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ARTICLE

Structure and Growth Behavior of Centimeter-Sized Helical Oleate Assemblies Formed under Assistance of Medium-Length Carboxylic Acids†

Cite this: DOI: 10.1039/x0xx00000x

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Received 00th January 2012,

Accepted 00th January 2012

DOI: 10.1039/x0xx00000x

www.rsc.org/

The nonequilibrium organization of self-assemblies from small building-block molecules offers an attractive and essential means to develop advanced functional materials and to understand the intrinsic nature of life systems. Fatty acids are well-known amphiphiles that form self-assemblies of several shapes. Here, we found that the lengths of helical structures of oleic acid formed in a buffered aqueous solution are dramatically different by the presence or absence of certain amphiphilic carboxylic acids. For example, under the coexistence of a small amount of *N*-decanoyl-L-alanine, we observed the formation of over 1-centimeter-long helical assemblies of oleate with a regular pitch and radius, whereas mainly less than 100 μm -long helices formed without this additive. Such long helical assemblies are unique in terms of their highly dimensional helical structure and growth dynamics. Results from the real-time observation of self-assembly formation, site-selective small-angle X-ray scattering, high-performance liquid chromatography analysis, and pH titration experiments suggested that the coexisting carboxylates assist in elongation by supplying oleate molecules to a scaffold for oleate helical assembly.

Introduction

There is increasing interest in the use of highly organized self-assemblies of small building-block molecules for the development of advanced functional materials.¹⁻³ Research has focused on the spatiotemporal behavior of molecular assembly and, especially, the dynamics of these materials when utilized in life systems^{4,5} and soft devices.^{6,7} Various experimental and theoretical studies on assembly behavior have been reported and reviewed.⁸⁻¹⁰

Fatty acids are well-known amphiphilic building blocks that can form soft self-assemblies of several shapes, depending on the pH value of the aqueous solution.^{11,12} The apparent $\text{p}K_{\text{a}}^{\text{app}}$ ($\text{p}K_{\text{a}}^{\text{app}}$) values of self-assembled fatty acids differ from the $\text{p}K_{\text{a}}$ values of carboxylic acid groups of water-soluble aliphatic acids (e.g., propionic, butyric, and hexanoic acid; Figure 1), which are generally around 4.8.¹³ For example, Shah *et al.* reported that the $\text{p}K_{\text{a}}^{\text{app}}$ of decanoic acid (capric acid) was 7.1–7.3¹⁴ and the $\text{p}K_{\text{a}}^{\text{app}}$ of oleic acid was 9.85.¹⁵ Therefore, in alkaline aqueous solutions (pH 7–10), fatty-acid assemblies are composed of two types of amphiphiles: a neutral carboxylic acid form and a carboxylate anion form.¹⁶⁻¹⁹ The higher $\text{p}K_{\text{a}}^{\text{app}}$ values of assembled fatty acids are due to the interaction between carboxylates^{14,15,17} and the characteristic dielectric properties and proton activities around the self-assembly

surface.¹⁷ These properties change temporally during the nonequilibrium self-assembly process; thus, the acid dissociation of fatty acids fluctuates greatly. For instance, Sugawara *et al.* reported that several 10-micrometer-sized helical assemblies of oleates in aqueous solution showed spontaneous winding-rewinding motions during helical structure formation, probably owing to fluctuation of the ratio of neutral oleic acid to oleate anion in the assembly.²⁰

In the present study, we found that 10-millimeter-sized helical assemblies were formed in an aqueous dispersion of sodium oleate (**ONa**) with 0.1% (w/w) of *N*-decanoyl-L-alanine (**1**)²¹⁻²³ (Figure 1), whereas in the absence of **1**, the helical assemblies were less than 300 μm . It is quite rare for such long and well-ordered helical lyotropic assemblies to be formed by the noncovalent assembly of small molecules, such as fatty acids. To elucidate the reason for this elongation of helical assemblies by the additional acid, we investigated the effect of increasing the chain length of the additional aliphatic acids on the elongation of helical assemblies. Here, we describe the observed elongation behavior of helical assemblies derived from the addition of several aliphatic acids, and the structure of helical assemblies according to small-angle X-ray scattering (SAXS). We also propose a possible mechanism for the aliphatic acid-mediated growth of long oleate assemblies, on the basis of the results of growth dynamics observations, pH

titration experiments, and high-performance liquid chromatography (HPLC) analysis of the composition of helical assemblies.

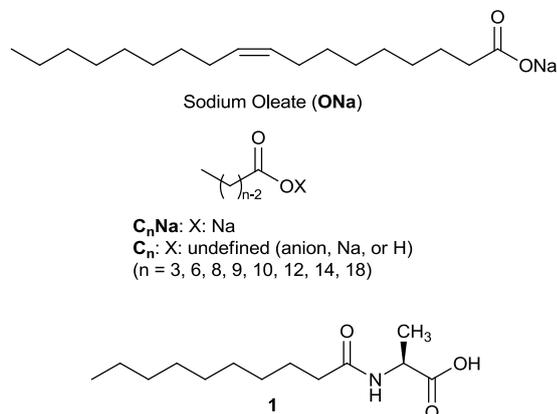


Figure 1. Structures of the compounds used in this study.

