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Diguanidinocalix[4]arenes as Effective and Selective Catalysts of the Cleavage of Diribonucleoside Monophosphates

Riccardo Salvio,*a Roberta Cacciapaglia,a Luigi Mandolini,a Francesco Sansoneb and Alessandro Casnati*b

Calix[4]arenes derivatives 1 and 2, featuring two guanidine units at the upper rim, catalyze the transesterification of diribonucleoside monophosphates much more effectively than that of HPNP. Rate accelerations relative to background range from $10^3$ to $10^4$-fold, and approach $10^5$-fold with the most favorable substrate-catalyst combinations.

Introduction

The inertness of phosphodiesters towards hydrolysis has challenged many research groups to the design of artificial phosphodiesterases with the purpose of achieving efficient and selective cleavage of polynucleotides and polyribonucleotides. The potential application of these enzyme mimics to health related goals is an attractive target of investigation in this field.

Metal cations, notably copper(II) and zinc(II), are at the core of most artificial phosphodiesterases, but nonmetallic active units as well have received some attention. In a recent work we found that upper rim diguanidino-cone-calix[4]arenes 1 and 2 catalyze the cleavage of the RNA model compound 2-hydroxypropyl $p$-nitrophenyl phosphate (HPNP). It was shown that the catalysts are active in their protonated forms $1H^+$ and $2H^+$, in which the guanidine-guanidinium dyad combines the general base action of the neutral guanidine with the electrophilic/electrostatic activation of the protonated guanidine (Fig. 1).

Since conclusions drawn from the cleavage of activated phosphodiester do not necessarily apply to the cleavage of unactivated phosphodiesters, it seemed worthwhile to investigate the catalytic activity of 1 and 2 in the transesterification of a series of diribonucleoside 3',5'-monophosphates $NpN'$, eqn (1), as more appropriate RNA models. The results of such an investigation are reported herein.

Results and discussion

Catalytic runs were carried out under the same conditions used for the cleavage of HPNP, namely, pH 10.4, 10 mM Me$_4$NClO$_4$, DMSO-H$_2$O 80:20 (v/v), hereafter referred to as 80% DMSO. The sole difference is the higher temperature, 50 °C rather than 25 °C, dictated by the lower reactivity of diribonucleoside monophosphates compared to HPNP. Solutions of precatalyst - 1·2HCl or 2·2HCl - were exactly half neutralized with 1 mol equiv of Me$_4$NOH to give buffer solutions at pH 10.4 (pOH 8.0) that were used for the catalytic experiments. According to the previously reported distribution diagrams of the species as a function of pH, these solutions contain the maximum concentration of monoprotonated species $1H^+$ and $2H^+$, amounting to a mole fraction of 0.86 in both cases. The kinetics were monitored by HPLC analysis of aliquots of the reaction mixture withdrawn at time intervals in the early stages of the reaction, as previously described. Initial rates of nucleoside $N'$ formation were translated into pseudo-first-order specific rates $k_{obs}$.

![Fig. 1 General-base/general-acid mechanism of HPNP cleavage catalyzed by monoprotonated diguanidino compounds.](image-url)
Typical plots of reaction percentage vs time related to the cleavage of GpU catalyzed by 1 are shown in Fig. 2a. The diagram of $k_{obs}$ vs buffer concentration (Fig. 2b) shows a good adherence of data points to a straight line with zero intercept, and this indicates (i) that the contribution of background hydrolysis to the overall rate is negligibly small and (ii) that the catalyst works under subsaturating conditions, i.e., binding of the catalyst to the substrate is too low to affect the kinetics in the investigated concentration range ($K < 25 \text{ M}^{-1}$). An analogous result was obtained in our previous studies of the cleavage of HPNP.\(^5\) This finding not only confirms that in the reactant state binding of guanidinium to the negatively charged phosphate moiety is insignificant, but also indicates that any possible stabilizing interaction between guanidine/guanidinium units and nucleobases $B$ and $B'$ is negligibly small.

