

Giant Vesicles Based on Self-Assembly of a Polymeric Complex Containing a Rodlike Oligomer

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In this Letter we report a neat method for preparing polymeric giant vesicles. Self-assembly of a rigid oligomer, polyether imide (PEI) with amino groups at its two ends and stearic acid (SA) in chloroform/cyclohexane, which was a selective solvent for SA, led to the giant vesicles. However, PEI and low-molecular-weight polystyrene with a carboxyl end (CPS) formed micelles instead of vesicles in the solvent mixture. Furthermore, morphology transition from micelle to vesicle was observed when SA was added to the micellar solution of PEI/CPS.

Introduction

In recent years, self-assembled vesicles have received special attention due to their potential applications and academic interest in many interdisciplinary fields.¹ Among various kinds of vesicles, those made of lipids have been extensively studied. However, their insufficient stability may have prevented them from wider applications. Therefore, great efforts have been made to construct vesicles using different building blocks, mainly block copolymers.^{2,3} In addition, it was reported that vesicles could be obtained from a random copolymer pair with hydrogen-bonding interacting sites⁴ as well as from a series of small molecular bipolar ion-paired amphiphilics.⁵

In our research group, advances have recently been achieved in constructing polymer micelles or hollow spheres via complexation between polymers with interacting sites.⁶ Here we report that ordered supramolecular structures, i.e., giant vesicles, can be made by self-assembly using polymeric complexes as building blocks composed of subunits of rigid oligomers and short hydrocarbon chains. This assembly is driven by the specific interactions between the amino and carboxyl end groups in the subunits as well as by the propensity to parallel packing of the rigid chains.⁷ This building block differs

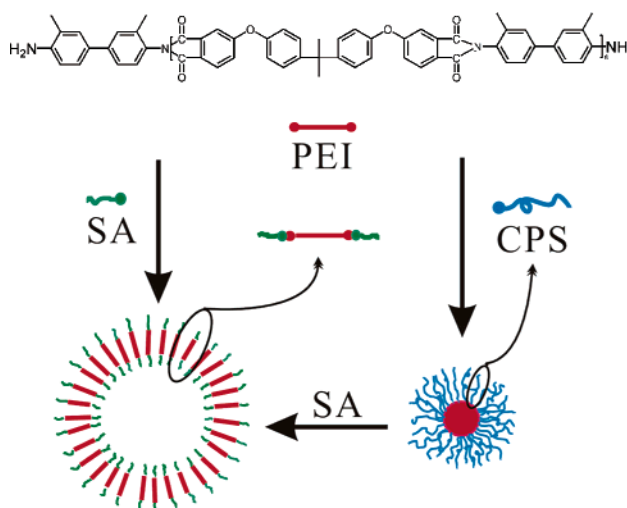


Figure 1. The chemical structure of PEI and a schematic representation of the spherical micelles and giant vesicles.

from the block copolymer used in most studies on macromolecular self-assembly where the subunits were connected by covalent bonds.

Results and Discussion

The materials used in this work include polyether imide (PEI), stearic acid (SA) and carboxyl-terminated polystyrene (CPS) (Figure 1). The PEI used here is a rigid oligomer with amino groups at its two ends and a number-average molecular weight of 4600. We worked on three combinations, SA/PEI, CPS/PEI, and SA/CPS/PEI. A solvent mixture of chloroform/cyclohexane (1/1 or 1/2, v/v) was used as a selective solvent for both SA and CPS, because chloroform is a common solvent for all the three components while cyclohexane is a strong precipitant for PEI only.