Experimental

General

For microscopic observation, differential interference contrast microscopy (Nikon TE2000 and Olympus IX71S1F) was used. Movies were recorded by USB-CCD cameras (Sentech STC-TC152USB and TOSHIBA JK-TU52H). Movie files were edited and compacted by the Sony Vegas Movie Studio Platinum 9.0 and the Microsoft Movie Maker software packages. An automatic volumetric titrator (Metrohm 877 Titrino Plus) equipped with a pH combination electrode (Lutron PE-11) was used for potentiometric pH titration. Except for the titration experiments, a pH/mV meter (SK-Sato SK-620PH) with the same pH combination electrode was used to determine the pH values of solutions. All pH values were determined by using a standard curve of the measured voltages, obtained with three pH standard solutions (pH 4.01, 6.86, and 10.01). For HPLC analysis, a JASCO LC2000 system, equipped with an Agilent 1260 evaporating light scattering (ELS) detector and an octylsilica reversed phase column (GL-Science C8-3), was used. $^1\text{H-NMR}$ spectra of solutions were recorded on a JEOL JEX 270 spectrometer, with tetramethylsilane as an internal reference.

Materials

Extra-pure-grade **ONa** was purchased from Junsei Chemical Co., Ltd. and used without further purification. To prove the reliability of observed phenomena, similar experiments were performed while using reagents with different purities purchased from Nacalai Tesque Inc. and Tokyo Chemical Industry Co., Ltd. The formation and elongation of helical assemblies were observed by using reagents purchased from different suppliers. All reagents and distilled water were purchased and used without purification.

Preparation of *N*-decanoyl-L-alanine (**1**)²¹⁻²³

To a mixture of L-alanine (891 mg, 10 mmol) and NaOH (400 mg, 10 mmol) in water (10 mL), 3.5 mL (17.2 mmol) of decanoyl chloride and 14 mL of 1 M NaOH(aq) were added alternately by pipet at 0 °C. After stirring for 1 h at 0 °C and for 1 h at room temperature, 15 mL of 2 M HCl(aq) were added with vigorous stirring. The colorless wet residue obtained after filtration was dissolved in CH_2Cl_2 . The solution was dried over Na_2SO_4 , and the solvent was removed under reduced pressure to obtain 3.76 g of crude material. Purified material (colorless crystals, 554 mg, 23% yield) was obtained by recrystallization twice from 10:1 AcOEt: EtOH. $^1\text{H-NMR}$ δ (CDCl_3 , 270 MHz): 0.88 (t, $J = 6.3$ Hz, 3H), 1.14–1.38 (m, 12H), 1.47 (d, $J = 7.3$ Hz, 3H), 1.58–1.70 (m, 2H), 2.24 (t, $J = 7.6$ Hz, 2H), 4.52–4.64 (m, 1H), 5.99 (br, 1H).

General method for the formation of helical assemblies and observation of their growth

A 2:1 chloroform: methanol solution (0.5 mL) containing **ONa** (4.0 mg/mL) and **1** (0.04 mg/mL) was poured into a glass vial. Solvent was evaporated to form a mixed thin film of **ONa** and **1**. One milliliter of bicine-buffered solution (70 mM, pH 7.8) or phosphate-buffered saline (PBS; 75 mM, pH 7.6) was added to the film. The substrates were dispersed by ultrasonication. The dispersion was placed on a glass slide and sealed by a frame-seal (17 × 28 mm) incubation chamber (Bio-Rad). After incubation at 25 °C for 2 h to 7 days, the sample was observed under a microscope. Assemblies with or without other aliphatic acids were observed in a similar manner by using PBS, the pH of which was adjusted between 7.4 and 7.6 to form helical assemblies.

Compositional analysis of helical assemblies by HPLC

A dispersion of oleate self-assemblies was prepared by mixing **ONa** (2.4 mg, 7.9 μmol) and **1** (0.031 mg, 0.13 μmol) in 1.2 mL of PBS and incubating the mixture for 10 days at 25 °C. Large assemblies were obtained from the dispersion by absorbing the aqueous phase that included small assemblies, such as micelles and vesicles, with a filter paper. The residue of the large assemblies was dissolved in MeOH and analyzed by HPLC with an ELS detector and an eluent of MeOH: 0.05% TFA(aq) of 78:22. The temperature of the nebulizer was 40 °C, the evaporator was kept at 60 °C, and the flow rate of N_2 gas was 1.00 standard liter per minute. For the reference of the HPLC experiments, a MeOH solution of **ONa** and **1**, and the aqueous phase of the dispersion were measured by using the same analysis method. Additionally, the decrease of oleate concentration in the aqueous phase obtained by filtration of dispersion utilized a 450 nm filter was determined by the same HPLC system with an eluent of MeOH: 0.05% TFA(aq) of 90:10.

General method for potentiometric pH titration

Concentration of titrant, 0.5 M HCl solution, was measured using a Na_2CO_3 standard solution as a reference. Clear dispersions of a mixture of **ONa** (120 mg, 394 μmol) and additional aliphatic acid sodium salt (39.4 μmol) in 0.1 M

NaCl(aq) (60 mL) were prepared in test tubes by ultrasonication. Samples were incubated at 25 °C for approximately 10 min in a water incubation bath, and titrant was added slowly (by 10- μ L stepwise additions) to the test tubes under continuous vigorous stirring to obtain the points on the titration curves.

