Oriented Crystallization of Calcium Carbonate under Self-Organized Monolayers of Amide-Containing Phospholipids


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Introduction

Crystal formation in Nature is often mediated and regulated by highly organized organic surfaces of biopolymers.1 The processes involving crystallization are very well controlled, and the resulting crystals possess shapes and sizes that are distinctly different from those obtained under abiotic conditions.2 The relationship between the templating biomolecular substrate and the inorganic phase lies in the epitaxial matching of lattice spacings of templating biomolecular substrate and the inorganic phases.3 To mimic and to promote the growth of calcium salts in the presence of calcium ions amide-containing phospholipid 1 self-assembles to form well-defined two-dimensional domains at the air–water interface. These domains act as templates for the crystallization of calcium carbonate that efficiently nucleate the growth of [10.0] oriented calcite irrespective of the surface concentration of the lipid. Responsible for this preference for nucleation at the (10.0) face is the formation of an intramolecular hydrogen bond between the phosphate group and the phenoxy moiety which forces the phosphate group to adopt a bidentate orientation toward the aqueous phase. It was shown that when this hydrogen bond was absent, that is, when the phosphate group is monomethylated, lateral pressure was required in order to enforce a similar conformation and accomplish the nucleation of [10.0] oriented calcite.

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on the crystallization processes. Also, the mobility of the molecules in the monolayer turned out to have significant influence, viz. on the homogeneity and nucleation density of the crystallization as well as on the morphology of the overgrowth. Later hydrogen bonding functionalities, such as amide bonds, were introduced in the surfactants which could interlink the amphiphilic molecules into larger arrays, overcoming the necessity to compress the molecules into the desired organization in which they exert their nucleation effect.16

In previous work we reported on the aggregation behavior of amide-containing phospholipid surfactants which form highly organized, chiral aggregates in water and at the air–water interface.17 The expression of chirality on the supramolecular level could be achieved by fine-tuning the interactions between the molecules, for example by pH variation or metal ion complexation. In this work we already demonstrated that the aggregate morphology of the amide-containing phospholipid 1 (Chart 1) can be altered through compensation of headgroup charge. It was expected, therefore, that addition of calcium ions could be used to further structure the highly organized assemblies of phospholipid 1. It was anticipated that such assemblies of these self-organized amphiphilic molecules could serve as well-defined templates directing the crystallization of inorganic compounds, in particular CaCO3.

**Experimental Section**

**Synthesis.** Thin-layer chromatography analyses were performed on Merck precoated silica gel 60 F254 plates (0.25 mm) using the solvent mixtures indicated, and spots were visualized with UV and/or using ammonium molybdate (25 g/L) and ceric sulfate/formic acid spray. Flash column chromatography was performed on Merck kieselgel 60H (0.005 mm) using a pressure of 40 psi. Mass spectrometric analyses were performed on a Varian Saturn 2000 electrospray ionization mass spectrometer. Nuclear magnetic resonance spectra were recorded on a JEOL JNM-LA 500 spectrometer at 500 MHz for 1H and 125 MHz for 13C. 31P NMR (121 MHz) and 27Al NMR (20 MHz) spectra were recorded on a Jeol AL 300 spectrometer. Infrared spectra were recorded on a Perkin-Elmer 1760 spectrometer. IR spectra are given in Table 1. Melting points were measured on a Reichert thermoman microscope.