The solution of self-assembled SA/PEI (group molar ratio of carboxyl to amino 1:1) was obtained by mixing proper volumes of SA and PEI solutions in chloroform. Then a suitable volume of cyclohexane was added to get the aggregate solution (Supporting Information). A preliminary insight into the morphology of the aggregates in chloroform/cyclohexane (v/v, 1:1) was gained from phase contrast optical microscopy (PCM) as the aggregates were very large. The obtained micrographs of the solutions

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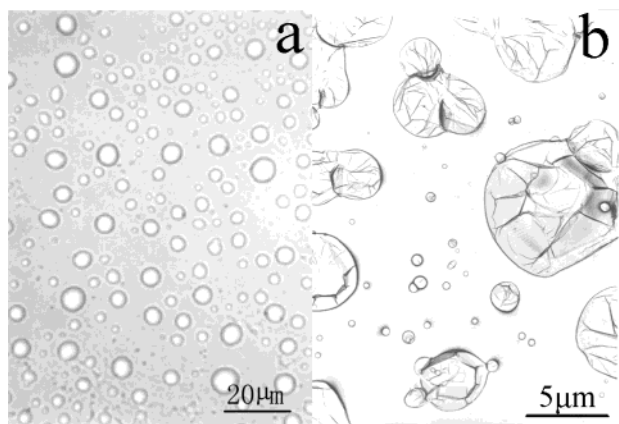


Figure 2. Micrographs of SA/PEI aggregates with molar ratio of amino to carboxyl of 1:1 in chloroform/cyclohexane (v/v, 1:1): (a) PCM; (b) TEM.

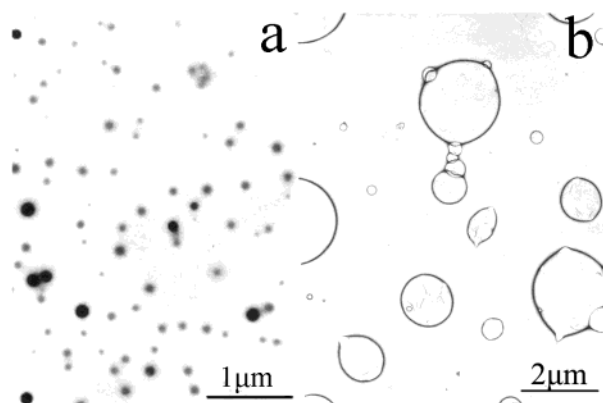


Figure 3. TEM micrographs of aggregates of (a) CPS/PEI (carboxyl/amino 1:1) in chloroform/cyclohexane (v/v 1:1) and (b) SA/CPS/PEI (carboxyl/carboxyl/amino 5:1:1) in chloroform/cyclohexane (v/v 1:1).

clearly display spherical aggregates with a broad size distribution, but most of the spheres are in the range of 1–10 μm (Figure 2a).

The detail of the giant vesicular structures can be identified with transmission electron microscopy (TEM) because of the obvious contrast between the contour and the center of the aggregates (Figure 2b). The aggregate sizes revealed by TEM coincide with those by PCM. The morphology of the larger vesicles under TEM observations resembles broken air balloons made of tough rubber film. A similar conclusion follows from scanning electron microscopy (SEM) observations (Supporting Information). A close examination of the contour curves gives a thickness of the vesicle shell of 20–30 nm, which is thicker than that of the natural liposomes (3–4 nm) by a factor of about 7. However, the shell seemed still too thin to sustain the pressure induced by vacuum during the sample preparation. As recently reported by Discher et al., the vesicles of diblock polymers with a thickness of ca. 8 nm proved to be 5–50 times as tough as the vesicles made of phospholipids and cholesterol.⁸ Therefore, we expect that our spherical membranes have good mechanical property.

Both CPS and SA have carboxyl end groups which can interact with amino groups of PEI; however, as shown in Figure 3a, rather than forming vesicles, the CPS/PEI formed spherical particles with sizes over tens of nanom-

eters. The observed micelles of CPS/PEI probably contain cores of irregularly packed PEI stabilized by the solvated CPS shell. Although these micelles were formed in the selective solvent, no clear core-shell structure was found. One possible reason is that the chain density in the shell composed of the solvated CPS is too low to be observed.

Although CPS/PEI failed to form vesicles, it was found that morphology transition from micelles to vesicles took place when a certain amount of SA was added to CPS/PEI solution. Figure 3b shows the morphology of the aggregates in the three-component solution. The desired solution with a composition of SA/CPS/PEI (molar ratio of functional groups 5/1/1) in chloroform/cyclohexane (v/v 1/1) was prepared by adding an excess amount of SA solution into the CPS/PEI micellar solution. Although the size of the vesicles (0.5–2 μm) composed of the three components is smaller than that in the case of SA/PEI, they showed a similar shell thickness. It is interesting to see that when the solvent mixture of chloroform/cyclohexane for SA/CPS/PEI was changed from 1:1 to 1:2, much smaller vesicles around 50–100 nm, similar to most of the polymeric vesicles reported in the literatures, were produced (Supporting Information).