Observation of the shape of oleate assemblies in solutions between pH 9.4 and 6.8

Clear dispersions of ONa (118 mg, 389 μ mol) in 0.1 M NaCl(aq) (60 mL) were prepared in test tubes by ultrasonication. Each sample was incubated at 25 °C for 10 min in a water bath, and titrant HCl(aq) was added slowly to the test tube by a potentiometric volumetric titrator. At several pH values between pH 9.4 and 6.8 during titration, a small amount of the dispersion was transferred to a slide glass. The sample was subsequently sealed, incubated for 9 h at 25 °C, and observed under a microscope.

SAXS using synchrotron microbeam X-ray radiation

SAXS measurements for individual assemblies were carried out at the BL-4A at PF-KEK in Japan.²⁴ The incident beam was monochromated with a multilayer mirror to be 10 keV and focused to smaller than 5 μ m \times 5 μ m by Kirkpatrick–Baez mirrors. To control the focus and the area of the X-ray beam, an optical microscope system was used. The aqueous sample was placed on a thin glass slide (Matsunami NEO Cover Glass No. 00; thickness: 0.06–0.08 mm) and sealed by a frame-seal incubation chamber. Two-dimensional (2D) images of SAXS patterns were recorded with a 1024 \times 1024-pixel ICCD camera (Hamamatsu). To calculate the *d*-spacing from the 2D images, silver behenate diffraction peaks were used as an external reference.²⁵

Results

Growth of oleate assemblies by the addition of 1

Mixtures of oleic acid and oleate in an aqueous dispersion self-organize into assemblies of several shapes in a pH-dependent manner.^{11,16,20,26} There are two methods for constructing macroscopic tubular, cylindrical, or helical assemblies of oleates. One method is similar to that used in the formation of myelin figures of phosphatidylcholine.^{27–32} Namely, an ONa paste is hydrated by contact with aqueous buffered solution to grow tubular assemblies from the interface between the paste and the aqueous solution. We previously described another method,^{20,33} in which ONa is dispersed in an aqueous buffered solution by ultrasonication. Then, the dispersed colloidal oleates gather together to form macroscopic tubular, cylindrical, or helical assemblies, with micelles and vesicles in the bulk solution. In this report, we prepared helical assemblies by the latter method and observed them by differential interference contrast microscopy.

The oleate helical assemblies that were formed without **1** after incubation for 2 days had lengths between 10 and 300 μ m, with most assemblies being shorter than 100 μ m. When the oleate helical assemblies were formed with 1% (w/w) **1**, millimeter-length helical assemblies were observed after a 2-h incubation.³⁴ These assemblies showed winding dynamics, and one of their edge was linked to aggregates named the “terminal scaffold” (Figure 2). After incubation for 1 day, we observed over 0.5-centimeter-long helical assemblies showing a winding motion (Figure S1 in the Electronic Supplementary Information [ESI]). Similar assemblies of greater than 1 cm in length were observed with the addition of 0.1% (w/w) **1**, in both bicine-buffered solution (70 mM, pH 7.8; Figure S2 in the ESI) and PBS (75 mM, pH 7.4–7.5). More than 10 helical assemblies of millimeter length were observed in a 120- μ L chamber. Assembly shapes included helical assemblies (length = 10–1000 μ m), giant vesicles (radius < 100 μ m), and block-style aggregates³³ (radius < 10 μ m).

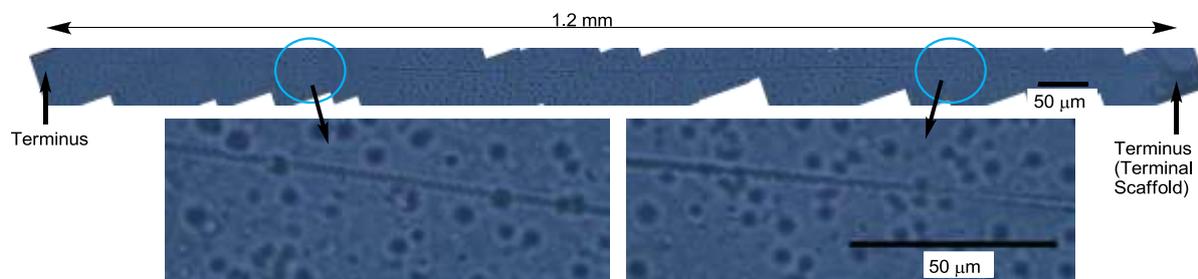


Figure 2. Millimeter-length helical assembly composed of oleate formed in the presence of **1** (1% (w/w)) in 70 mM bicine-buffered solution, observed after incubation for 2 h. To show the long-length assembly, figures captured from a movie file were arranged. The lower two images are zoomed-in pictures that clearly show the helical structure. Because of the winding motion of the helical assembly and the Brownian motion of colloidal assemblies, several parts of the assemblies seem to have ruptured.



Figure 3. Helical assemblies of oleates formed in the presence of fatty acids. (a) ~2-millimeter-long assembly in the presence of sodium pelargonate (C_9Na , 1% (w/w)). (b) ~3-millimeter-long assembly in the presence of sodium caprate ($C_{10}Na$, 1% (w/w)). Bars indicate 0.1 mm.

