and 3'MANT-2'd-ITP are interesting future candidates as potential novel CyaA inhibitors. Further increase in potency and selectivity of PMEApp may be achieved by changing the adenine base to hypoxanthine and by introducing a MANT/ANT substituent.

Like CyaA, *Bacillus anthracis* AC toxin edema factor also bears a phenylalanine residue close to the catalytic site (Guo et al., 2005). Structural comparison of CyaA with edema factor revealed that Phe306 of CyaA is the analog of Phe586 in edema factor, forming hydrophobic interactions with the MANT group, thus increasing direct fluorescence of MANT nucleotides. The inhibitory profile of edema factor differs considerably from that of CyaA. In particular, MANT-ATP inhibits catalytic activity of CyaA with almost 25-fold lower potency than catalysis by edema factor (Gille et al., 2004). In the case of 3'MANT-2'd-GTP, 3'MANT-2'd-ATP, and MANT-ADP, the decreases in potency of CyaA inhibition compared with edema factor inhibition were 22-, 25-, and 40-fold, respectively. Based on these differences in enzymological properties, it is also reasonable to assume that the fluorescence analysis of edema factor with MANT and TNP nucleotides will give very different results than with CyaA.

We have solved the crystal structure of mammalian C1:C2 AC in complex with MANT-GTP, MANT-ATP, and TNP-ATP (Mou et al., 2005, 2006). Based on crystallographic studies, we have developed a tripartite model for mammalian AC with a binding site for the base, the ribosyl substituent, and the phosphate tail (Mou et al., 2005, 2006). In this model, the base site possesses the smallest influence, whereas the ribosyl substituent has a strong impact. This model can also be applied to CyaA (Fig. 6). In particular, a variety of purine and pyrimidine nucleotides inhibit CyaA, suggesting that the base does not greatly determine the potency of 2',3'-ribosyl substituted inhibitors. In contrast, introduction of a MANT/ANT group increased inhibitor potency at CyaA up to 170-fold (e.g., ITP versus MANT-ITP), pointing to the critical importance of the ribosyl substituent. However, TNP substitution showed a much smaller effect on inhibitor affinity for CyaA than for C1:C2 (Mou et al., 2006) (Table 1), highlighting the substantial structural differences between the binding. In particular, mammalian AC possesses a large hydrophobic pocket consisting of several amino acids accommodating the 2',3'-ribosyl substituent (Mou et al., 2005, 2006), whereas in case of CyaA, just one amino acid, Phe306, participates in hydrophobic interactions with MANT and TNP nucleotides (Fig. 6).

**The Role of Divalent Cations.** It is also important to emphasize that in future studies, inhibitors should be studied both under  $Mg^{2+}$ - and  $Mn^{2+}$ -conditions because there are differences in the rank order of potency of compounds under those conditions. Moreover, exchange of  $Mn^{2+}$  against  $Mg^{2+}$  increases  $V_{max}$  and decreases  $K_m$  (Table 1). Crystallographic studies are required to understand those substantial differences between  $Mn^{2+}$  and  $Mg^{2+}$ . It is reasonable to assume that under physiological conditions,  $Mg^{2+}$  rather than  $Mn^{2+}$  is relevant. It is most likely that  $Mn^{2+}$  is only an (important) experimental tool to facilitate molecular analysis of CyaA. In particular, in the presence of  $Mg^{2+}$ , detection of significant increases in FRET and direct fluorescence with MANT nucleotides was impossible (data not shown).

**CaM-Independent Interaction of CyaA with Nucleotides.** The fact that fluorescence of TNP nucleotides increased upon interaction with CyaA in the absence of the activator CaM (Fig. 5) indicates that the nucleotide-binding site of CyaA is already functional in the catalytically inactive toxin. However, our data suggest that CyaA does not bind MANT nucleotides in the absence of CaM, because FRET and direct fluorescence with MANT nucleotides was completely dependent on CaM (Figs. 1–4). In contrast to CyaA, mammalian C1:C2 does bind MANT nucleotides, to some extent, in the absence of the activator forskolin (Mou et al., 2005, 2006), again supporting the concept of substantial structural differences between mammalian and bacterial AC. These data also imply that binding of CaM to CyaA induces a conformational change in the toxin that allows MANT nucleotides to bind. The identification of the precise nature of this conformational change requires crystallization of CyaA complexes with TNP nucleotides in the absence and presence of CaM as well as of CyaA with MANT nucleotides in the presence of CaM. The opposite fluorescence responses of TNP nucleotides and MANT nucleotides to CaM are in agreement with the modeling studies showing that the TNP and MANT groups adopt similar but not identical positions in the catalytic site of CyaA (Fig. 6D). The dramatic differences in fluorescence responses of TNP- and MANT nucleotides in the absence and presence of CaM also demonstrate that these nucleotides are extremely sensitive probes for detecting small differences in nucleotide/CyaA interactions.

Another implication of the CaM-independent binding of TNP nucleotides to CyaA is that the catalytic site of CyaA possesses different binding properties than the site in the presence of CaM, offering additional possibilities for inhibitor design and increasing inhibitor selectivity. Comparison of inhibition profiles of nonfluorescent nucleotides on TNP nucleotide fluorescence bound to CyaA in the absence and presence of CaM is a feasible approach. With respect to catalysis, such comparison is impossible because enzymatic activity obligatorily depends on CaM (Ladant and Ullmann, 1999; Shen et al., 2002).

## Conclusions

In the present study, we have shown that the catalytic site of CyaA possesses unique pharmacological properties compared with other mammalian and bacterial ACs. The spacious catalytic site of CyaA accommodates a broad variety of 2',3'-substituted nucleotides, even di-MANT nucleotides. Some inhibitors can bind to CyaA even in the absence of CaM, and there is evidence for distinct interaction of CyaA with MANT nucleotides and TNP nucleotides. Finally, the fluorescence assays described in this study can be used for identification of novel CyaA inhibitors, ultimately resulting in the development of novel drugs for prophylaxis of whooping cough.

## Acknowledgments

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**Address correspondence to:** Dr. Roland Seifert, Department of Pharmacology and Toxicology, Institute of Pharmacy, University of Regensburg, Universitätsstrasse 31, D-93053 Regensburg, Germany. E-mail: roland.seifert@chemie.uni-regensburg.de