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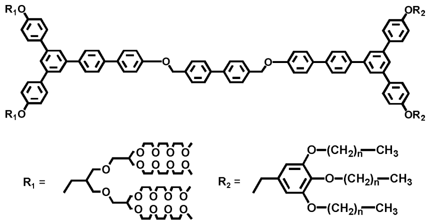
# Nanorings from the Self-Assembly of Amphiphilic Molecular Dumbbells

Jung-Keun Kim, Eunji Lee, Zhegang Huang, and Myongsoo Lee*

*Center for Supramolecular Nano-Assembly and Department of Chemistry, Yonsei University, Seoul 120-749, Korea*

Received July 30, 2006; E-mail: mslee@yonsei.ac.kr

The exploitation of aromatic rod-like building blocks for the engineering of synthetic nanostructures is a promising area of research.[1] Thus, diverse molecular structures are being created as a means of manipulating aggregation structure. For example, incorporation of a rigid rod segment into amphiphilic molecular architectures leads to a number of well-defined nanostructures, including bundles, barrels, tubules, ribbons, and vesicles, in solution state.[2] Recently, we have demonstrated that dumbbell-shaped molecules consisting of an aromatic stem segment and hydrophilic dendritic branches, in aqueous solution, self-assemble into helical nanofibers in which the rod segments stack on top of each other with mutual rotation.[3] The primary driving force responsible for the helical arrangement of the aromatic rods was proposed to be the energy balance between repulsive interactions among the adjacent hydrophilic dendritic segments and attractive $\pi-\pi$ stacking interactions. These results imply that incorporation of hydrophobic branches at one end of a molecular dumbbell further extends the supramolecular organization capabilities of stiff rod-like segments due to enhanced hydrophobic interactions.



**1** *n*= 5, **2** *n*=9, **3** *n*=13

We present here the formation of nanorings from the aqueous self-assembly of amphiphilic dumbbell-shaped molecules based on a rod segment that is grafted by hydrophilic polyether dendrons at one end and hydrophobic branches at the other end (Figure 1).[4] The synthesis of the dumbbell-shaped molecules started with the preparation of an aromatic scaffold containing two oligoether dendrons according to the procedures described previously.[5] The final dumbbell-shaped molecules were synthesized by etherification with an excess of 4,4′-dibromomethylbiphenyl and subsequent etherification with corresponding aromatic scaffolds containing hydrophobic alkyl chains. The resulting molecules were characterized by $^1$H NMR spectroscopy, elemental analysis, and MALDI-TOF mass spectroscopy and are shown to be in full agreement with the structures presented.

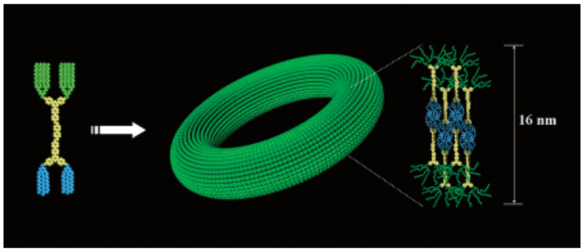


***Figure 1.*** Schematic representation of nanorings from amphiphilic molecular dumbbells.

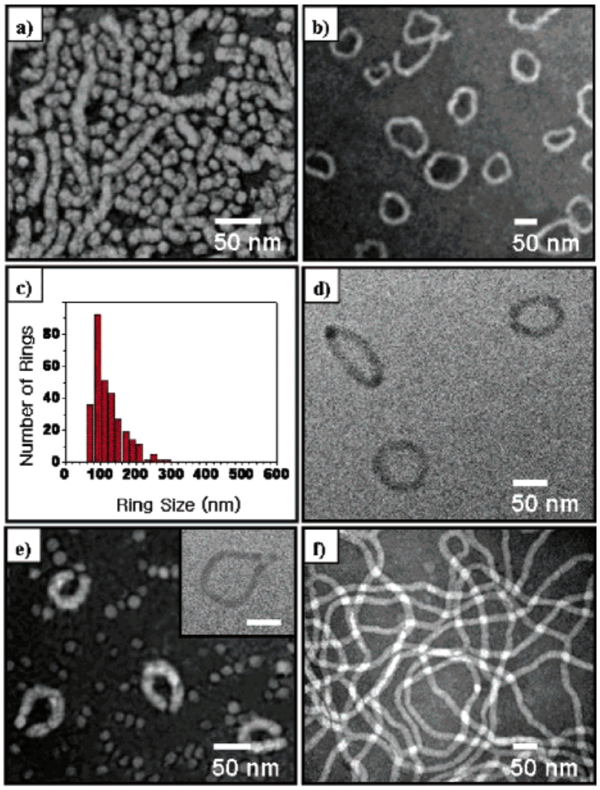


***Figure 2.*** TEM images of (a) spherical, short cylindrical morphology of **1** and (b) toroidal morphology of **2** in aqueous solutions (0.01 wt %). (c) Size distribution of nanorings, measured from TEM wide fields. (d) Cryo-TEM image of **2** and (e) TEM image of **2** at the initial stage without annealing. Inset: cryo-TEM image (scale bar = 50 nm). (f) TEM image of long cylindrical morphology of **3** in an aqueous solution (0.01 wt %).

