

Synthesis, Crystal Structure, and Spectroscopic Investigation of C-Cyanophenyl Pyrogallol[4]arene

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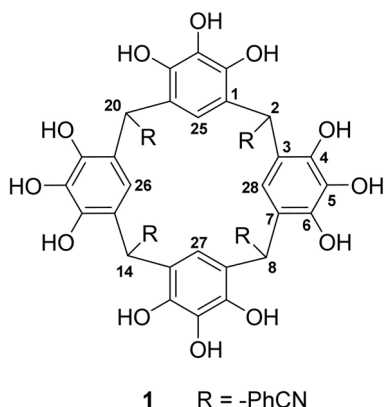
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Pyrogallol[4]arenes have drawn much attention since their emergence as new hydrogen-bonded hexameric¹ or metal-seamed^{2,3} capsule-forming molecular receptors. Pyrogallol[4]arenes often form a variety of superstructures other than hexameric capsules⁴⁻⁷ including dimeric capsules⁸ and bilayers depending on the selection of solvent conditions.^{1,9-12} It is well established that the substitution of aryls for alkyls on methine units connecting the pyrogallols of pyrogallol[4]arene yields a chair conformation, while alkyl-substituted pyrogallol[4]arene mostly adopts a cone conformation. In these reports, the hydroxyl groups of pyrogallols were acetylated to enhance solubility because of the poor solubility of unacetylated forms in common organic solvents.¹³ Herein, we describe the synthesis, crystal structure, and spectroscopic investigation of C-cyanophenyl pyrogallol[4]arene (**1**) without any modification of the hydroxyl groups of pyrogallols, which might be the first crystal structure formed in unacetylated aryl-substituted pyrogallol[4]arenes. These findings might be useful for the design of receptors based on pyrogallol[4]arenes for the construction of the superstructure derived from hydrogen bonds or metal coordinations.



Experimental Section

All the chemicals were used as received without further purification. The synthesis of pyrogallol[4]arene were performed according to the method in the literature method.¹³ The ¹H NMR and ¹³C NMR spectra were recorded on a

Bruker AVANCE II spectrometer at a Larmor frequency of 400.13 MHz. The infrared (IR) spectra were recorded on a MIDAC M series IR spectrometer. MALDI-TOF mass spectra were obtained on a Bruker Reflex III MALDI-TOF mass spectrometer. Data collection for **1** was performed with the beamline (6C1 MXII) at the Pohang Accelerator Laboratory (PAL).

Synthesis of 2,8,14,20-cyanophenyl pyrogallol[4]arenes (1). The synthesis of **1** has been reported elsewhere.¹ Briefly, equimolar amounts of pyrogallol (1.2 g, 10 mmol) and 4-cyanobenzaldehyde (1.3 g, 10 mmol) were mixed in a round-bottom flask containing 30 mL of ethanol and 10 mL of concentrated HCl with a flow of nitrogen; the solution was stirred under a reflux at 70–80 °C for 1 day. The resulting solution was cooled to room temperature. Filtration and washing with water and ethanol several times followed by drying in vacuum gave the desired product (yield = ~65%). ¹H NMR (DMSO-*d*₆, 400 MHz, 25 °C) δ = 4.70 (s, 2H), 5.74 (s, 8H), 5.89 (s, 2H), 6.78 (d, *J* = 8.0 Hz, 8H), 7.38 (d, *J* = 8.0 Hz, 8H), 7.87 (s, 2H), 7.90 (s, 8H), 8.13 (s, 2H). ¹³C NMR (DMSO-*d*₆, 100 MHz, 25 °C) δ = 108.11, 119.23, 120.50, 121.55, 130.30, 131.39, 132.29, 142.77, 143.27, 150.70. MALDI-TOF mass: *m/z* = 1032.1 [M + 2K⁺ – 2H⁺]⁺. Elemental Analysis Calcd. for C₅₆H₄₂N₄O₁₅: C, 66.53; H, 4.19; N, 5.54; Found: C, 66.42; H, 4.17; N, 5.26.

Crystal Structure Determination of 1. Details about the crystal structure and structure refinement for **1** are listed in Table 1. Diffraction from a single crystal of **1** was too weak to be measured by the Siemens SMART CCD diffractometer due to the small size of the crystal. Therefore, diffraction data of **1** with dimensions of 0.10 mm × 0.10 mm × 0.05 mm, mounted on a loop, were collected at 90 K with a ADSC Quantum 210 CCD diffractometer using synchrotron radiation (λ = 0.90000 Å) at the Macromolecular Crystallography Beamline II (6C1), PAL, Pohang, Korea. Data reduction and adsorption correction were performed using the HKL2000 package. The structure was resolved by direct methods and refined by the full-matrix least-squares method using the SHELXTL package. The contributions of the disordered solvents were removed using the SQUEEZE routine of PLATON software.¹⁴ All the non-hydrogen atoms were anisotropically refined. The hydrogen atoms of **1** were added to their geometrically ideal positions.