**Disodium (−)-(2S)-3-Phenoxy-2-octadecanoylamino-1-yl Phosphate (1).** This compound was synthesized according to the procedure of Sommerdijk et al.15 MP 145–147 °C. Rf = 0.30 (MeOH/H2O/OCH3Cl, 39/10/67, v/v/v). tR = 14.20 min (capillary electrophoresis). 1H NMR (CDCl3, 500 MHz): δ = 7.36–6.88 (m, 10H, CH2OMe), 6.34 (m, 1H, NH), 5.07–5.03 (m, 2H, OCH2CH3), 4.50–4.48 (m, 3H, OCH2(O)N(CH3)2), 3.93–3.95 (m, 4H, OCH2(O)N(CH3)2), 2.98–2.93 (m, 1H, OCH2(O)N(CH3)2), 2.42 (m, 3H, OCH2(O)N(CH3)2), 1.39–1.20 (m, 28H, CH2(O)N(CH3)2). 13C NMR (CDCl3, 125 MHz): δ = 173.90 (O(NH)), 158.81 (quart CH2(O)N(CH3)2), 136.22, 136.14 (quart P(O)(OCH3)(OCH2)CH3), 120.30 (P(O)(CH2)(O)(OCH2)CH3), 129.40 (P(O)(CH2)(O)(OCH2)CH3), 129.31 (P(O)(CH2)(O)(OCH2)CH3), 128.65 (P(O)(CH2)(O)(OCH2)CH3), 121.95 (P(O)(CH2)(O)(OCH2)CH3), 115.17 (P(O)(CH2)(O)(OCH2)CH3), 70.35, 70.27 (P(O)(CH2)(O)(OCH2)CH3), 66.02, 65.78 (P(O)(CH2)(O)(OCH2)CH3), 55.18, 55.10 (P(O)(CH2)(O)(OCH2)CH3), 32.57–32.33 (CH2(CH2)2CH2CH2(O)N(CH3)2), 14.76 (CH3(CH2)2CH2CH2(O)N(CH3)2). 31P NMR (CDCl3, 121 MHz): δ = −2.14, −2.20 ppm. MS (FAB−/m/z): [M−H]+ = 640 [M + Na]+, 618 [M + 1]+. 

**Sodium (−)-(2S)-3-Phenoxy-2-octadecanoylamino-1-yl Methyl Phosphate (2).** Benzylic (−)-(2S)-3-Phenoxy-2-octadecanoylamino-1-yl methyl phosphate (142 mg, 0.230 mmol), dissolved in methanol (50 mL), was subjected to hydrogenolysis for 1 h with Pd/C as the catalyst. The catalyst was removed under vacuum, the filtrate was concentrated in vacuo. Dichloromethane (25 mL) was added to the residue, and the filtrate was concentrated in vacuo to a volume of approximately 25 mL before 10 mL of water containing NaOH (4.5 g, 0.113 mmol) was added. This solution was treated with Dowex 50WX20 (Na+ form) and lyophilized to afford 126 mg (100% of 2) as a white hygroscopic, fluffy powder. Rf = 0.50 (CHCl3/MeOH/H2O, 67/39/10). tR = 12.91 min (capillary electrophoresis). [α]d20 = +3.83 (c = 1.6, CHCl3). 1H NMR (CDCl3, 500 MHz): δ = 7.62 (H, aryl), 7.40 (H, aryl), 7.35 (H, aryl), 7.20 (H, aryl), 7.12 (H, aryl), 7.05 (H, aryl), 6.90 (H, aryl), 6.76 (H, aryl), 6.53 (H, aryl), 5.41 (H, aryl), 4.34 (H, aryl), 2.01 (H, CH2(O)N(CH3)2), 1.70 (H, CH2(O)N(CH3)2), 1.34, 1.30 (H, CH2(O)N(CH3)2). 31P NMR (CDCl3, 200 MHz): δ = −1.88. IR (KBr, cm−1): ν3000–3200 (H2O), 3030 (C–H aromatic), 2918, 2850 (C–H alkyl), 1643 (Am1), 1543 (Am1), 1467 (C–H deformation, alkyl), 1246 (P=O) (MS (FAB−/m/z): 1121 [M2 + Na]+, 572 [M + Na]+, 550 [M + 1]+. Anal. Calcd for C49H88NO2PNa4•H2O: C, 52.70; H, 8.30; N, 2.19. Found: C, 52.40; H, 8.10; N, 2.14.

**−(2R)-3-Phenoxy-2-octadecanoylamino-1-ol (3).** Sodium iodide (10 mg, 0.067 mmol) was added to a stirred solution of (−)-(2S)-1-octadecanoyloxy-2-phenoxymethylaziridine18 (172.8 mg, 0.417 mmol) in dry acetonitrile (25 mL). The reaction mixture was heated under reflux for 2 h, and the resulting mixture was concentrated in vacuo. Dichloromethane (25 mL) was added to the residue, and the solution was washed with water (3 × 10
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M. L. The separated organic layer was dried (NaSO4), and the solvent was removed in vacuo. The residue (169.1 mg) was dissolved in ethanol (15 mL), and thus no solution was added of oxalic acid (60 mg, 0.67 mmol). The reaction mixture was heated under reflux for 3 h and then concentrated in vacuo. The residue was purified by flash chromatography (Si2O, hexane/ethyl acetate, 1:1). Mp 87.2 °C. [22] Kitano, Y. Bull. Chem. Soc. Jpn. 1962, 32, 1980. For further experimental details, see: (b) Rajam, S.; Heywood, B. R.; Walker, J. B. A.; Mann, S.; Davey, R. J.; Birdall, J. D. J. Chem. Soc. Faraday Trans. 1987, 87, 727. (c) Heywood, B. R.; Rajam, S.; Mann, S. J. Chem. Soc., Faraday Trans. 1987, 87, 735.

