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題目(和文)	液-液相分離液滴界面を利用した機能性DNAオリガミマイクロカプセルの構築
Title(English)	Construction of functional DNA origami microcapsules using a liquid-liquid phase-separated droplet interface
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論 文 要 約

THESIS OUTLINE

The development of functional microcapsules has significant potential in fields such as drug delivery, synthetic biology, and material science. Among various approaches, DNA nanostructures have emerged as promising candidates for creating advanced functional microcapsules due to their programmability and precise structural control. In particular, DNA origami offers a versatile method for fabricating nanoscale structures by folding long single-stranded DNA molecules into arbitrary shapes. These DNA origami nanoparticles can provide tailored functionality and stability to microcapsules. Previous research has demonstrated that microcapsules constructed using programmable DNA origami nanoparticles can accumulate at the interface of water-in-oil microdroplets. However, despite their potential, the requirement to remove the oil phase limits the use of this technique with delicate molecules such as biomolecules. To address this limitation, I developed a method for constructing DNA origami microcapsules utilizing the interface of water-in-water microdroplets, offering a more biocompatible alternative.

In this doctoral dissertation, two types of liquid-liquid phase separated (LLPS) droplet interfaces were utilized to construct functional DNA origami microcapsules. LLPS droplets were classified into two types: segregative LLPS droplets and associative LLPS droplets. The dextran-rich droplets were used as segregative LLPS droplets (Chapter 2), and the DNA condensates were used as associative LLPS droplets (Chapter 3). In Chapter 4, a summary of functional DNA origami microcapsules and the prospects of functional DNA origami microcapsules as an artificial cell were discussed.

In Chapter 2, an aqueous two-phase system (ATPS) emulsion composed of dextran-rich droplets immersed in a polyethylene glycol (PEG)-rich phase was utilized for microcapsule formation. DNA origami nanostructures accumulated at the interface of dextran-rich droplets and formed a capsular structure. The capsular structures consisted of only DNA origami nanoparticles. The triangle origami with about 100 nm was localized at the interface of the dextran-rich droplet. In comparison, the mini-triangle origami with sides of about 20 nm was distributed both in the PEG phase and inside the dextran-rich droplets. Thus, the construction of DNA origami microcapsules using the interface of dextran-rich droplets was affected by the size of DNA origami nanoparticles. The structural stability of DNA origami microcapsules was successfully improved by connecting DNA origami nanoparticles. Strand displacement reactions disconnected the connected state of the DNA origami nanoparticles reversibly. Stimuli-responsive properties were introduced into our DNA origami microcapsules. The functional DNA origami microcapsules could be collapsed by changing the external environment through UV irradiation. These functional DNA origami microcapsules were capable of recognizing sequence information. Furthermore, these stimulus-responsive DNA origami microcapsules could communicate with different types of artificial cells, such as photo-responsive DNA hydrogels.

In Chapter 3, the DNA condensates were composed of DNA nanostructures called DNA motifs. These DNA motifs and 3D DNA origami nanoparticles were connected via hybridization to accumulate 3D DNA origami nanoparticles at the interface of the DNA condensates. When one side of the 3D DNA origami nanoparticles was bound to the DNA motif, the 3D DNA origami nanoparticles localized to the interface of the DNA condensates. When both sides of 3D DNA origami nanoparticles were bound to the DNA motif, the distribution of DNA origami extended from the interface to the interior of the DNA condensates. Thus, the construction of DNA origami microcapsules using the interface of DNA condensates was affected by the binding method between 3D DNA origami nanoparticles and DNA motifs. When DNA origami localized at the interface were connected by adding single stranded DNAs called connector sequences, unintended fusion between connected DNA origami microcapsules was prevented. This connected DNA origami membrane can be applied to construct artificial multicellular populations. Furthermore, the connected DNA origami microcapsules had membrane semipermeability. Our microcapsule construction approach is highly controllable because fusion and permeability can be changed before and after the addition of the connector.

Based on the results presented in Chapters 2 and 3, Chapter 4 provides a comprehensive discussion on the construction and functionalization of the functional DNA origami microcapsules described in this thesis, along with the remaining challenges and prospects. Furthermore, the limitations of the applicability of the method and directions for future research are discussed.

To summarize this doctoral dissertation, the construction of functional DNA origami microcapsules utilizing an aqueous two-phase droplet interface was demonstrated. The functional DNA origami microcapsules were shown to possess stimuli responsiveness. Furthermore, they were revealed to enable intercellular communication between different types of artificial cells. This work is believed to contribute to the development of intelligent artificial cells and artificial multicellular populations in the future.