Composition of large oleate assemblies grown in the presence of **1** and change of oleate concentration in the aqueous phase

Through HPLC analysis with an ELS detector, the compositions of the large assemblies, including the helical assemblies and terminal scaffolds, were determined. For large assemblies prepared from **ONa** in the presence of 1.3% (w/w) **1**, only the oleic acid and impurities of the purchased sodium oleate were detected; the amount of **1** was below the lower detection limit of the ELS detector (Figure S3a-c in the ESI). This result indicates that the ratio of **1** in the large assemblies was less than 0.1% (w/w) for **ONa**. It was also revealed that the oleate concentration in the supernatant was quickly decreased by the presence of **1** (Figure S3d in the ESI).

Growth of oleate assemblies by the addition of various aliphatic acids

Although alanine derivative **1** turns out to be an excellent additive for the elongation of helical assemblies, we are interested in fatty acids as a simpler additive for the same purpose. Several aliphatic acid sodium salts, including propionate (C_3Na), caproate (C_6Na), caprylate (C_8Na), pelargonate (C_9Na), caprate ($C_{10}Na$), laurate ($C_{12}Na$), myristate ($C_{14}Na$), and stearate ($C_{18}Na$), were mixed with **ONa** and dispersed in PBS (75 mM, pH 7.5) to form helical assemblies. Substantial elongation was observed only in the presence of C_9Na or $C_{10}Na$, and moderate elongation longer than 300 μm was observed in the presence of C_8Na or $C_{12}Na$ (Figure S4). In the presence of C_9Na and $C_{10}Na$ (1% (w/w)), helical assemblies of several millimeters in length formed (Figure 3). These results indicate that the chain length of the aliphatic acid is a key to the elongation of the helical assemblies of oleates. The specificity of middle-length fatty acid is also found in pH titration experiments.

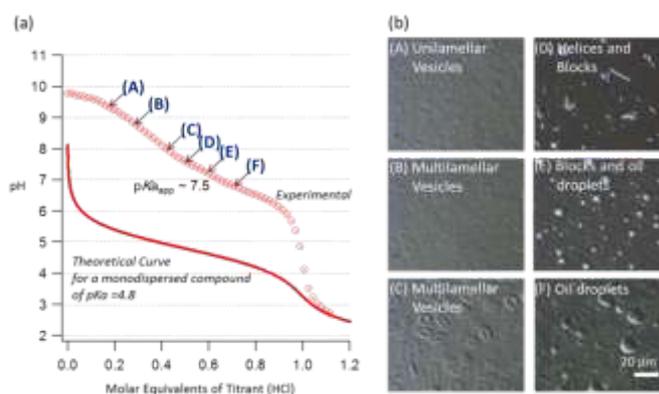


Figure 4. (a) Titration curve of 6.6 mM **ONa** in 0.1 M NaCl(aq), with 0.5 M HCl(aq) as the titrant (circles). The line shows the curve calculated by the Henderson–Hasselbalch equation for the sodium salt of a water-soluble acid ($pK_a = 4.8$), considering the experimental conditions, including ionic strength. (b) Micrographs of assemblies collected at the pH values in (a).

The pH titration curves of oleate assemblies

Potentiometric pH titration is a fundamental method for estimating or characterizing molecular and colloidal aggregation.^{11,14–16,19,35} Cistola *et al.* reported the equilibrium titration curves for potassium oleate at 6 and 40 °C, and discussed the pH-dependent phase behavior of oleates.¹¹ Their titration curves showed different pK_a^{app} values from those reported by Shah, likely because of the use of different conditions.¹⁵ We determined the pH titration curve for 6.6 mM **ONa**, using 0.5 M HCl(aq) as the titrant in 0.1 M NaCl(aq) at 25 °C. The pK_a^{app} value was approximately 7.5 (Figure 4). The slope of the curve in Figure 4 was related to the macroscopic structure of the oleate assemblies. Helical assemblies were found when the ratio of oleate to oleic acid was approximately 1:1, consistent with the value estimated previously (ca. 3:2) by ¹³C-NMR.²⁰