The molecular dumbbells, when dissolved in a selective solvent for one of the blocks, can self-assemble into an aggregate structure because of its amphiphilic characteristics.[6] Aggregation behavior of the molecules was subsequently studied in aqueous solution by using transmission electron microscopy (TEM). TEM studies showed that all of these molecular dumbbells self-assemble into stable micellar aggregates. Figure 2a shows a micrograph obtained from a 0.01 wt % aqueous solution of **1** based on hexyl hydrophobic chains cast onto a TEM grid. The negatively stained sample with uranyl acetate shows the coexistence of spherical and short cylindrical micelles with undulation. Both micelles are 15 nm in diameter, which is suggestive of an interdigitated bilayer packing of molecular dumbbells, considering the fully extended length of the molecule to be ~8.3 nm (from CPK).

Notably, molecular dumbbell **2** containing hydrophobic decyl chains self-assembles into a toroidal structure. When the sample

10.1021/ja065487b CCC: $33.50

was cast from a 0.01 wt % aqueous solution and then negatively stained with uranyl acetate, the images show predominantly ring-shaped micelles together with a few short cylinders against a dark background (Figure 2b). The cross-sectional diameter is 16 nm, and the ring sizes in diameter range from 70 to 300 nm which gives an average value of 120 nm (Figure 2c). Comparison with the estimated length of a fully extended molecular unit of about 8.8 nm suggests that the 16 nm diameter arises from a bilayer packing within cylindrical domains. To further corroborate the formation of toroidal micelles in aqueous solution, cryo-TEM experiments have been performed with 0.01 wt % aqueous solution. Figure 2d shows dark toroidal objects with a uniform diameter of 12 nm against the vitrified solution background, demonstrating that the solvent evaporation process on the TEM grid does not change the aggregation structure formed in solution. It should be noted that the observed diameter is smaller than the result obtained from the cast film (16 nm). This is because hydrated polyether dendrons do not provide enough contrast for direct observation.[7,8] The dimension of 12 nm is in reasonable agreement with twice the length of the hydrophobic segments, including the rod and alkyl chains, again demonstrating the bilayer packing.

To understand the mechanism of ring formation, TEM experiments have been performed at an initial stage without annealing (Figure 2e). The image shows the coexistence of spherical and curved cylindrical micelles with open ends. However, these micelles were observed to change slowly into toroidal micelles on the time scale of a week, demonstrating that the toroidal aggregates are stable objects.[9] These results suggest that, at the initial stage, the molecules aggregate into spherical micelles consisting of a hydrophobic core surrounded by hydrophilic dendritic chains. Subsequently, the spherical micelles coalesce into a ring-like structure to reduce the contact between hydrophobic segments and water molecules. This is further supported by the presence of a number of the short cylinders with undulations at the initial stage. The enhanced stability of the toroidal micelles relative to the short cylinders with open ends can be attributed to the strong hydrophobic association within the core consisting of the stiff rod-like units and the longer alkyl chains.[10]

To further increase attractive hydrophobic interactions, we have synthesized a molecular dumbbell (**3**) based on longer tetradecyl alkyl chains. When the 0.01 wt % aqueous solution is allowed to stabilize for 1 week and then cast on the TEM grid, the image stained with uranyl acetate shows long, entangled cylindrical micelles that have a uniform diameter of 18 nm and lengths of at least several micrometers (Figure 2f). This result indicates that increasing the length of hydrophobic alkyl chains decreases the interfacial curvature and thus can give rise to the transformation of discrete toroidal micelles to extended cylindrical aggregates.

The results described here demonstrate that aggregation structures, from spherical micelles, toroids to long cylinders, can be regulated by systematic variation in the hydrophobic chain length of the molecule.[11] This variation of micellar structures can be rationalized by considering the relative volume fraction of hydrophilic headgroups to hydrophobic segments.[12] The relative volume fraction of a hydrophilic headgroup decreases with increase in the hydrophobic chain length. Thus, the interface between the hydrophilic and hydrophobic domains changes from a highly curved to a more flat interface, causing a small interfacial area and resulting in the increase of the aggregate size, from spherical toroids to long cylinders.

The remarkable feature of the molecular dumbbells investigated here is their ability to self-assemble into toroidal micelles as an intermediate structure between discrete spherical and long cylindrical micelles. This unique self-assembling behavior is likely to originate from side by side connections of discrete bundles through the combination of strong hydrophobic interactions and anisotropic aggregation of rod segments.[10] Consequently, the enhanced attractive forces within the hydrophobic core would give rise to the formation of stable ring-like micelles. This result suggests that our approach of controlling self-assembled nanostructures using dumbbell-shaped molecular architectures by only a small variation in the length of grafted alkyl chains allows unusual cyclic nanostructures to be produced.

**Acknowledgment.** This work was supported by the National Creative Research Initiative Program of the Korean Ministry of Science and Technology. We would like to thank Prof. S. S. Han and Mrs. K. E. Lee at the Laboratory of Cell Imaging & 3D Structure and Korea University for use of the cryo-TEM facility. E.L. and Z.H. thank the Seoul Science Fellowship Program.

**Supporting Information Available:** Synthetic and other experimental details. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA065487B