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Bond Rotation in an Aromatic Carbaporphyrin: Allyliporphyrin**

Jung-Ho Hong, Adil S. Aslam, Min-Sung Ko, Jonghoon Choi, Yunho Lee, and Dong-Gyu Cho*

Dedication ((optional))

Abstract: Allyliporphyrin is a carbaporphyrin that has replaced one pyrrole with an allyl group. Dynamic behavior (bond rotation) was observed by variable temperature ¹H NMR and 2D-NOESY NMR spectroscopy and theoretically examined by DFT calculations. These studies revealed that well-defined bond rotation was first observed in the limited space of the carbaporphyrin from 2 through *cis*-2 and the calculated rotational barrier was low enough, with the relative energy level of *cis*-2 only 0.65 kcal/mol higher than 2. The synthesized allyliporphyrin (2) is a strongly aromatic macrocycle as indicated by the chemical shifts of its inner NH and CH signals. However, its palladium complex displayed reduced aromaticity due to the tilted thiophene of Pd-2.

Bond rotations are considered as the most fundamental movements in molecular machines.^[1, 2a] Although bond rotation of aromatic [18]annulene was reported in the 1960s (Figure 1),^[3] such primitive motions could not be considered as mechanical motions due to their undefined bond rotations. While the bond rotations of isoporphycenes were reported in the late 1990s, [2c, ^{2d]} in the porphyrin skeletons, pyrrole (or its thiophene analogue) flipping was observed.^[2a, 2b] Historically, to support [18]annulene model of porphyrin, meso-unsubstituted dideazaporphyrin (a porphyrin without two pyrrolic NHs, 1a) was first synthesized by two consecutive McMurry coupling reactions.^[4] Then, the flexible nature was recognized^[5] in the form of meso-substituted dideazaporphyrin (1b) while synthesized by removing two tellurium atoms from meso-substituted telluraporphyrin.[6] Its conformer (trans-1b) was observed in equilibrium^[6] without a metal in its core.^[7] Although a minimum number of double bonds between the two pyrroles (or meso-carbons) is necessary to observe the bond rotation, stepwise bond rotations have not been proposed due to the complexity from the multiple double bond rotations and higher symmetry of dideazaporphyrin (1b) like [18]annulene. Thus, the model compound (2) was designed to examine stepwise bond rotations in a minimum number of

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double bonds. Synthetically, allyliporphyrin (2) is a challenging carbaporphyrin.^[8] Thus, the replacement of one pyrrole of porphyrin with an allyl group (or removal of the two peripheral carbons of the pyrrole) has not been reported to date. However, its synthesis could be accomplished by the modified synthetic routes that our group has developed to obtain *meso*-fused carbaporphyrins.^[9] Other synthetic routes for the target could be complicated.^[10] Herein, we report the detailed synthesis and general properties of allyliporphyrin supporting [18]annulene model of porphyrin by removing a different part (**1b** *vs* **2**).^[4] Particularly, well-defined bond rotation was first observed in the limited space of the carbaporphyrin.



Figure 1. Different aspects of allyliporphyrin (2) from 21,23-dideazaporphyrin (1a and 1b) and structure of [18]annulene

The syntheses of carbaporphyrin (2) and its Pd-2 were accomplished as summarized in Scheme 1. Retrosynthetic analysis of the carbaporphyrin revealed that the condensation reaction of diol (8) and dipyrromethane affords the target compound. To obtain diol (8), the oxidation reaction of (Z)-3iodo-3-phenylprop-2-en-1-ol^[11] with MnO₂ afforded acrylaldehyde (3) in an 80% yield. The Horner-Wadsworth-Emmons reaction of acrylaldehyde (3) followed by DIBAL reduction and MnO₂ oxidation afforded dienylaldehyde (6). The subsequent Suzuki coupling of thiophen-2-ylboronic acid with dienylaldehyde (6) led to the corresponding dialdehyde (7) in a 63% yield. The key intermediate, diol (8), was obtained via a Grignard reaction from dialdehyde (7). Finally, a Lewis-acidcatalyzed [2+2] reaction^[12] between diol (8) and dipyrromethane followed by in situ oxidation with chloranil produced the target macrocycle 2 in a 6.3% yield. The central cavity composed of "NNCS" (nitrogen-nitrogen-carbon-sulfur) donors from allyliporphyrin (2) could result in a square-planar complex with palladium(II). Such C-H bond activations often facilitate unique skeleton modifications.^[13] Thus, the reaction of free bases 2 with palladium(II) acetate was performed according to Scheme 1. However, no signals corresponding to the inner NH or CH in the ¹H NMR spectrum of the complex indicated palladium coordination (Pd-2) in the central cavity (Figure S6, ESI).