Having established that the kinetics of the reaction of GpU catalyzed by 1 were not complicated by a pre-association equilibrium, the whole set of catalytic runs listed in Table 1 were carried out using a fixed precatalyst concentration of 2.0 mM, under the assumption that subsaturating conditions applies to all runs. Table 1 shows that both catalysts effectively cleave all of the investigated substrates, with a marked preference for GpU, GpG and UpU (entries 1–3), while the possible stabilizing interaction between guanidine/guanidinium very critical way on the identity of both nucleobases slowly, clearly indicates that catalytic efficiency depends in a much less reactive than GpU, and that both ApG and GpA react reactions of the remaining substrates experience a much lower.

There is a definite tendency for the 1,2-vicinal regioisomer 1 to be a better catalyst than its 1,3-distal regioisomer 2 in the reaction of most substrates, but the range of $k_{vicinal}/k_{distal}$ ratios (Table 1) is within a factor of 5. Modest inversions are observed for the reaction of GpA and CpA (entries 5 and 7), for which the 1,3-distal regioisomer is a slightly better catalyst, as it is for the cleavage of HPNP,\(^5\) for which $k_{vicinal}/k_{distal} \approx 0.5$.

Interestingly, the $k_{vicinal}/k_{distal}$ ratio for the cleavage of CpA, UpU, and HPNP catalyzed by bimetallic complexes 3-Cu\(_2\) and 4-Cu\(_2\) (H\(_2\)O, pH 7.0) are 2.8, 114, and 28, in the given order.\(^2d\) Although the comparison is based on a limited set of substrates, it appears that the relative position of the two catalytic units in the diguanidinocalix[4]arenes has but a moderate influence on catalytic efficiency. This suggests the existence of a certain degree of flexibility in transition states in which contacts between catalyst and substrate are primarily provided by proton bridges (Fig. 1). In contrast, the marked preference exhibited the kinetics (Fig. 2b). As suggested by CPK molecular models, interaction between the relatively large and conformationally mobile catalyst and substrate molecules generates a large number of potentially attractive and repulsive secondary interactions involving distal part structures of the reactants. In the lack of information of spectroscopic nature, a rational interpretation of the role played by uracil and guanine bases appears to be out of reach.

![Fig. 2](image-url) Cleavage of 0.10 mM GpU catalyzed by 3.0–4.0 mM 1 (80% DMSO, pH 10.4, 10 mM Me\(_4\)NClO\(_4\), 50.0 °C). (a) Reaction percent vs. time, for experiments carried out at the given catalyst concentration. (b) Plot of $k_{obs}$ vs. total catalyst concentration $C_{cat}$. 

$$\begin{align*}
\text{HO} & \quad \text{HO} \\
\text{OH} & \quad \text{OH} \\
\text{O} & \quad \text{O} \\
\text{B, B'} & = \begin{array}{c}
\text{NH}_2 \\
\text{NH}_2 \\
\text{NpN'} \end{array} \\
\text{2',3'-Ncp} & \quad \text{N'} \\
\end{align*}$$

\(\text{HO} \quad \text{OH} \quad \text{O} \quad \text{B, B'} = \begin{array}{c}
\text{NH}_2 \\
\text{NH}_2 \\
\text{NpN'} \end{array} \quad \text{2',3'-Ncp} \quad \text{N'}\)
by UpU and HPNP for the 1,2-vicinal catalyst 3-Cu$_2$ is most likely ascribable to the more stringent geometrical requirements of coordinative bonds to copper(II) involved in the double Lewis acid activation.

In order to compare the catalytic efficiency of 1 and 2 in the cleavage of diribonucleoside monophosphates vs HPNP, catalytic rates relative to background ($k_{\text{obs}}/k_{\text{bg}}$) are required. Initial rates of the hydroxide catalyzed cleavage of CpA and GpU, measured in the presence of 1.0 mM Me$_2$NClO$_4$; 80% DMSO, pH 10.4, 50.0 °C. $^b$ Pseudo-first order specific rates $k_{\text{obs}}$ calculated from initial rates of HPLC monitored nucleoside liberation. Error limits on the order of ±10%. $^c$ For HPNP $k_{\text{vicinal}}/k_{\text{distal}}=0.5$, see ref 5.