Results and Discussion

We describe the synthesis, crystal structure, and spectroscopic investigation of **1**. We synthesized **1** by the acid-catalyzed condensation of pyrogallol and 4-cyanobenzaldehyde. Aryl-substituted pyrogallol[4]arenes are known to be insoluble in most of the common organic solvents, so their hydroxyl groups were acetylated to enhance solubility.¹⁵ We found that **1** exhibited good solubility in DMSO. Crystals were grown from the diffusion of MeOH into the DMSO solution saturated with **1**. The diffraction from a single crystal of **1** was too weak to be measured by the Siemens SMART CCD diffractometer due to the small size of the crystal. Therefore, the diffraction data of **1** were collected by using synchrotron radiation at the Macromolecular Crystallography Beamline II (6C1), PAL. The crystallographic data for the refinement of **1** are listed in Table 1. The X-ray crystal structure of **1** revealed that the only isolated product was an isomer with a chair conformation, as shown in Figure 1. This is probably due to the steric hindrance among the aryl groups during the formation of cyclic tetramer. This finding is consistent with the previous reports on aryl-substituted pyrogallol[4]arenes.^{13,15} Therefore, to the best of our knowledge, it is the first crystal structure of unacetylated aryl-substituted pyrogallol[4]arene. The structure of **1** exhibits C_2 symmetry around the centroid of pyrogallol[4]-arene and is also linear. Two 4-cyanophenyl substituents

Table 1. Crystal data and structure refinement for **1**

Empirical formula	$C_{59.07}H_{45.76}N_4O_{13.81}S_{1.26}$
Formula weight	1072.95
Temperature	90(2) K
Wavelength	0.90000 Å
Crystal system	Triclinic
Space group	$P-1$
Unit cell dimensions	$a = 12.548(3)$ Å $\alpha = 73.75(3)^\circ$ $b = 15.506(3)$ Å $\beta = 88.54(3)^\circ$ $c = 19.017(4)$ Å $\gamma = 69.65(3)^\circ$
Volume	$3320.0(11)$ Å ³
Z	2
Density (calculated)	1.073 g/cm ³
Absorption coefficient	0.208 mm ⁻¹
F(000)	1118
Crystal size	$0.10 \times 0.10 \times 0.05$ mm ³
Theta range for data collection	1.85 to 30.32°
Index ranges	$0 \leq h \leq 14, -14 \leq k \leq 17, -21 \leq l \leq 21$
Reflections collected	6986
Independent reflections	6986 [R(int) = 0.0000]
Completeness to theta = 30.32°	71.1%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9897 and 0.9795
Refinement method	Full-matrix least-squares on F ²
Data/restraints/parameters	6986/78/754
Goodness-of-fit on F ²	1.300
Final R indices [I > 2sigma(I)]	$R_1 = 0.1018, wR_2 = 0.2697$
R indices (all data)	$R_1 = 0.1097, wR_2 = 0.2829$
Extinction coefficient	$0.007(3)$
Largest diff. peak and hole	1.000 and -0.313 e.Å ⁻³

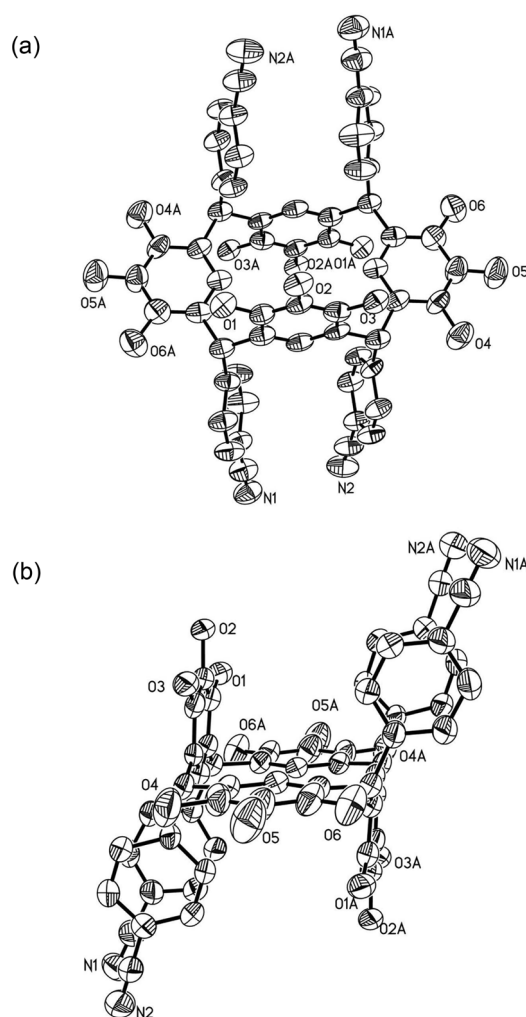


Figure 1. (a) Crystal structure of **1** and (b) its side view. Displacement ellipsoids are drawn at 50% probability. Hydrogen atoms are omitted for clarity.

pointing along the same direction are facing each other to maximize the π - π interaction between the cyanophenyl rings, even though the distance between the two facing cyanophenyl rings is larger than that typically required for π - π interaction in phenyl rings.¹⁶ The facing phenyl rings come closer when moving outwards. The distance between C9 and C16 (symmetry code: x, y, z) is $4.904(6)$ Å, while at the terminal of the cyanophenyl ring, the distance between N1 and N2 (symmetry code: x, y, z) is estimated to be $3.588(6)$ Å, which is fairly close to the distance corresponding to the π - π interaction between the phenyl rings.