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Scheme 1. Synthetic scheme of allyliporphyrin (2) and its Pd^{II} complex

The ¹H NMR spectrum of **2** has characteristics of an aromatic polypyrrolic molecule evidenced by the internal NH and CH resonance signals at -2.93 and -5.06 ppm at -50 °C in CDCl₃. These values are comparable to those of the two inner NHs of tetraphenylporphyrin (\approx –2.80 ppm) in the same solvent.^[14] The dynamic behavior of allyliporphyrin was easily recognized by the very broad peripheral signals of protons (H16 and H18) at 25 °C in Figure 3b. In contrast, the peaks sharpened into two doublet signals at 10.24 and 10.14 ppm at -25 °C. At the same temperature, small signals in the aromatic region started to appear. The 2D nuclear Overhauser effect spectroscopy (NOESY) spectrum of 2 showed that the small signals exchanged with the signals of 2 (Figure S1, ESI). For example, the small signal (H18cis-2) at 9.20 ppm exhibited an exchange cross-peak with H18 while the H16 signal at 10.14 ppm exhibited an exchange cross-peak with H16cis-2 at -5.14 ppm (Figure S2, ESI). In addition, the small signal (dd, J = 15.1, 10.9Hz, H17_{cis-2}) at 9.92 ppm exhibited an exchange cross-peak with H17 of 2 at -5.21 ppm, although the signal (H17_{cis-2}) was more clearly resolved at -50 °C. The two coupling constants of H17cis-2 signal indicated that H17cis-2 should have cis and trans-double bond connectivity. Thus, the predicted exchanged structure should be cis-2, as shown in Figure 2. From the exchanged peaks, most important signals of 2 were absolutely assigned, as shown in Figure 3. In addition, another small signal behaving differently from those of cis-2 was clearly observed at 10.76 ppm (Figure 3a). For instance, the diagonal signals were not clearly observed at -25 °C and their exchange cross-peaks (H18 and H16) were clearly observed in the 2D NOESY spectra of 2 (Figure S1, ESI). In contrast, all signals arising from cis-2 had clear diagonal peaks with exchange cross-peaks at -25 °C, although the intensity of the cross-peaks became very weak at -50 °C (Figure S3, ESI). The observed coupling constants of the two doublet peaks at 10.76 ppm (J = 13.7 and J = 13.2 Hz, respectively) were similar to those of H16 (d, J = 13.8 Hz) and H18 (d, J = 13.6 Hz) measured for 2. Other signals related to the



Figure 2. (a) Detected conformer (*cis-2*) in equilibrium with its two resonance structures **2a** and **2b** of **2.** (b) Undetected conformers (*cis-2*' and **2**₀) and possible tautomer (*tau-2*) of the allyliporphyrin (**2**) in equilibrium. The bond rotation was assessed by changing the dihedral angle highlighted in red.





peak at 10.76 ppm were not detected due to the overlap of the expected small peak sets with larger signals. Although it is difficult to deduce a reasonable structure from the limited information from the signal at 10.76 ppm, the allyl group should adopt a structure similar to that of **2**. Thus, another conformer derived from the signals could be related to the NH tautomer of **2** or **2**_x (x denotes both the dihedral angles in Figure 2). The dynamic behavior of the allyliporphyrin was also studied by

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increasing the temperature in a o-dichlorobenzene-d₄ solvent instead of the typical low boiling point NMR solvent (CDCl₃). As the temperature increased, the two broad H18 and H16 signals observed at 25 °C became much broader and gradually shifted to a higher magnetic field (Figure 3c and S5, ESI). The two inner protons (NH at -3.19 and CH at -5.40 ppm) individually became much broader at 40 °C. The inner CH signal slowly disappeared at 70 °C although the inner NH signal was clearly visible even at 120 °C (Figure 3c). Similarly, one of the two peripheral signals (H18 and H16) appeared at 9.77 ppm (d, J = 13.2 Hz, 1H) at 120 °C (Figure S5b, ESI). Thus, we concluded that the C17-C16 bond rotation around C18 and C15 (from 2a to cis-2, Figure 2) was monitored over a wide temperature range. Unfortunately, the average signal expected from the proton exchange between the inner proton and outer proton from the bond rotation was not observed at higher temperatures. [3a] This could be due to the expected peak being very broad or overlapping with others at high temperatures.



