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DNA-Directed Assembly of Polyanilines: Modified Cytosine Nucleotides Transfer Sequence Programmability to a Conjoined Polymer

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An enormous challenge in the creation of functional nanoscale materials is the development of general techniques for the construction of designed molecular assemblies having nonrecurring, irregular structures. It has been recognized that the self-recognition and self-assembly properties of DNA offer unique advantages for the preparation of such materials.[1] In particular, synthetic methods based on the sequence programmability of DNA could enable production of the complex, nonperiodic structures[2] that are required for molecular electronic applications.[3] However, it is now appreciated that DNA itself may be unsuitable for electronic devices,[4,5] and innovative approaches are being developed to create suitably modified DNA-based materials.[6]

Polyanilines (PANI) are a novel class of conducting polymers that have attracted enormous interest because of their relative ease of synthesis and their unique electrical and optical properties.[7,8] Especially relevant to this work is the important discovery that aniline can be polymerized enzymatically under mild conditions using DNA as a template.[2,9] However, this method yields a homopolymer that cannot take advantage of the sequence information intrinsic to DNA. We report here the synthesis of a PANI oligomer having the properties of a conducting polymer by the enzyme-initiated reaction of oriented aniline monomers covalently linked to nucleobases of duplex DNA. These findings provide a method to apply the sequence programmability of DNA to the preparation of unique nanoscale materials with tailored electronic properties.

We prepared[10] the DNA oligomers shown in Figure 1 that contain cytosines modified by replacement of the 4-amino group by an *N*-(2-aminoethyl)aniline (abbreviated as nucleobase X).[11,12] In B-form duplex DNA, one proton of the cytosine 4-amino group participates in hydrogen bonding with its paired guanine; the other extends into the major groove. Molecular modeling indicates that the aniline groups of the modified duplexes will similarly reside in the major groove.

DNA(1) is a normal, unmodified 22-mer duplex that was prepared for comparison with modified structures DNA(2) through DNA(6). Each of these oligomers contains an embedded $(G)_6$ segment with a variable number of complementary C or X nucleobases. For example, in DNA(6) all of the complementary cytosines in the $(G)_6$ segment have been replaced by aniline-bearing nucleotide X. The composition of each DNA oligomer was confirmed by ESI mass spectrometry, which revealed a parent ion of appropriate mass.[10] The incorporation of nucleotide X results in the destabilization of the duplexes as revealed by decreases in their melting temperatures (T_m): DNA(6) melts cooperatively at 39 °C, which is 18 °C below that of DNA(1), and the other modified duplexes have intermediate T_m values. The circular dichroism (CD) spectrum of DNA(6) reveals an overall B-form structure with the characteristic peaks shifted to 285 and 225 nm and a valley at 240 nm.[13] However, it is clear from inspection of this spectrum[10] that incorporation of six *N*-(2-aminoethyl)aniline groups on contiguous cytosines causes significant structural perturbation of the DNA.

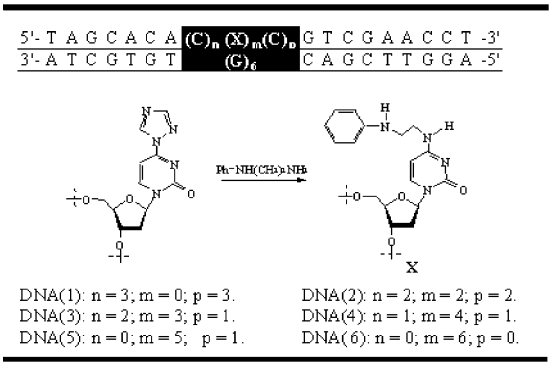

Figure 1. Sructures of aniline-linked DNA oligomers used in this work.

These DNA duplexes were treated with H_2O_2 and horseradish peroxidase (HRP) under conditions previously reported to cause aniline polymerization.[2,9,14] The reactions were monitored by absorption spectroscopy, which provides a reliable indication of PANI formation.[15] Not surprisingly, addition of H_2O_2 and HRP to DNA(1) causes no significant change to its absorption spectrum. Similarly, no new bands appear when DNA(2) or DNA(3) are treated with H_2O_2 and HRP. However, absorptions characteristic of PANI and conducting oligoanilines[16−19] result from the reaction of duplexes having four, five, or six contiguous *N*-(2-aminoethyl)-aniline groups aligned in the major groove, see Figure 2. The products of these reactions exhibit HOMO−LUMO (H−L, $\pi-\pi^*$) absorption bands at ca. 420 nm and, most significantly, characteristic PANI bands with maxima at ca. 730 nm (0 → 0, ca. 850 nm).[20]