Although the detailed mechanism for the formation of the giant vesicles is not yet clear, it is reasonable to think that in the common solvent for both PEI and SA, the polymeric complex composed of a central block of PEI and side short blocks of SA chains formed due to the specific interaction between the amino and carboxyl end groups. When the selective precipitant cyclohexane for the PEI was added, no macroscopic precipitation occurred as the PEI aggregates were stabilized by the solvated SA chains. Furthermore, the effective packing of the rigid block facilitates the formation of the aggregates with a central cavity just as has been reported for the formation of hollow spheres for the rod-coil block copolymers by Jenekhe et al.⁹ and for the rod-coil hydrogen-bonding "graft copolymers" by our group.⁷ In addition, the present complex is extremely asymmetric in composition similar to the copolymers which Eisenberg et al.¹⁰ reported to form readily the so-called "crew-cut" aggregates and particularly vesicles. In fact, the measured thickness of 20–30 nm of the vesicles is in accordance with the extended length of PEI, which indicates that the rigid PEI chains are parallel and radially arranged to form the vesicle shell as shown schematically in Figure 1. It is clear that, in the case of CPS/PEI, the long flexible CPS chains cannot form regular and asymmetric interpolymer complexes with PEI. Therefore, the parallel packing of PEI leading to vesicles is not possible.

It is worth noting that the micelle-vesicle morphology transition could not be observed if the TEM samples were prepared soon after adding the SA into the CPS/PEI solutions. A rather long standing time of the solutions was found necessary before such changes were observed. Dynamic light scattering was used to trace this process (Figure 4). After adding SA into the CPS/PEI solutions, the hydrodynamic radius of the aggregates increased relatively quickly at first and then much more slowly. It took about 100 h to see the aggregate size to approach its equilibrium value. This is understandable as the morphology transition is actually caused by the SA chains replacing the CPS chains surrounding the PEI, which should be a rather slow process due to the poor mobility of the polymer chains. In addition, replacing CPS by the

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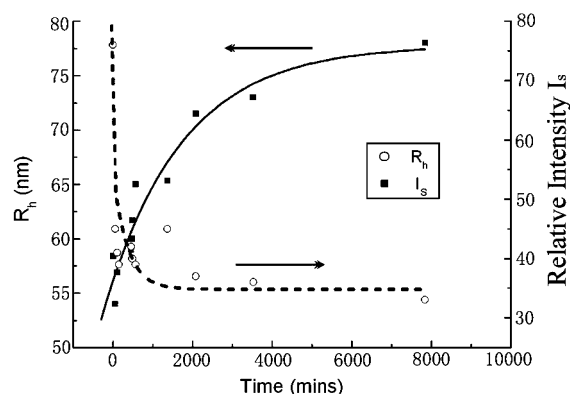


Figure 4. Time dependence of hydrodynamic radius (R_h) and scattering light intensity (I_s) after adding SA into CPS/PEI solutions.

short SA chains caused an apparent decrease of the mass of the aggregates, which was reflected in the decrease of the relative light intensity in Figure 4.

Conclusion

In summary, a new approach to polymeric vesicles is suggested. Rigid polyether imide is connected at both ends

to short hydrocarbon chains of stearic acid to form polymeric complex due to specific interaction, similar to the triblock copolymer in terms of chain architecture. The complex is found to be able to self-assemble further into giant vesicles in selective solvent. The vesicles are much thicker and expected to be tougher than the natural ones. This approach to preparing vesicles has simplicity and avoids costly and time-consuming synthesis of block copolymers. In addition, the vesicle composition is adjustable, as there are no chemical bonds connecting the layers in the vesicle shell.

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Supporting Information Available: Experimental details for the materials and the preparations of the samples, and the SEM and TEM images of the vesicles in the solvent mixture with different compositions. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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