Figure 1. Electron micrographs taken from 0.1% (w/w) dispersions of (a) (Pt shadow technique, bar 250 nm), (b) after addition of 10 mM CaCl2 (negative staining, bar 500 nm), and (c) after addition of 10 mM CaCl2 (negative staining, bar 500 nm).

Carbon dioxide gas was bubbled through a stirred aqueous solution containing 25 mL of a 1% (w/w) solution of these compounds in water followed by sonication at 60 °C for 15 min and subsequent aging overnight. Inspection of the samples with transmission electron microscopy revealed the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm. The finding that addition of calcium ions caused the formation of tubular structures (Figure 1b) with diameters ranging from 0.2 to 40 nm.
enhances the organization of these phospholipid molecules in the aggregates suggested that Langmuir films of these molecules could indeed be interesting templates for the crystallization of CaCO₃.

For a Langmuir monolayer of compound 1, surface pressure–surface area (π–A) isotherms were recorded from which a molecular area of 50 Å² was estimated by extrapolation of the curve to zero pressure. When spread on a subphase containing 9 mM CaCl₂, compound 1 exhibited a significant interaction with the calcium ions present, as was deduced from a faster build-up of the surface pressure upon compression (Figure 2a). However, calcium complexation did not induce changes in the extrapolated molecular area. The observed higher lift-off area in the presence of Ca²⁺ suggests an increase in steric interactions between the molecules upon compression of the monolayer, which is attributed to interlinking of neighboring “amide polymer chains” through complexation of calcium ions. The film collapses at a limiting molecular area of 36 Å² when calcium ions are present and at 30 Å² when Ca²⁺ is absent, indicating that Ca²⁺ ions position themselves between the lipid headgroups.

**Crystallization Experiments.** Crystallization of calcium carbonate beneath a monolayer of 1 in its liquid state (A = 60 Å², π = 3 mN/m) resulted in the formation of oriented and discrete calcite crystals. Viewed from above the monolayer surface, the crystals had prismatic shapes with two (10.4) faces being expressed with opposite to these faces a roughened side, as was observed with scanning electron microscopy (Figure 3a). In most cases a flat apex was observed indicative of the location where the monolayer acted as a nucleation site. When a monolayer of 1 in a more solidlike state was used (A = 40 Å²; π = 25 mN/m), the nucleation density was increased viz. from 330 to 490 mm⁻². In both cases these values are high compared to values (>10⁶ mm⁻²) reported for the nucleation of CaCO₃ under monolayers at the air–water interface; much higher values were obtained for self-

![Figure 2. π–A isotherms of monolayers of (a) 1, (b) 2, and (c) 3 at 20 °C on (−) H₂O and (---) aqueous 10 mM CaCl₂. Inset to part c: Brewster angle micrograph of a surface monolayer of 3 on water at 20 °C and π = 0 mN/m.](image1)

![Figure 3. Scanning electron micrographs of calcite crystals grown (a) under liquidlike (60 Å²/molecule, π ~ 3 mN/m) and (b–d) in solidlike (40 Å²/molecule, π ~ 25 mN/m) monolayers of 1 and (e and f) under a solidlike (40 Å²/molecule, π ~ 25 mN/m) monolayer of 2. Bars represent 10 μm.](image2)

(23) In studies on templating monolayers, the formation of two types of calcite is observed; see ref 22b and: Mann, S.; Heywood, B. R.; Rajam, S.; Walker, J. B. A. ACS Symp. Ser. 1991, 444, 28. Type I exhibits pseudo-C₂ᵥ symmetry with all four basal (10.4) faces expressed. Type II has pseudo-C₂ᵥ symmetry and is triangular in projection with only two of the four basal edges being expressed. Type I calcite was formed through nucleation from different faces, that is, [0.01] (n-eicosyl sulphate) and [1–10] (stearic acid). The calcite formed in the present case is of type I and has nucleated from the (10.0) face. Type I calcite is thought to arise from a realignment and subsequent secondary growth of type II calcite at the monolayer surface.