Figure 4. Relative energy diagrams obtained from the bond rotation of **2**; •• from **2** through *cis*-**2**, •• from **2** through *cis*-**2**', and •• from **2** through **2**₀. All bond rotations were depicted as their dihedral angles shown in Figure 2. Thus, all three rotations started at different dihedral angles of **2**.

To confirm the presence of the proposed conformers at equilibrium, conformers at local energy minima were obtained by changing the dihedral angle followed by structural optimization using DFT calculations (relaxed potential energy scan), as shown in Figure 4. Specifically, cis-2 was obtained by rotating the C16-C17 bond of 2a to change the dihedral angle between C17-H17 and C18-H18 bonds while cis-2' by rotating the C18-C17 bond of 2b to change the dihedral angle between C16-H16 and C17-H17 bonds. Structurally, both of cis-2 and 2 have similar flatness (Figure S8 and S9, ESI), and compared to the energy level of 2, cis-2 is only 0.65 kcal/mol higher. △G° of the equilibrium from 2 to cis-2 obtained from Van't Hoff equation (1.02 kcal/mol) also supported the DFT calculation as well (Figure S14, ESI). In contrast, a larger energy difference between cis-2 and cis-2' arose from the steric hindrance between H18 and the longer C-S bond of cis-2', which also shifted the allyl group of cis-2' out of the plane (Figure S9, ESI). Thus, the energy level of cis-2' was calculated to be 18.20 kcal/mol higher than that of 2 (Figure 4). The rotation barriers for cis-2 and cis-2' were calculated to be 16.28 and 24.60 kcal/mol, respectively, from the energy of 2, although the two values are relatively similar. These calculations indicate that cis-2 is likely more abundant than cis-2' at equilibrium at 25 °C. In addition, the energy levels of 2_x (Figure 2) were examined by changing both dihedral angles at the same time in 2. These restricted rotations enabled the allyl group to rotate at an angle with respect to the macrocyclic mean plane defined as C5, C10, C15, and C19 in Figure 4. The energy level of 20 (19.91 kcal/mol, two protons in the macrocycle, Figure 2) is similar to that of cis-2'. However, the rotational barrier going from 2 to 290 was estimated to be 57.73 kcal/mol. This value is slightly lower than the calculated energy of the 90° twisted triplet 2-butene diradical relative to the energy of trans-2-butene (65.7 kcal/mol obtained from the same B3LYP DFT parameters).^[15] Thus, the full rotation (2 through 290) should be prohibited. The relative energy of the NH tautomer of 2 is 2.33 kcal/mol higher than that of 2 (Figure S16, ESI). The NH tautomer is likely more dominant at equilibrium when compared to cis-2' and 2_0 . Thus, the signals at 10.76 ppm (labeled as H18_{ta} and H16_{ta}) in the ¹H NMR spectrum of 2 likely arise from the NH tautomer of 2.^[16] Considering the data discussed above, it can be reasonably concluded that the bond rotation of 2 mainly occurs through cis-2 at all temperatures discussed herein.



Figure 5. X-ray crystal structures of (a) the top view of 2 and (b) Pd-2. Thermal ellipsoids are scaled to the 50% probability level. Most hydrogen atoms and disordered components are omitted for clarity.