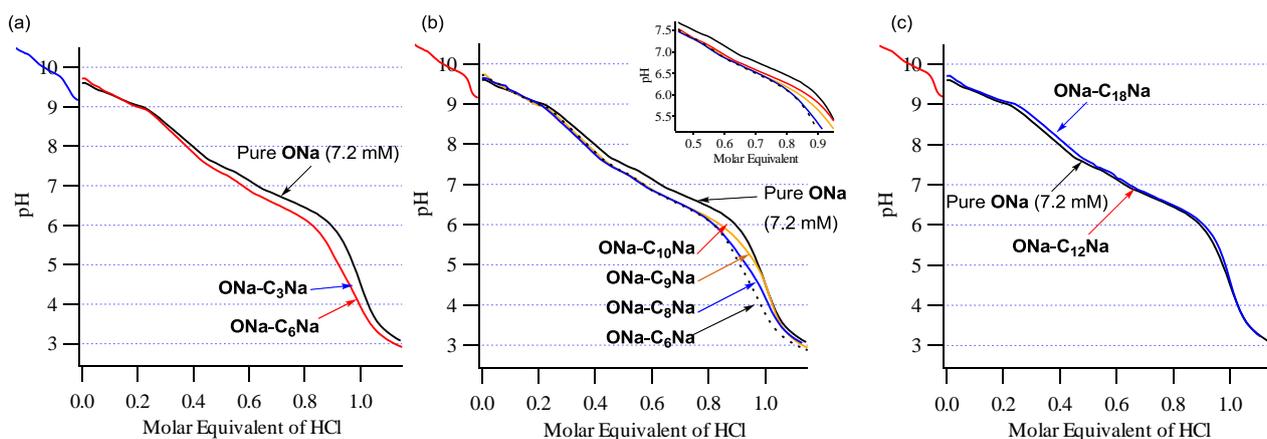


Figure 5. Titration curves of 7.2 mM **ONa** (black line in each graph) and mixtures of 6.6 mM **ONa** and 0.66 mM aliphatic acid sodium salts (a) with short-chain carboxylates: **C₃Na** (blue) and **C₆Na** (red); (b) with medium-chain carboxylates: **C₆Na** (dashed), **C₈Na** (blue), **C₉Na** (orange), and **C₁₀Na** (red); and (c) with long-chain carboxylates: **C₁₂Na** (red) and **C₁₈Na** (blue). The titration curves in (b) are zoomed in the insert.

Titration results for the mixture of **ONa** and 10 mol% aliphatic acid sodium salts (e.g. 3.1% (w/w) **C₃Na** and 9.1% (w/w) **C₁₈Na**) are shown in Figure 5.³⁶ Titration curves of the mixture of **ONa** and 10 mol% **C₁₂Na** or **C₁₈Na** were similar to the curve of **ONa** (Figure 5c). This result indicates that as titrant was added, the protonation of the long-chain carboxylates occurred concurrently with the protonation of oleate. Thus, the thermodynamic properties of carboxylate protonation for oleic acid and long-chain aliphatic acids were unable to be distinguished in the mixed dispersions. On the other hand, short-chain carboxylates were protonated independently of oleate protonation in the mixed dispersion of **ONa** and 10 mol% **C₃Na** or **C₆Na** (Figure 5a). This result indicates that the short-chain aliphatic acids dissolved in water and did not interact with the oleate assemblies.

Titration curves of **ONa** with 10 mol% medium-chain aliphatic acid sodium salts (**C₈Na**, **C₉Na**, and **C₁₀Na**) are shown in Figure 5b. The curves clearly show the existence of an interaction between the medium-chain aliphatic acid and oleate at pH values less than 7.4 (for **C₁₀Na**), 6.8 (for **C₉Na**), and 5.8 (for **C₈Na**), whereas the medium-chain aliphatic acid dissolved in solution and did not interact with the oleate assemblies at higher pH values. These results suggest that **C₉** and **C₁₀** carboxylates were able to disperse dynamically in both bulk solution and oleate assemblies around pH 7, and that the **C₈** carboxylate was able to disperse similarly around pH 6, although the shorter-length carboxylates localized in solution and the longer-length carboxylates localized in the oleate assemblies.

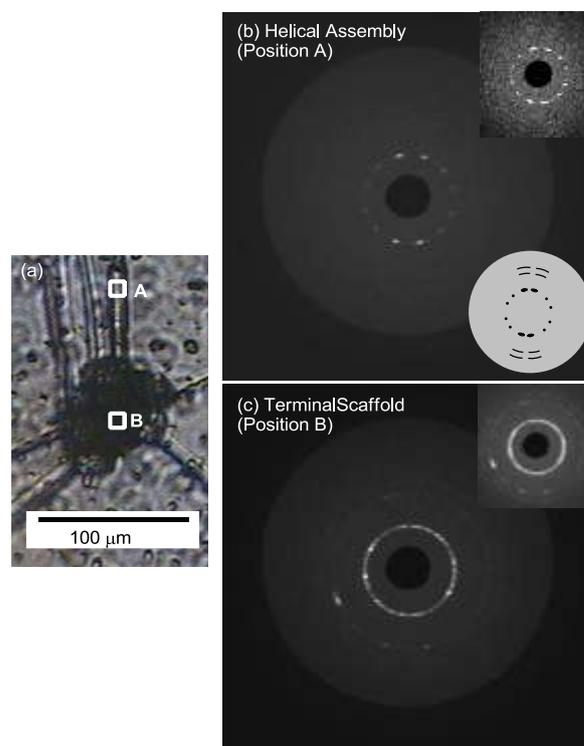


Figure 6. Site-selective SAXS for oleate assembly prepared from **ONa** and **C₉Na** (1% (w/w)), obtained by synchrotron microbeam X-ray diffraction (KEK PF BL-4A). (a) Optical micrograph of oleate assembly, indicating the two positions (A and B) of analysis. (b) 2D image of the μ SAXS pattern collected from the helical assembly at position A in the micrograph. Upper right insert shows the same fringe image with the contrast changed. Lower right insert shows an illustration of the fringe image. (c) SAXS pattern image of the terminal scaffold at location B in the micrograph. The insert shows the same fringe image with the contrast changed.