### Table 1 Cleavage of diribonucleoside 3',5'-monophosphates NpN' in the presence of guanidinocalix[4]arenes 1 and 2 $^{a,b}$

| Entry | NpN'  | $10^6 \times k_{\text{obs}}$ (s$^{-1}$) | $k_{\text{rel}}$ | $10^6 \times k_{\text{obs}}$ (s$^{-1}$) | $k_{\text{rel}}$ | $k_{\text{vicinal}}/k_{\text{distal}}$ |
|-------|-------|-------------------------------------|-----------------|-------------------------------------|-----------------|----------------------------------|
| 1     | GpU   | 65                                  | 88              | 24                                  | 38              | 2.7                              |
| 2     | GpG   | 62                                  | 84              | 14                                  | 22              | 4.4                              |
| 3     | UpU   | 14                                  | 19              | 9.8                                 | 16              | 1.4                              |
| 4     | ApG   | 2.4                                 | 3.2             | 1.2                                 | 1.9             | 1.7                              |
| 5     | GpA   | 1.0                                 | 1.3             | 1.2                                 | 1.3             | 0.8                              |
| 6     | CpC   | 2.2                                 | 3.0             | 0.92                                | 1.5             | 0.8                              |
| 7     | CpA   | 0.74                                | 1.0             | 0.63                                | 1.0             | 3.0                              |
| 8     | UpG   | 1.9                                 | 2.6             |                                      |                 |                                   |

$^a$ 2.0 mM precatalyst, 0.10 mM NpN', 10 mM Me$_2$NClO$_4$; 80% DMSO, pH 10.4, 50.0 °C. $^b$ Pseudo-first order specific rates $k_{\text{obs}}$ calculated from initial rates of HPLC monitored nucleoside liberation. Error limits on the order of ±10%. $^c$ For HPNP $k_{\text{vicinal}}/k_{\text{distal}}=0.5$, see ref 5.

As a final comment, the close similarity of $k_{\text{bg}}$ values measured for CpA and GpU is consistent with the fact that rates of background cleavage of the phosphodiester bond of diribonucleoside monophosphates are affected by nucleobase identity to a moderate extent. $^a$ It seems therefore reasonable to assume that the $k_{\text{bg}}$ values actually measured for two members of the series are representative of the whole series and, consequently, that rate enhancements as high as $10^2$–$10^5$ characterize the performances of catalysts 1 and 2 in the cleavage of the eight NpN' investigated substrates. These values are comparable in magnitude with rate accelerations reported by other metal complexes and macrocycles with similar functionalities.

### Table 2 Cleavage of CpA, GpU, and HPNP catalyzed by 1 and 2 in 80% DMSO, pH 10.4. Catalytic rate enhancements relative to background, $k_{\text{obs}}/k_{\text{bg}}$. $^{a,b,c,d}$

| Catalyst | CpA $^{a,b}$ | GpU $^{a,c}$ | HPNP $^{d}$ |
|----------|--------------|--------------|-------------|
| 1        | $1.3 \times 10^3$ | $6.6 \times 10^4$ | $1.4 \times 10^2$ |
| 2        | $1.6 \times 10^3$ | $2.4 \times 10^4$ | $2.9 \times 10^2$ |

$^a$ At 50.0 °C. $k_{\text{obs}}$ values from Table 1. $^b$ $k_{\text{bg}} = (5.7 \pm 0.4) \times 10^{-10}$ s$^{-1}$. $^c$ $k_{\text{bg}} = (9.8 \pm 0.4) \times 10^{-10}$ s$^{-1}$. $^d$ At 25.0 °C; calculated from data in ref 5.
for artificial di- and trimetallic phosphodiesterases.\textsuperscript{2d,3,10,14}

