http://dx.doi.org/10.5012/bkcs.2014.35.1.21

Communications

Formation of DNA-Silica Complexes with Deoxyguanosine Oligonucleotides

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Received September 9, 2013, Accepted October 29, 2013

Key Words : DNA, Deoxyguanosine oligonucleotide, Silica, Silicification, Quaternary ammonium cation

The mechanistic studies on biogenic silica formation occuring in nature (biosilicification) have suggested the use of bioinspired templates, such as polypeptides[1] and synthetic macromolecules,[2] to chemically synthesize siliceous structures under mild conditions. Most of the bioinspired, catalytic molecules employed so far possess amine groups, which play an important role in the condensation of silicic acid and its derivatives and/or the aggregation of fundamental silica nuclei. For example, silica thin films were fabricated by template-assisted silicification on the surfaces coated with polyelectrolyte multilayers of poly(diallyldimethylammonium chloride) or poly(ethyleneimine) and poly(sodium 4-styrenesulfonate) by layer-by-layer assembly[3,4] or grafted with poly(2-(dimethylamino)ethyl methacrylate) by surface-initiated polymerization.[5,6] The scope of substrates for silica thin films/shells was expanded further to individual living cells owed primarily to the mild, cytocompatible conditions of bioinspired silicification, and the resulting silica nanoshells modulated cellular activities and conferred the protection ability against physical and chemical stresses.[7-9] Nevertheless, the anthropogenic approaches to the formation of silica have not yet reached the high degree of complexity and hierarchical intricacy found in nature.[10]

DNA is a nanometric building block, the self-assembly process of which is highly controllable, leading to the chemical generation of stable and intricate nanostructures under biologically relevant conditions.[11-13] In addition to the two- and three-dimensional DNA nanostructures in structural DNA nanotechnology, DNA and its self-assembled structures also have been used as a template for the fabrication of inorganic metal structures. For example, we reported the synthesis of a hollow silver microcapsule based on the interactions between λ-DNA and Ag(I).[14] In contrast to the DNA-templated formation of metallic structures, DNA has been used little for generation of silica structures,[15-17] albeit DNA could act as a catalytic template for *in vitro* silicification, and its self-assembled structures would lead to the generation of intriguing silica structures. Che *et al.* has recently reported the synthesis of a DNA-silica complex with the two-dimensional *p*4*mm* DNA structure,[15,16] but the catalytic activities of a specific nucleotide for silicification remained unknown. In this work, we tested the catalytic activity of each base (A, T, G, or C) for silicification as a first step towards DNA-catalyzed and -templated formation of three-dimensional silica structures under physiologically mild conditions. Specifically, single-stranded pentadecadeoxynucleotides (dN15: dA15, dT15, dG15, and dC15) were subjected to the *in vitro* silicification reaction.

Figure 1 shows the experimental procedure employed in this study. We used the 1:1 mixture of *N*-trimethoxysilylpropyl-*N*,*N*,*N*-trimethylammonium chloride (TMAPS) and tetraethyl orthosilicate (TEOS) as silica precursors, because TMAPS would diminish the electrostatic repulsion between the phosphate backbone of the dN15 and orthosilicic acid derivatives. The quaternary ammonium cation in TMAPS could not only reduce the strong negative charge of DNA, but also act as the potential seed moiety that interacts intimately with the oligomers of silicic acid. The concentration of dN15 was fixed to be 0.1 mM in water, and to this aqueous solution were added the two silicate precursors (TMAPS: 25 mM; TEOS: 25 mM). After overnight incubation, the solution containing dG15 turned opaque, and white precipitates were obtained by centrifugation. In contrast, the other solutions containing dA15, dT15, or dC15 yielded

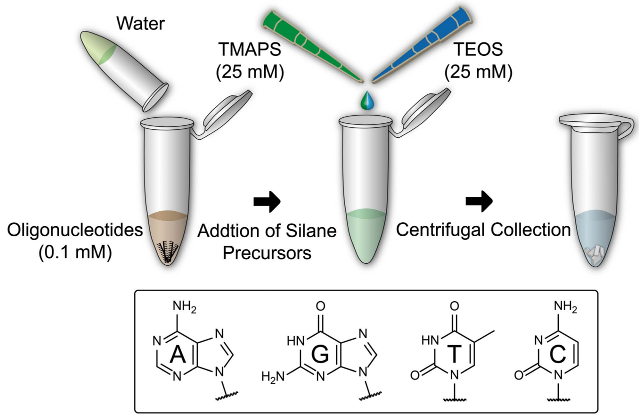

Figure 1. Experimental procedure for the formation of DNA-silica complexes.