Structure of oleate assemblies

Using the synchrotron microbeam small-angle X-ray scattering (μ SAXS) system at BL4A at KEK,²⁴ we site-specifically measured the microscopic structures of the helical

assemblies. Figure 6b shows the fringe image of part of the helical assembly (Figure 6a), which was prepared by dispersing the mixture of **ONa** and 1% (w/w) **C₉Na** in PBS (75 mM, pH 7.5). Due to the instability of the assemblies in the presence of the high-brightness X-ray, it was difficult to obtain a highly contrasted fringe image. The diffraction spots were found to lie on three circles (circular arcs) with a Bragg spacing ratio of 1:√3:2 ($hk = 10, 11, 20$), findings that are typical for a hexagonal liquid crystal. The 12 spots on the first ring represented two groups of 6 spots, present every 60 degrees. This finding indicates that there were two hexagonal lattices, both of which belonged to one helical tube (the front and back sides of one helix). The d -spacing (5.47 ± 0.08 nm) was calculated by using silver behenate powder ($d = 5.838$ nm)²⁵ as a reference. On the basis of the μ SAXS data, we assume that the helical assemblies had hierarchical structures constructed by hexagonal bundling of inverted tubular micelles of oleates (Figure 7). These helices are macroscopically similar to myelin figures, but their fringe patterns were different from those of myelin figures. Micrographs and SAXS fringe images of dioleoylphosphatidylcholine (DOPC) myelin figures measured using the same apparatus are shown in Figure S5 in the ESI with a schematic illustration of the structure. The ratio of the radius of the first and second fringe circles is 1:2 ($d = 6.1 \pm 0.1$ nm),³⁷ and the spots are not located in a hexagonal pattern but located in a pattern of rotational symmetry, typical for a multilamellar tubular liquid crystal.

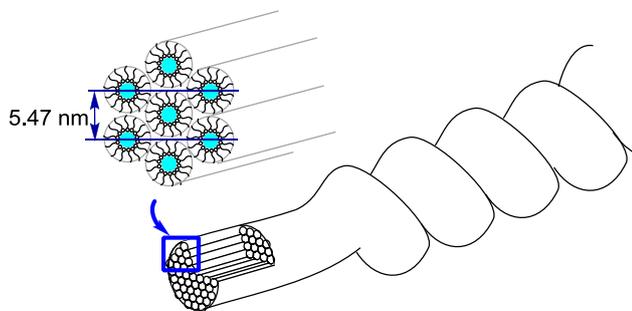


Figure 7. Schematic illustration of the oleate helical assembly based on the μ SAXS data.

We also measured the terminal scaffold of the helical assembly (Figure 6c). The distributed spots on the circles indicate the macroscopic roughness of the terminal scaffold, but the three circles with a Bragg spacing ratio of 1:√3:2 ($d = 5.47 \pm 0.08$ nm) indicate that the terminal scaffold was in the inverted hexagonal phase.

Growth dynamics of helical assembly

We successfully captured a movie of the elongation dynamics of a large-diameter helical assembly in the presence of 0.1% (w/w) **1** at the initial stage of growth (Figure 8 and Movie in the ESI). The helical assembly grew one spire in length with a one-circle winding motion, and this cycle repeated to form a long helical assembly. During elongation of the helical assembly, the size of the terminal scaffold remained

almost unchanged. From this evidence, we speculate that oleate molecules dispersed in the bulk solution were continuously supplied to the terminal scaffold during the growth of the long helical assemblies.

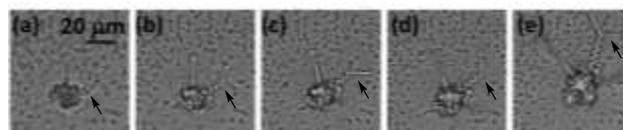


Figure 8. Elongation dynamics of a large-diameter helical assembly of oleate in the presence of **1** (0.1% (w/w)). The movie is available in the ESI.

Discussion

The growth dynamics of molecular assemblies with molecular transport have been of great interest in the fields of material science and nonequilibrium physics for many decades.^{38–45} For myelin figures and related assemblies, not only growth dynamics^{28,30–32,46–48} but also macroscopic coiling dynamics^{29,31,49–53} have been widely studied with experimental and theoretical methods. Although oleate helical assemblies are similar to myelin figures in that they are built from low-molecular-weight surfactant and have helical macroscopic shapes, our experiments revealed that the inner structure and the observed growth and coiling dynamics of oleate helices are different from those of myelin figures.

In the presence of **1**, millimeter-to-centimeter-scale helical assemblies were formed. Menger and Lee also reported extra-long molecular fibers of several centimeters composed of 5-hexadecyloxy-1,3-benzenedicarboxylate.⁵⁴ The detailed structure of the fiber was uncertain, but they assumed that the fiber was constructed by the stacking of disk-like molecular units composed of multiple molecules. On the other hand, we assume that the oleate helical assembly formed in this study had a coiled structure of hexagonally bundled inverted tubular micelles, according to the μ SAXS experimental results. Thus, the growth mechanism of the oleate assembly should be different from that of the 5-hexadecyloxy-1,3-benzenedicarboxylate assembly. As Huang *et al.* mentioned,⁵⁵ one-dimensional surfactant self-assemblies in solution usually have a length within the nanometer-to-micrometer range. Therefore, we believe that it is important to propose a hypothesis for the growth mechanism of long helical assemblies of oleate.