Conclusions

To sum up, we have shown that diguanidinocalix[4]arenes 1 and 2 catalyze the cleavage of diribonucleoside monophosphates much more efficiently than the cleavage of HPNP, most likely on account of a greater negative charge development on the nonbridging oxygen atoms in the transition state of the reaction of phosphodiesterases with bad leaving groups. To the best of our knowledge, reactivity data related to the cleavage of a series of diribonucleoside monophosphates catalyzed by nonmetallic synthetic catalysts are here presented for the first time. When combined with data from previous studies, the data reported in this work reinforce the notion that cone-calix[4]arenes are useful platforms for the design of efficient bifunctional catalysts.\textsuperscript{15} The good catalytic efficiency and selectivity of the diguanidino derivatives described in this work encourages further studies in the cleavage of RNA polynucleotides.

Experimental

Instruments and General Methods

Materials. DMSO, purged 30 min with argon, and mQ water were used in the preparation of 80% DMSO. Calixarenes 1 and 2 were available from previous investigations.\textsuperscript{5} Diribonucleoside 3',5'-monophosphates UpU, GpG, and ApG were purchased from Sigma-Aldrich, while UpG, CpC, GpA, GpU, and CpA were from Dharmacon Research (Lafayette, CO). Pure samples of NpN\textsuperscript{4} and their aqueous solutions were stored at −20 °C.

Warning! Care was taken when handling tetramethylammonium perchlorate because it is potentially explosive. No accident occurred in the course of the present work.

Kinetic Measurements. Cleavage of diribonucleoside 3',5'-monophosphates NpN\textsuperscript{4} was monitored by HPLC analyses of aliquots of the reaction mixture withdrawn at appropriate time intervals. Reactions were carried out at 50.0 °C, pH 10.4, on 0.10 mM NpN\textsuperscript{4}, and 1–4 mM catalyst solutions in 80% DMSO, 10 mM Me\textsubscript{4}NClO\textsubscript{4}. The pH of the solution was measured by a microglass pH electrode. Experimental details and procedures for the electrode calibration were as previously reported.\textsuperscript{3} In a typical experiment, half-neutralization of precatalyst was carried out by addition of a solution of Me\textsubscript{4}NOH in 80% DMSO until pH 10.4 was reached. The mixture was thermostated at 50.0 °C for 30 min and the reaction was started by addition of a calculated small volume of a 5.0 mM solution of NpN\textsuperscript{4} in water. At proper time intervals, aliquots (80 µL) of the reaction mixture were withdrawn and quenched with 80 µL of a 10 mM solution of HClO\textsubscript{4} in 80% DMSO. After addition of p-hydroxybenzoic acid (internal standard) in 80% DMSO, the solution was filtered and subjected to HPLC analysis by elution with H\textsubscript{2}O (0.1% trifluoroacetic acid)/MeCN, linear gradient from 100:0 to 85:15 in 25 min, flow 0.9 ml/min. The pseudo-first-order rate constant for the hydroxide catalyzed cleavage of CpA and GpU was measured at 50.0 °C in the presence of 1.0 mM Me\textsubscript{4}NNOH (pOH 3.0), 10 mM Me\textsubscript{4}NClO\textsubscript{4}, by HPLC monitoring of the nucleoside liberation (initial rate method).

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Notes and references

\textsuperscript{a} Dipartimento di Chimica and IMC - CNR Sezione Meccanismi di Reazione, Università La Sapienza, 00185 Roma, Italy.
E-mail: riccardo.salvio@uniroma1.it
\textsuperscript{b} Dipartimento di Chimica, Università degli Studi di Parma, Parco Area delle Scienze 17/A, 43124 Parma, Italy
\textsuperscript{†}Electronic Supplementary Information (ESI) available: HPLC chromatograms for the monitoring of NpN\textsuperscript{4} cleavage. See DOI: 10.1039/b000000x/

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