(24) Under liquid expanded monolayers also a small amount of type I vaterite was formed (approximately 15% of the crystals). When the experiments were performed under compressed monolayers, this number was reduced to approximately 8%.
assembled monolayers on gold. The morphological form of these crystals still was prismatic; however, in this case stepped surfaces were observed (Figure 3b). These stepped faces suggest a significant interaction of the growing crystal with the lipid monolayer. In contrast, when viewed from below the monolayer, smooth rhombohedral faces were observed, indicating that with time the crystals grow free of the constriction of the monolayer and down into the calcium carbonate solution (Figure 3d). Electron diffraction studies were performed on crystals removed from the two crystallization assays after 10-30 min (Figure 4a). The observed patterns confirmed the formation of the calcite nature of the crystals and showed that the (10.0) face had been nucleated by the monolayer in both cases. This is remarkable, since monolayers both of phosphates and of phosphonates have been shown to nucleate the (00.1) face of calcite. In these cases the orientation of the carbonate ions was found to match the lattice of the template in which the phosphate and phosphonate headgroups possess a “tridentate” orientation, that is, an orientation in which three of the phosphate oxygen atoms are in the plane of the nucleated crystal face.

It was demonstrated in previous work that the amide hydrogen bonds fix the molecules of 1 in a linear array with an intermolecular distance of approximately 5 Å. Furthermore, it was indicated by FT-IR studies in conjunction with molecular modeling that an intramolecular hydrogen bond between one of the P–O–H groups and its ether oxygen was formed when the charges on the phosphate headgroups were compensated by protonation. In this situation the molecules of 1 adopt an arrangement in which the phosphate groups bend back, leaving only two of the phosphate oxygen atoms in contact with the aqueous phase, parallel to the “amide polymers” (Figure 4b). We propose that the charge compensation arising from calcium ion binding leads to a similar bidentate headgroup structure with a 5 Å repeat distance (Figure 4c). This motif indeed matches the orientation and spacing (4.99 Å) of the carbonate ions along the b-axis in the (10.0) crystal face of calcite. In contrast, the molecular area of 50 Å² suggests that the interarray distance is 10 Å, which does not correspond very well to the carbonate–carbonate repeat distance of 8.53 Å in this plane. However, the π–A isotherm shows that the molecules can be compressed to an area of 36 Å²/molecule before the film ruptures, implying that a more dense packing which better matches the lattice spacings is well possible. Moreover, it has been demonstrated that the stereochemical and electrostatic matching can override quite well the necessity of exact epitaxial matching of the lattice dimensions.

**Effect of Headgroup Orientation on Epitaxial Matching.** To verify the proposed templating mechanism, that is, the necessity of hydrogen bond formation and bidental orientation of the headgroup for the epitaxial matching of the (10.0) crystal plane, compound 2 was prepared which carried one methyl substituent on its phosphate group. Under the conditions applied, the methylated phosphate moiety of 2 cannot form a hydrogen bond with the phenoxy group, and therefore, its headgroup will be conformationally less restricted than the phosphate group of 1. The interaction of 2 with calcium ions was again investigated first in aqueous dispersion, leading to the formation of left-handed helically wound multilayered multilayered...

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**Figure 4.** (a) Transmission electron micrograph and selected area electron diffraction pattern of an early [10.0] oriented calcite crystal grown under a monolayer of 1. (b–c) Computer generated models (b) of an assembly of molecules of 1 (viewed along the y-axis) showing the hydrogen bond between the phosphate group and the ether oxygen (the number of methylene groups in the alkyl chains is reduced for reasons of clarity) and (c) of the epitaxial matching of the (10.0) face of calcite (generated with Cerius, "+" signs represent Ca²⁺ ions) with the phosphate oxygens in an assembly of molecules of 1. The Cartesian axes (x, y, z) match the crystallographic axes (a, b, c).