The oleate helical assemblies were grown from terminal scaffolds, both of which were in the inverted hexagonal phase. The growth was assumed to be a continuous reordering of the kinetically formed preorganized aggregates (terminal scaffolds) to thermodynamically stable ordered structures (helical assemblies). The rate of transformation to a helical assembly in the presence of **1** (0.1% (w/w) or 1% (w/w)) was roughly estimated to be between 10^6 and 10^8 molecules per second for each helical assembly, according to real-time observations (Figure S1 and Movie in the ESI). If only transformation proceeds, then the terminal scaffold must become smaller and

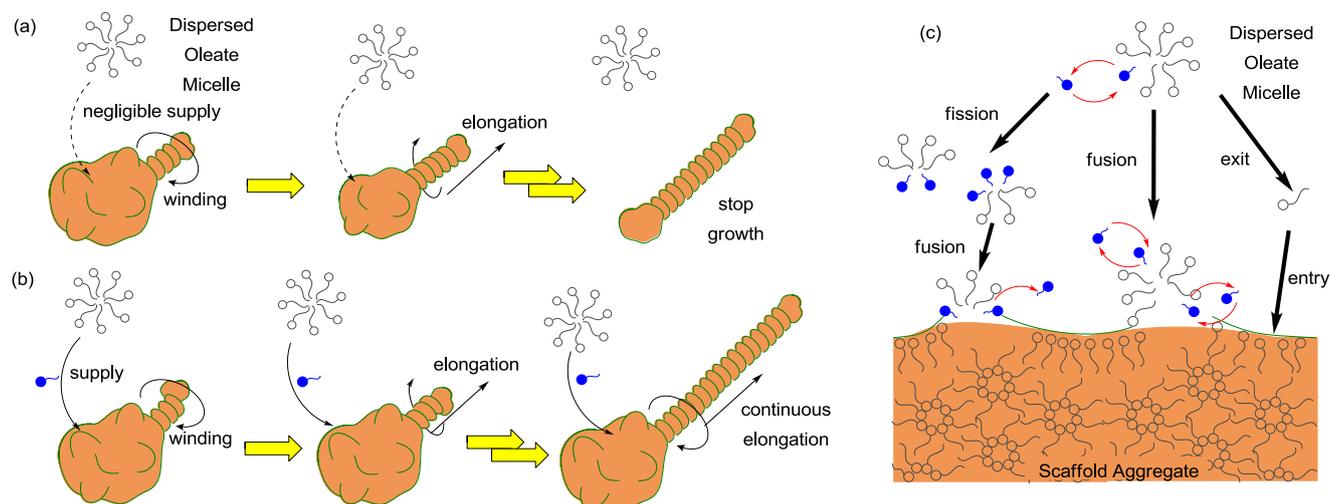


Figure 9. Schematic illustration for the elongation of helical assemblies of oleates (a) without and (b) with medium-chain aliphatic acids (indicated by blue color). (c) Three plausible mechanisms, fission-fusion, fusion, and exit-entry, for mediator-assisted molecular supply to the terminal scaffold.

the helical structure must cease to elongate within a few days (Figure 9a). In fact, helical assemblies prepared from only **ONA** grew several hundred micrometers within one day after dispersion, and they stopped growing due to a shortage of terminal scaffold. Similarly, the formation of oleate helical assemblies in the presence of **C₃Na**, **C₆Na**, or **C₈Na** (localized in bulk water at pH 7) and **C₁₂Na**, **C₁₄Na**, or **C₁₈Na** (localized in oleate assemblies) also failed to proceed after the terminal scaffolds were consumed.

On the other hand, in the presence of **C₉Na** or **C₁₀Na**, which are phase-transferable between the phases of the oleate assembly and bulk water around pH 7 (Figure 5b), the size of the terminal scaffolds remained unchanged. Therefore, the growth of the helical assemblies continued for a long time. Although it is difficult to assume phase-transfer property of **1** from the pH titration experiment because of its lower pK_a value (Figure S6 in the ESI), this characteristic property of **1** can be realized from two facts. First, the longer hydrophobic chain lengths of **1** than **C₁₀** suggest that **1** is favorably adsorbed in the oleate assemblies. Second, the lower pK_a of **1** compared to aliphatic carboxylates suggests that **1** is easy to desorb from oleate assemblies in comparison with **C₉** because it should exist in the hydrophilic anion form not only in bulk water but also in the oleate assembly.⁵⁶

Therefore, we propose the following hypothesis for the growth mechanism of long helical assemblies of oleate. During the transformation process of the terminal scaffold into a helical assembly, externally added medium-length aliphatic acids mediate the continuous supply of oleate molecules from the dispersed micelles to the terminal scaffold (Figure 9b). These aliphatic acids make the oleate micelles unstable, transfer oleic acid to the terminal scaffold, and then leave from the terminal scaffold. This hypothesis is supported by their phase-transfer property, the fact that **1** was not incorporated in the large helical

assemblies, and the fact that the decrease of oleate concentration in the aqueous phase was promoted by **1**.