The packing diagram along the c -axis shows a layered structure, where the hydroxyl groups of **1** form the hydrogen bonds with the hydroxyl groups of neighboring **1** and oxygen atom of DMSO solvent molecules, as shown in Figure 2. Typical distances (D-A) include O2-O203 ($2.851(4)$ Å), O3-O202 ($2.850(4)$ Å), and O201-O2S ($2.631(7)$ Å). Such a hydrogen-bonded network could not be obtained when using acetylated aryl-substituted pyrogallol[4]arenes.

Spectroscopic evidence for the formation of intermolecular hydrogen bonding between pyrogallol[4]arenes was

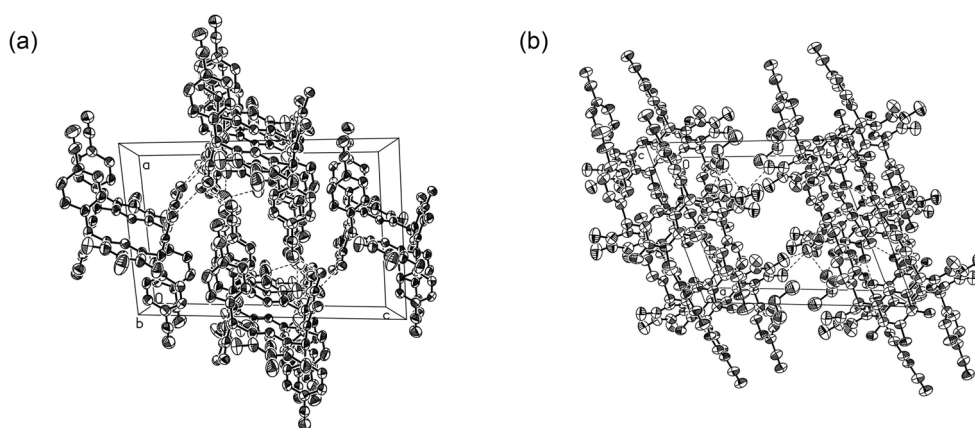


Figure 2. Packing structures of **1** along the (a) b-axis and (b) c-axis. Displacement ellipsoids are drawn at the 50% probability. Hydrogen atoms are omitted for clarity.

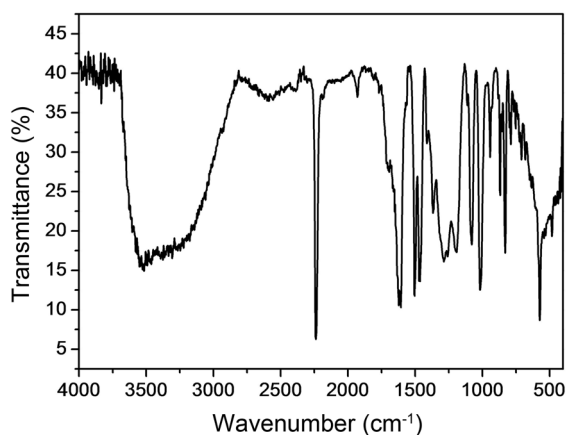


Figure 3. IR spectrum of **1** in KBr.

provided by the IR spectrum. Figure 3 shows the presence of intermolecular hydrogen-bonded O-H stretching vibrations (3300 cm^{-1}).¹⁷ In addition, a sharp peak at 3517 cm^{-1} buried in the broad peak corresponds to a free O-H stretching vibration frequency. A sharp peak at 2239 cm^{-1} originates from the aromatic CN vibration frequency. This IR spectrum is consistent with the formation of hydrogen bonds between pyrogallol[4]arenes, which was shown in the crystal structure. The ^1H and ^{13}C NMR spectra and the elemental analysis conform to the molecular structure. The MALDI-TOF mass spectrum of **1** exhibited a molecular ion peak coupled with the potassium ion at m/z 1032.1.

In summary, the synthesis and crystal structure of **1** revealed that it adopts the chair conformation due to steric hindrance among the phenyl rings during the formation of cyclic tetramer and the hydroxyl groups form hydrogen bonds with the neighboring hydroxyl groups and DMSO. The presence of cyano groups at the para position of phenyl rings may offer binding sites for metal ions. Taken together, these findings might be useful for the design of receptors based on pyrogallol[4]arenes for the construction of superstructures derived from hydrogen bonds or metal coordinations.

Supplementary Material. Crystallographic data for the structure reported here have been deposited with the

Cambridge Crystallographic Data Centre (Deposition No. CCDC-700882 for **1**). The data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

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