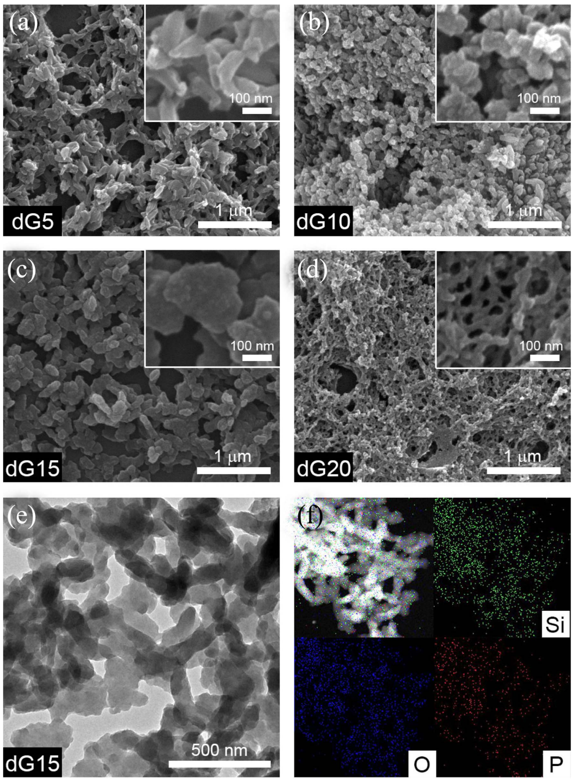

Figure 2. FE-SEM micrographs of DNA-silica complexes yielded from dGONs with various lengths: (a) pentadeoxynucleotide (dG5), (b) decadeoxynucleotide (dG10), (c) pentadecadeoxynucleotide (dG15), and (d) icosadeoxynucleotide (dG20). (e) TEM micrograph and (f) STEM-EDS elemental mapping diagram of dG15-silica complexes.

only negligible amount of precipitates. The screening result indicated that dG15 was the only molecule that catalyzed the silicification among the four oligodeoxynucleotides. After confirming the catalytic activity of deoxyguanosine oligonucleotide (dGON), we varied the length of dGONs to 5, 10, 15, and 20 to investigate the effects of the length on silica morphology. All of four dGONs (dG5, dG10, dG15, and dG20) yielded silica precipitates with TMAPS and TEOS, and the resulting silica structures were examined by field-emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM). In the FE-SEM micrographs, we observed silica nuggets in the case of dG5 and dG15, while silica aggregates or networks were observed in the case of dG10 and dG20 on the nanometer scale (Figure 2(a)-(d)). These results indicated that the length of dGONs had a deterministic effect on the silica structures formed. Further characterization with TEM gave the detailed information on the interior structures and the atomic distributions of the DNA-silica complexes: the dG15-silica structures had the closely-packed structures (Figure 2(e)). The elemental mapping of silicon, oxygen, and phosphine for the dG15-silica structures, obtained by dark-field scanning TEM-energy dispersive X-ray spectroscopy (STEM-EDS), confirmed that dG15 was occluded in the silica structures (Figure 2(f)).

In summary, we reported the catalytic ability of guanine (G) for the bioinspired silicification of *N*-trimethoxysilylpropyl-*N*,*N*,*N*-trimethylammonium chloride (TMAPS) and tetraethyl orthosilicate (TEOS) in the aqueous solution, among four bases (A, G, T, and C). The resulting DNA-silica structures were dictated by the length of dGONs, which implies that DNA-based nanomaterials could be combined with bioinspired, DNA-catalyzed silicification to generate the structures of DNA-silica hybrids in a controllable fashion, which, we believe, would widen the scope of silica-based applications in nanobiotechnology and biomedical sciences.

Acknowledgments. This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2011-0011950).

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