According to the studies on micellar dynamics, three mechanisms are considerable for the transport of amphiphiles between self-assemblies: exit-entry, fission-fusion, and fusion (Figure 9c).⁴⁰⁻⁴³ If the supply proceeds via the exit-entry mechanism, then the mediator should act as a surface-active reagent to make the micelles unstable, thus enhancing dissociation of oleate from the micelles.⁵⁷ However, we assume that this mechanism does not operate, because the concentration of monodispersed oleic acid was limited by the critical micelle concentration and, therefore, the kinetics of adsorption to the terminal scaffold were limited. If the supply proceeds via the fission-fusion mechanism, then the mediator acts as a surface-active reagent to stabilize the divided aggregate on the fission process, and decreases the barrier for close contact and adhesion of the divided aggregate to the terminal scaffold on the fusion process. If the supply proceeds via the fusion mechanism, then the mediator decreases the barrier for close contact and adhesion of the micelles to the terminal scaffold. We expect that the mediator molecules promote the fission-fusion or fusion mechanism.⁵⁸

Conclusions

Helical assemblies of oleate in water are unique because they are well organized, even though the components are assembled by weak noncovalent interactions. From the perspectives of soft-matter physics and supramolecular machine synthesis, helical assemblies are attractive because of their organized macroscopic dynamics. Their spontaneous winding-rewinding dynamics are probably induced by intrinsic fluctuations of the helical assembly,²⁰ and their rotation-rotation motions are actuated by photoisomerization of an azobenzene derivative loaded as a minor component in the helical assembly.³³

Here, we have described the growth dynamics of a centimeter-length helical assembly from a terminal scaffold in the presence of additional carboxylates. To date, only millimeter- and centimeter-length self-assemblies, such as fibers and microtubes composed of amphiphilic molecules, have been reported.^{54,55,59,60} The long helical assembly described here is unique in terms of its hierarchical helical structure and growth dynamics.

We have proposed a possible mechanism for the growth dynamics, in which the small molecules act as mediators to transport building blocks to the terminal scaffold. Although many studies have focused on the nonequilibrium dynamics of molecular assembly, the full mechanism of helical assembly growth has yet to be elucidated. Even if the mediator-assisted elongation of assemblies is a unique phenomenon in the oleate system, the mechanistic aspects of elongation associated with molecular transport can have potential applications in the fields of crystal growth, molecular architecture, and drug delivery systems.

Acknowledgment

This work was funded by the Sasakawa Scientific Research Grant from the Japan Science Society, JSPS KAKENHI (No. 23750142 and 25620002), and JST PRESTO (Molecular Technology) from MEXT Japan. Microbeam SAXS experiments were performed with approval from the Photon Factory Program Advisory Committee (Proposal No. 2012G747). Y.K. would like to thank Prof. Atsuo Iida (KEK), Dr. Hiroyuki Kitahata (Chiba Univ.), Dr. Mafumi Hishida (Tsukuba Univ.), Dr. Yoshiko Takenaka (AIST), Dr. Yutaka Sumino (Tokyo Univ. of Science), and Dr. Kentaro Suzuki (Kanagawa Univ.) for support on the SAXS measurements, and Dr. Taro Toyota (Univ. Tokyo) for supplying reagents and instruments.

Notes and references

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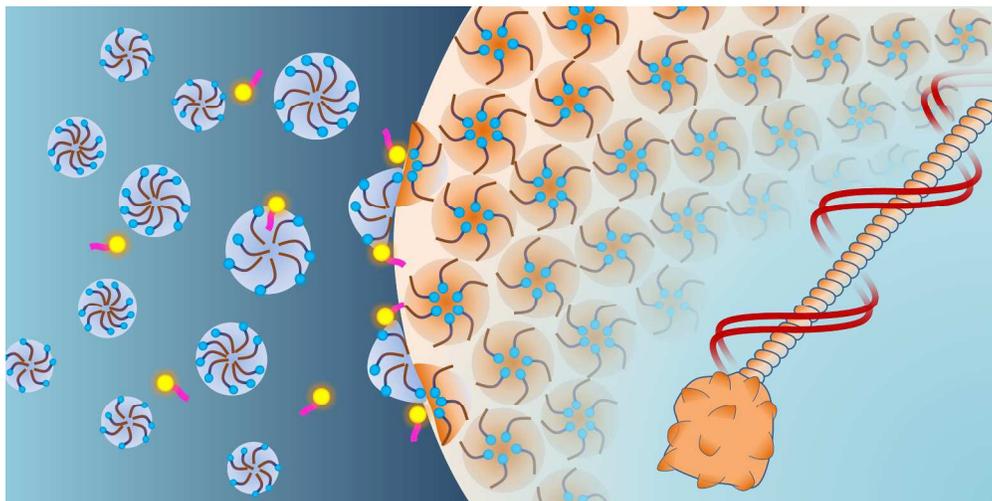
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† Electronic Supplementary Information (ESI) available: The micrographs of centimeter-sized oleate helical assemblies in the presence of a small amount of **1** are shown in Figure S1–S2. Chromatographs for composition analysis are shown in Figure S3. Micrographs of oleate helical assemblies in the presence of several fatty acids are shown in Figure S4. Site-selective SAXS images for DOPC myelin figures and illustration of inner-structure of them are shown in Figure S5. pH Titration curve of mixture of **ONa** and **1** is shown in Figure S6. The growth dynamics of the helical assembly at the initial stage of growth is shown in the Movie. See DOI: 10.1039/b000000x/

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Medium-length aliphatic acids promote the continuous formation of helical self-assembly of oleate
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