(25) Lowering the pH also resulted in a higher degree of headgroup organization and in the formation of helical ribbons.
ribbons (Figure 1c) with widths of 300–400 nm and a pitch of 1.0 µm.

The π–A isotherms obtained from this compound (Figure 2b) showed that the higher conformational freedom and the larger steric repulsion of the methylated phosphate groups lead to the formation of a less preorganized monolayer. The complexation of calcium ions led to an increase in the organization of 2, but the observed lift-off area and compressibility indicate that the molecules still have a lower tendency to pack in a compressed monolayer than those of 1. The compression isotherm revealed a molecular area of 48 Å²/molecule (deduced by extrapolation of the high-pressure part of the curve), which is close to the value obtained for compound 1. Molecular models again suggested an intermolecular distance of 5 Å and showed that upon application of lateral pressure a headgroup structure similar to that of 1, that is, a bidentate motif of the phosphate groups, is possible (Figure 4b). From this it was expected that only compressed monolayers of 2 could match the (10.0) face of calcite.

Indeed, CaCO₃ grown under monolayers of 2 in the liquid expanded state gave almost no oriented crystals but randomly intergrown rhombohedral calcite (not shown). However, when monolayers in the compressed state were used as templates (A = 40 Å², π = 23 mN/m), oriented calcite crystals were observed (Figure 3e and f). These crystals had distorted trigonal bipyramidal shapes with a small apex on the top. The presumption that in a compressed monolayer the arrangement of the phosphate headgroups of 2 matches the (10.0) face of calcite was confirmed by electron diffraction performed on crystals recovered from the assay after 10–30 min. The nucleation density of oriented crystal growth using films consisting of molecules of 2 was found to be significantly lower than that of 1 (approximately 50 mm⁻²), reflecting the lower degree of molecular organization in the template.²⁶

To unequivocally establish the specificity of the templating effect, that is, to prove that the action of the phosphate group is essential and that the selective nucleation of the (10.0) face is not due to the presence of the other parts of the molecules, compound 3 was used as a control. Surface pressure–surface area (π–A) isotherms were recorded from which it was calculated that on a water subphase compound 3 had a molecular area of 38 Å²/molecule.²⁷ This compound was found to generate a condensed film upon compression (Figure 2c). Brewster angle microscopy (BAM) revealed that already at zero pressure very large 2D crystalline domains with dimensions on the order of millimeters were present. (Figure 2c, inset).²⁹ When 3 was spread on an aqueous 9 mM CaCl₂ subphase, both the isotherm and BAM images were identical to those obtained on pure water, suggesting that the calcium ions did not interact with the monolayer. Crystallization experiments under monolayers of 3 did not reveal any interactions between the organic and the inorganic phases. After 20 h the predominant polymorph was calcite in the form of randomly intergrown rhombohedral crystals (not shown) which displayed no evidence of any preferred crystallographic orientation.

Conclusion

We have demonstrated that, in the presence of calcium ions, amide-containing phospholipid 1 self-assembles to form well-defined two-dimensional domains that subsequently serve as templates for the crystallization of calcium carbonate. This leads to the efficient nucleation and growth of [10.0] oriented calcite irrespective of the surface concentration of the lipid. Responsible for this unexpected preference for nucleation at the (10.0) face is the high degree of organization in the self-assembled monolayers, in conjunction with the restricted conformational freedom of the headgroup of the molecule. This limited mobility is due to the formation of an intramolecular hydrogen bond between the phosphate group and the phenoxy moiety which forces the phosphate group to adopt a bidentate orientation toward the aqueous phase. It was shown that when this hydrogen bond was absent, lateral pressure was required in order to enforce a similar conformation and accomplish the nucleation of [10.0] oriented calcite.

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(26) In addition, a significant amount of vaterite crystals was observed.

(27) Surfactant 3 was insoluble in water, and no distinct aggregate morphology could therefore be detected by transmission electron microscopy.


(29) The high degree of organization of the molecules of 3, as apparent from the Brewster angle micrographs, suggests the presence of a strong hydrogen bonding network. CPK models indeed indicate that, in addition to the expected formation of linear arrays of amide groups, hydrogen bonds could be formed between the hydroxyl functions and the oxygen atoms of the phenoxy groups in neighboring molecules. The molecular area of 40 Å² deduced from these models is in good agreement with the value obtained from the π–A isotherm.