Melting temperature and CD experiments reveal that these PANI-linked oligomers maintain a duplex DNA structure. After polymerization, DNA(6) has a broad but cooperative and reversible T_m at 32 °C. A transition at the same temperature is observed in the CD spectrum of the absorption band at 730 nm, which confirms the duplex structure. The reaction of single stranded DNA containing an $(X)_6$ segment with H_2O_2 and HRP does yield oligoanilines, but the appearance of an additional absorption band at 550 nm in this spectrum[10] signals branching and loss of conjugation.[21] Moreover, the oligoaniline formed from reaction of the single strand does not show cooperative melting behavior and fails to form a duplex with its complementary strand, which confirms that it is structurally distinct from the product formed from duplex DNA-(6). Interestingly, a related oligomer containing a $(CX)_4/G_8$ segment gives weak absorption bands characteristic of PANI when treated

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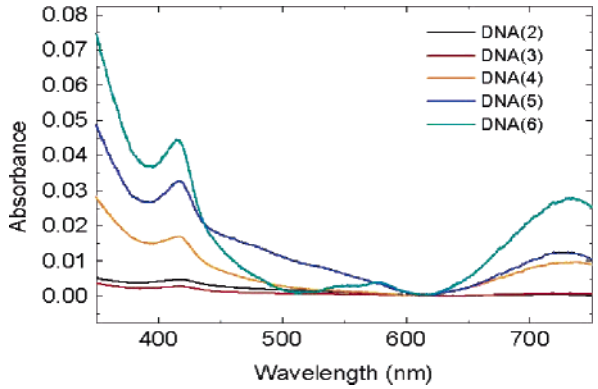

Figure 2. Absorption spectra of PANI oligomers formed by treatment of DNA(2) through DNA(6) with H_2O_2 and HRP. Note that DNA(5), the blue curve, has an unusual feature centered at ca. 500 nm, which we see in other oligoanilines containing an odd number of monomers. This may reflect the fact that a "closed" polymer requires an even number of monomers.

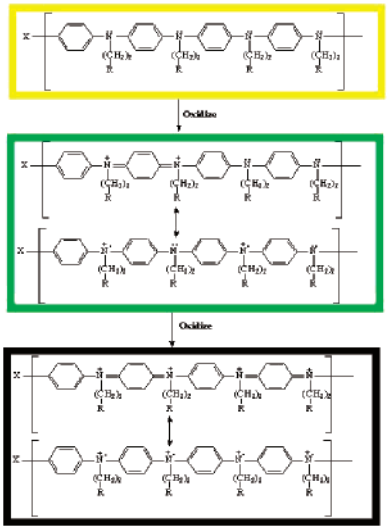

Figure 3. Three oxidation states of poly(*N*-alkyl)anilines. In these cases, R corresponds to the cytosine amino group of the conjoined DNA. The "yellow" form represents the leuco oxidation state, the "green" form the emeraldine oxidation state, and the "black" form the pernigraniline oxidation state of polyaniline.

with H_2O_2 and HRP, which suggests that oligomerization is not restricted to contiguous arrays of anilines.

Polyanilines and poly(*N*-alkyl anilines) exist in oxidation states traditionally referred to as leuco, emeraldine, and pernigraniline that have characteristic spectroscopic and physical properties,[15,20] see Figure 3. The absorption spectrum of the PANI oligomer formed from DNA(6) indicates that it corresponds to the conducting "pseudo-proton doped" emeraldine form.[16] Polymerization of six *N*-(2-aminoethyl)aniline groups requires significant structural distortion of the conjoined DNA duplex. Computational analysis gives a structure, see Figure 4, in which the nucleobase positions are distorted and the Watson−Crick hydrogen bonds of the duplex are broken in the region of the oligoaniline. However, the duplex is intact in the flanking regions and largely undistorted, which may provide scaffolds for connecting "leads" necessary for molecular electronic applications of these unique materials.

The findings reported here provide a method to exploit the self-recognition, self-assembly, and sequence programmability of DNA in the formation of conducting polymers. It is clear that by utilizing variously modified nucleotides this method may be used to generate materials having nonrecurring, irregular structures. Experiments are currently underway to expand this discovery.

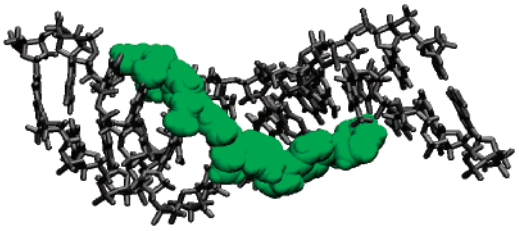

Figure 4. A structural model showing six aniline groups bonded head-to-tail conjoined to a DNA oligomer. The model for building the PANI oligomer was obtained by finding torsion angels for the bonds connecting the aniline monomers such that the resulting helical structure has rise and twist compatible with DNA. The polyaniline was joined to the DNA, and the energy of the structure was minimized using JUMNA.[22]

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Supporting Information Available: Preparation of aniline-modified DNA oligomers, mass spectrometric characterization of modified sequences, melting temperature data for modified duplexes, CD spectra, UV spectra of duplexes possessing consecutive and alternating aniline modifications. This material is available free of charge via the Internet at http://pubs.acs.org.

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