Figure 6. UV-Vis absorption spectra of 2 and Pd-2 in CH_2CI_2

The structures of the allyliporphyrin (2) and its associated Pd complex (Pd-2) were unambiguously elucidated by X-ray crystallography after crystal growth in CH₂Cl₂/MeOH (Figure 5).^[17] In the solid state, the two molecules of allyliporphyrin overlapped and aligned at 180°. The disordered components and protons were omitted for the structural clarity in Figure 5. Structurally, the thiophene and pyrrole C ring lie flat while the pyrrole B ring and allyl group are tilted by 10.90, and 17.85°, respectively, from the macrocyclic mean plane (Figure S20 and S21, ESI). Some bond distances were quite unusual, such as the C9-C10 (1.184 Å), C13-C14 (1.207 Å), and C17-C18 (1.266 Å) bond, which are shorter than typical carbon double bonds. On the other hand, the C18-C19 (1.625 Å) and C15-C16 (1.524 Å) bonds between the allyl group are particularly longer than other bonds, which may reflect a rotation of the allyl group within a limited angle from 2 to 290. In contrast, the abnormal bond lengths of 2 were not observed in its Pd complex. For example, the longest and shortest bonds (C18-C19 and C9-C10) of 2 changed to 1.401 and 1.402 Å, respectively, for Pd-2. The two pyrroles and allyl group of Pd-2 were relatively flat except for the thiophene which was titled 23.98° from the mean plane (C5, C10, C15, and C19), as shown in Figure S24. This tilt disturbs the planarity of the molecules and reduced the aromaticity of **Pd-2**. The upfield shifted β -protons of thiophene in the ¹H NMR spectrum and nucleus-independent chemical shifts (NICS) values of Pd-2 as compared to those in 2 further indicated reduced aromaticity of Pd-2 (Figure S6, S17 and S18 in ESI).

The UV-visible absorption spectrum of **2** in CH₂Cl₂ (Figure 6) shows a characteristically intense Soret band at 422 nm (ε = $2.82 \times 10^5 \text{ cm}^{-1} \text{ M}^{-1}$) accompanied by weak and broad Q-like bands at 516, 549, and 624 nm. The spectroscopic features of 2 very similar to those of (meso-unsubstituted) were carbachlorins.^[18] The Soret band of 2 was red shifted by 21 nm while the Q-like bands of 2 were blue shifted by 27 nm compared to those of carbachlorins.^[18a] Interestingly, both the Soret and Q-like bands of 2 are very broad compared to those of other carbaporphyrins.^[8] The bands of the Pd complex were redshifted compared to those of its free ligands. Typically, the Soret band of Pd-2 was red shifted by 36 nm from the Soret band of 2. In addition, the molar absorption coefficient (ϵ) of Pd-2 was quite smaller than that of 2. The distorted thiophene in the solid state likely reduced molar absorption coefficient (ϵ) of Pd-2. Thus, the electronic structure and optical properties of 2 and Pd-2 were studied by time-dependent density functional theory (TDDFT at B3LYP/6-31G(d, p). TDDFT calculations predicted that the oscillator strengths of the Soret and Q-like bands of Pd-2 decreased by a half of those of 2 (Figure S11 and S12, ESI).

In summary, to examine bond rotation of aromatic polypyrrolic macrocycles with a limited number of carbon double bonds, allyliporphyrin (2) was synthesized. Structurally, allyliporphyrin is an interesting carbaporphyrin where one pyrrole is replaced with an allyl group. The dynamic behavior (bond rotation) was observed by variable temperature ¹H NMR and 2D-NOESY NMR spectroscopy. These studies revealed that bond rotation occurs from 2 through *cis-*2 in three sp² carbons between the two *meso*-carbons. The calculated rotational barrier was low and relative energy level of *cis-*2 was only 0.65 kcal/mol higher than that of 2. Two different rotational pathways, represented by *cis-*

 2° and 2_{0} , were not observed by the spectroscopic studies and these observations were also supported by DFT calculations. In addition, allyliporphyrin (2) is a strongly aromatic macrocycle, judged by the chemical shifts of its inner NH and CH signals, although its palladium complex displayed reduced aromaticity due to its tilted thiophene. The current synthesis also supported [18]annulene model of porphyrin.

Keywords: porphyrin • carbaporphyrin • bond rotation • allyliporphyrin • aromaticity

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Porphyrinoid: Allyliporphyrin (2) was synthesized that has replaced one pyrrole with an allyl group. The current studies revealed that well-defined bond rotation occurs from 2 through *cis*-2 in three sp² carbons between the two *meso*-carbons.

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